桑野研究室

様々な土の顔ー 支える、滑る・流れる、沈む・落ちる・崩れる ー



人間・社会系部門

地盤機能保全工学

工学系研究科 社会基盤学専攻

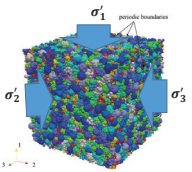
https://geo.iis.u-tokyo.ac.jp/

様々な地盤挙動のメカニズムの解明

支える地盤

地盤＝土は、構造物を支える重要な役割を担っており、砂や粘土などの土粒子とその間隙にある水で構成されます。土の力学挙動は、粒子のサイズ、形状、かみ合わせなどの構造、含水・排水条件、拘束圧など、様々な因子の影響を受けます。

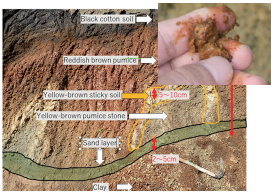
土要素内の応力伝達メカニズムや地盤の力学挙動を、実験や数値解析で探っています。



DEM解析による応力伝達における粒子形態の影響の検討

滑る・流れる地盤

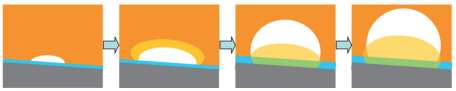
普段は安定している地盤も、地震や豪雨などで刺激を受けると豹変し、土石流や地すべり、液状化など、甚大な地盤災害を引き起こすことがあります。



北海道胆振東部地震（2018年9月)に起因する滑り・流動が起きた超高間隙構造土（内部に水を含む多孔質の火山性軽石）

沈む・落ちる・崩れる地盤

地下水の流れにより地盤が削られる内部侵食

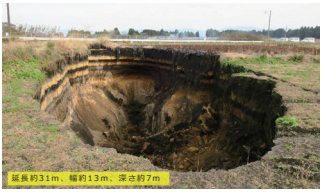


地下の水みちに沿って地盤の一部が侵食され空洞の芽ができ

侵食が進んで空洞・ゆるみが成長

空洞天井部が崩落

それらを繰り返して空洞部が拡大しながら上方に移動



都城・宮崎県の畑で起きた、豪雨によるシラス層の内部侵食による陥没（2016年9月）

自立しない土層の下に抜け道があることによる土の亡失



流出孔から地下水位以下の土砂が水と共に流れ出し空洞が生成・拡大

空洞天井部が地表面近くまで達し、空洞上部が不安定

空洞上部の土が崩落し陥没



室内模型実験による、土砂流出、空洞生成・拡大、陥没メカニズムの再現

KUWANO LAB.



Various soil behaviour- Supporting, Sliding/Flowing, Sinking/Falling/Collapsing -

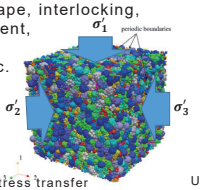
Department of Human and Social Systems

Geotechnical and Geo-environmental Engineering
Department of Civil Engineering, Graduate School of Engineering https://geo.iis.u-tokyo.ac.jp/

Mechanisms of various ground behaviours

Supporting

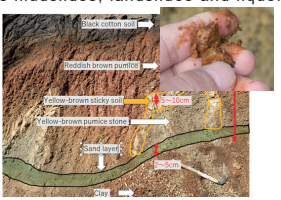
Ground = Soil plays an important role in supporting structures. It consists of soil particles such as sand/clay and water in the void spaces. The mechanical behaviour of soil is influenced by a variety of factors, including particle size, shape, interlocking, soil structures, water content, drainage conditions, confining pressure and etc. Mechanisms of stress transfer in soil are explored by experiments and numerical analysis.



DEM analysis of stress transfer in Investigation of the effect of particle morphology

Sliding/Flowing

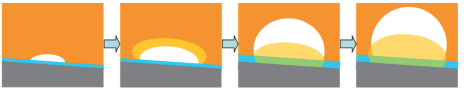
Ground that is normally stable can change drastically when stimulated by earthquakes or heavy rainfall, causing severe ground disasters such as mudslides, landslides and liquefaction.



Ultra-high pore structure soil (porous volcanic pumice with water inside) that underwent slip and flow resulting from the Hokkaido Iburi Tobu earthquake (2018)

Sinking/Falling/Collapsing

Internal erosion due to the flow of ground water



Formation of small cavity due to erosion at some point

Erosion progressed. Cavity and surrounding loosened area expand

Failure of cavity ceiling

By repetition of erosion and failure of cavity ceiling, a cavity moves upward



Sinkhole caused by internal erosion in volcanic "Shirasu" layer in Miyakonojo, Miyazaki (Sept. 2016)

Leakage of unbounded soil through a hole



Soil below the ground water level flows with water through the hole. A cavity can expand.

Ceiling of the cavity reaches near the ground surface.

Collapse of the soil above the cavity



Simulation of road cave-in accident by laboratory model test

Apparatus for laboratory soil testing
Institute of Industrial Science, the University of Tokyo

Element Test Equipment
要素試験装置

Triaxial Apparatus (IIS Style)





微小ひずみ($\sim 10^{-3}$%)での繰り返し載荷が精密に実施可能
It can precisely conduct cyclic loading with small-strain ($\sim 10^{-3}$%)

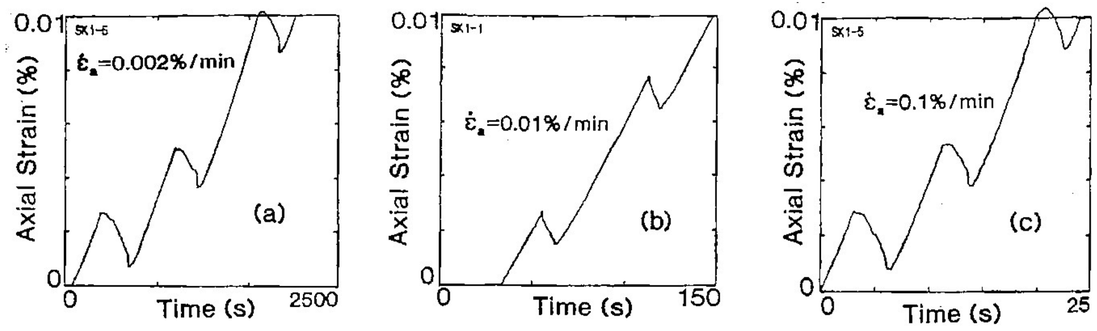


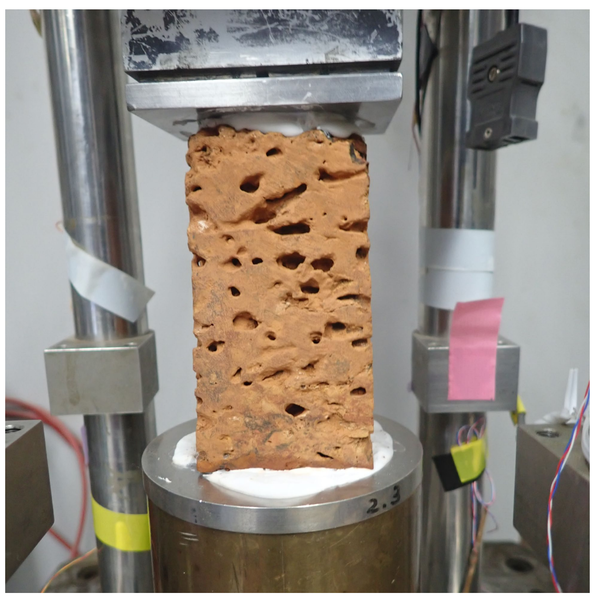
図5　異なるひずみ速度に対する載荷初期の軸ひずみ～時間関係　Sato et al., 1991

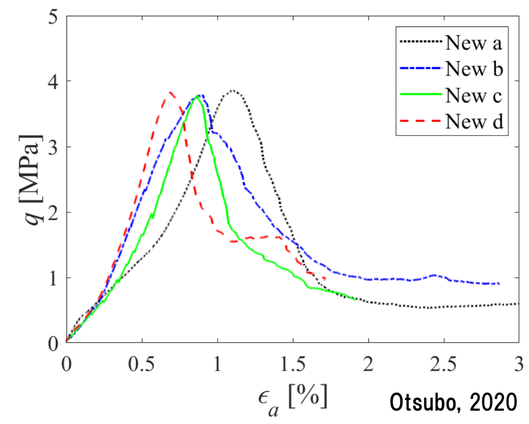
Hydraulic Triaxial Apparatus



Maximum axial load: 100kN

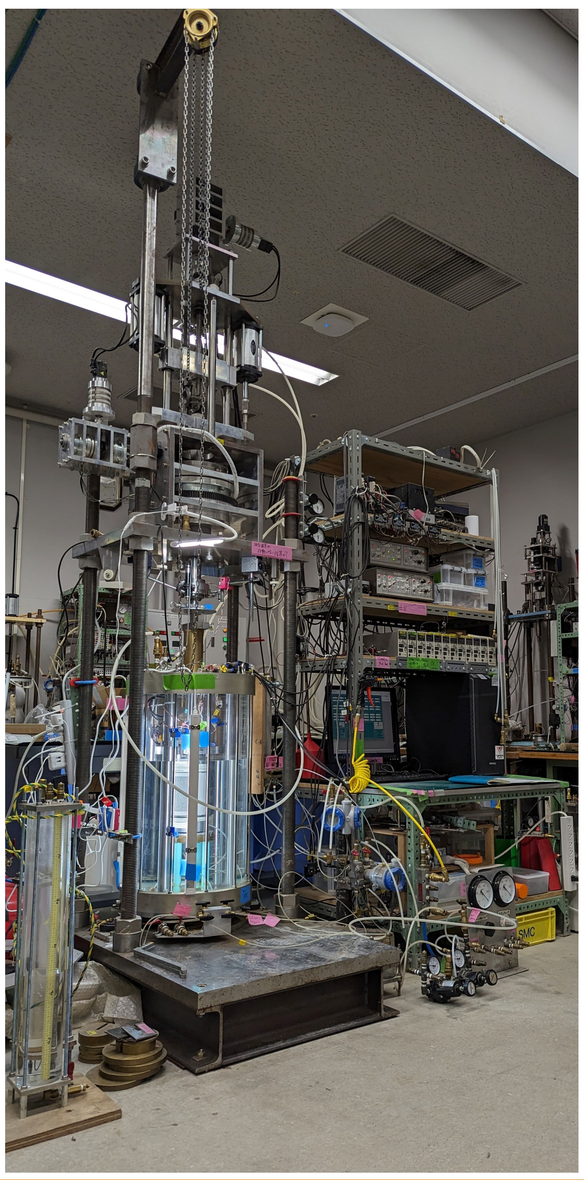
ラテライトの一軸圧縮試験
Uniaxial compression test of laterite

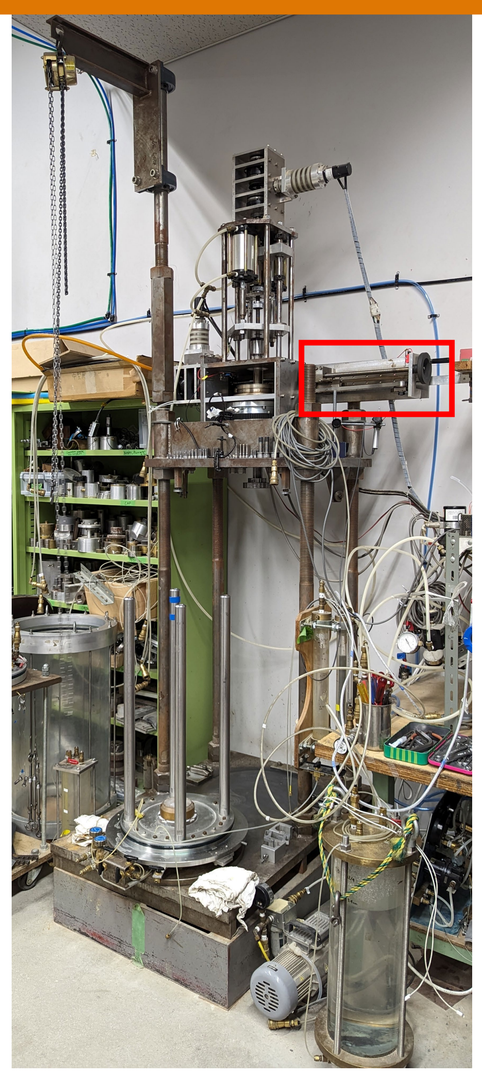




Otsubo, 2020

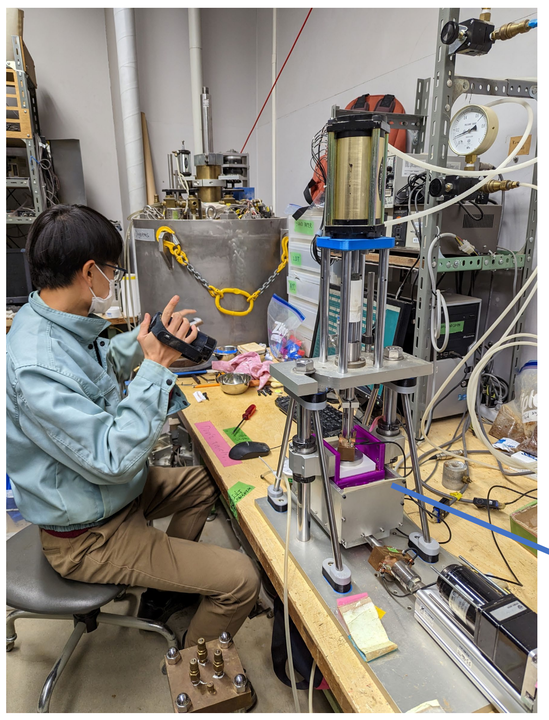
Hollow Cylindrical Torsional Shear Apparatus





It can apply large shear strain (more than 100%).

Direct Shear Test Apparatus

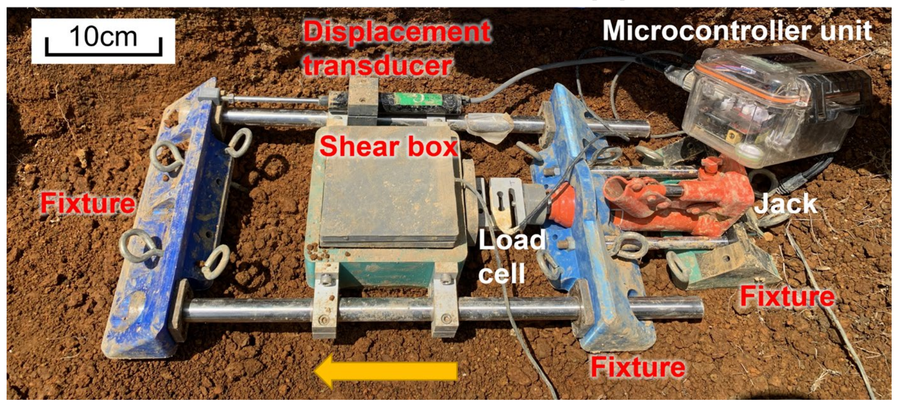




せん断箱をそのまま用いた不攪乱サンプリング
Undisturbed sampling with a shear box

供試体全体を水浸させ、高含水状態を再現可能
Specimen can be immersed in water to reproduce high water content condition

In-situ Direct Shear Test Apparatus



For further information, contact below.
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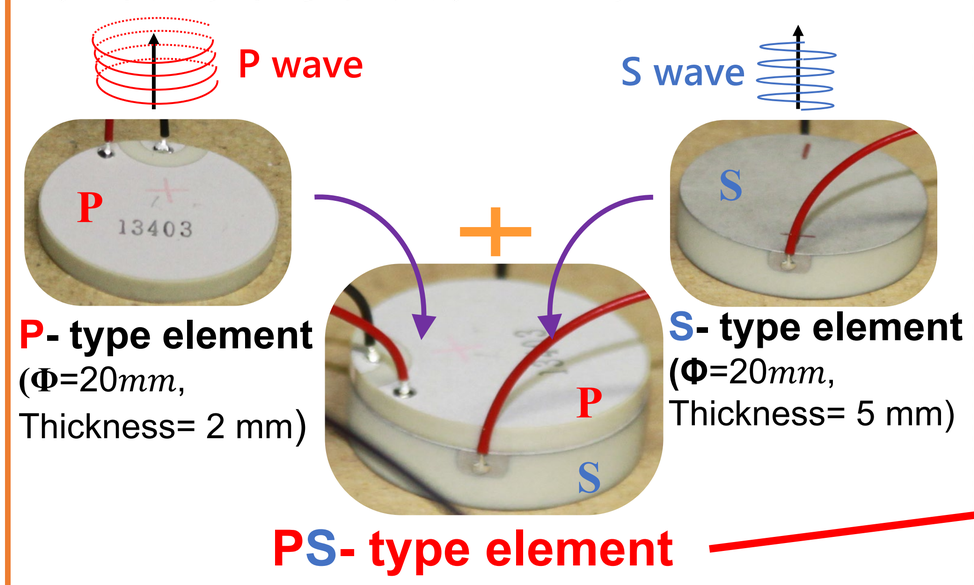
桑野研究室 (2023)
東京大学 生産技術研究所 Bw-304
電話: 03-5452-6843
E-mail: kuwano@iis.u-tokyo.ac.jp

Apparatus for laboratory soil testing
Institute of Industrial Science, the University of Tokyo

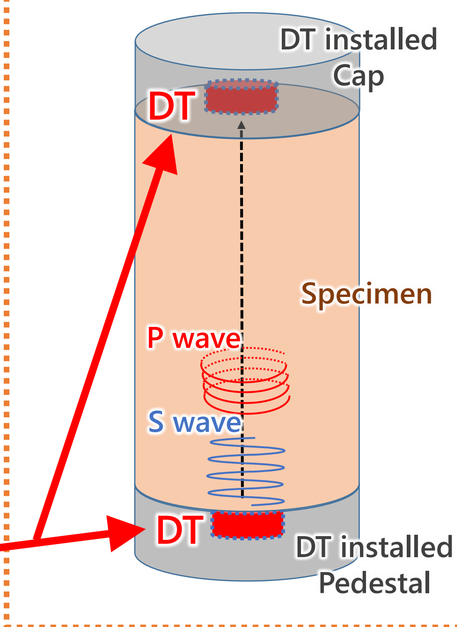
Elastic Wave Measurement, Suffusion test
弾性波計測・内部侵食試験

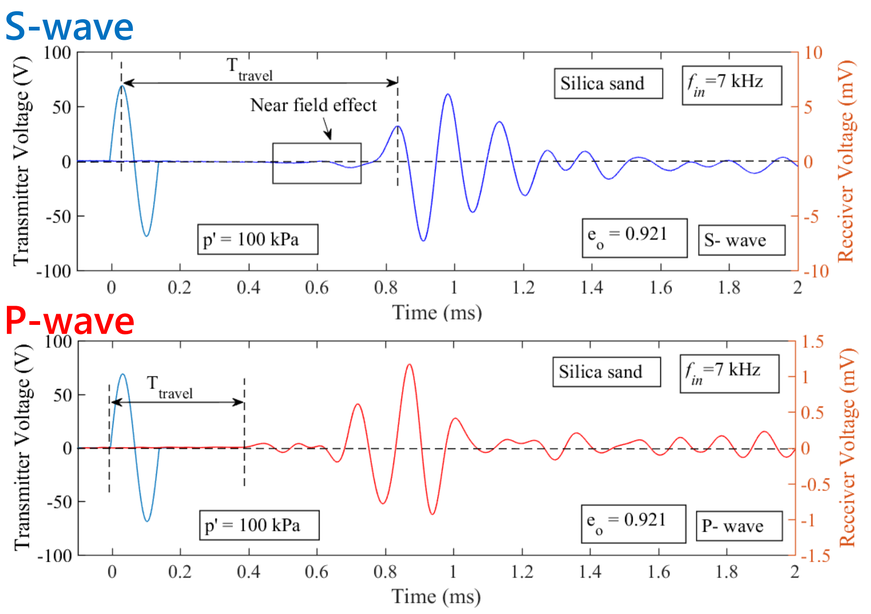
Elastic Wave Measurement using Disk Transducer
ディスクトランスデューサーによる弾性波の計測

Disk Transducer (DT)
ディスクトランスデューサー



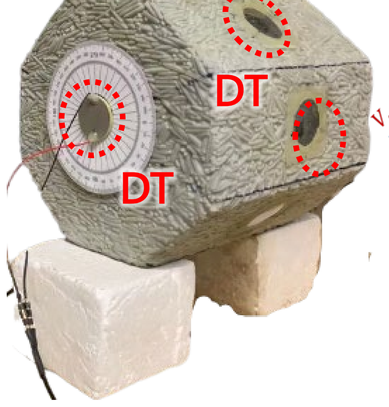
Installation in triaxial apparatus 三軸供試体への導入





Effects of propagation and vibration direction of S-wave S波の伝播・振動方向の影響の評価

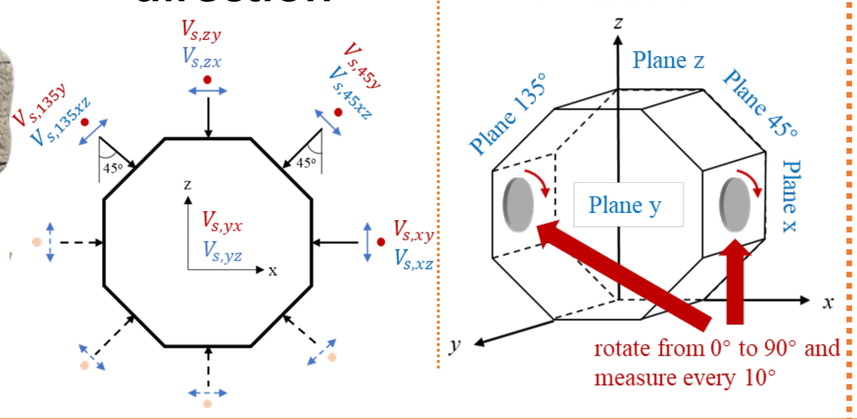
Eight prismatic membrane cell



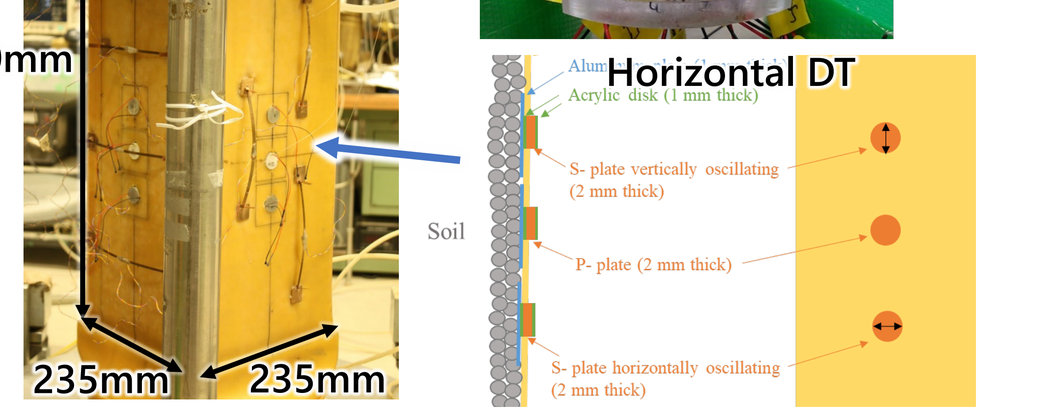
Variation of S-wave

propagation direction

oscillation direction



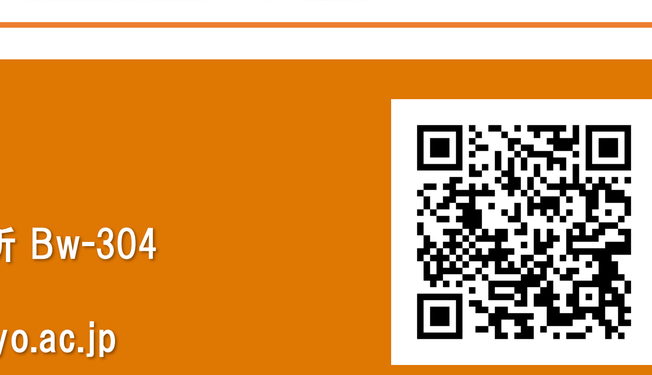
Installation in large triaxial apparatus 大型三軸供試体への導入



Internal Erosion Tests
内部侵食試験

Internal Erosion
内部侵食とは

Triaxial apparatus for Internal Erosion
細粒分流出を許した三軸試験機



Pedestal and cap with holes (allowing fine particle removal) and DT (monitoring of vertical S-wave during erosion)

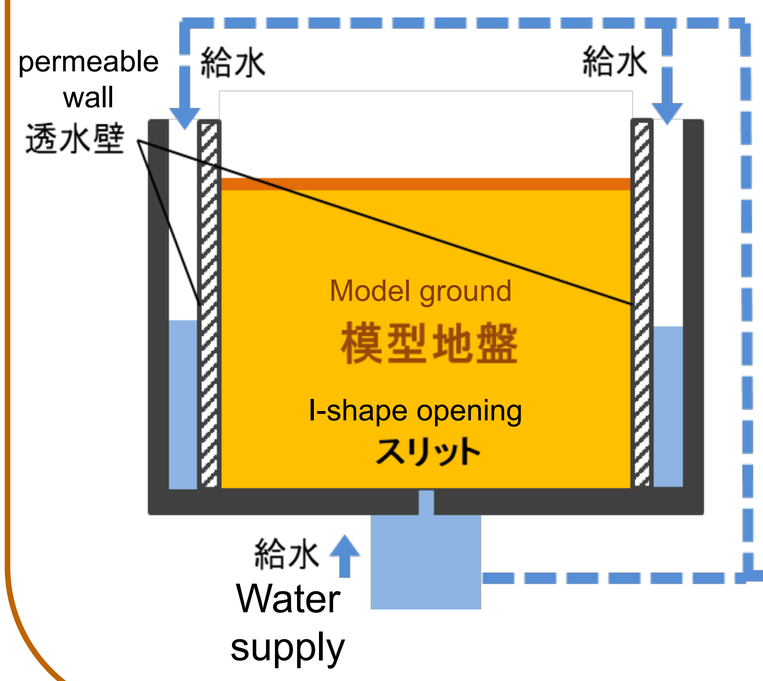
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電話: 03-5452-6843
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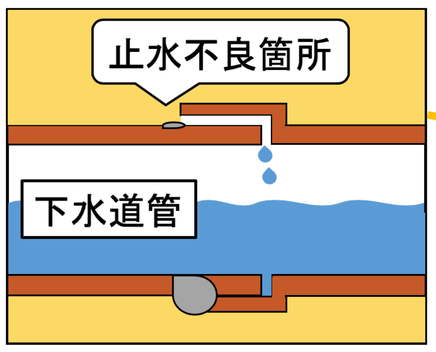
Apparatus for laboratory soil testing
Institute of Industrial Science, the University of Tokyo

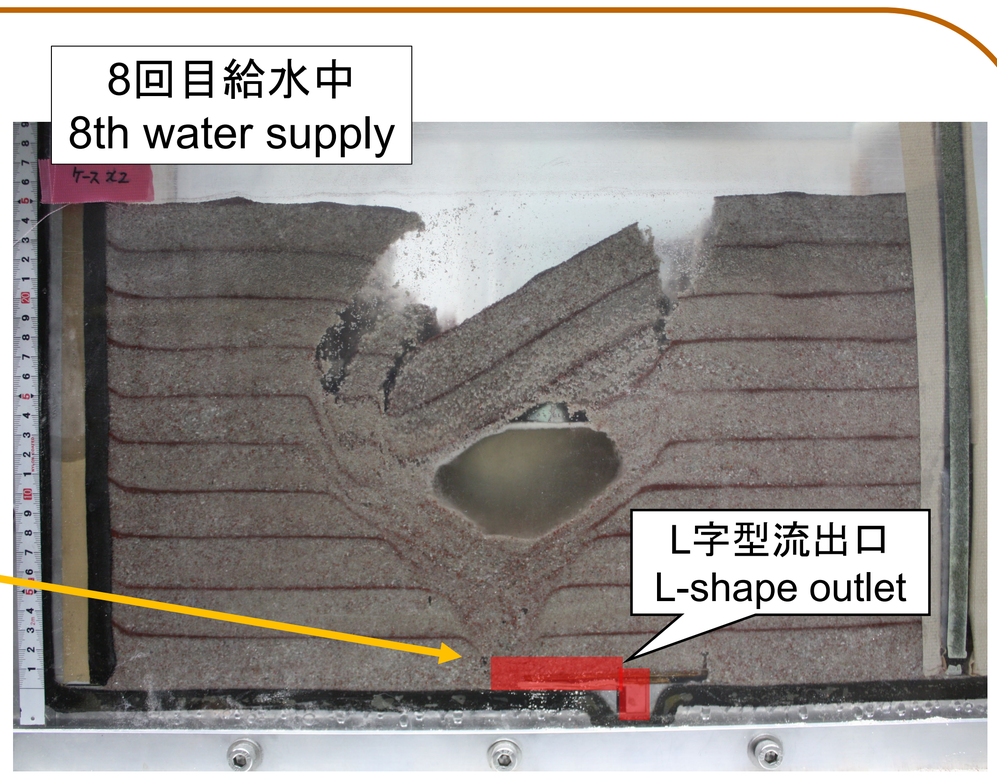
Model test apparatus
模型実験

Cavity test soil tank　空洞実験土槽



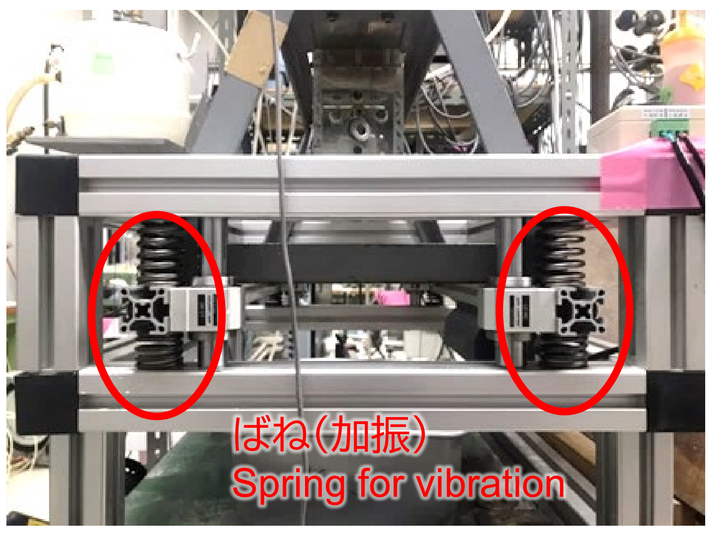
埋設管接合部の
止水不良個所を模擬
Simulating poor water sealing at buried pipe joints





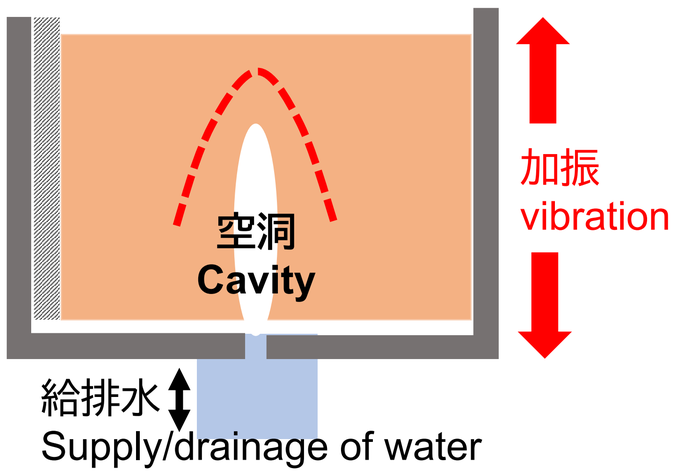
空洞崩壊を確認
Surface soil collapsed.

Cavity test soil tank with vibration　加振型空洞実験土槽



frequency ≒ 5 Hz
acceleration = Max 1000gal

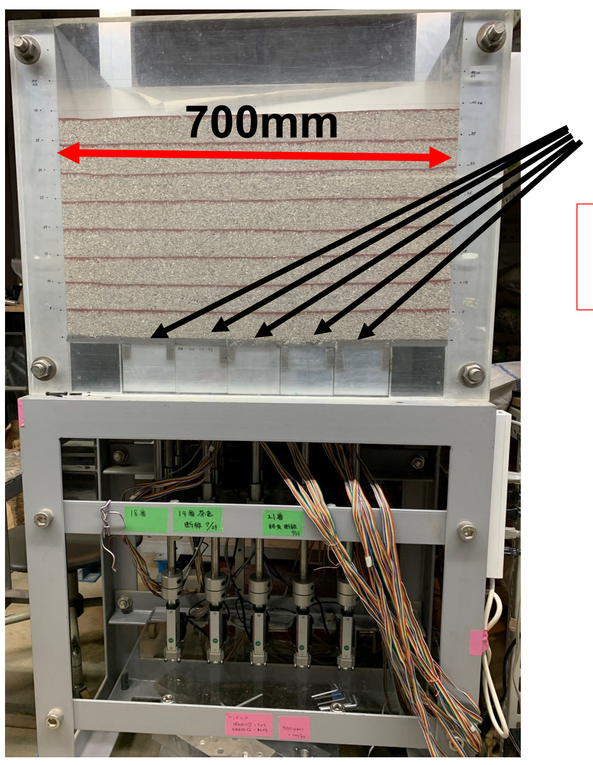
ばねによる鉛直加振
➢ 地震動による地盤陥没を研究
Vertical acceleration by springs
➢ Behaviour of subsurface cavities due to seismic motion





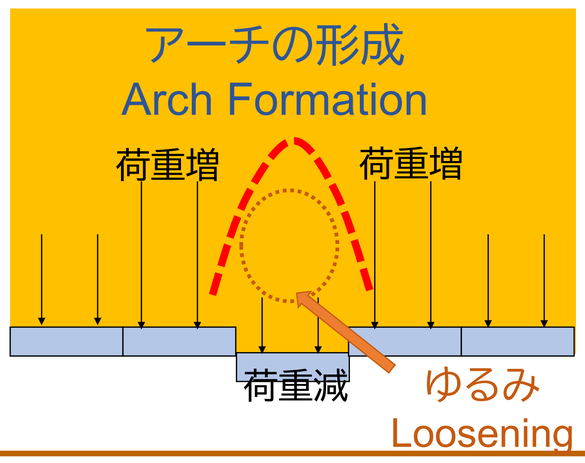
空洞崩壊を確認
Surface soil collapsed

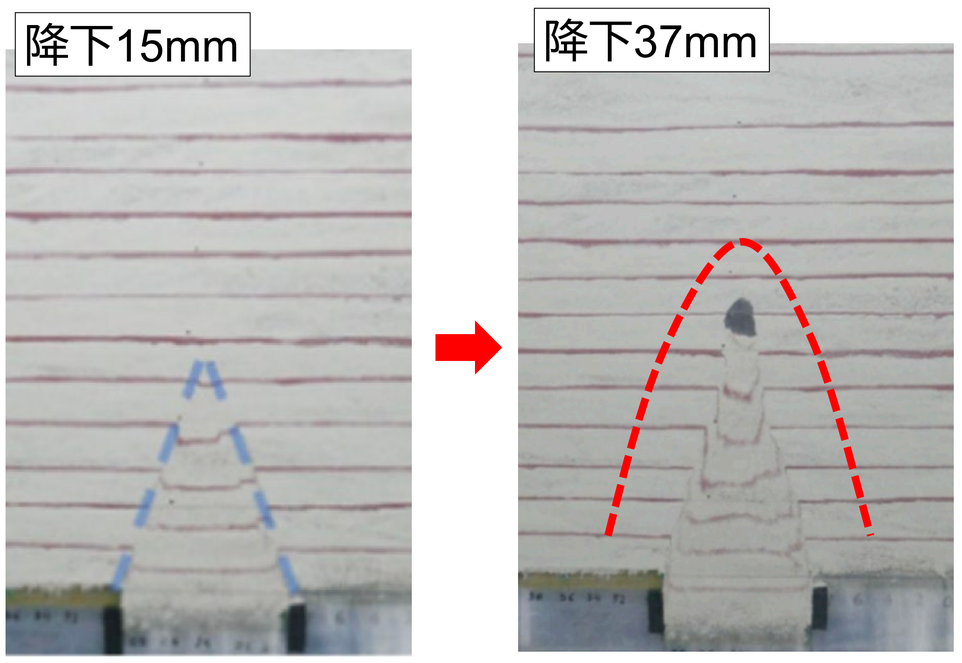
Trapdoor test apparatus　落とし戸試験装置



ロードセルを備えた5つの移動床
5 moving blocks with load cells

地盤材料に生じるアーチング
Studying Arching in Geomaterials





中央ブロックの降下に伴い空洞が生成
Cavities are generated as the center block descends

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ELASTIC WAVE MEASUREMENT
VARIOUS TYPES OF TRANSDUCERS IN IIS

室内土供試体の弾性波速度測定

The elastic wave measurement is becoming popular to obtain small strain stiffness of soil. In IIS, various types of transducers are currently used, including bender element (BE), trigger-accelerometer (TA), trigger-bimorph element (TB) and disk transducer (DT). The waveform of each transducer on Toyoura sand specimen is presented.

地盤材料の微小ひずみ剛性は、供試体内の弾性波の伝播速度を測定することにより求めることができます。様々なセンサーを用いて砂供試体内のP波およびS波の伝播速度を測定して比較しています。

Various types of Transducers

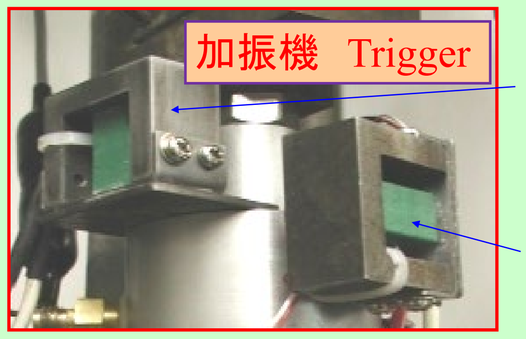
波の送受信に使われる圧電素子はメタルケースの中に収められ、さらに三軸試験装置のトップとペデスタル内に装着する。
Piezo-ceramic elements are used for both transmitter and receiver. Coated elements are encapsulated into metal housing and then installed into top cap and pedestal.

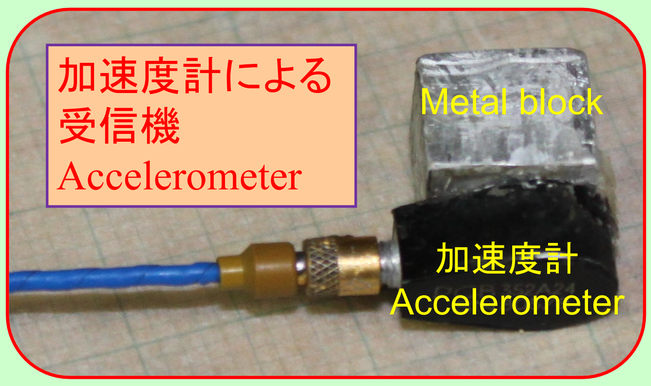


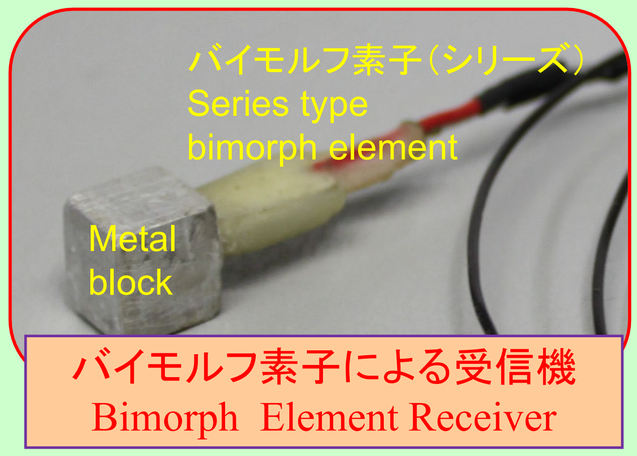


Trigger Accelerometer method
Trigger Bimorph element method

トップに装着した加振機によって送信し、供試体側面2箇所につけた受信機で波を捉える。
The signal is actuated by triggers attached to the top. A pair of sensors put on lateral surface of the specimen receive the signal.

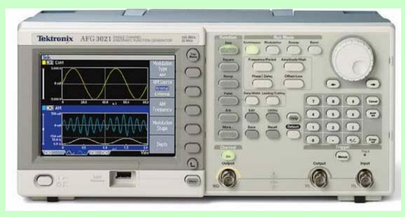






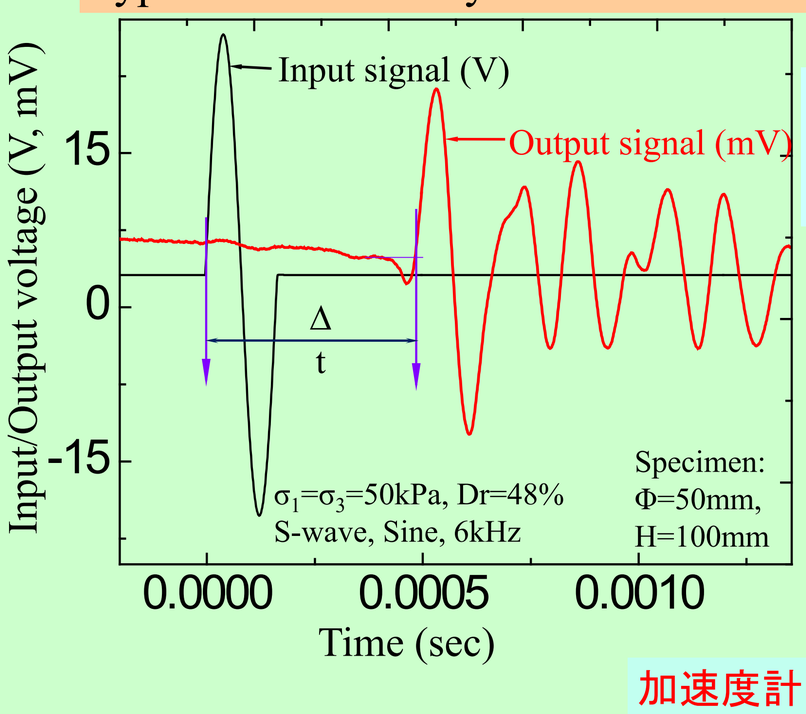
TEST ON TOYOURA SAND

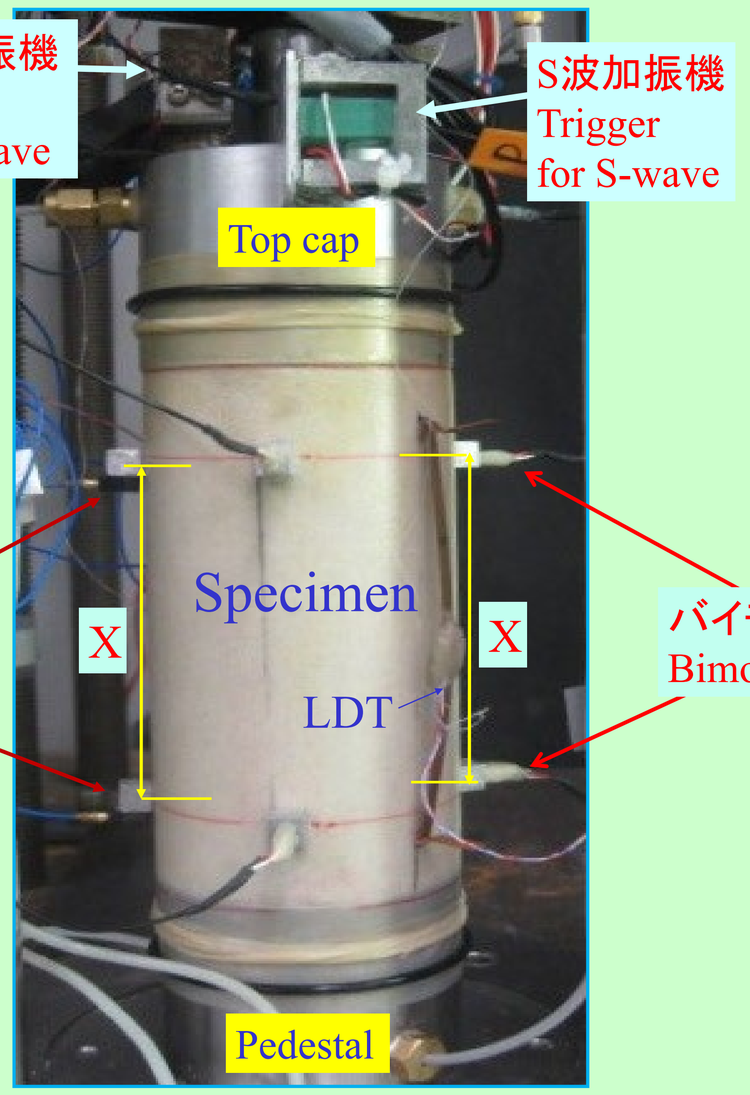
Function Generator



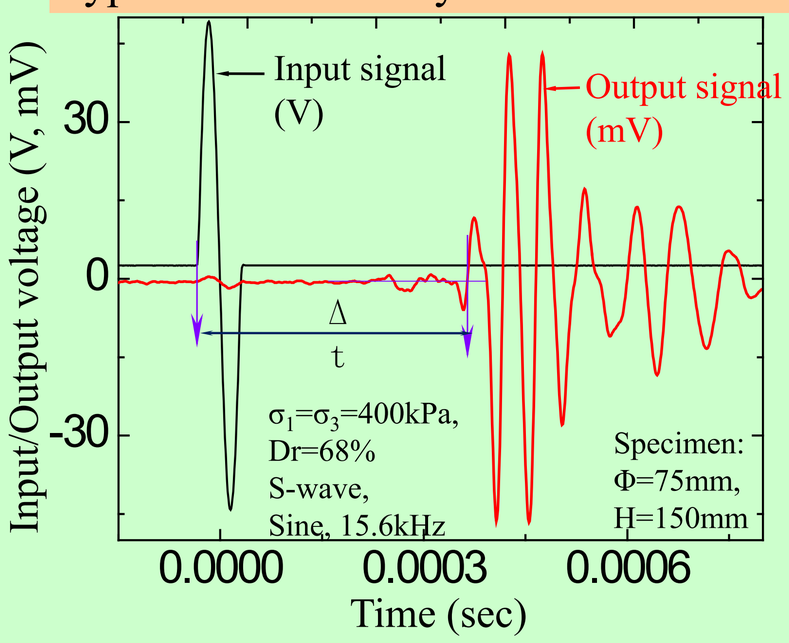
送信波
Input wave

Typical waveform by Bender Element

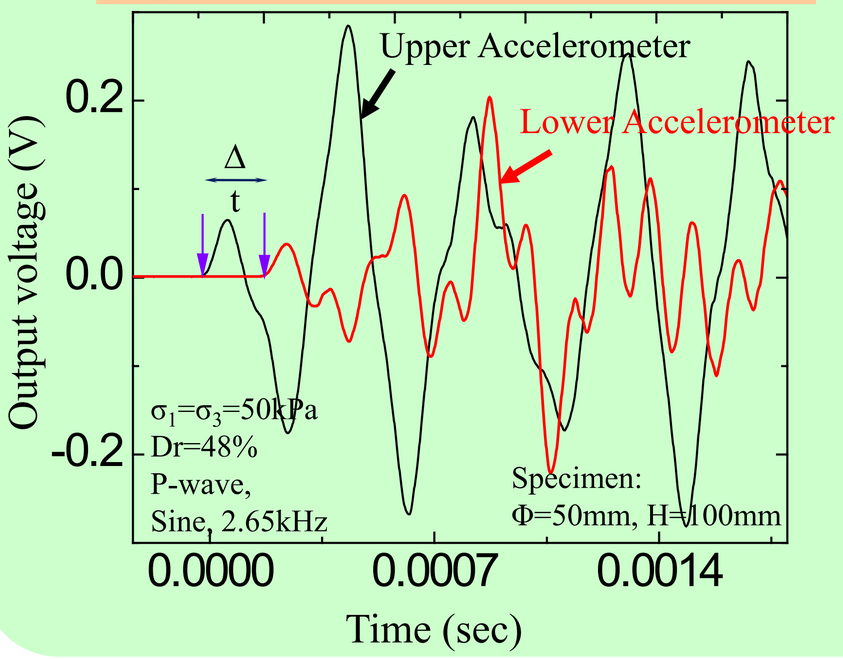




Typical waveform by Disk Transducer



Typical waveform by Accelerometer

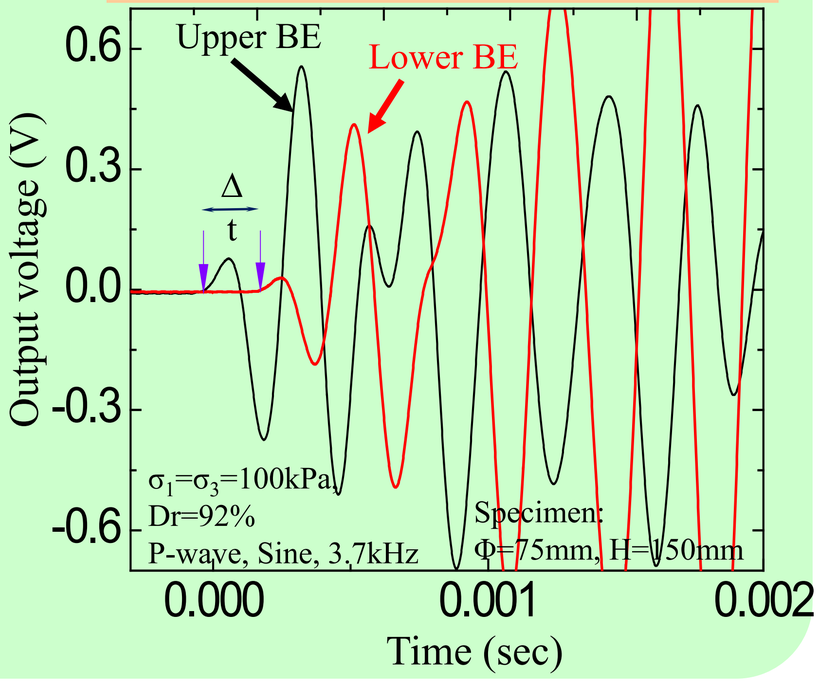


Oscilloscope



送信波と受信波の取得
Monitoring of input and output signal

Typical waveform by BE Receiver



本研究に関する担当研究室は桑野研究室です.
部屋は東京大学生産技術研究所B棟3階のBw-304

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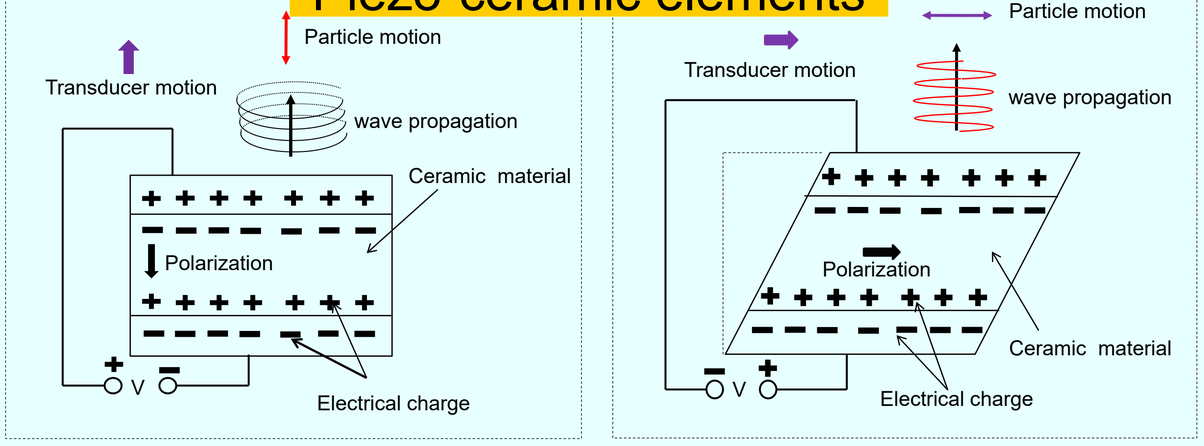
DISK TRANSDUCER

SENSORS FOR P & S WAVE MEASUREMENT

室内土供試体のP波・S波測定用センサの開発

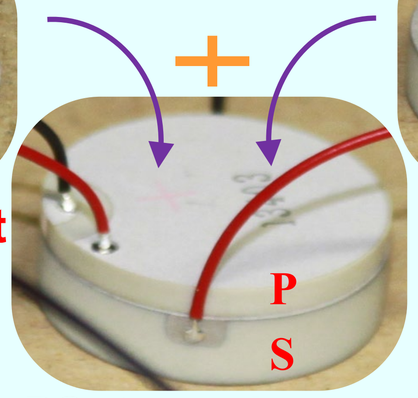
A flat disk shaped transducer was developed to measure elastic waves propagating in a laboratory soil specimen. It is capable of measuring both compressional and shear (P and S) waves in an identical specimen. The typical wave forms obtained on granular materials by this method are presented.

Piezo-ceramic elements

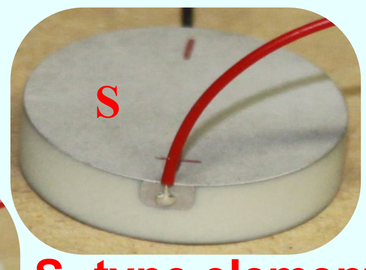




P- type element
(Φ=20*mm*,
Thickness= 2 mm)



PS- type element

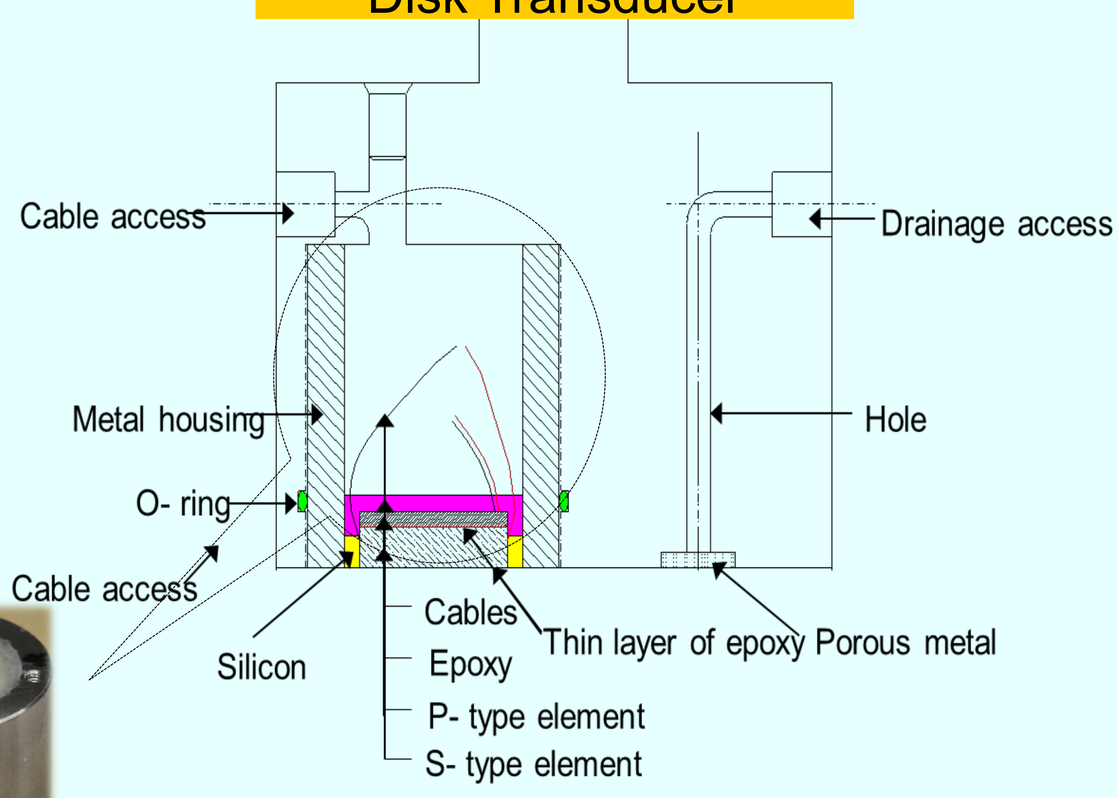


S- type element
(Φ=20*mm*,
Thickness= 5 mm)



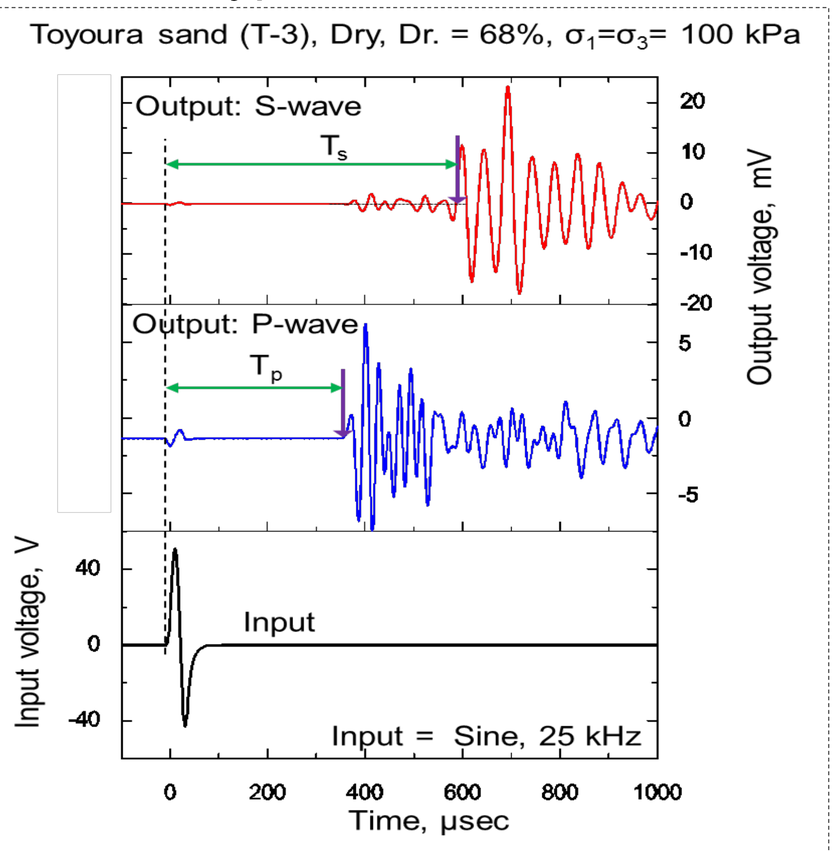
Disk Transducer

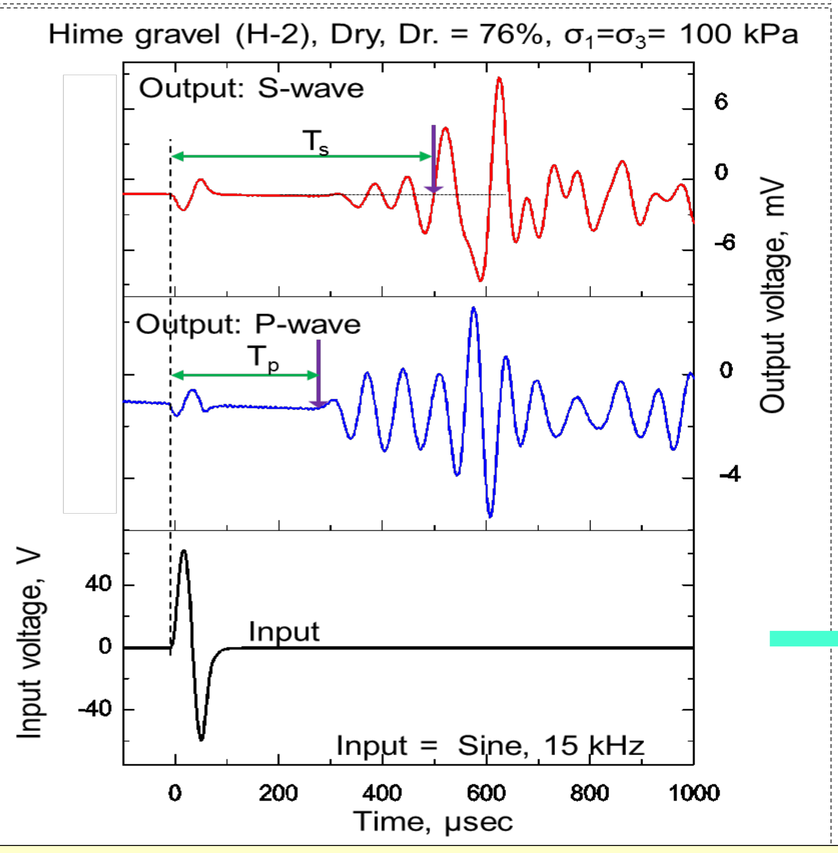
Disk Transducer



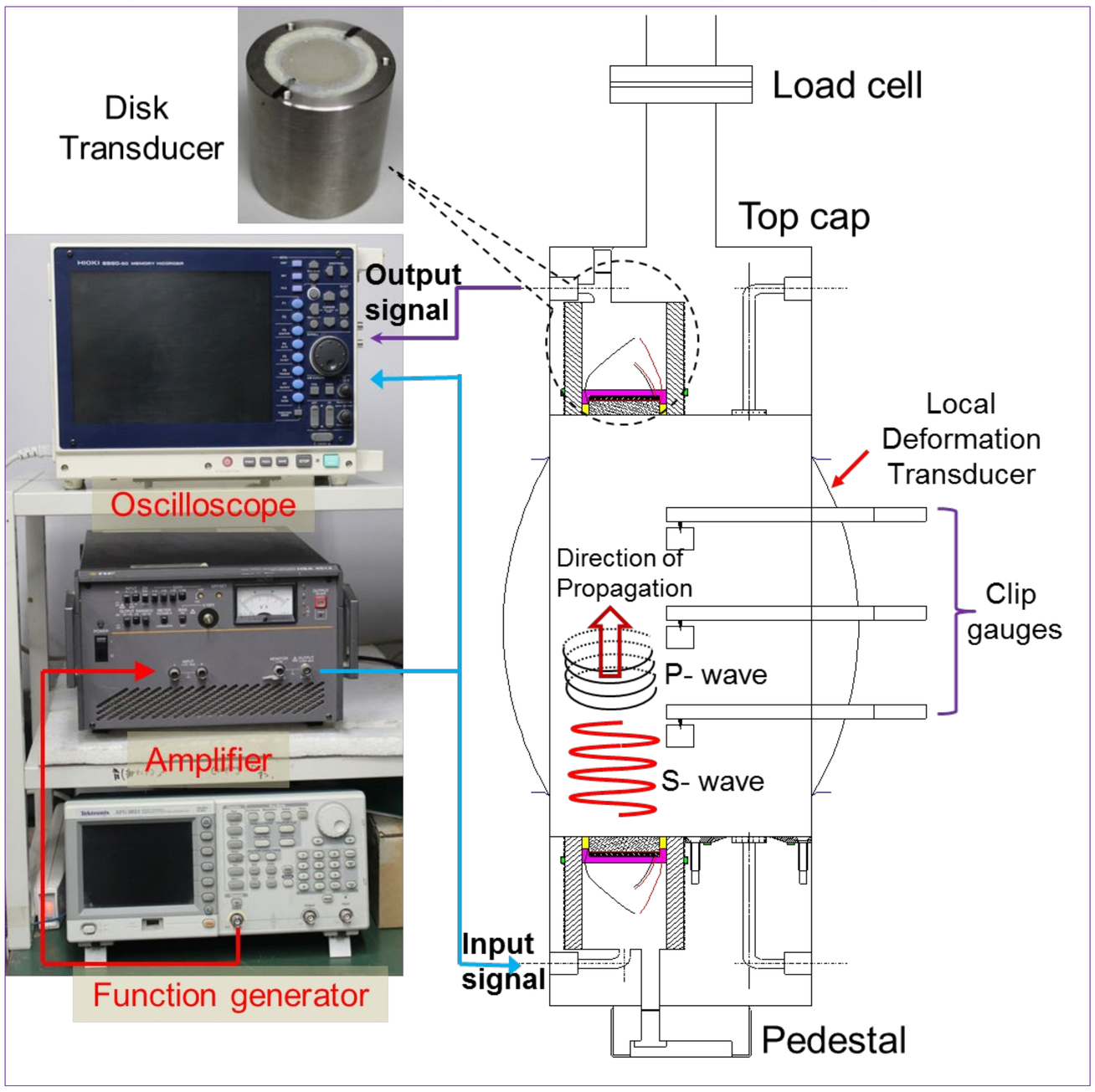
Details of top cap including disk transducer

Typical waveforms





Experimental set up and data acquisition process



Velocity of signals

$$V_P = \frac{h}{T_p} \qquad Vs = \frac{h}{T_s}$$

h is height of specimen

Material's properties are evaluated in terms of wave velocity.

Material's properties

$$M = \rho * V_p^{\,2} \qquad G = \rho * V_s^{\,2}$$

$$E = \frac{M(1-2\nu)(1+\nu)}{(1-\nu)}$$

$$\nu = \frac{\left(0.5V_p^{\,2} - V_s^{\,2}\right)}{V_p^{\,2} - V_s^{\,2}}$$

$$G = \frac{E}{2(1+\nu)}$$

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Laxmi Prasad Suwal (2010)

Optimum Shape of Disk Transducer

ディスクトランスデューサーの最適形状に関する検討

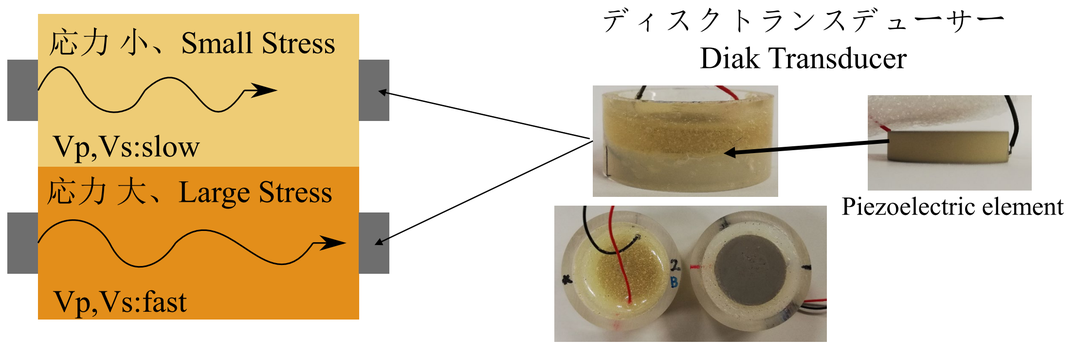
One type of soil dynamic measurement methods is a method using a disk transducer (DT). In recent years, elastic wave measurement of soil using DT has been widely performed, but there are few studies examining optimum shape/size of DT. Since the output voltage of elastic wave measurement is generally significantly lower than the input voltage, DT capable of outputting a larger voltage is required. Therefore we focused on the thickness of the piezoelectric element and examined the optimum shape of DT. In this study, we prepared disk-type piezoelectric elements of 20 mm in diameter with four thicknesses of 1, 2, 5 and 10 mm, and compared the magnitudes of the measured amplitudes.

土の動的計測法の一種にディスクトランスデューサー（以下、DT）を用いる方法がある。近年、DTを用いた土の弾性波計測が広く行われるようになりつつあるが、DTの最適な形状を検討している研究は少ない。弾性波計測の出力電圧は入力電圧に比べ著しく低下するのが一般的であるため、より大きな電圧を出力できるDTのデザインが求められる。そこで本研究では、圧電素子の厚みに着目し、DTの最適形状を検討した。1，2，5，10mmの4種類の厚みをもつ直径20mmのディスク型圧電素子を用意し、それぞれ出力電圧値の大きさを比較した。その結果、弾性波の送信側に用いる圧電素子は薄いほど，受信側に用いる圧電素子は厚いほど、出力電圧値が増加することを確認した。

１．はじめに　Introduction

土中を伝播する弾性波速度
Elastic wave velocity in soil

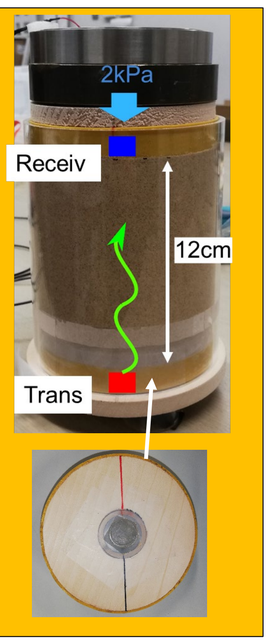
$$Vs, Vp = f\left(\begin{array}{c}\text{応力状態、密度}\\ \text{Stress state、Density}\end{array}\right)$$



２．実験概要　Materials and methods

1mm，2mm，5mm，10mmの4種類の厚みをもつ直径20mmのディスク型圧電素子を，それぞれ送信と受信に用いて16パターンの弾性波計測を行った。
We measured 16 patterns of elastic waves using a 20 mm diameter disk-shaped piezoelectric element with four thicknesses of 1, 2, 5, and 10 mm for transmission and reception, respectively.

	送信側Disk厚 Thickness of trans disk	受信側Disk厚 Thickness of receiv. disk	相対密度 Dr	入力電圧 Input V	周波数 Frequency
Case1	1mm	1mm、2mm、5mm、10mm	77.6%	140Vp-p	3kHz～20kHz
Case2	2mm	1mm、2mm、5mm、10mm	79.1%		
Case3	5mm	1mm、2mm、5mm、10mm	82.6%		
Case4	10mm	1mm、2mm、5mm、10mm	73.5%		



３．基礎原理と予想　Fundamental Principles and Forecasts

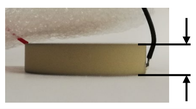
一般的に素子に力Fが加えられたときに発生する電圧Vは、

$$V = F \cdot \frac{d_{33}}{c_d} = F \cdot g_{33} \cdot \frac{t}{A}$$　（t：圧電素子の厚み）

であらわされる。上式を電圧と素子の厚みと応力の関係に直すと

$$V = \frac{F}{A} \cdot g_{33} \cdot t = \sigma \cdot g_{33} \cdot t$$

$$F = \sigma \cdot A = \frac{V \cdot A}{t \cdot g_{33}}$$



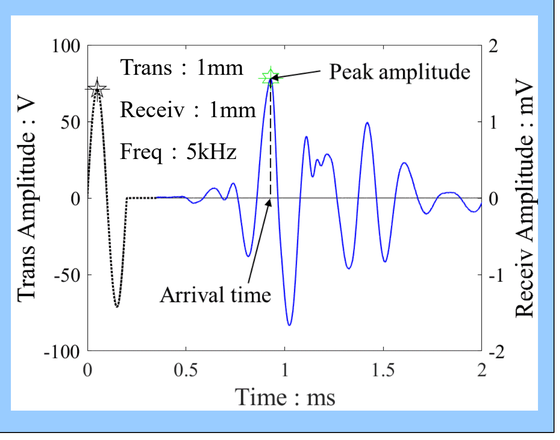
受信側のDTに発生する電圧は圧電素子の厚みに比例する
The voltage at the receiving DT is proportional to the thickness of the piezoelectric element.

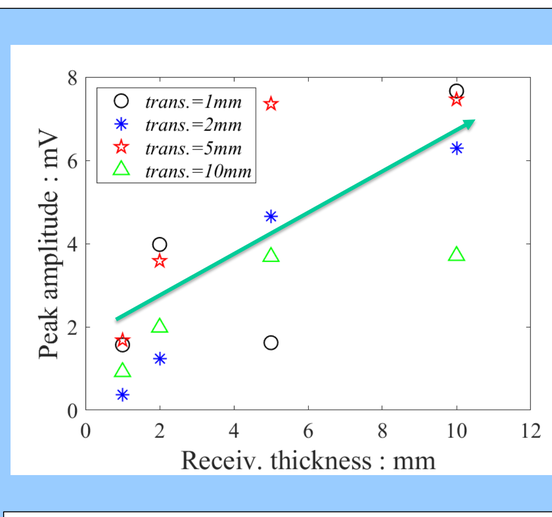
送信側のDT生ずる力は圧電素子の厚みに反比例する
The force of DT on the transmitting side is inversely proportional to the thickness of the piezoelectric element.

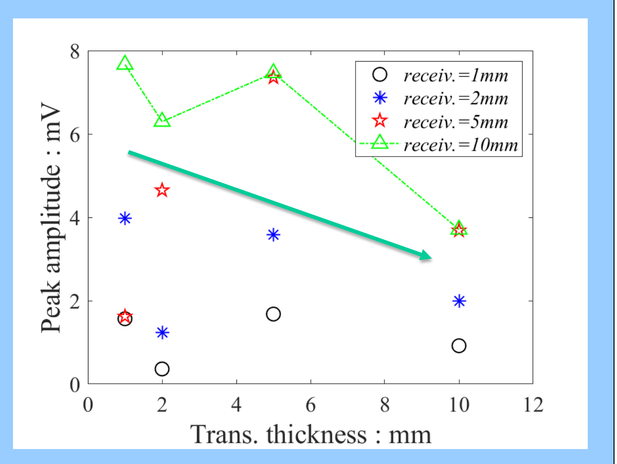
４．計測結果　Results

弾性波計測結果の一例（右図）。各Disk厚の組み合わせごとにピーク時電圧を算出し、大小を比較する。

This is an example of an elastic wave measurement result (right figure). Peak voltage is calculated each Disk thickness combination, and the magnitude is compared.





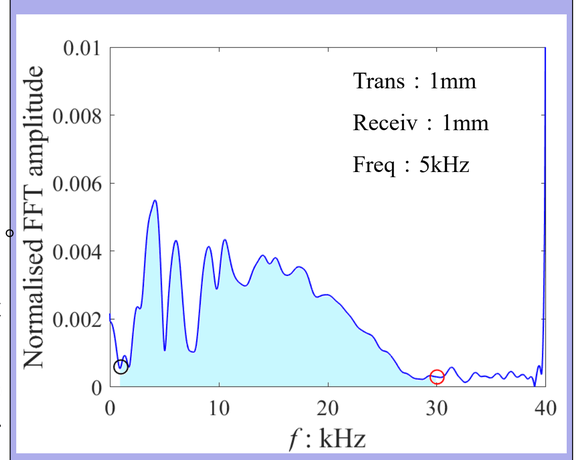


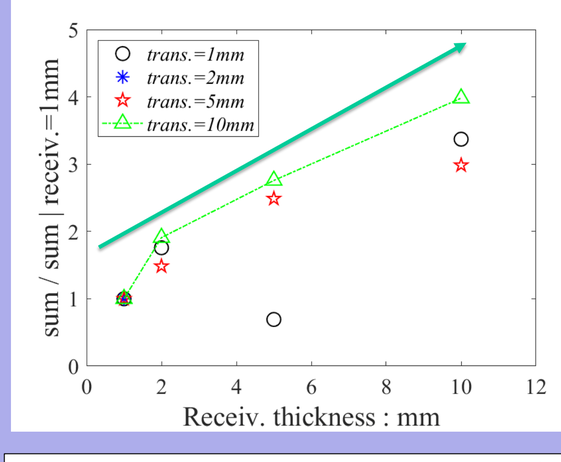
受信側のDiskが厚いほど、また、送信側のDiskが薄いほどピーク電圧は大きく、計測に適している。
As the Disk on the receiving side is thicker and the Disk on the sending side is thinner, the peak voltage is larger, which is more suitable for measurement.

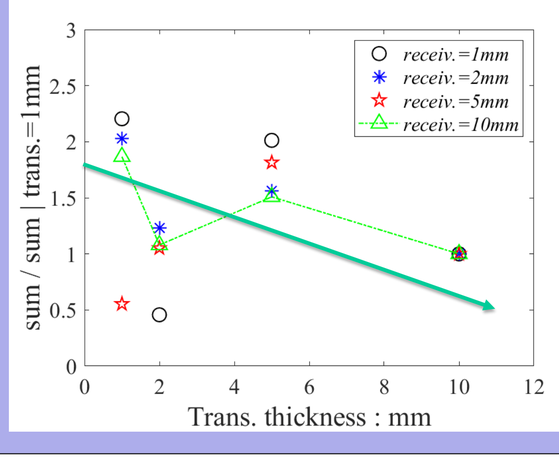
５．周波数解析　Frequency analysis

入力周波数20kHzの計測結果に対するフーリエ解析を行い、周波数応答を求め、スペクトルの下部面積を積分する（右図）ことでその応答振幅の指標とし、送信は1mmの結果を、受信は10mmの結果を基準として正規化した。

Perform Fourier analysis on the measurement results at an input frequency of 20 kHz. Integrate the lower area of the spectrum to quantify an index of amplitude (transfer normalized with 1 mm results, and receiver normalized with 10 mm results).







計測結果の傾向が、周波数の影響なく成り立つものであることを確認。
The tendency of the measurement result holds without the influence of the frequency.

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川口勇一郎 (2019)

ELASTIC WAVE MEASUREMENT

SIMULTANEOUSLY OBTAINED P & S WAVES BY DISK TRANSDUCER

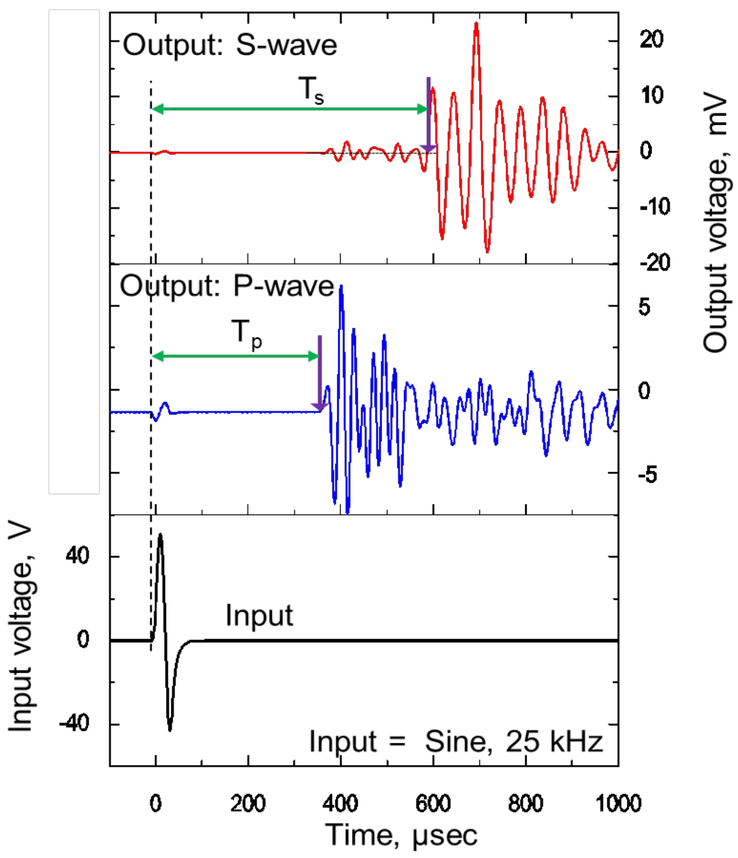
ディスクトランスデューサーによるP波・S波の同時測定

Recently developed flat disk shaped piezo-ceramic transducer, “Disk Transducer” is employed on the cylindrical triaxial specimen of 75 mm in diameter and 150 mm in height in several granular geo-materials. Both compressional and shear (P and S) waves were propagated exciting P type and S type piezo-ceramic elements together and the corresponding responses (received compressional and shear waves) are achieved simultaneously.

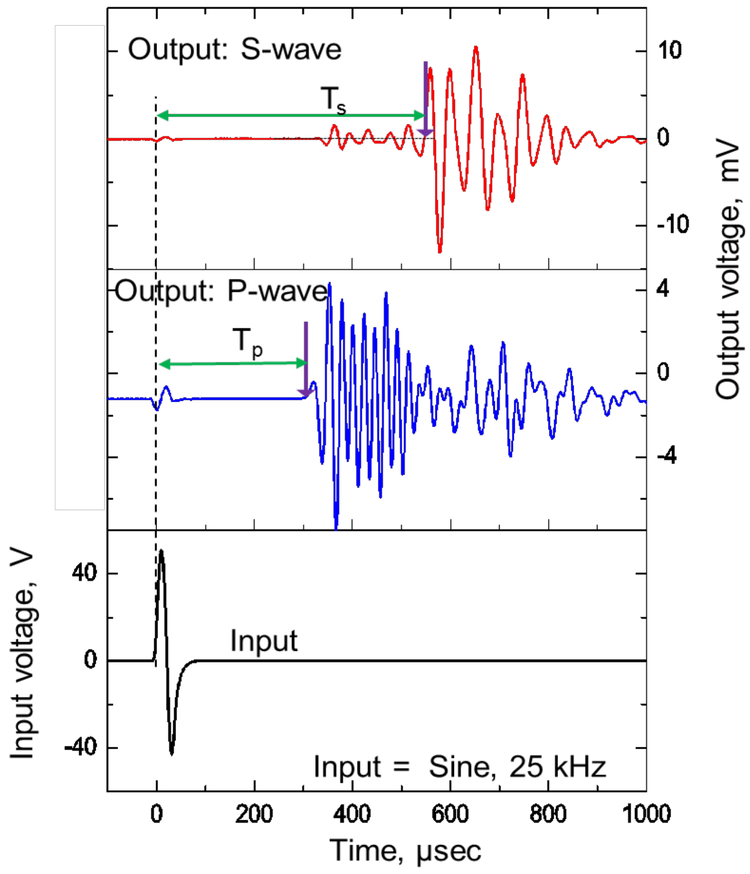
室内土供試体のP波とS波速度を同時に測定できる、ディスクトランスデューサーを開発しました。粒径の異なる3種類の砂で得られた結果を示します。

SIMULTANEOUSLY ACHIEVED COMPRESSIONAL AND SHEAR (P AND S) WAVES ON GRANULAR MATERIALS

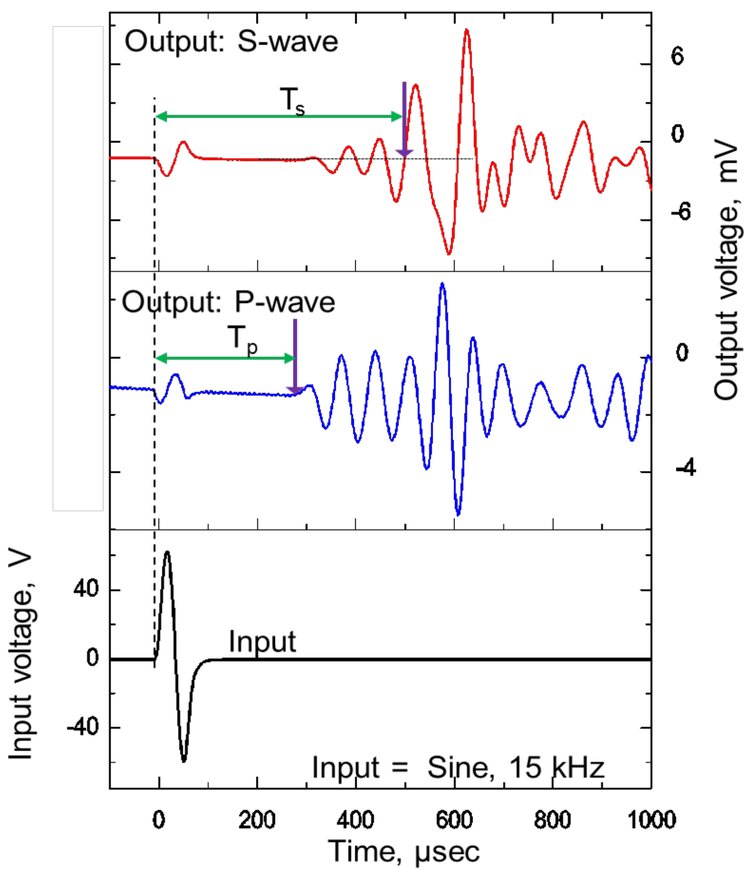
Waveforms obtained on Toyoura sand



Waveforms obtained on Silica sand



Waveforms obtained on Hime gravel



RELATIONS TO EVALUATE MATERIAL PROPERTIES

Relations used in elastic wave measurement

Velocity of the wave $V_P = \frac{H}{T_P}$ $V_s = \frac{H}{T_s}$

Poisson’s ratio in terms of velocity $\nu = \frac{(0.5V_p^2 - V_s^2)}{V_p^2 - V_s^2}$

Young’s modulus $E = \frac{M(1-2\nu)(1+\nu)}{(1-\nu)}$

Constrained modulus $M = \rho * V_p^{\,2}$

Conversion between G and E $G = \frac{E}{2(1+\nu)}$

Shear modulus $G = \rho * V_s^{\,2}$

H = Distance between two transducers (specimen height)

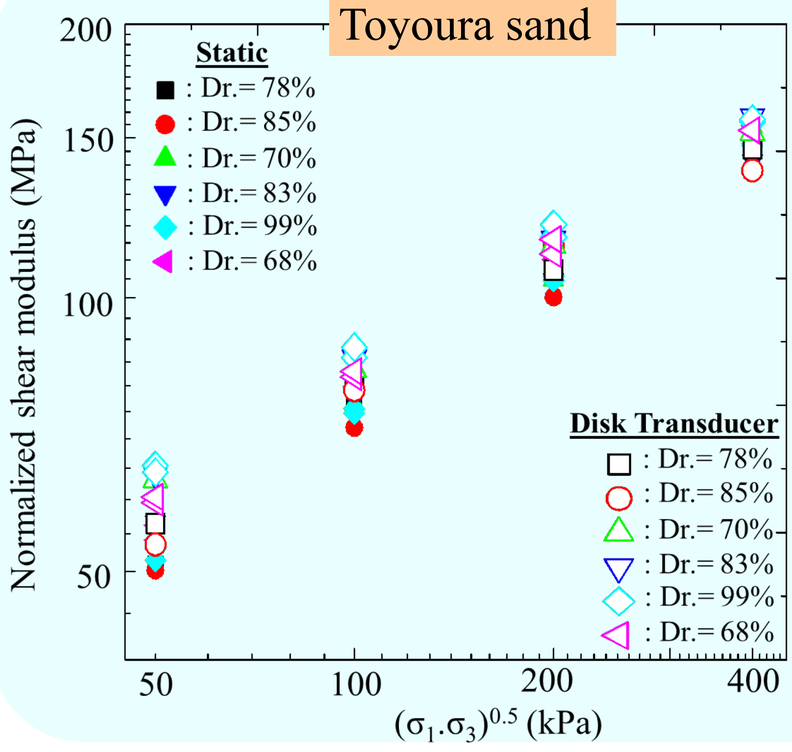
Static relations

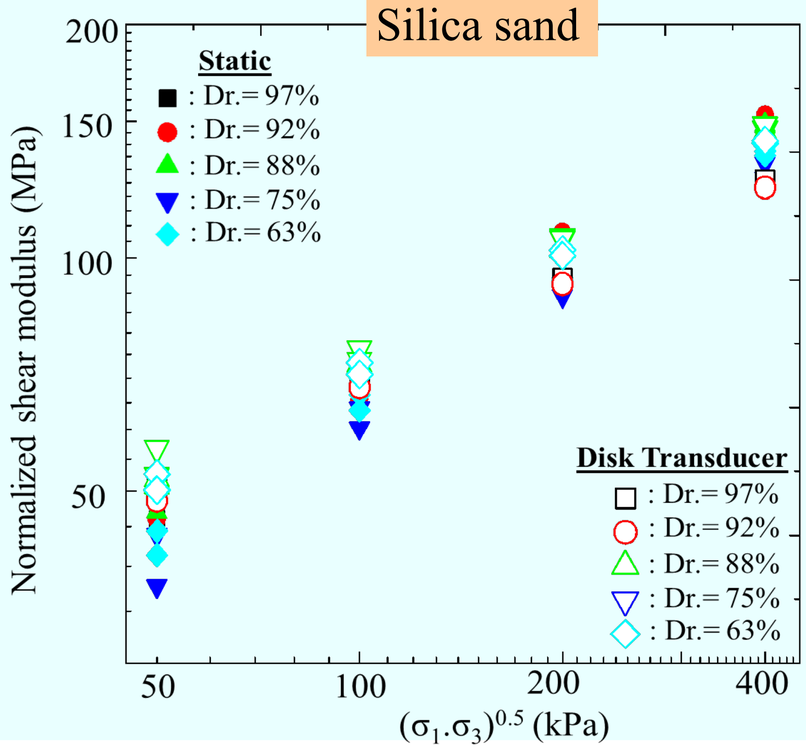
Axial (vertical) strain, $\varepsilon_a = -\int_{H_0}^{H} \frac{dH}{H} = -\ln(\frac{H}{H_0})$

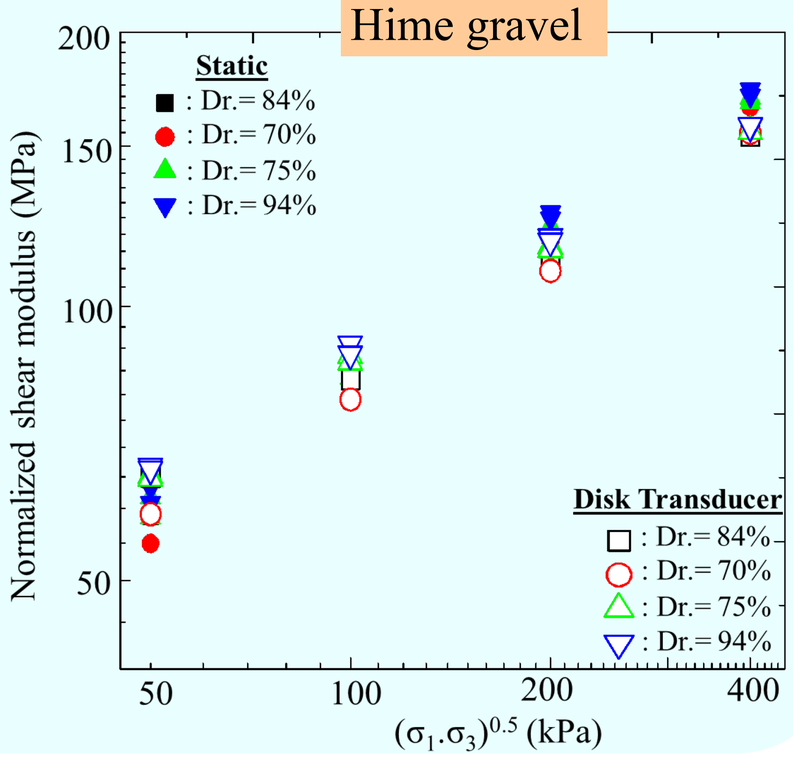
Radial (lateral) strain, $\varepsilon_r = -\int_{R_0}^{R} \frac{dR}{R} = -\ln(\frac{R}{R_0})$

Poisson’s ratio, $\nu = -\frac{\delta\varepsilon_r}{\delta\varepsilon_a}$ Young’s modulus, $E = \frac{\Delta\sigma}{\Delta\varepsilon_a}$

Stress-Stiffness relationship







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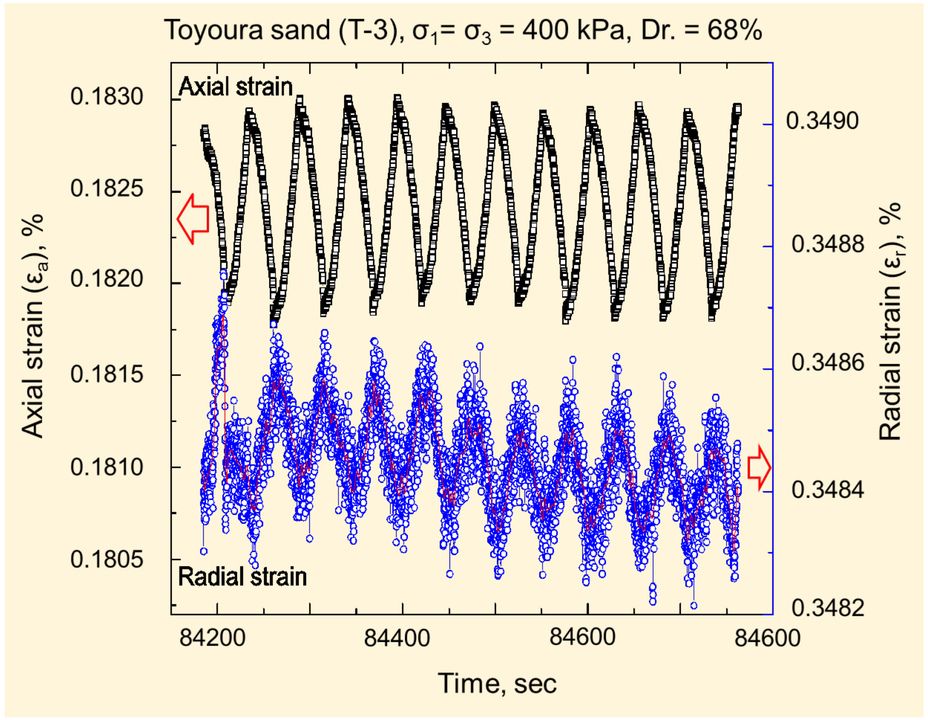
Laxmi Prasad Suwal (2013)

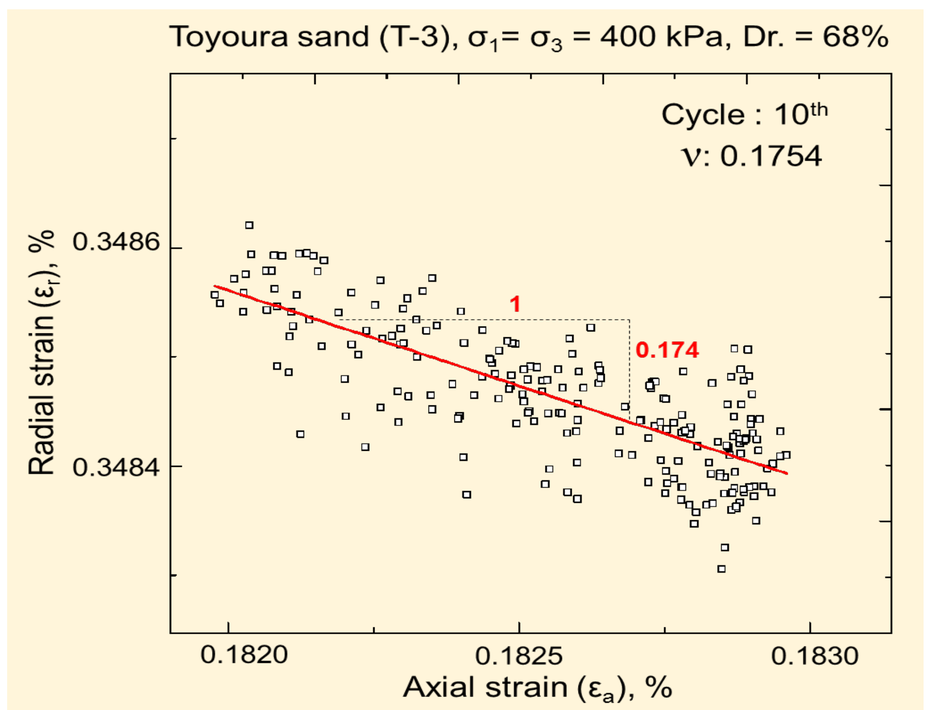
POISSON'S RATIOS EVALUATED BY STATIC AND DYNAMIC METHODS

静的および動的手法によって測定した砂供試体のポアソン比

Poisson's ratio is defined as the ratio of radial strain to axial strain. Axial and radial strains were precisely monitored using LDTs and clip gauges during small cyclic loadings and the strain increments in each cycle were evaluated statically. Disk Transducer method is able to evaluate both compressional and shear wave velocities in an identical specimen. With the obtained wave velocities, the Poisson's ratios were computed dynamically. This study is intended to evaluate the Poisson's ratios of the fine granular materials, Toyoura sand and Silica sand.

Static method

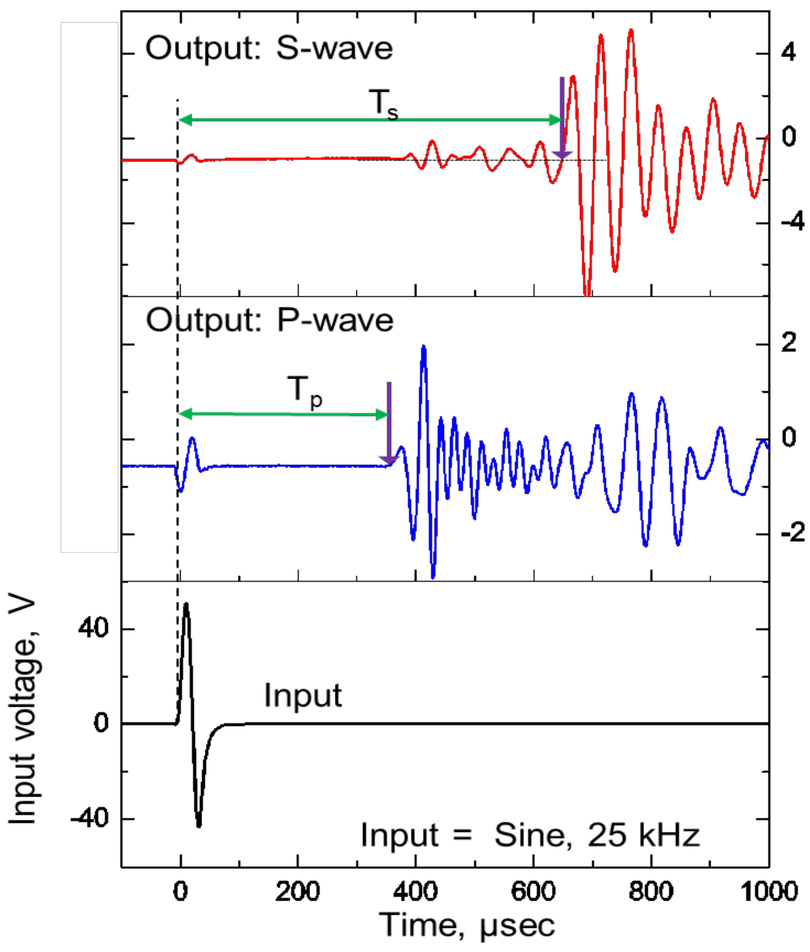




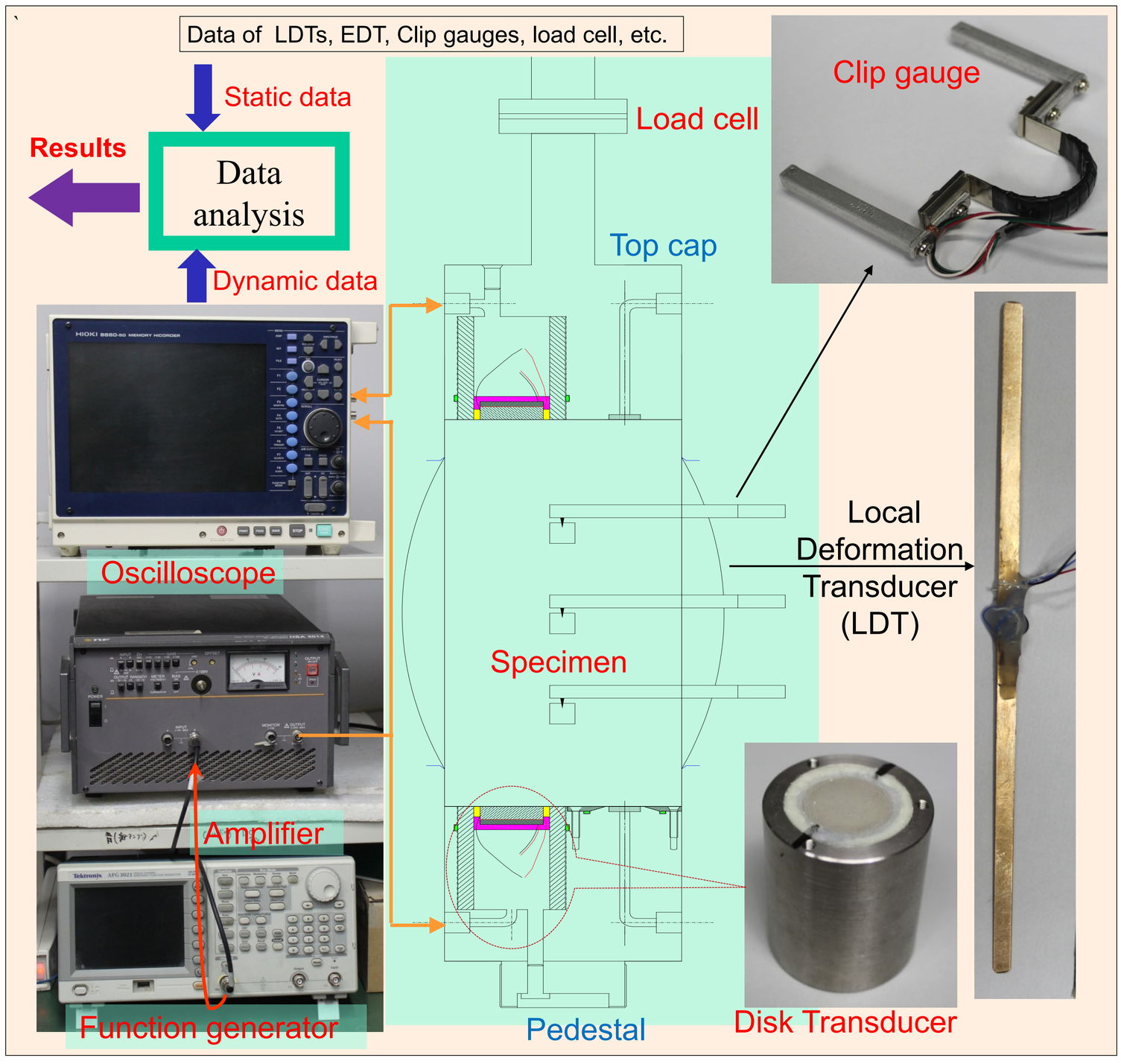
Poisson's ratio evaluation in each cycle

Dynamic method

Silica sand(S-1), Dry, Dr. = 88%, σ1=σ3= 50 kPa



Experimental set up

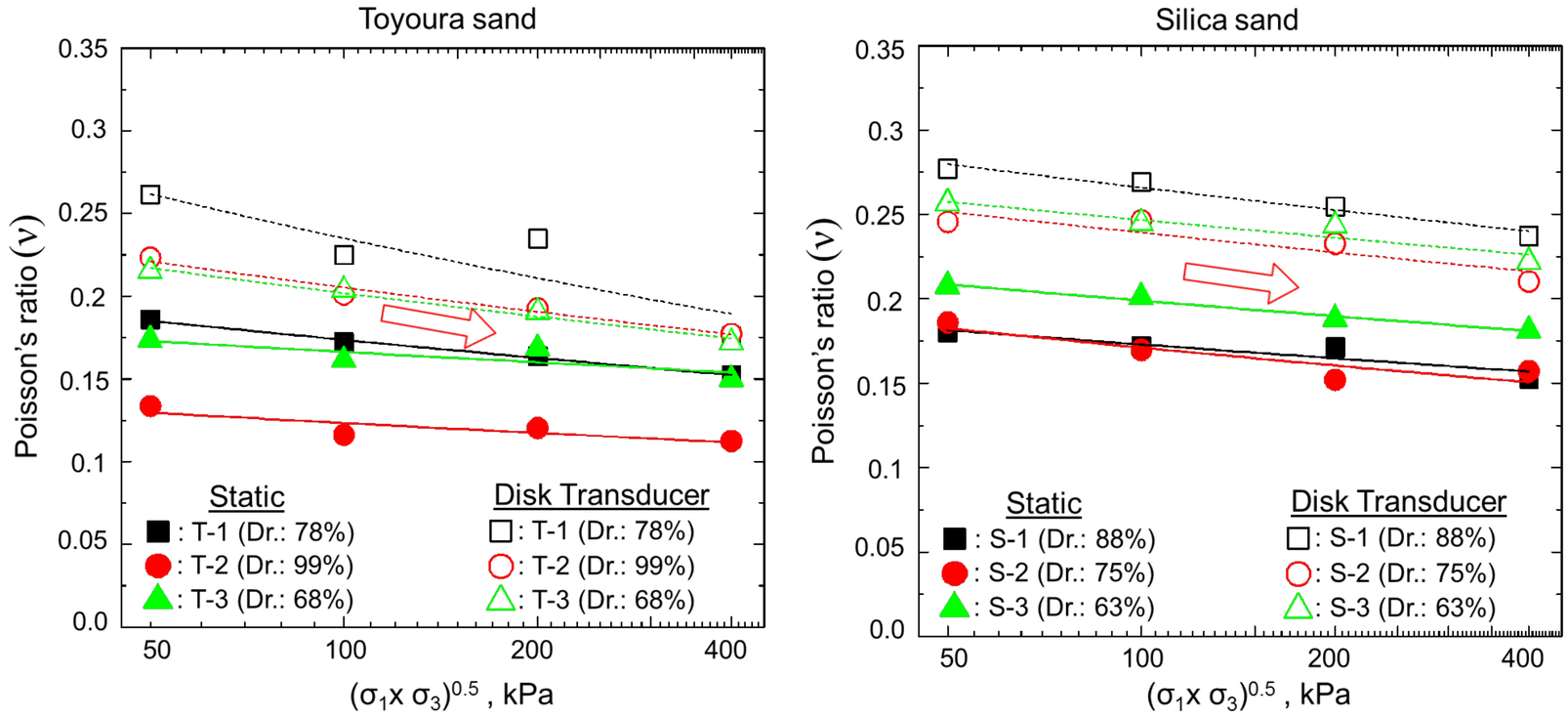


Poisson's ratio

Statically, $\nu = -\dfrac{\delta\varepsilon_r}{\delta\varepsilon_a}$ where, $\varepsilon_a = -\int_{H_0}^{H}\dfrac{dH}{H} = -\ln\left(\dfrac{H}{H_0}\right)$ & $\varepsilon_r = -\int_{R_0}^{R}\dfrac{dR}{R} = -\ln\left(\dfrac{R}{R_0}\right)$

Dynamically, $\nu = \dfrac{(0.5V_p^2 - V_s^2)}{V_p^2 - V_s^2}$ where, $V_P = \dfrac{h}{T_p}$ & $Vs = \dfrac{h}{T_s}$

Statically and dynamically evaluated Poisson's ratios



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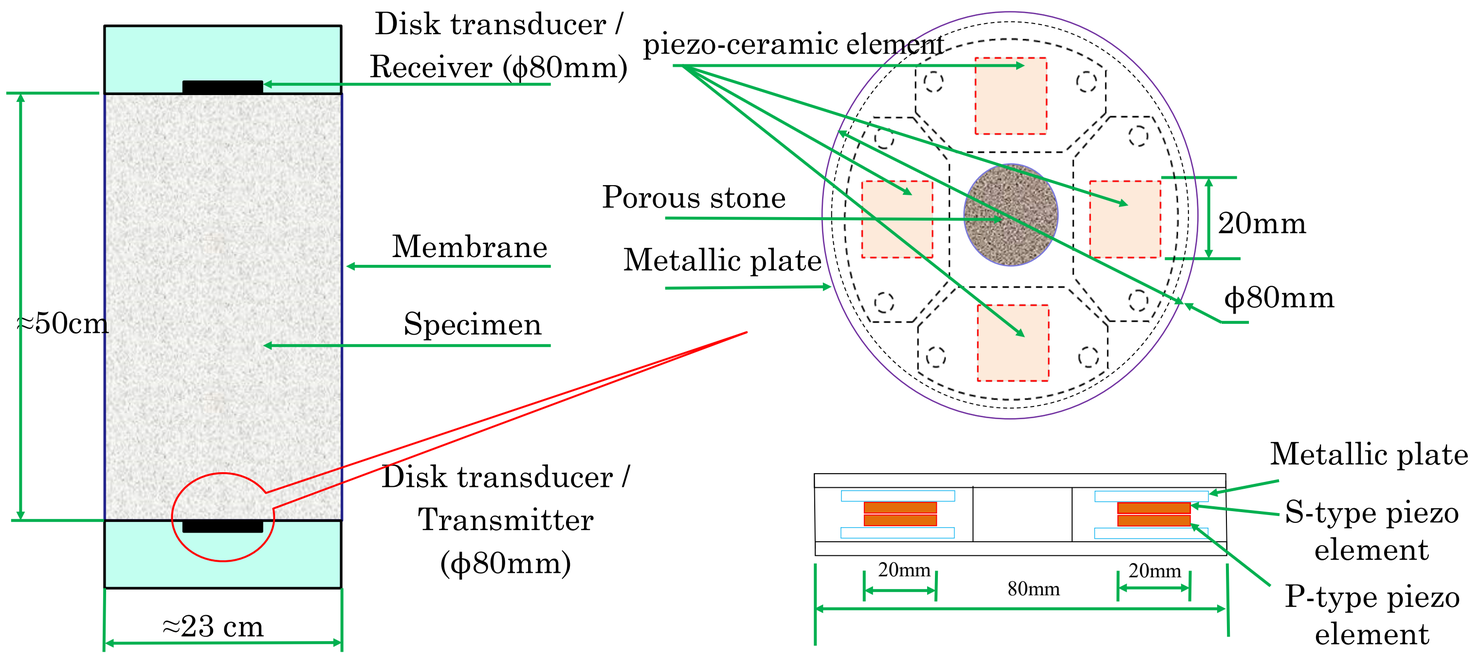
Laxmi Prasad Suwal (2013)

ELASTIC WAVE MEASUREMENT
Development of Large Size Disk Transducer

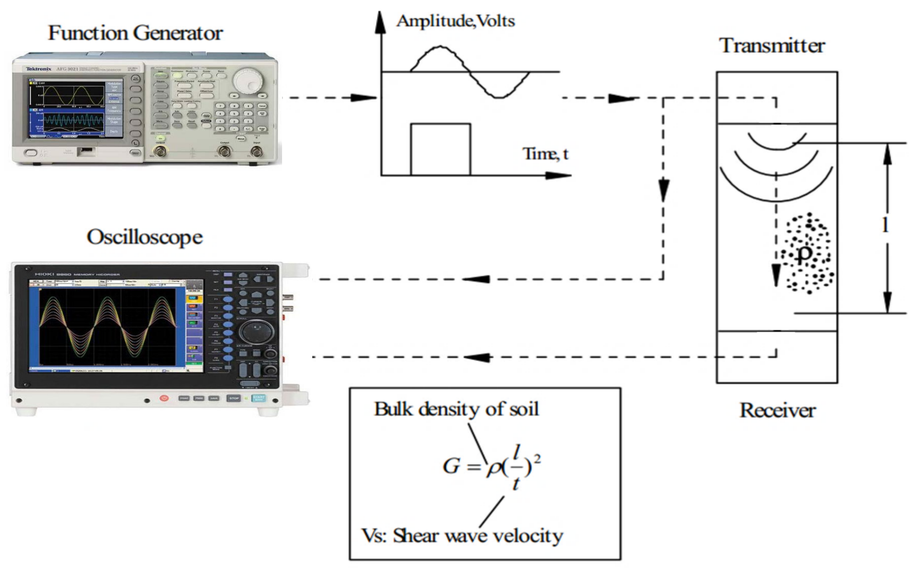
大型ディスクトランスデューサーの開発

The elastic wave measurement is becoming popular to obtain small strain stiffness of coarse granular materials. In IIS, various type of transducers are currently used, including bender element (BE), Trigger-Accelerometer (TA), Trigger-Bimorph element (TB) and disk transducer (DT). Recently, disk transducer method has been introduced to overcome the disadvantages of bender element method. The newly developed transducer is applicable to undisturbed sample, cemented specimen and stiff material, as it is not necessary to insert it into the specimen. But, to study the elastic wave of small to large grain size geomaterials on single apparatus is difficult, because of the limitation of size of piezo ceramic element available in market. So, large size disk transducer has been developed and employed on large triaxial apparatus. The development of disk transducer, waveform and elastic properties of Toyoura sand specimen is presented.

Large Size Disk Transducer

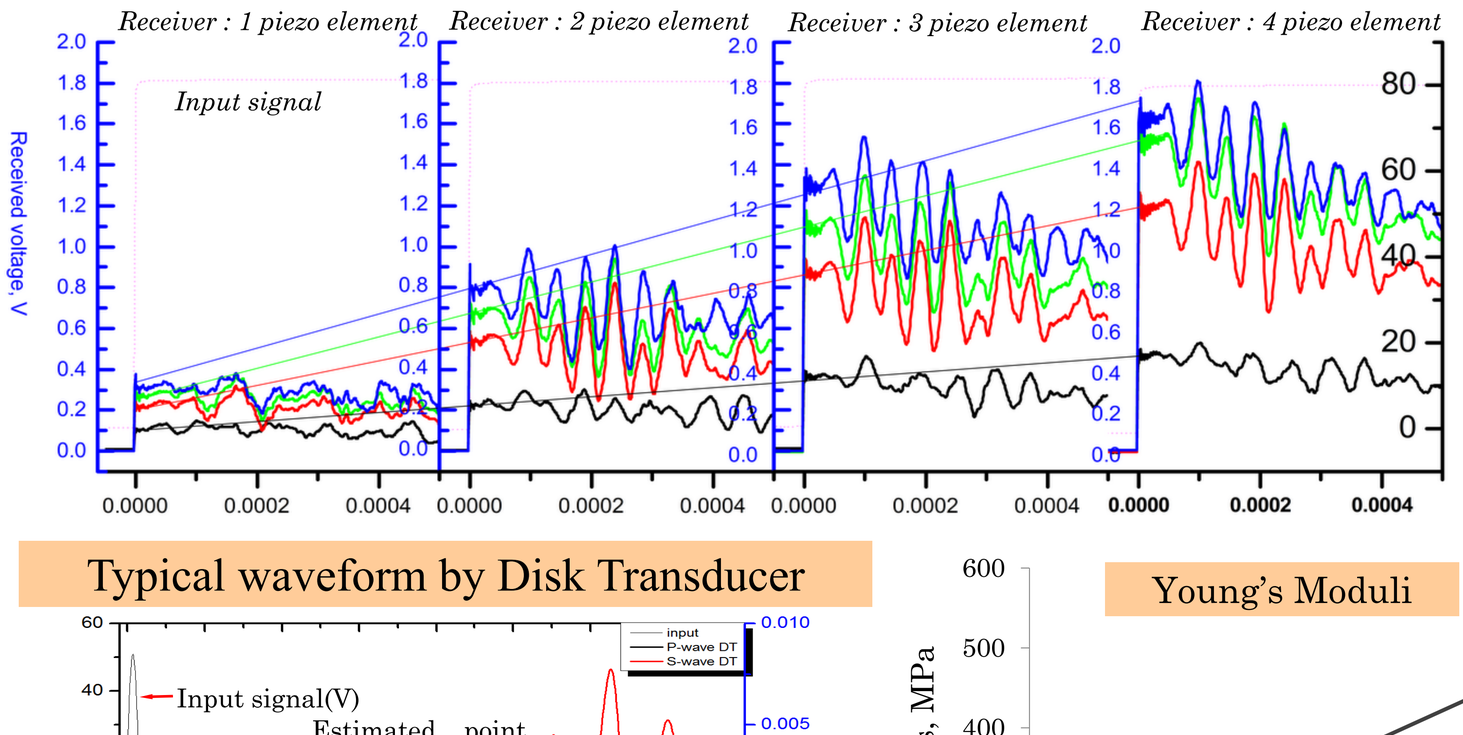


Shear wave measurement by Disk Transducer

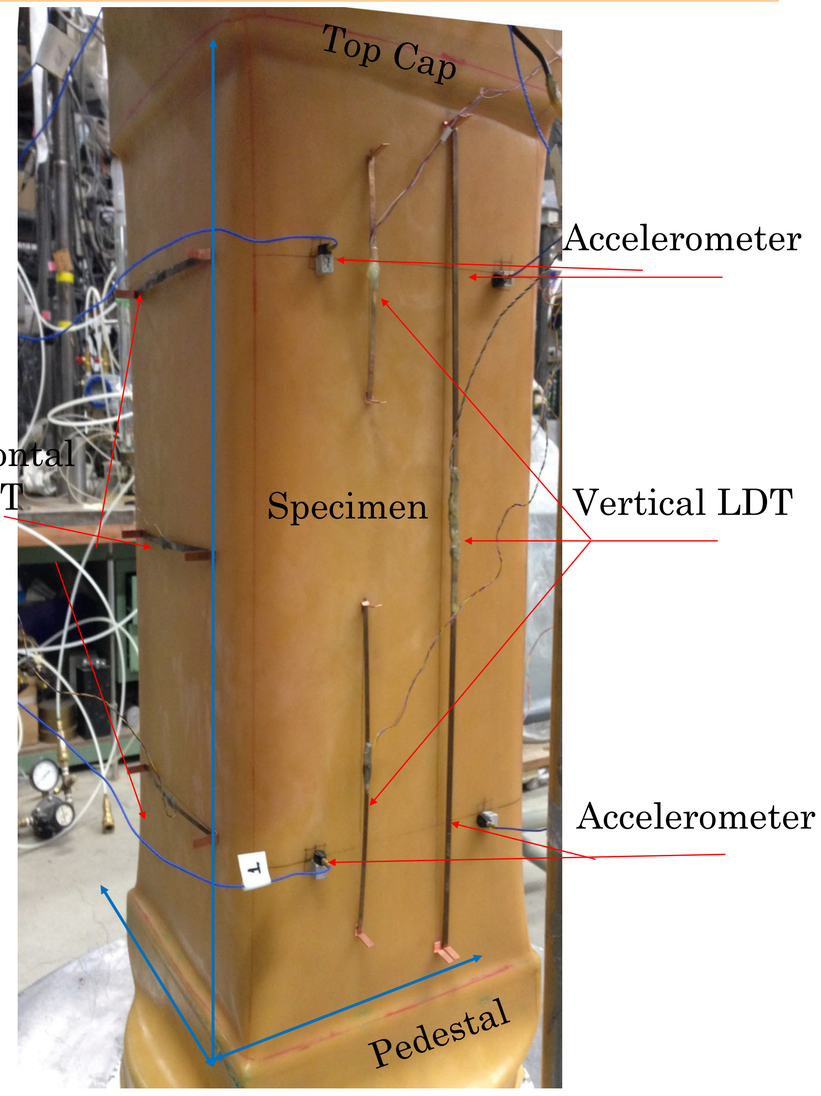


Shear moduli at small strains can be obtained

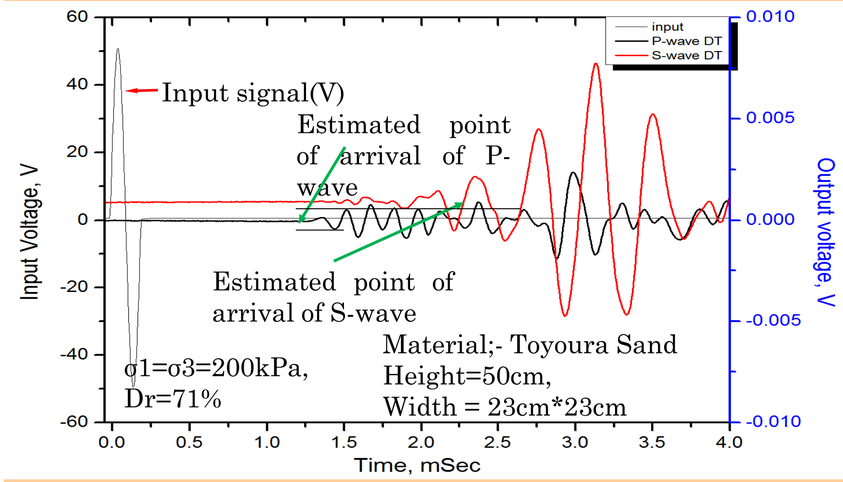
Received S-wave signal, receiver and transmitter disk are facing each other



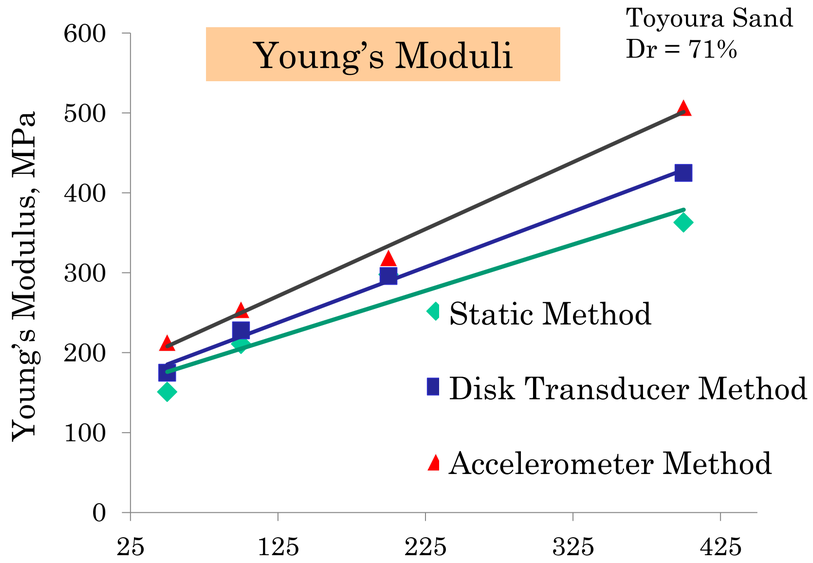
Specimen and attachment of LDT



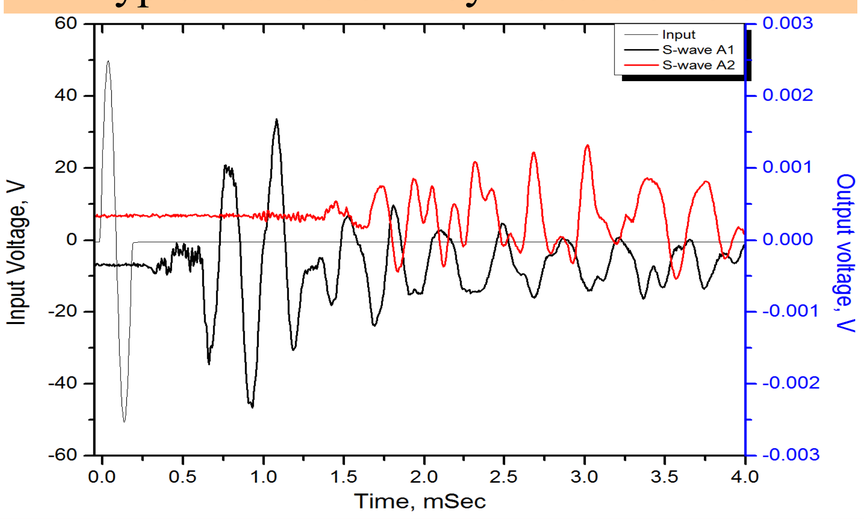
Typical waveform by Disk Transducer



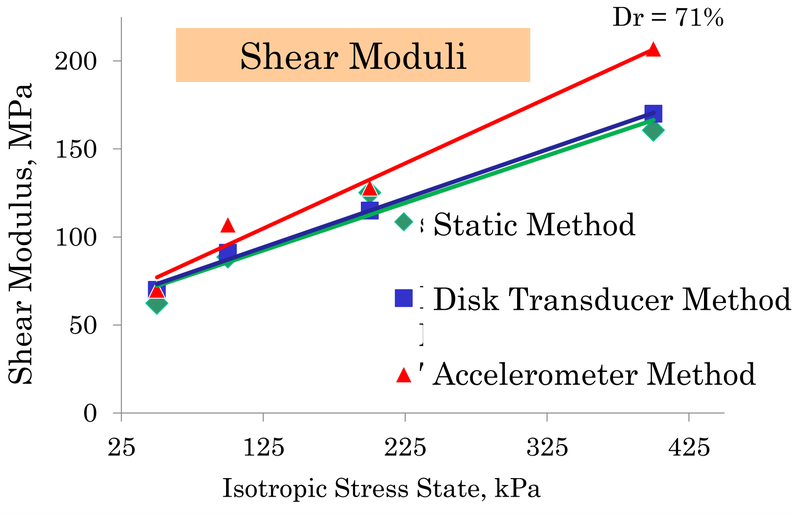
Young's Moduli



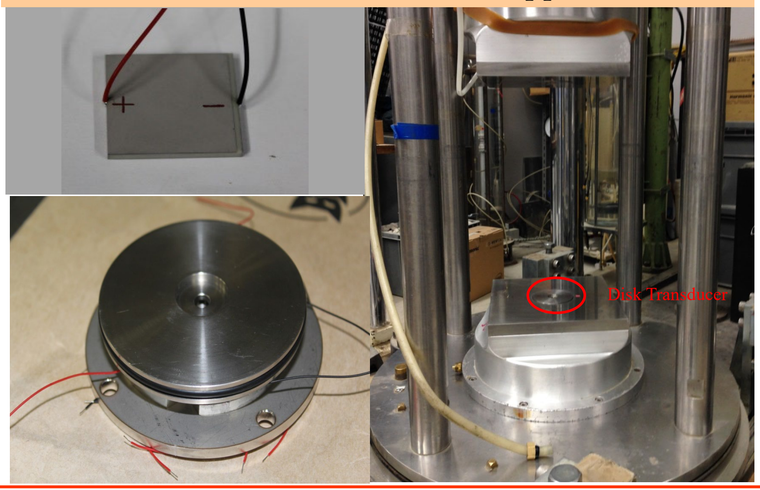
Typical waveform by Accelerometer



Shear Moduli



Used piezo-ceramic element and attachment of Disk Transducer in Triaxial apparatus



本研究に関する担当研究室は桑野研究室です.
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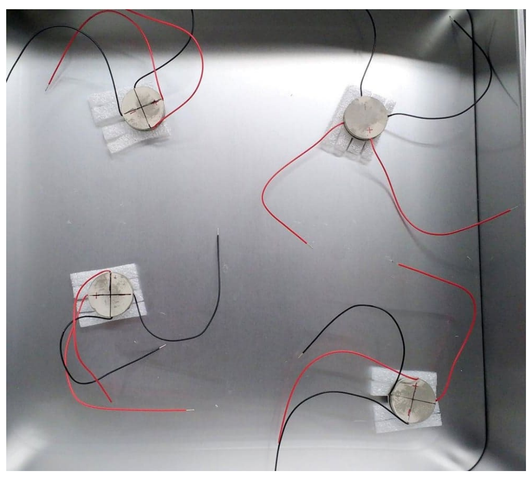
Abilash Pokhrel (2014)

Estimation of multidirectional stiffness using disk transducers in a large triaxial specimen

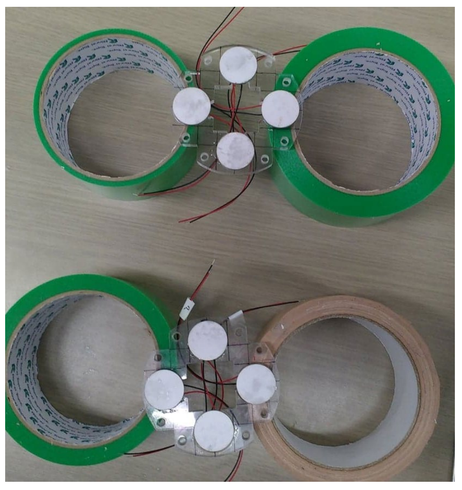
ディスクトランスデューサーを用いた大型三軸供試体の異方性の推定

Granular materials are observed to be inherently anisotropic in nature exhibiting dissimilar stiffness in vertical and horizontal directions during the process of deposition of the particles or during compaction. In the current research, the development of a novel test setup which employs disk transducers (DTs) for the measurement of vertical and horizontal small strain moduli to quantify stiffness anisotropy has been described. The disk transducers were installed in a large triaxial apparatus having rectangular specimen of dimension 235 × 235 × 500 mm. The test results indicated that the stiffness measured in the horizontal direction is greater than those calculated in the vertical direction. A good agreement has been detected between the dynamically (using DTs) and statically derived vertical small strain stiffness (by applying small cyclic loadings) verifying the suitability of the present test setup for stiffness estimation.

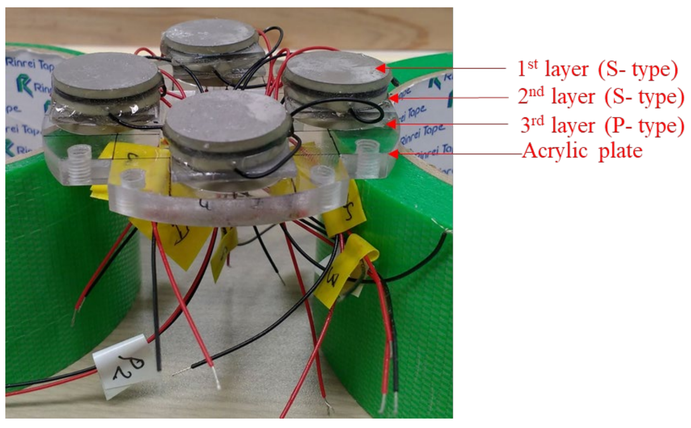
Development of Vertical Disk Transducers



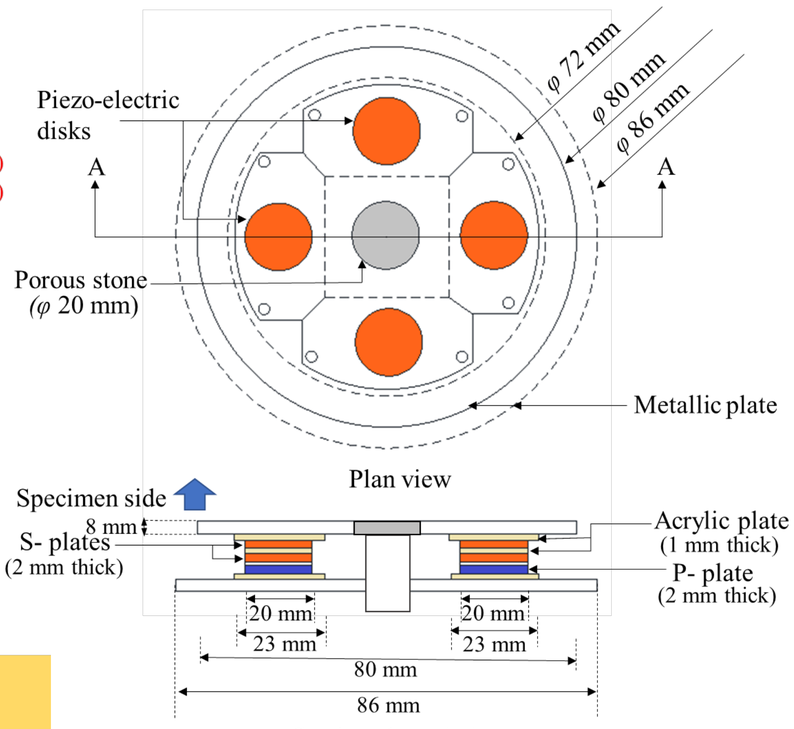
SS- pattern (oscillation in mutually perpendicular direction)



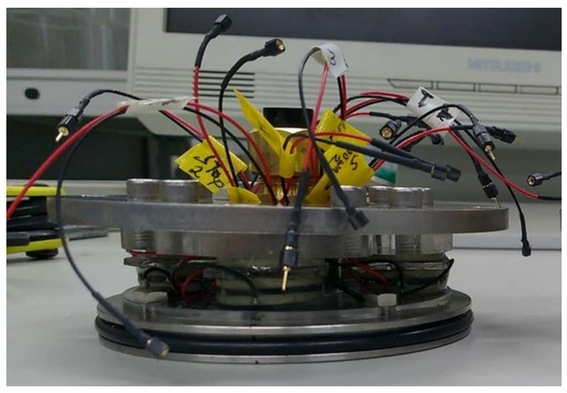
P- plate glued to acrylic disk



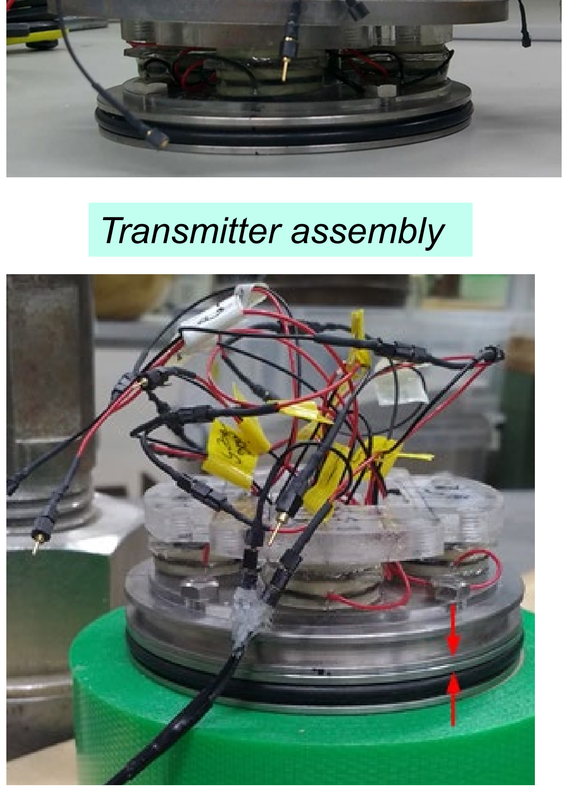
SSP- assembly of vertical DT



Schematic of vertical DT

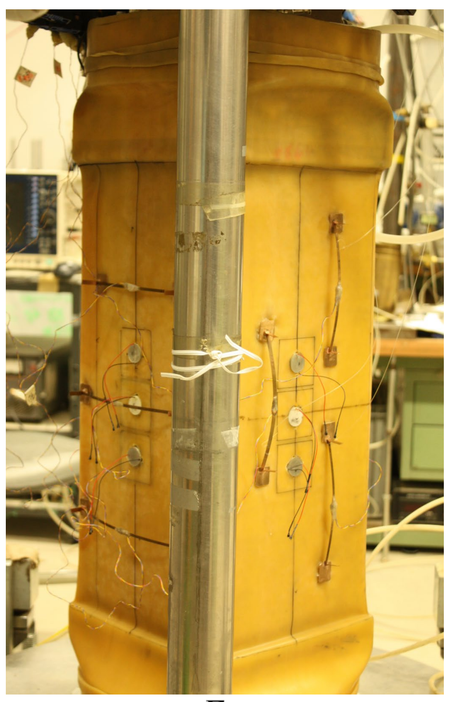


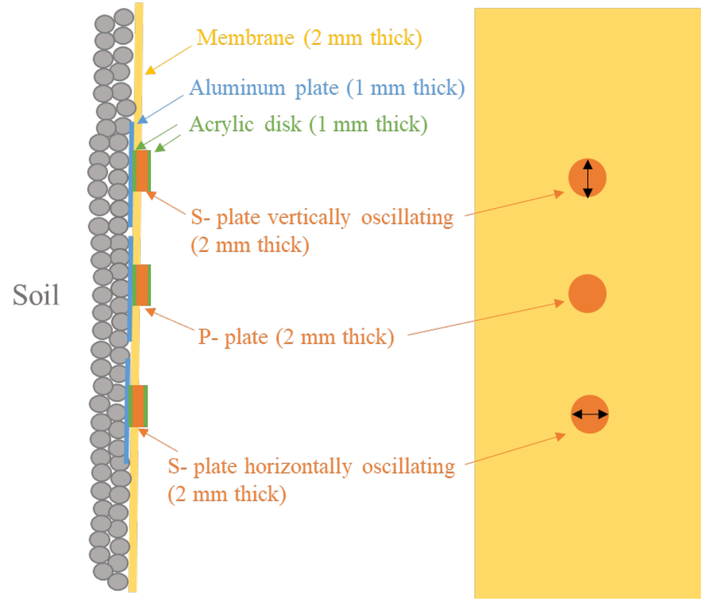
Transmitter assembly

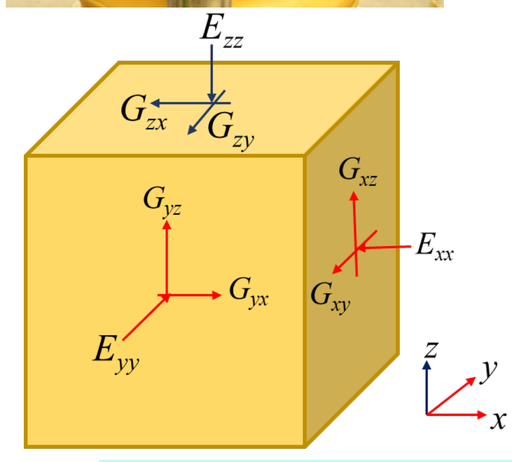


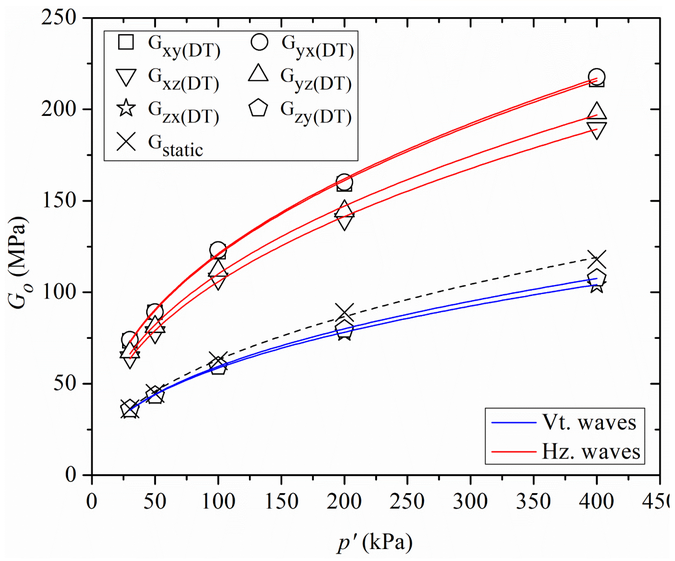
Calibration of vertical DT

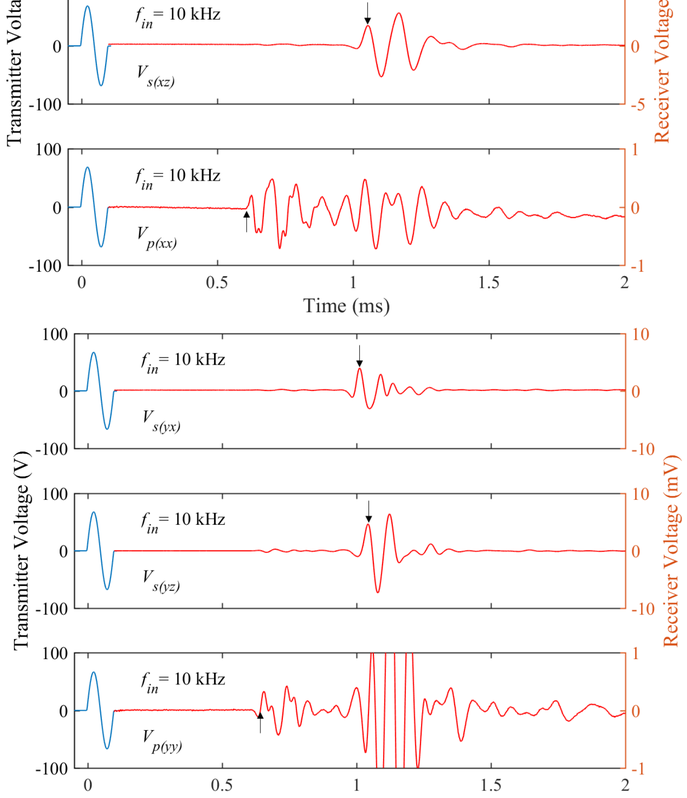
Horizontal Disk Transducers



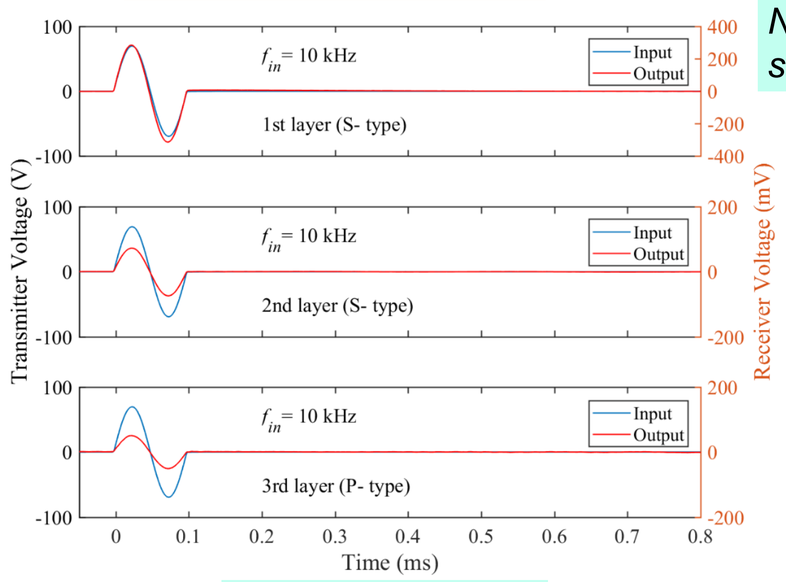


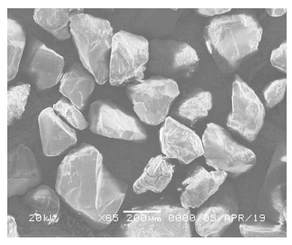




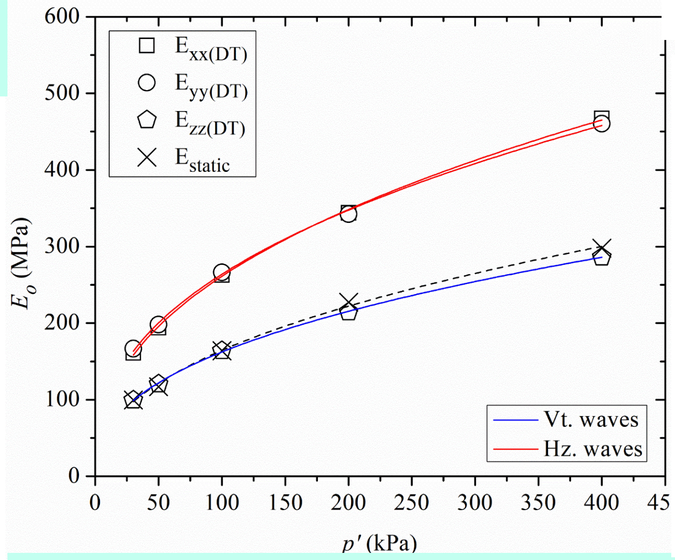


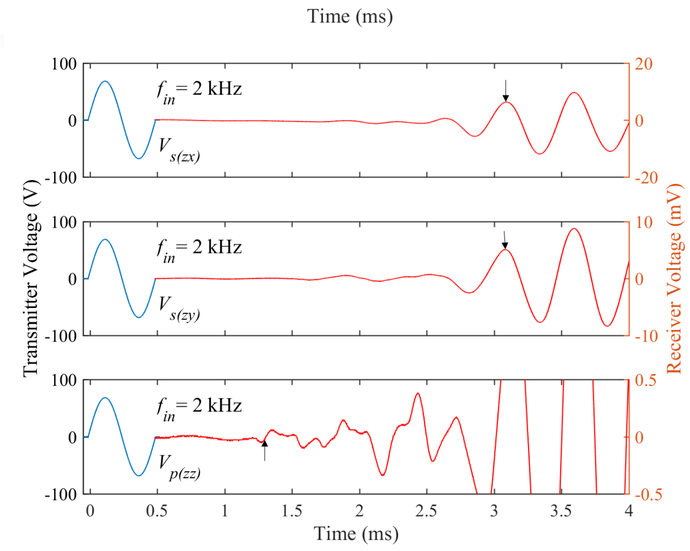
Notation of multidirectional stiffness





Toyoura sand





★ *Negligible time lag*

★ E_o & G_o in hozt. > E_o & G_o in vert.

★ *Comparable results from dynamic and static measurement*

Time domain responses (p´ = 50 kPa)

本研究に関する担当研究室は桑野研究室です.
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Troyee Tanu Dutta (2019)

Development of a soil box with multi-directional wave measurement

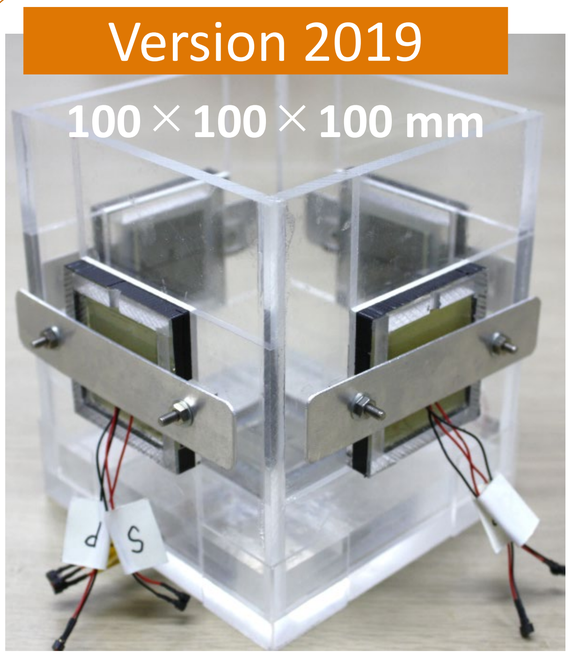
全方向ディスクトランスデューサー搭載立方体土槽の開発

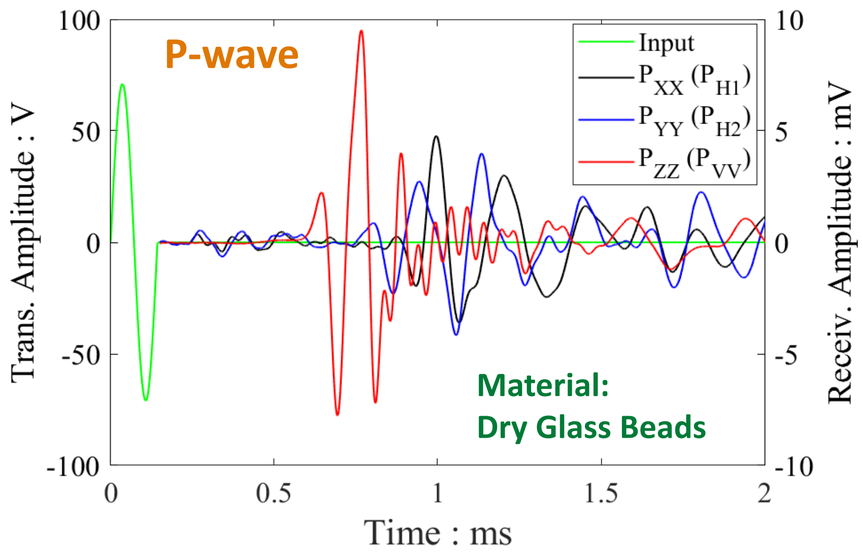
Research purpose 研究目的

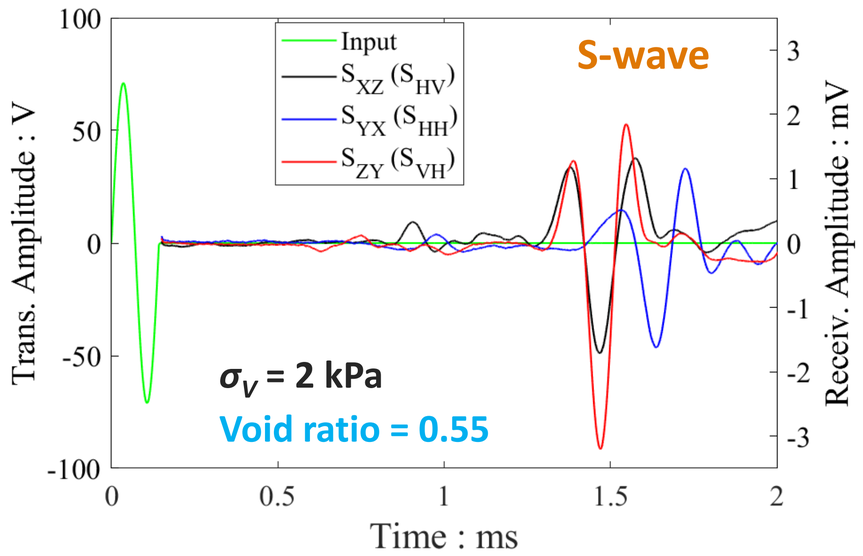
Soils are often considered to be anisotropic materials. However, the accurate measurement of soil stiffness in multi-directional directions is still a challenging research topic in the field of soil mechanics. To measure the stiffness anisotropy accurately, two soil boxes equipped with piezoelectric transducers have been developed since 2019.

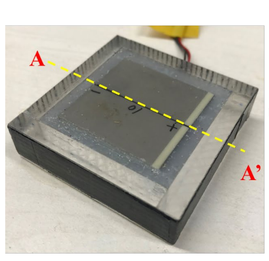
一般的な地盤材料は異方的性質を示すことが知られていますが，剛性の異方性を高精度に計測することは容易ではありません．当研究室では2019年以降，剛性異方性の計測を目的として，圧電素子センサーを多用した土槽の開発に取り組んでいます．2019度以降に開発した二種類の土槽の特徴と計測結果の例をを紹介します．

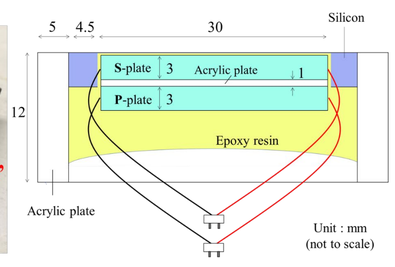
Version 2019

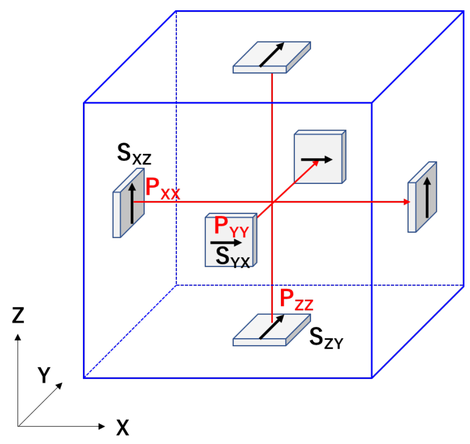








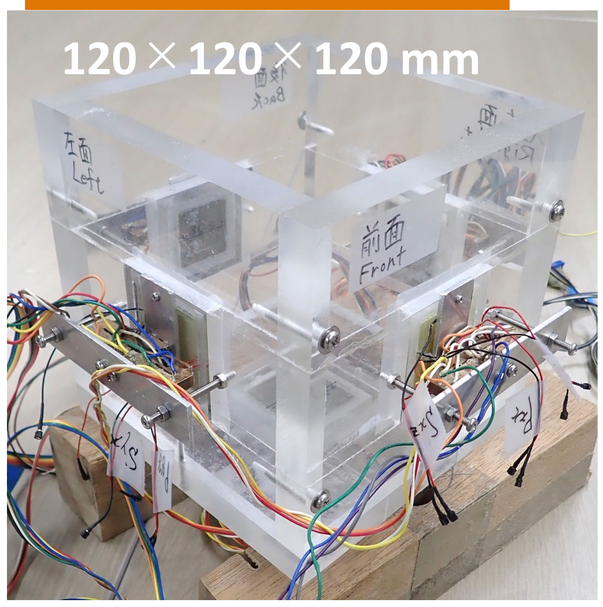




A preliminary design of soil box developed in 2019 is equipped with a pair of P-wave transducers and a pair of S-wave transducers in each principal direction, as schematically illustrated. Each piezoelectric transducer has its dimensions of 30 × 30 × 3 mm. A dense specimen composed of spherical glass beads was prepared in dry conditions with an overburden stress (σ_V) of 2 kPa. The results show that P-wave travels faster in the vertical direction compared to the horizontal directions. S-wave also travels faster when either propagation or oscillation is in the vertical direction, while the S-wave in the horizontal plane (S_{HH}) showed the slowest wave velocity. The larger vertical stress compared to the horizontal stress in the specimen is attributed to the larger wave velocities relating to the vertical direction.

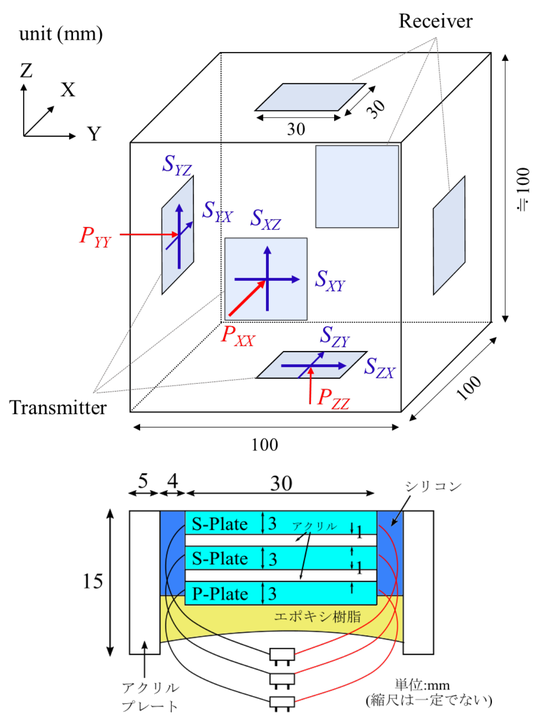
2019年度に試験的に開発した土槽はＰ波とＳ波の計測センサーを一組ずつ，図のように各主軸方向に設置しました．圧電素子センサーの形状は30×30×3mmであり，ガラスビーズで作製した密な地盤に上載応力2kPaを付加した状態で計測を行いました．Ｐ波は鉛直方向に速く伝播し，Ｓ波も鉛直方向に伝播あるいは振動する場合は速度が大きく，水平面内を伝播・振動する場合は速度が小最も小さいという結果を得ました．これは鉛直方向応力の方が水平方向応力よりも大きいためだと推察されます．

Version 2020



An enhanced design of soil box developed in 2020 is equipped with a pair of P-wave transducers and two pairs of S-wave transducers in each principal direction. Moreover, five loadcells are newly installed at the base and four side walls to measure the horizontal stress. This apparatus enables analyses between stress state in the specimen and nice kinds of elastic wave velocities.

2020年度に開発した改良版の土槽は，各主軸方向において，Ｐ波１組とＳ波２組の計測が可能です．また，底面と側方４面にロードセルを取り付け，新たに水平方向の土圧計測を可能としました．これにより，供試体内の応力状態と９方向の弾性波速度の関係について理解を深めることが可能となりました．



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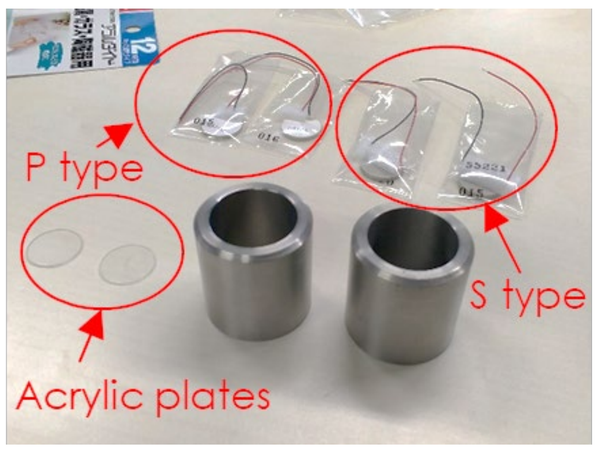
川口勇一郎 (2020)
桑野研究室
東京大学 生産技術研究所 Bw-304
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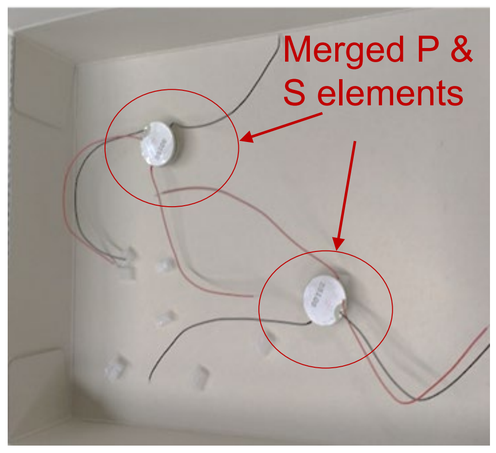
Evolution of Stress Wave Velocities During Triaxial Compression Using Disk Transducers

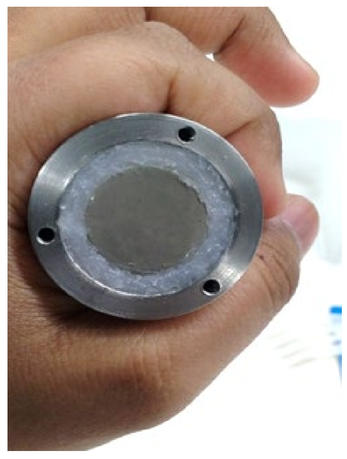
ディスクトランスデューサーを用いた三軸圧縮中の弾性波速度の評価

The precise assessment of stress wave velocities and stiffness is indispensable for the accurate design of structures as well as authentic geotechnical characterization of sediments. The development of the geophysical testing method is important to estimate the mechanical properties of in-situ soils. In the present study, planar piezoelectric transducers have been employed to measure the shear wave (V_s) and compression wave velocities (V_p) of silica sand in both isotropic and anisotropic stress states. Wave velocities of loose and dense specimens at large axial strain tend to converge similar to the stress-strain relationship. The increment of normal stress component (σ_1) has a significant influence on compression wave velocity as compared to shear wave velocity. This axial strain at which peak shear wave velocity is observed is comparable to the axial strain at which fabric of the specimen takes place.

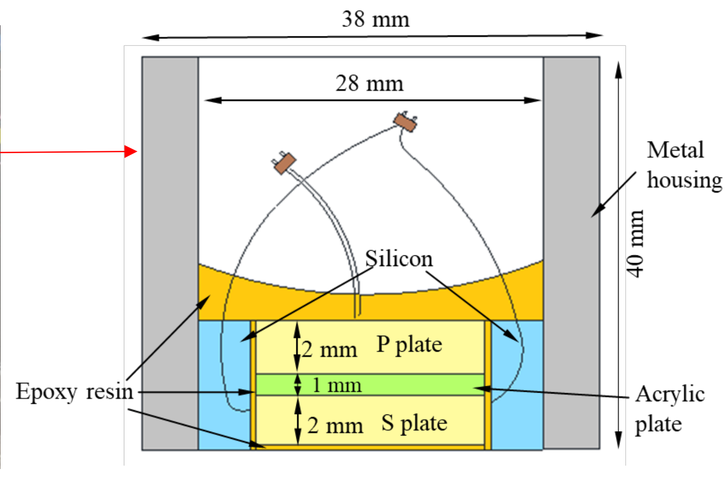
Development of Disk Transducers for Standard Triaxial Apparatus



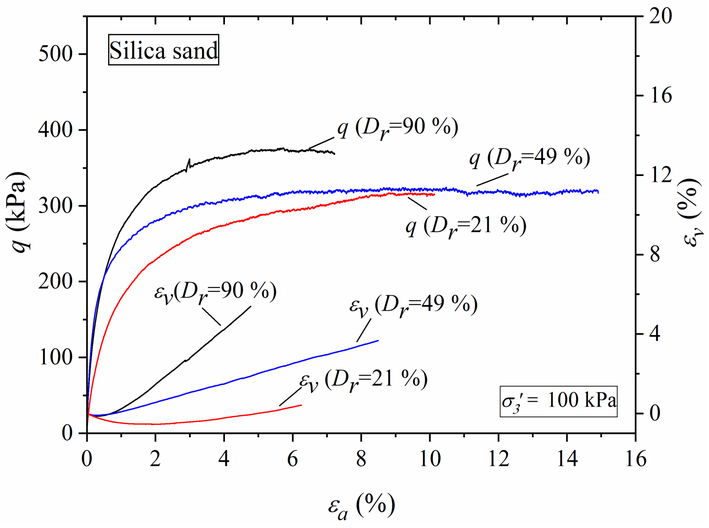




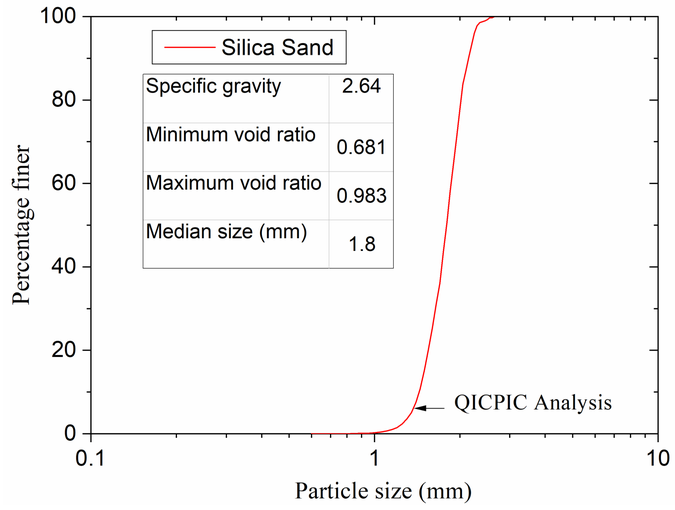


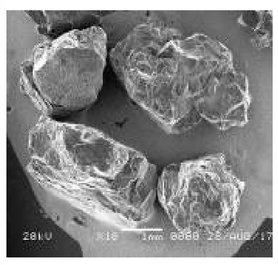


Deviator stress vs. axial strain

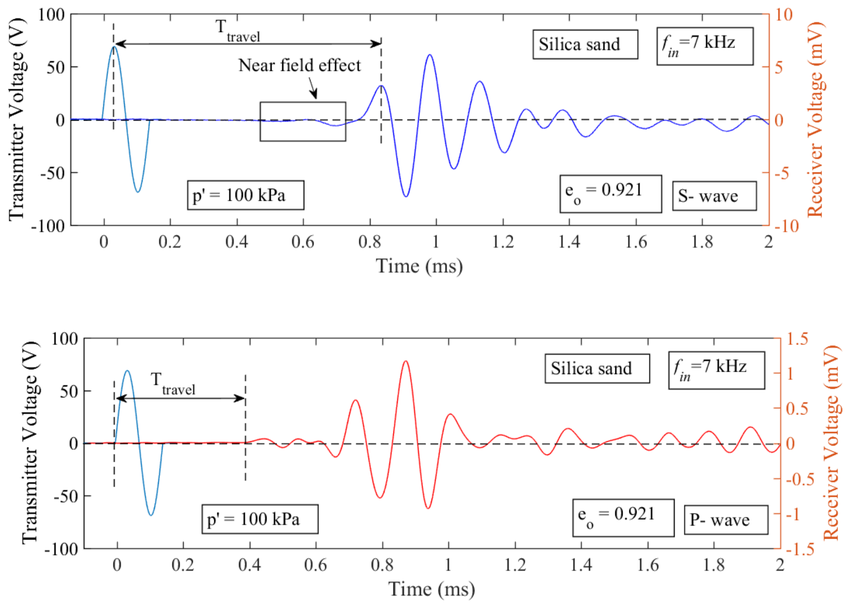


Tested Material

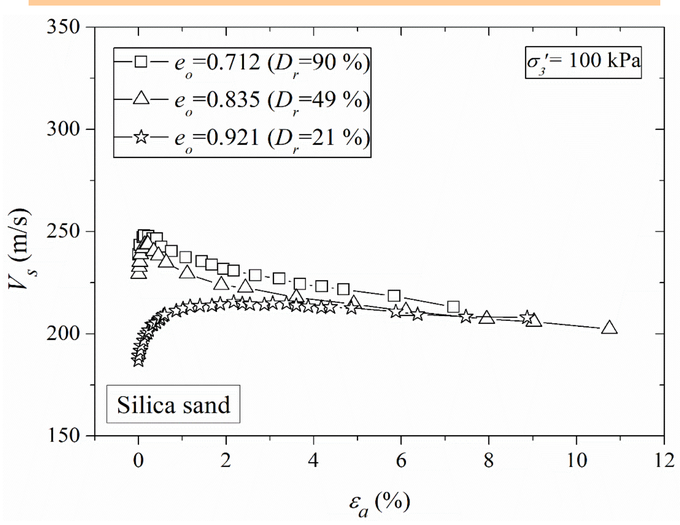


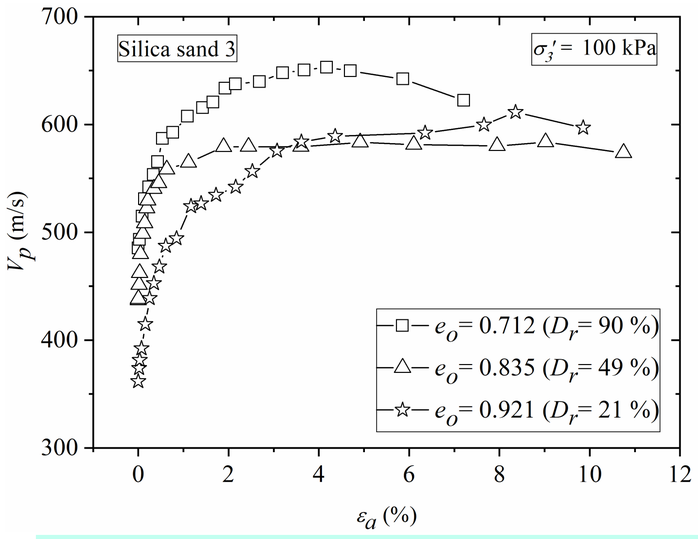


Silica sand



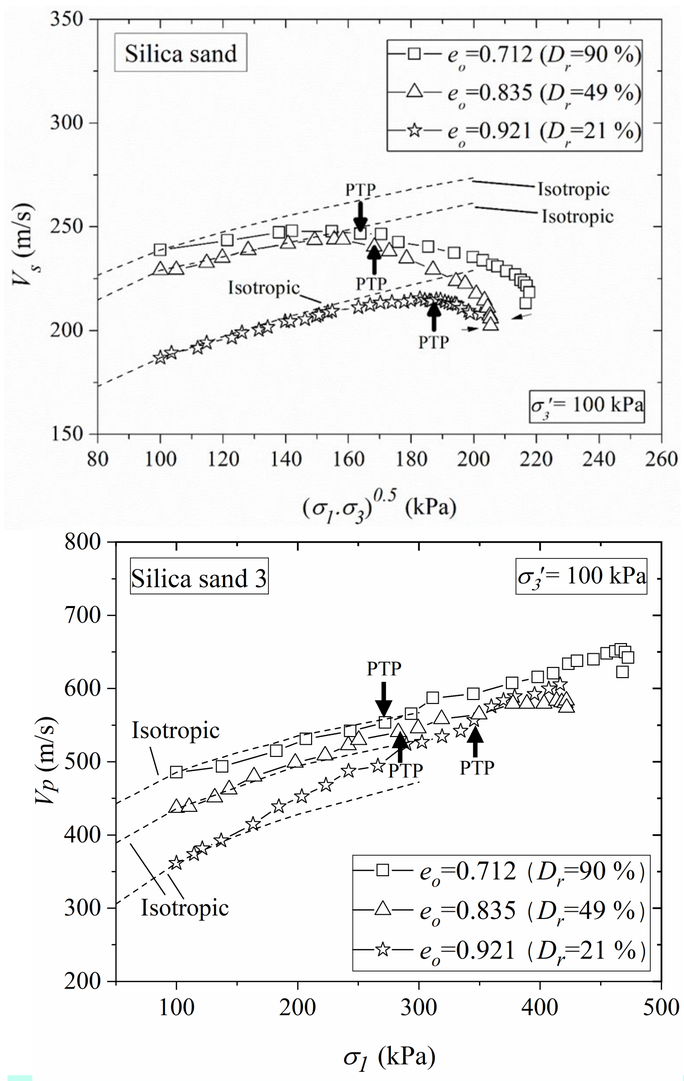
Wave velocities vs. axial strain



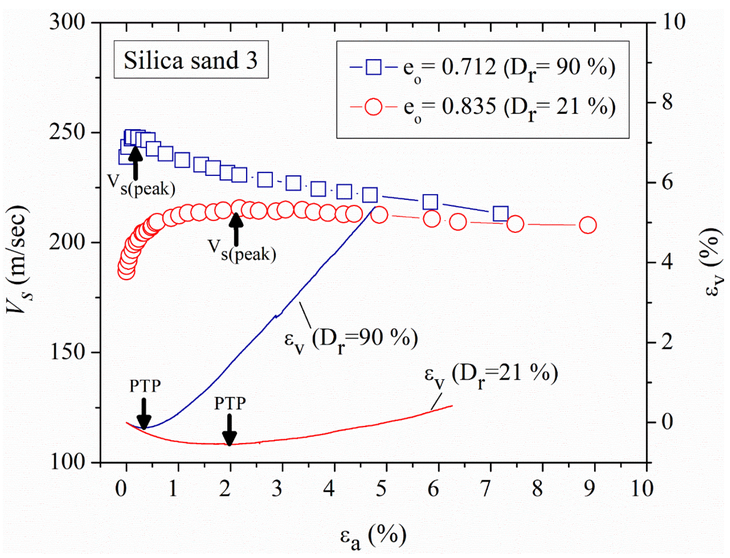


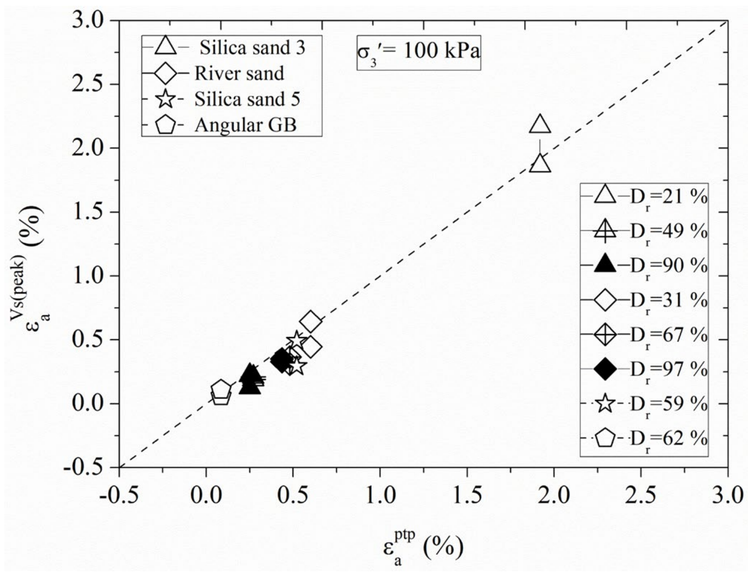
★ V_s & V_p of loose and dense specimens converge at large axial strain

Wave velocities vs. stress state



★ Increment of normal stress has substantial effect on V_p as compared to V_s





★ ε_a at peak Vs ≈ ε_a at which fabric of specimen changes

本研究に関する担当研究室は桑野研究室です.
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Troyee Tanu Dutta (2019)

Laboratory Test Measurement of Material Attenuation of Shear Waves Propagating in Sand

砂中でのせん断波伝播における内部減衰の室内試験測定

Abstract

The material attenuation characteristics of the ground are necessary for predicting the propagation of vibrations in the ground. This research focused on evaluating material damping of soil through laboratory tests using cylindrical specimens. Shear wave vibrations were measured on a cylindrical specimen. The validity of the method was examined by comparing the results of vibration tests conducted at a test field in Abira, Hokkaido, Japan, with the results of laboratory tests.

地盤内の振動伝播予測には、地盤の内部減衰特性の評価が必要である。本研究では、円柱供試体を用いた室内試験により地盤のせん断波の内部減衰特性を評価する手法を検討した。北海道安平町の試験場で採取したサンプル試料に対し室内試験によって内部減衰を評価し、同試験場で実施した振動試験の結果と比較した。伝播速度200m/sのせん断波において、室内試験と実地盤試験の内部減衰定数は概ね一致した。

Damping Formula

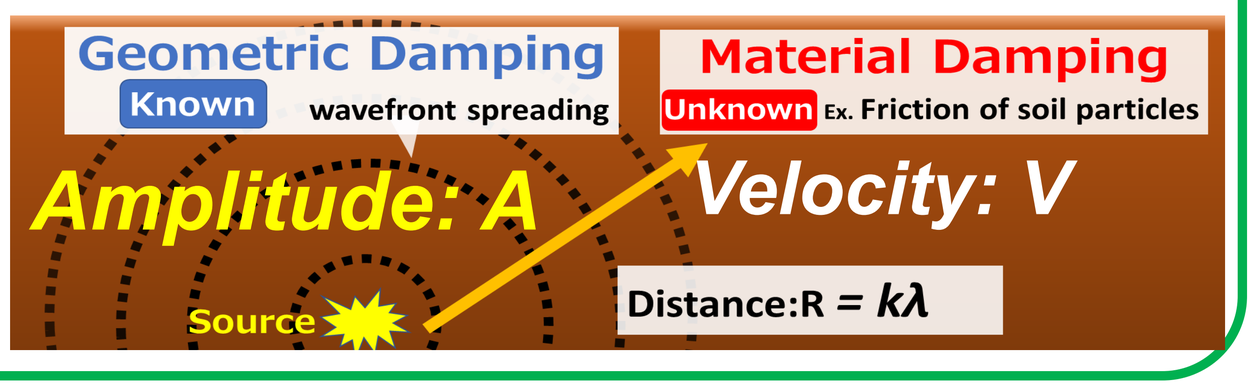
$$A = R^{-n} \times exp[-V \times \alpha_0 k]$$

1.Each wavelength of vibration has a specific amount of attenuation. [G. Bornitz , *J. Springer,* 1931]

Geometric damping is theoretically determined by the type of elastic wave and location of the source.

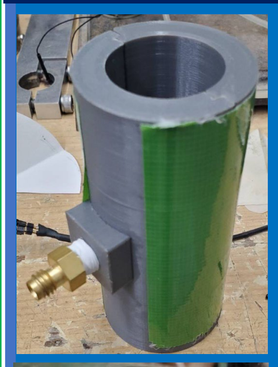
[*Geotechnical earthquake engineering and soil dynamics III*. No. 75, vol. 2, 1998. p. 1507-17.1]

1.**Material Damping is unknown factor** which depends on various factors such as friction of soil particles



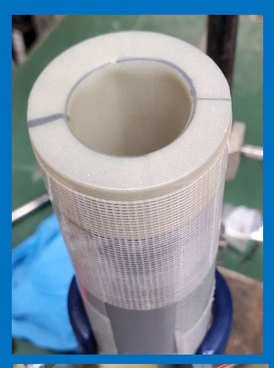
Laboratory test

How to make Specimens



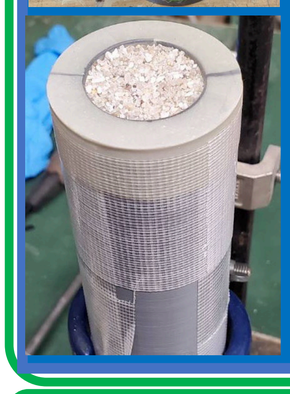
1.

The membrane is attached to the inside of the mold with an inner diameter of 30 mm.



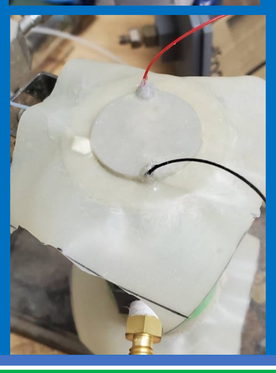
2.

Piezoelectric receiver is attached to the end of the membrane and attached with silicone glue



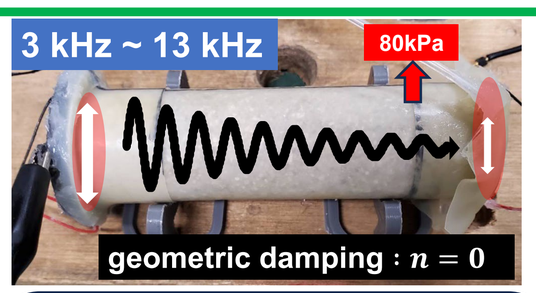
3.

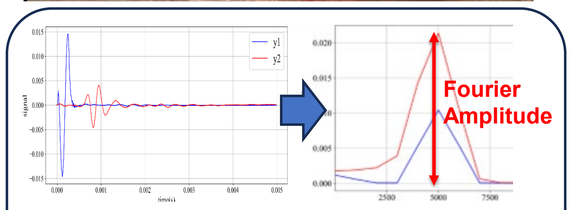
fill with material, tapping the side of the mold 30 times every 2cm



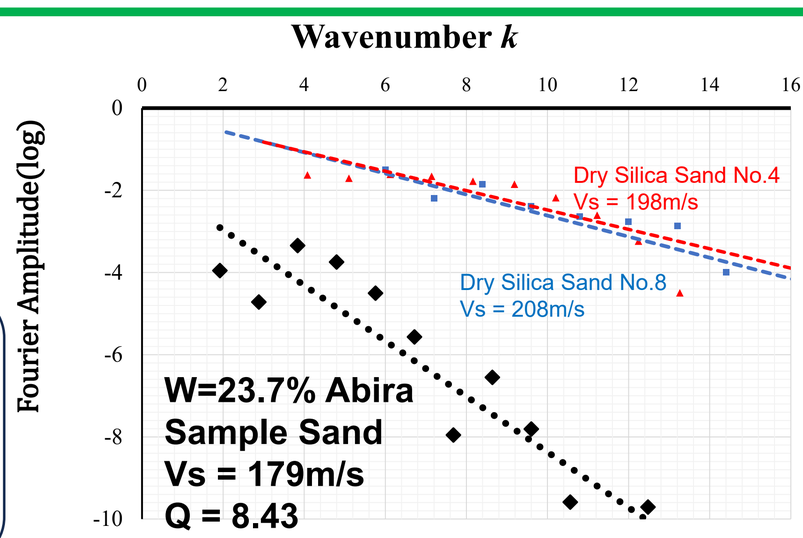
4.

membrane-covered PE on the receiver side was attached to cover the top surface.



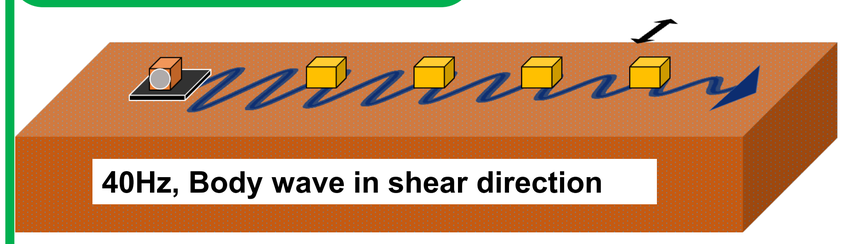


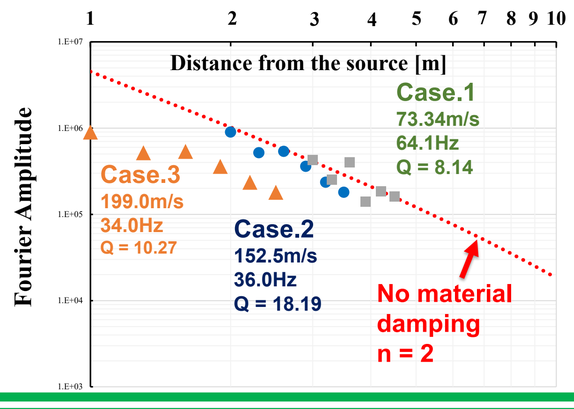
Amplitude attenuation was evaluated by discrete Fourier transform of the vibration



- **Excitation over the entire cross-section** results in excitation with **no wavefront extension (n=0)**
- The relationship between **the Fourier amp ratio** and frequency at the ends of the specimen and the **wavenumber conversion of the distance k**
- The Fourier amplitude ratio of vibration at the end face decreased as the excitation frequency increased.
- The sample sand from Abira town showed **about 49% of the amplitude was damped for every wavelength** advanced

Field test





- Calculate the energy decay constant α_0 by comparing the Fourier amplitude near the peak frequency with the propagating distance, then wavenumber conversion k
- The range of shear **wave velocity was 73.3~199 m/s**
- The calculated energy attenuation constant α_0 was $1.39 \times 10^{-3} \sim 10.1 \times 10^{-3}$, **about 20~50% of the amplitude was damped for every wavelength** advanced

Results

	Field test (n = 2)			Lab test (n = 0)
	Case 1	Case 2	Case 3	
Velocity [m/s]	73.34	152.53	199.0	204.5
Frequency [Hz]	64.1	36.0	34.0	3000~13000
$\alpha_0 \times 10^{-3}$ $[s/m]$	**10.1**	**1.39**	**2.38**	**3.78**
Q value	8.14	18.19	10.27	8.43

- Comparing the field tests and the laboratory tests on the Abira sand, the results were **consistent when propagation velocities were close to 200 m/s.**
- The calculated energy attenuation constants α_0 were $1.39 \times 10^{-3} \sim 10.1 \times 10^{-3}$, which were **close to those of the coarse-grained and loosely packed sand**(α_0 = $1.800 \sim 2.050 \times 10^{-3}$),
- About **20~50% of the amplitude was damped for every wavelength** advanced [XJ. Yang ,1995, Evaluation of man-made ground vibration]

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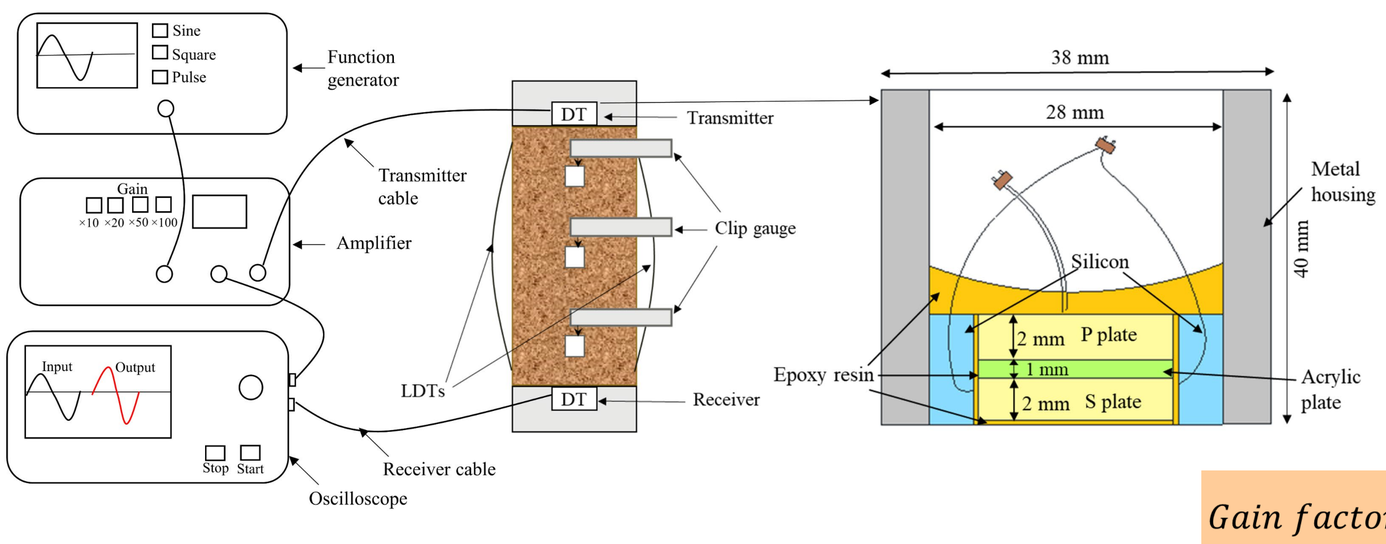
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Apparent particle size dependency and selection of ideal excitation frequency range

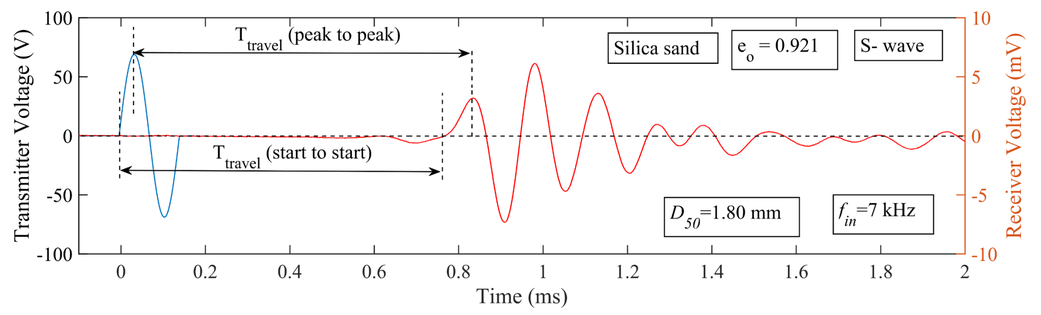
弾性波速度における粒径の影響と最適振動周波数の選択

For assemblies of spherical particles with Hertzian contacts, the stress wave velocities should not depend on median particles size (D_{50}). However, a link between D_{50} and stress wave velocity has been reported in experiments. To identify the reasons for discrepancies, wave velocity measurements were performed using disk transducers on four different D_{50} glass beads. The results indicate that shear (V_s) and compression (V_p) wave velocities are independent of D_{50}. The maximum frequency that can propagate through a granular assembly (lowpass frequency) reduces with increasing D_{50}. For V_s, selected input frequencies should match frequencies which exhibit largest gain factors and input frequencies should not exceed half of lowpass frequency. To determine V_p, it is suggested to adopt start to start method and to choose an input frequency which is slightly lower than the lowpass frequency.

Assembly for stress wave measurements



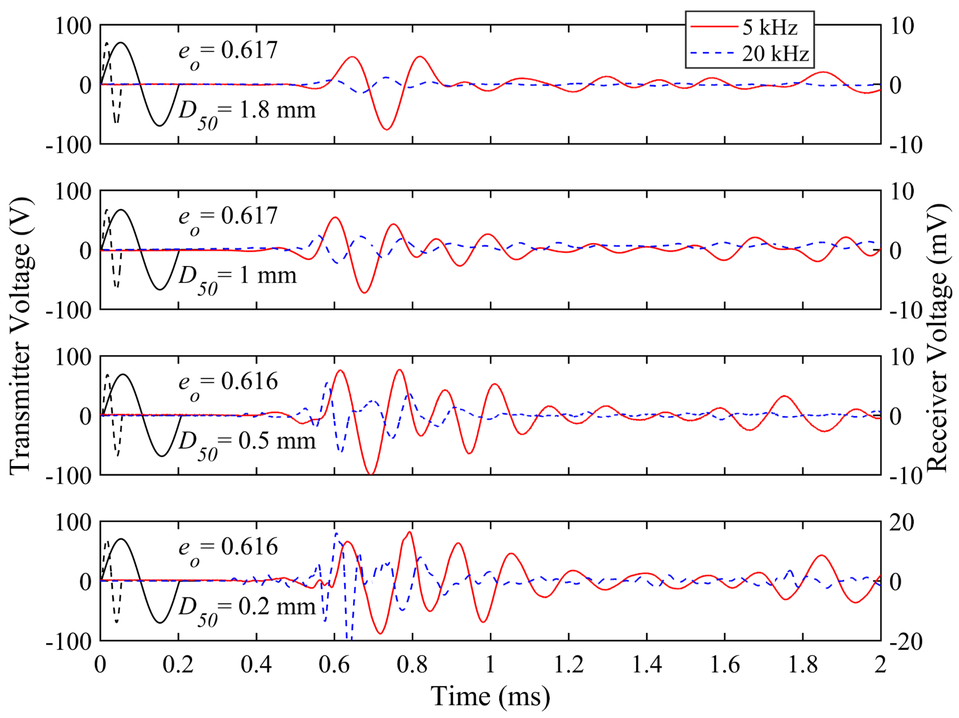
Two conventional methods for estimating travel time

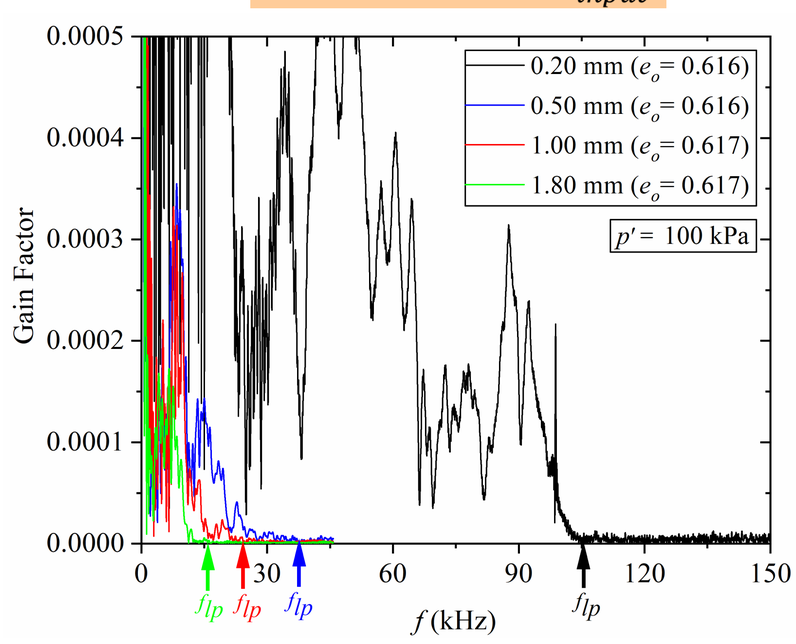


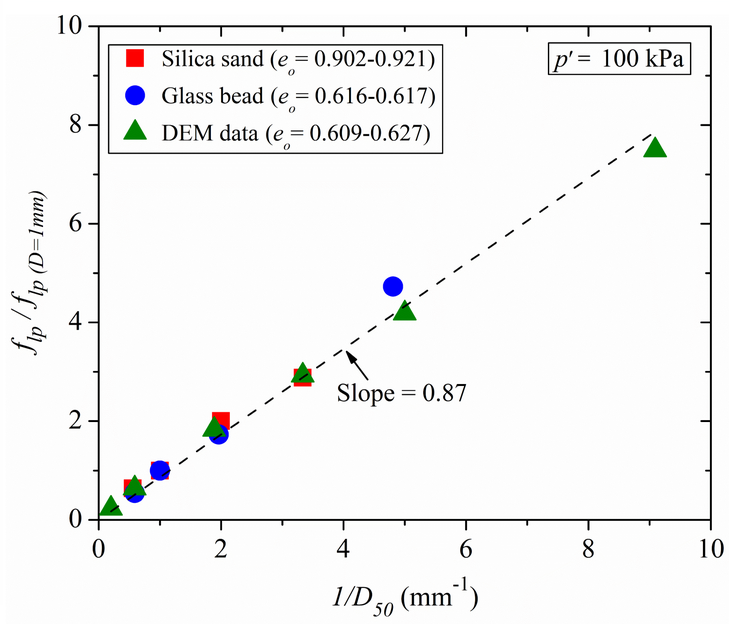
$V_s \propto L f_{lp}$ (from dispersion theory)

$$Gain\ factor = \frac{FFT_{output}}{FFT_{input}}$$

★ *Low pass frequency (f_{lp}) is the maximum transmitted frequency*



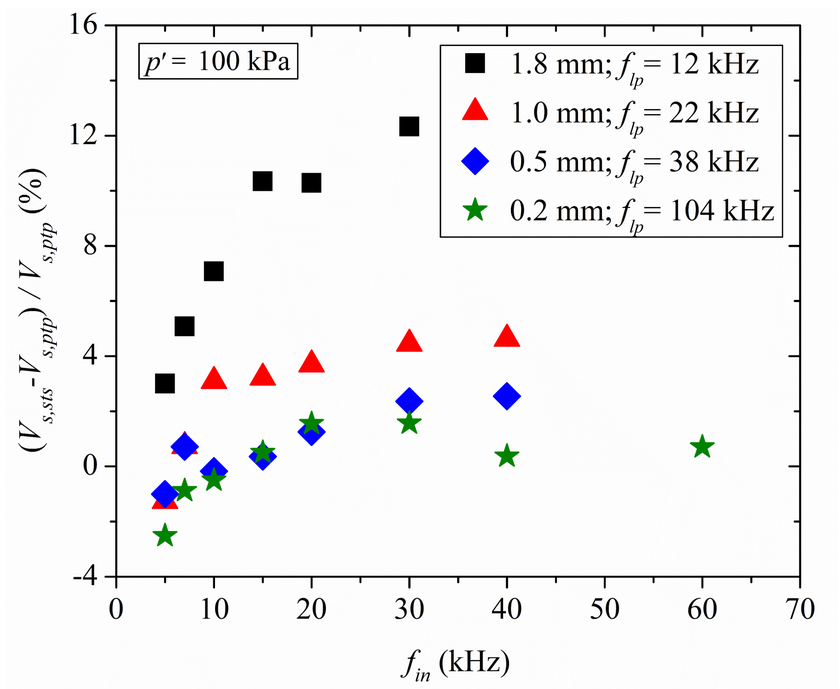


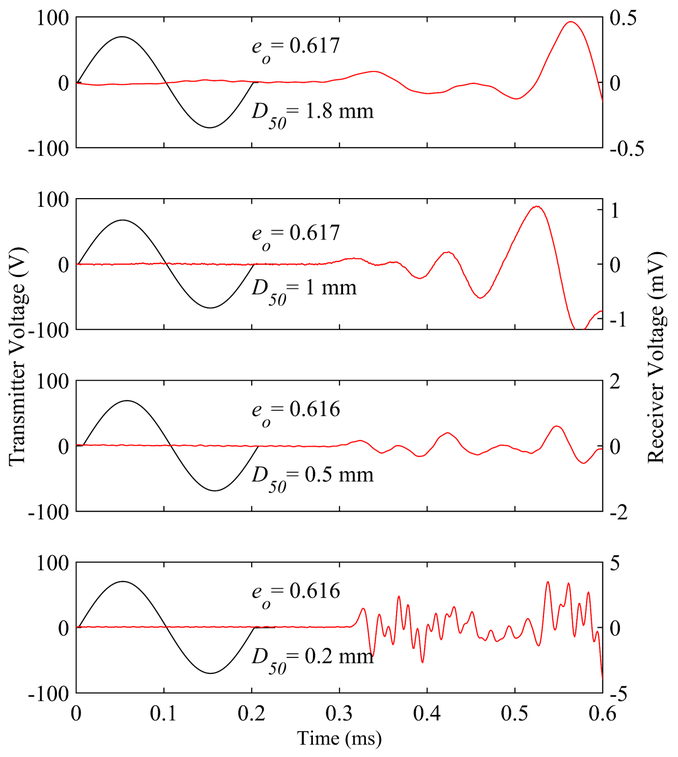


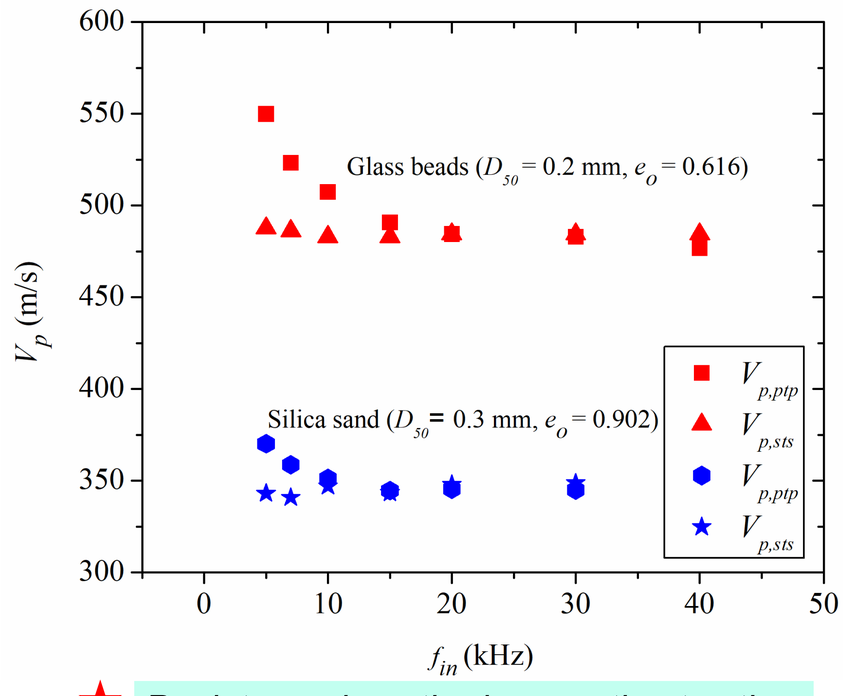
★ *S- wave travel time is independent of D_{50}*

★ *Range of frequency propagation increases with decreasing D_{50}*

★ *Low pass frequency varies linearly with $1/D_{50}$*







★ *% difference between V_s measured from sts and ptp increases, when $f_{in} < f_{lp}/2$*

★ *For V_s, f_{in} should match frequencies which have maximum gain factors and f_{in} should not exceed $f_{lp}/2$*

★ *P-wave travel time is independent of D_{50}*

★ *Wave lengths of output signal does not match input for lower D_{50} specimens*

★ *Peak to peak method overestimates the P- wave velocities*

★ *For V_p, start to start method and $f_{in} < f_{lp}$ should be used*

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Troyee Tanu Dutta (2019)

Anisotropy of Shear Wave Velocity
- Role Of Grain Shape -
せん断波速度の異方性 - 粒子形状の影響

The mechanical properties of granular soils such as soil stiffness or strength depend on the direction of measurement. Until now, fundamentals of stiffness anisotropy have not been fully understood. In this study, four types of granular materials: spherical glass bead, Toyoura sand, Indica rice and wild rice are used to figure out particle shape effects on anisotropy of shear wave velocities. Besides, this study developed a cubical box equipped with multi-directional shear plates by which both P- and S-waves can be generated and received to understand the effect of particle shape on the anisotropy of multi-directional shear wave velocities.

地盤材料のような粒状体は力学的に異方性を示す。特に、地盤剛性や最大強度に関しては長年にわたって議論されてきた。しかし、いまだ経験的な解釈に留まっているのが現状である。本研究では、地盤剛性の異方性に対する粒子形状の影響を明らかにするために、4種類の粒状体（ガラスビーズ、豊浦砂、インディカ米、ワイルド米）を用いて弾性波（P波、S波）の計測を行った。地盤剛性の固有異方性を精度良く評価するために、3主軸方向にディスクトランスデューサーを搭載した立方体土槽を新たに製作した。

(1) Introduction : Anisotropy is the property of being directionally dependent, as opposed to isotropy, which means homogeneity in all directions. It can be defined as a difference in one soil mechanical property along different directions. Soil stiffness is one of the most important material properties that describe the relationship between stress and strain. Accurate measurement of multi-directional soil stiffness is still a challenge for experimentalists. However, recently, disk-transducer comprised of piezoelectric materials (referred to here as shear plate) has gained its popularity with several advantages over bender elements: soil specimen is not disturbed during sample preparation, coarse grains can be tested, more planar P- and S-waves can be generated.

(2) Materials

Four types of non-cohesive granular materials were used, they have narrow ranges of particle size distribution.



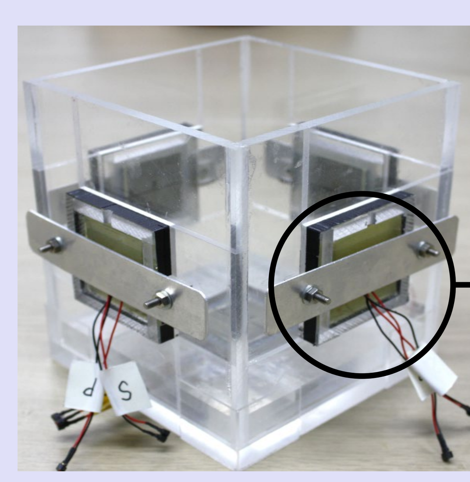
Glass Bead　Toyoura Sand　Indica Rice　Wild Rice

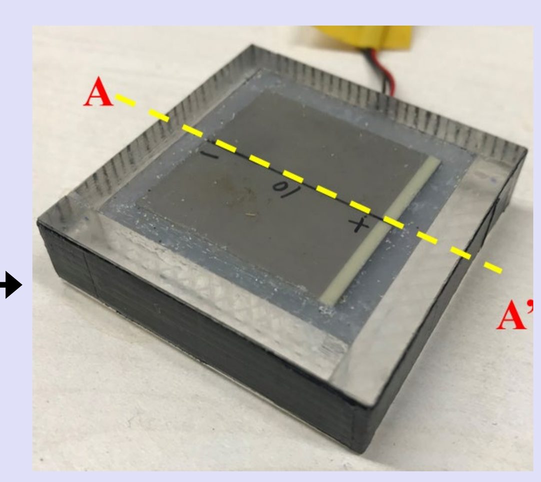
Material	Aspect Ratio	Dry Density g / cm³	$V_{S,HV}$ / $V_{S,VH}$	$V_{S,HH}$ / $V_{S,VH}$
GB	0.933	1.61	1.01	0.90
TS	0.592	1.63	1.04	1.13
IR*	0.221	0.916	1.00	1.23
WR	0.158	0.873	1.00	1.38

*Indica Rice : tested at $\sigma_{V'} = 1$ kPa; the others at $\sigma_{V'} = 2$ kPa

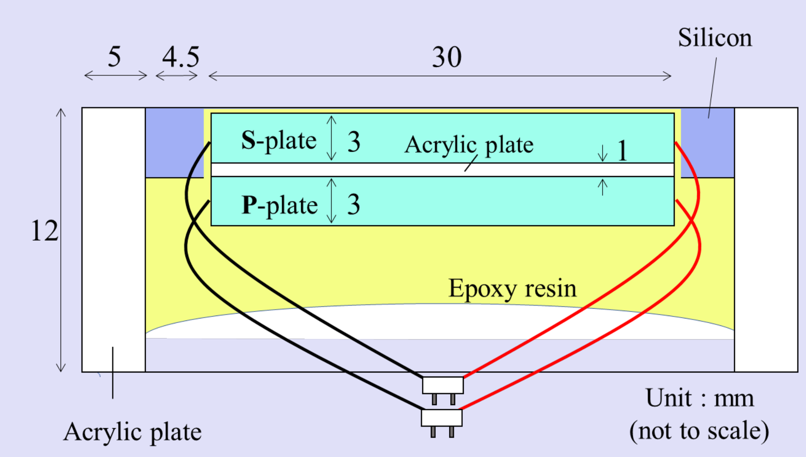
(3) Cubical Soil Box and Shear Plate Configuration

A cubical soil box made of acrylic plates was assembled (100×100×100 mm.) Each face of the soil box had a square hole and it can facilitate an assembly of shear plate transducers


Cubical Soil Box



Shear Plate Transducer

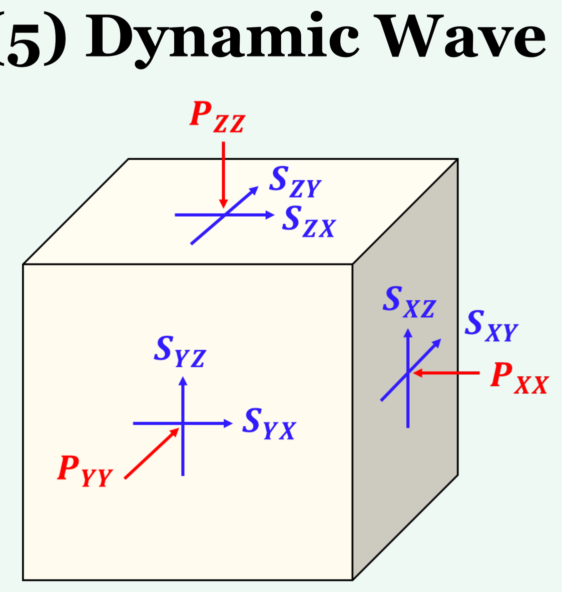


Schematic of design configuration of shear plate

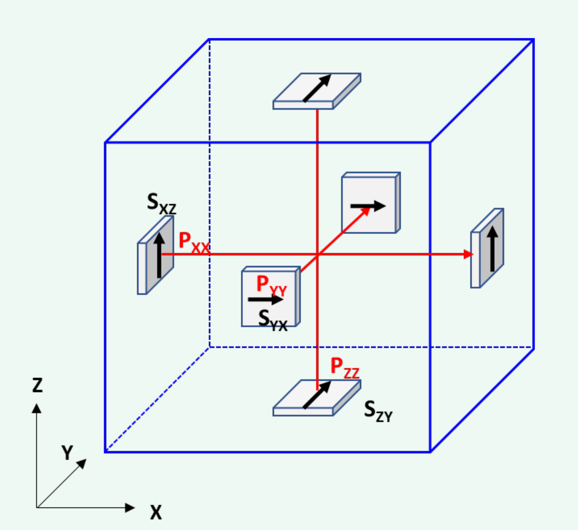
(4) Sample Preparation

- The materials were pluviated into the soil box with a dry condition.
- The height of each layer was approx. 10 cm.
- Wave measurements were conducted at three stress levels: $\sigma_{V'} = 0.3$, 1 and 2 kPa.

(5) Dynamic Wave Propagation Tests



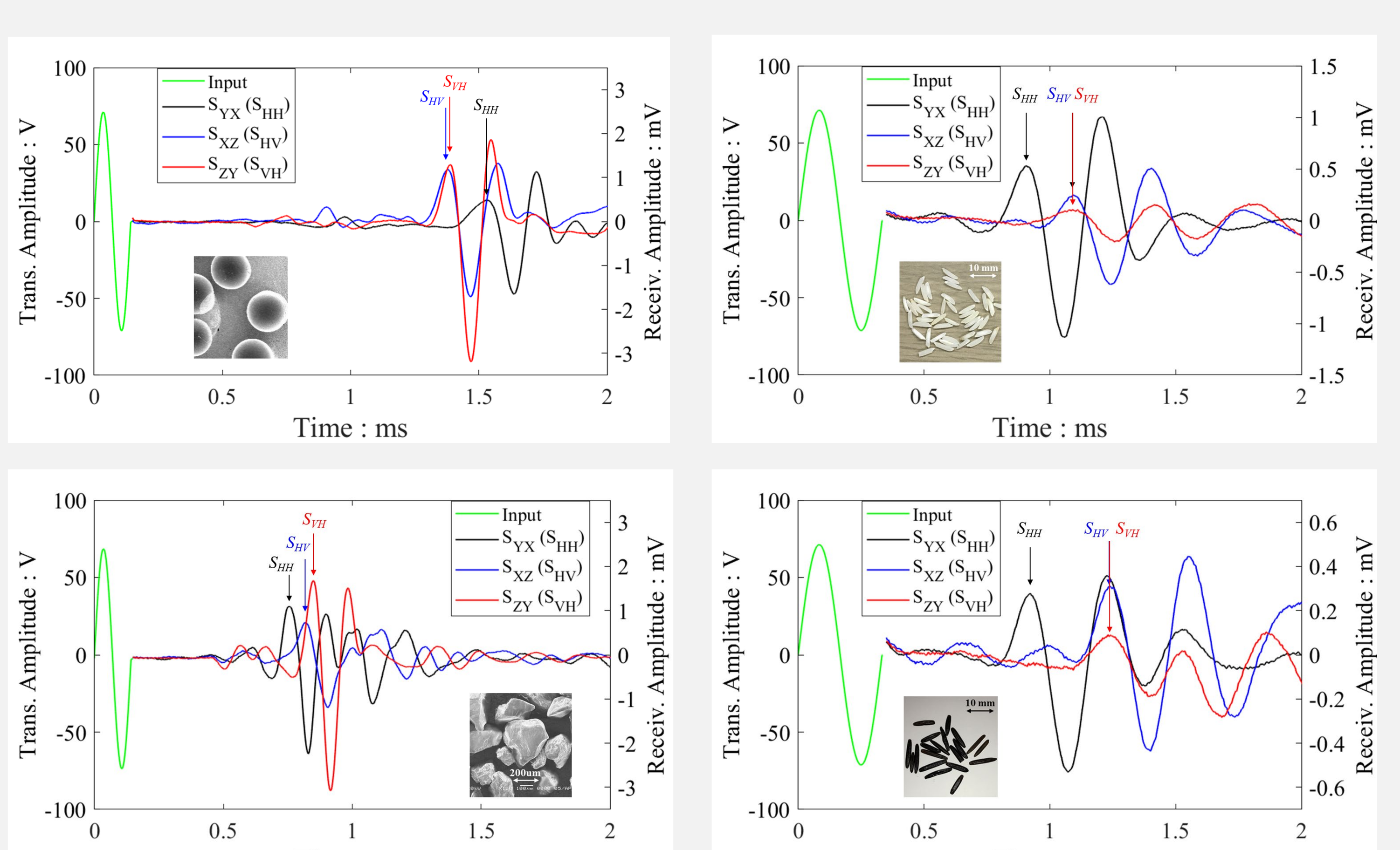
- There are nine types of elastic wave components as illustrated the left hand.
- The first subscript indicates the direction of wave propagation and the second subscript corresponds to the direction of wave oscillation.

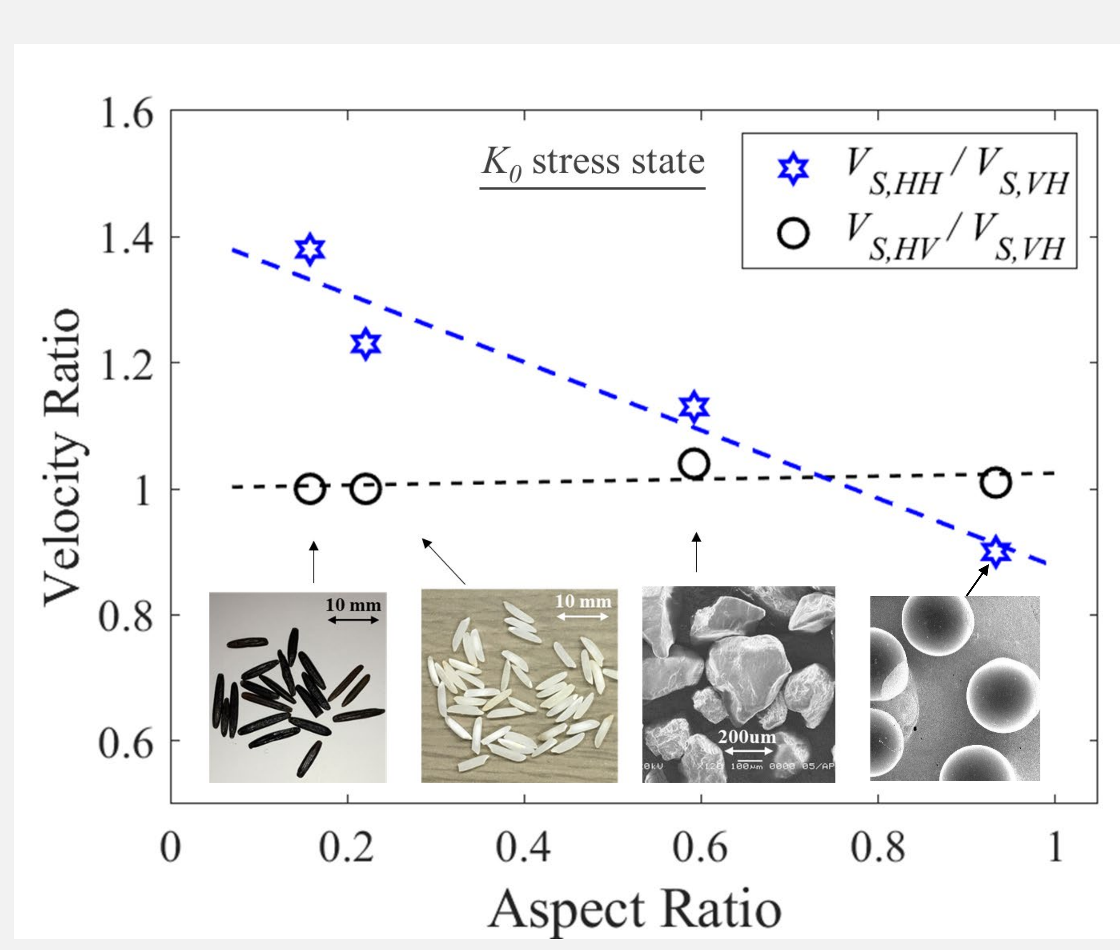


- The present test setup provides three types of P-waves, i.e. P_{XX}, P_{YY} and P_{ZZ}, and three types of S-waves, i.e. S_{YX}, S_{XZ} and S_{ZY}
- Homogeneous distribution of particle orientation in the horizontal plane is assumed. Horizontal components are expressed as H, while Z components are expressed as V. Therefore, the three S-wave components are S_{HH}, S_{HV} and S_{VH}.

(6) Experimental Results

The results focus only on S-wave signals to discuss the anisotropy of shear wave velocities.





- A decreasing trend of $V_{S,HH}/V_{S,VH}$ is observed for increased aspect ratio. The maximum value of $V_{S,HH}/V_{S,VH}$ is 1.38 for wild rice.
- $V_{S,HH} > V_{S,VH}$ in general. Only spherical glass bead shows $V_{S,VH} > V_{S,HH}$, probably due to larger stress in the vertical direction with insignificant inherent anisotropy of the specimen.
- The symmetry components, $V_{S,HV} \fallingdotseq V_{S,VH}$ under K_0 stress states .

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Junming Liu (2019)

Anisotropy of Shear Wave Velocity - Role of Grain Orientation -

弾性波伝播速度に現れる粒状体の異方性と粒子配列の関係

Anisotropic soil does not have the same physical properties such as soil stiffness when the direction of measurement is changed. Until now, fundamentals of soil stiffness anisotropy has not been understood comprehensively. In this study, a special elongated granular materials: wild rice was used to figure out the influence of particle orientation on the anisotropy of multi-directional shear wave velocities with the help of a cubical soil box equipped with multi-directional shear plates by which both compression and shear waves can be generated.

弾性波速度測定を用いて地盤材料の微小ひずみ剛性の異方性を把握する試みは、ベンダーエレメントを供試体の水平方向に導入するなどして検討されてきた。しかしながら、弾性波速度測定から得られる微小ひずみ剛性と微小繰返し載荷試験から得られる微小ひずみ剛性に差異があったり、対称性の成立が実験で確認できないなど、未だ不明な点を残している。本研究では、鉛直・水平方向の境界条件が同等な立方体の土槽に、P波・S波の同時測定が可能なディスクトランスデューサーを装着し、ワイルド米を用いて弾性波速度の異方性と粒子配列の関係を調べた。

(1) Introduction

Most soils display stiffness anisotropy, as the stiffness of soil assemblies depends on the direction. stiffness of a body is defined as the resistance of that body to deformation under applied force. And the stiffness properties, i.e. shear moduli G, can help to evaluate the degree of deformation. Stiffness anisotropy can be classified into stress-induced anisotropy due to anisotropic stress states, and fabric-induced anisotropy caused by the geometry of the soil particles and soil packing. However, there is limited research available on the influence of particle shape and packing characteristics, i.e. particle orientation, on the fabric-induced stiffness anisotropy of granular materials such as gravel and sand.

In evaluating fabric-induced anisotropy, three shear moduli, G_{hh}, G_{hv}, and G_{vh} (where the subscripts v and h refer to the vertical and horizontal directions), are usually evaluated by shear wave (S-wave) measurement methods.

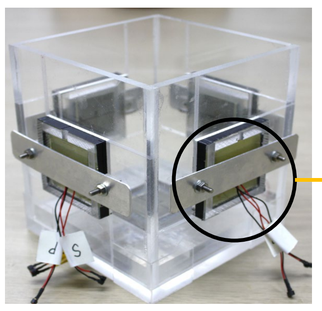
(2) Methodology and Apparatus

This research adopted shear wave measurement methods and three shear moduli G_{hh}, G_{hv}, and G_{vh} were calculated from the equation

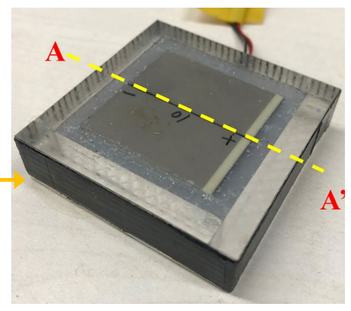
$$G = \rho v_s^2$$

where ρ is soil density; v_s is shear wave velocity measured by an acrylic cubical soil box.

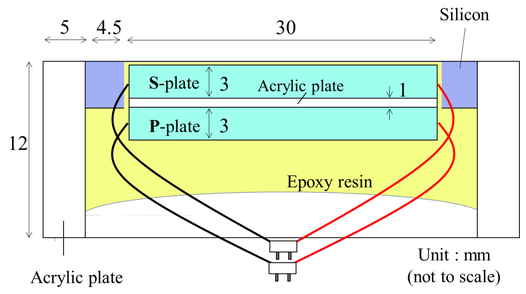
The cubical soil box was made of acrylic plates and was assembled in which a soil specimen can be prepared with dimensions of 100×100×100 mm. Each face of the soil box had a square hole and it can facilitate an assembly of planar piezoelectric transducers.



Cubical Soil Box



Shear Plate Transducer



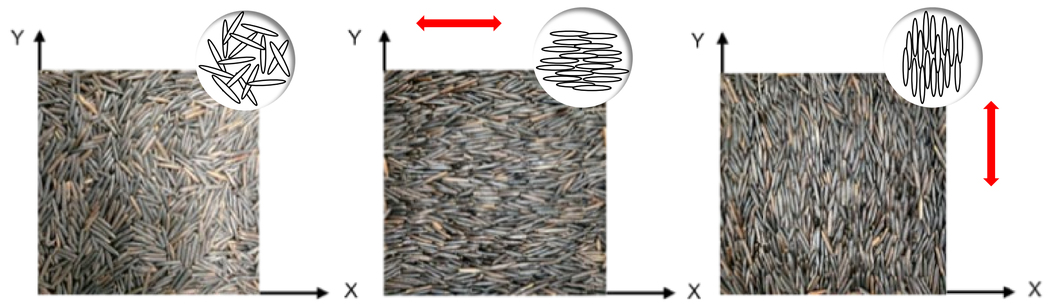
Schematic of design configuration of shear plate

(3) Sample Preparation

a special elongated granular materials: wild rice was used in this study because its longer axis can be easily placed along a specific direction.

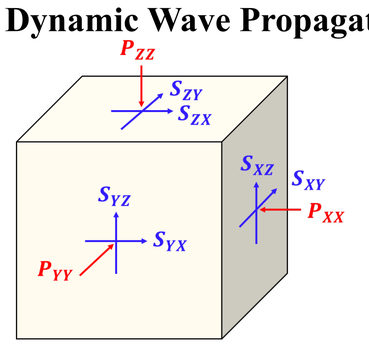
Four specimens with different particle orientation were prepared:

- **Random orientation condition**: wild rice was pluviated into the soil box under dry condition
- **One direction orientation condition**: 3 specimens were prepared under two orientation conditions: one was the X axis orientation specimen and the other two were Y axis orientation specimens

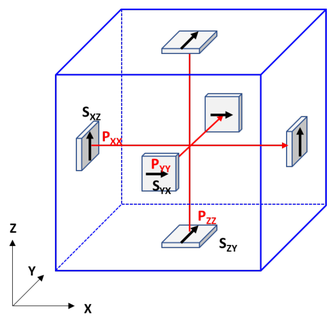


Random orientation　X axis orientation　Y aix orientation

(4) Dynamic Wave Propagation Tests



- Considering both P- and S-waves, there are nine types of elastic wave components as illustrated the left hand.
- The first subscript indicates the direction of propagation and the second subscript corresponds to the direction of oscillation.



- The present test setup provides three types of P-waves, i.e. P_{XX}, P_{YY} and P_{ZZ}, and three types of S-waves, i.e. S_{YX}, S_{XZ} and S_{ZY}
- Assuming homogeneous distribution of particle orientation in the horizontal plane, X and Y components can be treated equally, thus expressed as H, while Z component is treated as V in this study. Therefore, the three S-wave components are expressed as S_{HH}, S_{HV} and S_{VH}.

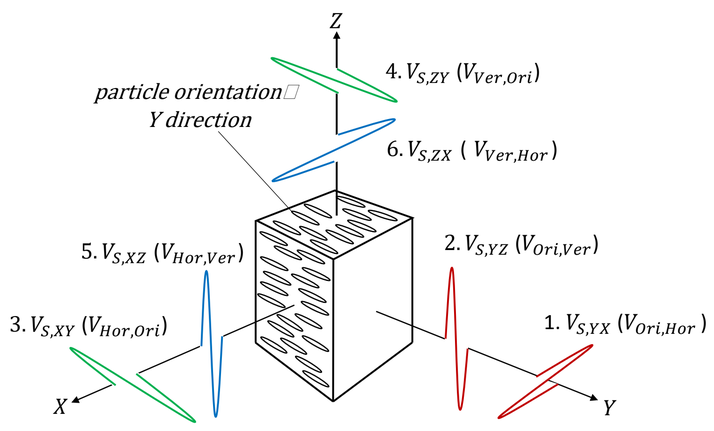
(5) Experimental Results

Three notations of Ori, Hor and Ver are used to represent the particle orientation, the direction perpendicular to particle orientation within horizontal plane and the vertical direction, respectively. According to the results above, the relative magnitude of shear wave velocities can be described as:

$$v_{Ori,Hor} > v_{Ori,Ver} > v_{Hor,Ori} > v_{Ver,Ori} > v_{Hor,Ver} > v_{Ver,Hor}$$

The first and second subscripts indicate the direction of the S-wave propagation and oscillation, respectively, i.e., $v_{Ori,Hor}$ represents the shear waves that propagate along particle orientation and oscillate within the horizontal plane; $v_{Hor,Ver}$ means the shear waves that propagate perpendicularly to the particle orientation within the horizontal plane and oscillate along the vertical direction.

In general, when the particle orientation is fixed, the direction of S-wave propagation is the most important direction to determine the relative magnitude of shear wave velocities, then the second important one is the direction of S-wave oscillation. The least important one is the vertical direction.



(6) Features and Uniqueness of the Research

- **Adoption of planar piezoelectric transducer developed at U-Tokyo**: compared with bender element, which is widely used in previous studies, planer transducer has several advantages: soil specimen is not disturbed during sample preparation, coarse grains can be tested, and more planar P- and S-waves can be generated to make accurate measurement of multi-directional stiffness
- **Consideration of the influence of particle orientation: t**hanks to the elongated wild rice, it is possible to dispose particles at specific directions. This makes the research unique, as it systematically discussed the effect of particle orientation ignored by previous studies.

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Anisotropy of Shear Wave Velocity
Role of Experimental Boundary Conditions

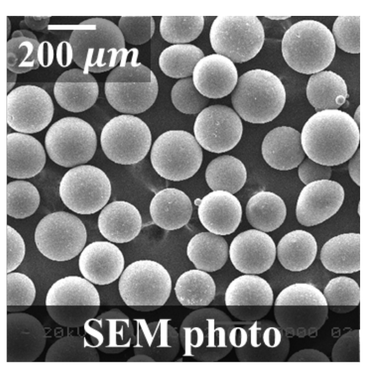
弾性波伝播速度に現れる粒状体の異方性と境界条件の関係

Natural soils display directional diversity in stiffness at small strains, which is significant for geotechnical engineering. However, the understanding of the stiffness anisotropy of soils is still limited. This research focuses on the extrinsic anisotropy induced by the experimental boundary conditions and conducts a series of shear wave propagation tests on specimens with various boundary conditions. Results reveal that a combination of rigid and flexible boundaries can cause greater stiffness anisotropy in the tested materials. Additionally, the mixed boundary conditions may induce the difference between the symmetric shear moduli G_{hv} and G_{vh}

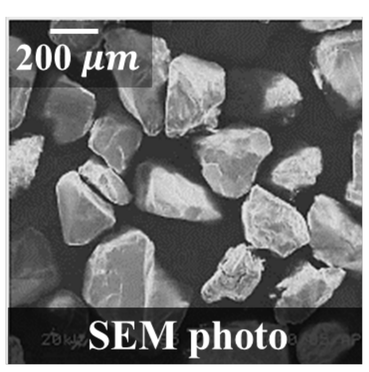
自然地盤では微小ひずみ領域にて剛性の異方性があります。しかし、地盤剛性の異方性への理解は未だ限定的であり、その一因は実験条件の制約にあると考えられます。本研究では、実験時の境界条件に起因する見かけの異方性に焦点を当て、様々な境界条件における供試体内部のせん断波の伝播特性を調べました。その結果、剛な壁面とメンブレンを用いた柔な壁面を併用した場合に、対称的なせん断弾性率（G_{hv} と G_{vh}）の値に差異が生じ、材料特性に由来しないと思われる異方性が見られました。

Materials and Apparatus

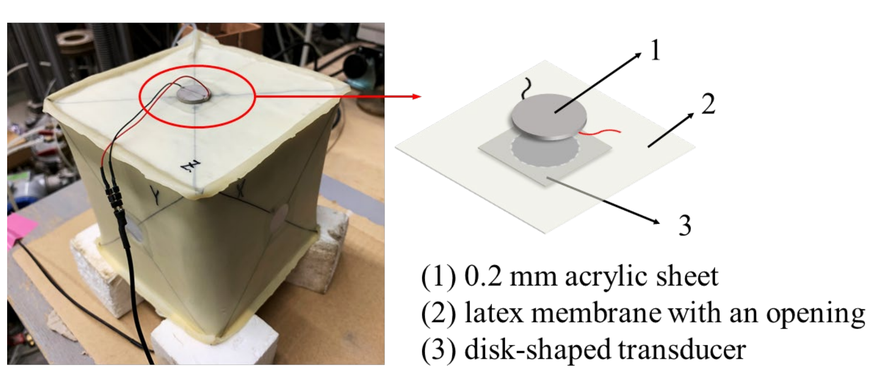
Discussions in this study are based on experimental results of two granular materials: spherical glass beads (GB) and Toyoura sand (TS). The tested materials were contained in the flexible boundary cubical cells under isotropic confinement.



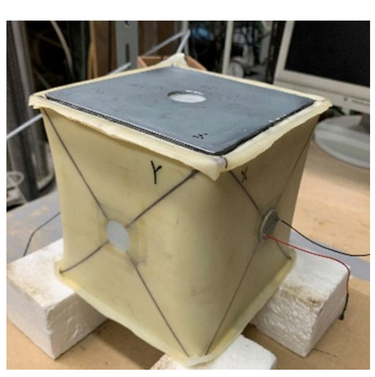
Spherical glass bead



Toyoura sand



Preparation of flexible boundary specimen



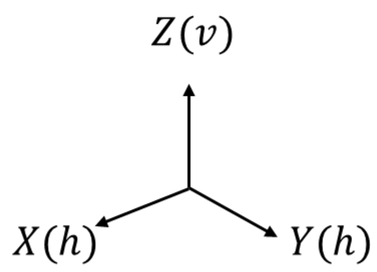
A specimen with mixed boundaries

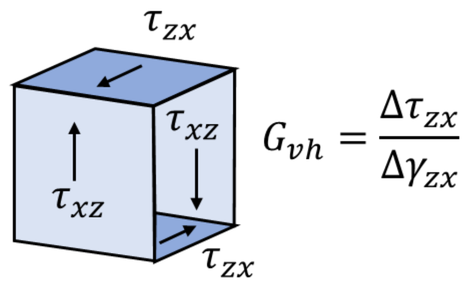
Methodology and Dynamic Wave Propagation Tests

- In S-wave propagation tests, G_0 can be calculated from shear (S-) wave velocities (V_s) according to the following equation (where ρ is soil density):

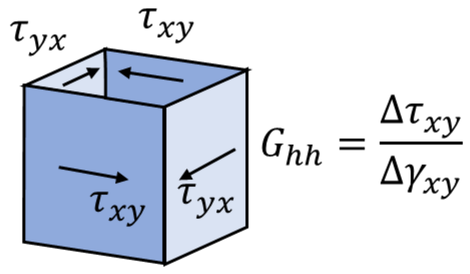
$$G_0 = \rho V_s^2$$

- The S-wave propagation tests were conducted using piezoelectric disk-shaped transducers

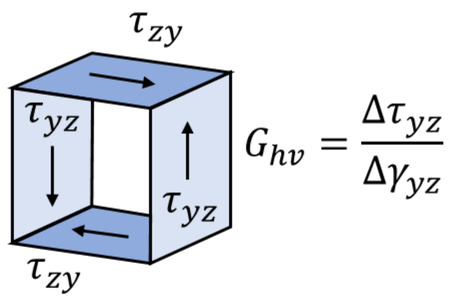




shear: zx −direction



shear: xy −direction

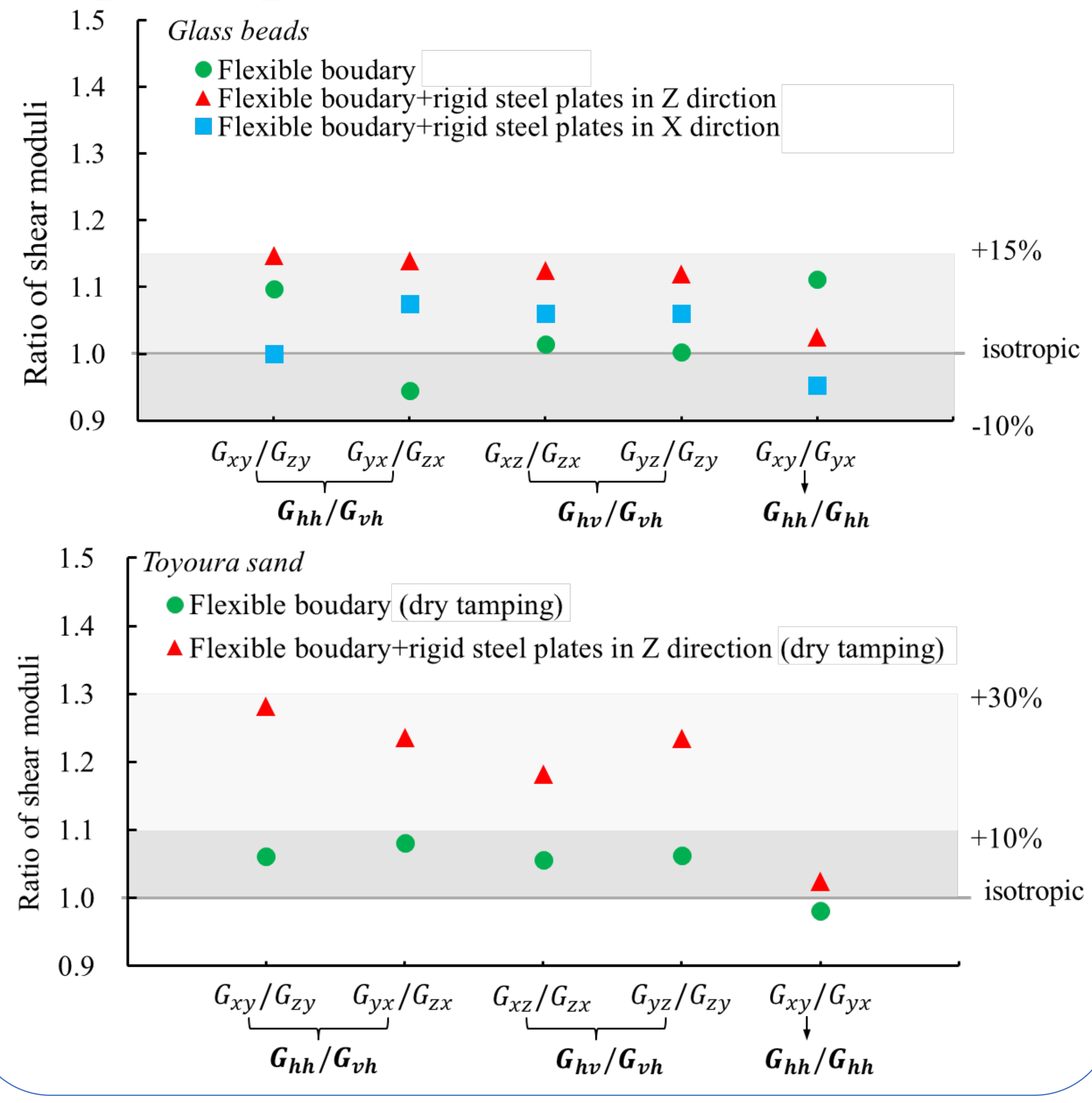


shear: yz −direction

Schematic definition of shear moduli

Experimental Results

- Mixed boundaries may contribute to larger degree of anisotropy of tested material
- Mixed boundaries may induce the discrepancy between G_{hv} and G_{vh}.



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Effects of propagation and oscillation directions of shear waves transmitted in granular materials

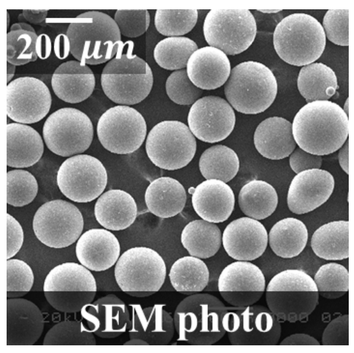
粒状体内を伝播するせん断波の伝播方向と振動方向の影響

Shear wave (S-wave) propagation, as the most versatile and portable method to obtain the small-strain stiffness of soils, has been widely used to monitor and characterize soil seismic behaviors. However, little attention has been paid to the effects of S-wave propagation and oscillation directions on the received wave signals. This research developed an original apparatus which can study the S-wave evolution in granular materials by changing either the propagation direction or the oscillation direction. Experimental results confirm that both propagation and oscillation directions are sensitive to soil inner fabric.

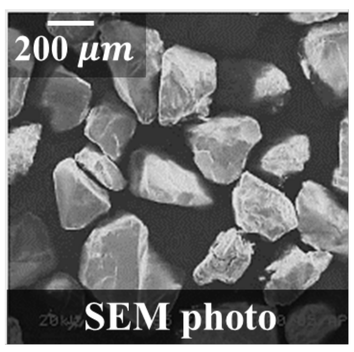
せん断波（S波）は，土の微小ひずみ剛性を得るための汎用的な方法として，土の動的特性評価に広く用いられている。しかし、S波の伝播方向や振動方向が受信波信号に与える影響についてはあまり注目されていない。本研究では，伝播方向と振動方向のいずれかを変化させて，粒状材料中のS波の変化のパターンを調べることができる独自の装置を開発した。実験の結果より、S波の伝播方向と振動方向がともに土の内部構造の影響を受けることを確認した。

Materials and Apparatus

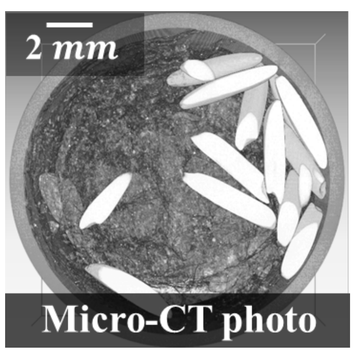
Discussions in this study are based on experimental results of four granular materials: spherical glass beads (GB) Toyoura sand (TS), basmati rice (BR) and wild rice (WR).



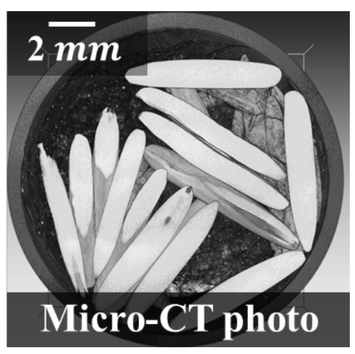
Spherical glass bead



Toyoura sand

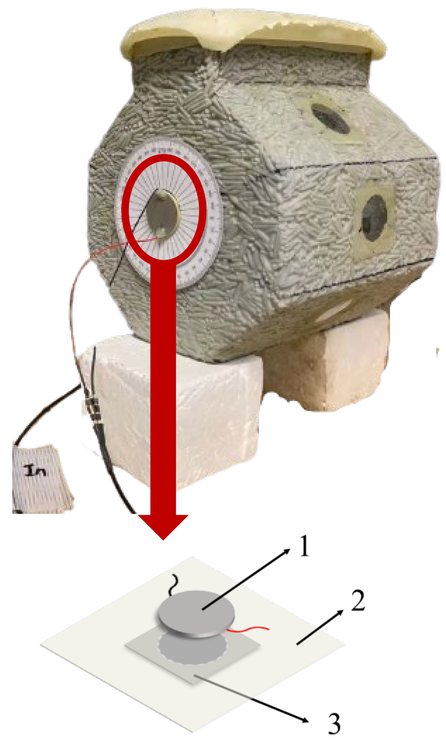


Basmati rice



Wild rice

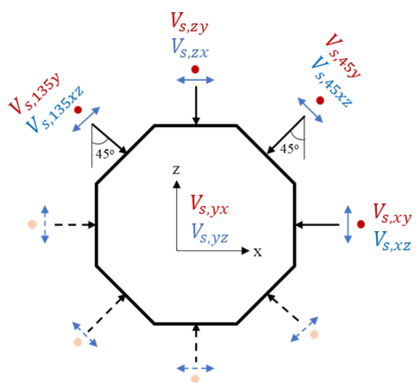
The tested materials were enclosed in the so-called eight prismatic membrane cell developed by Kuwano lab to conduct S-wave propagation tests. The apparatus can measure not only S-waves in the horizontal and vertical directions, but also in two oblique directions in 45° with respect to the vertical axis by disk-shape shear plates.



(1) 0.2 mm acrylic sheet
(2) latex membrane with an opening
(3) disk-shaped transducer

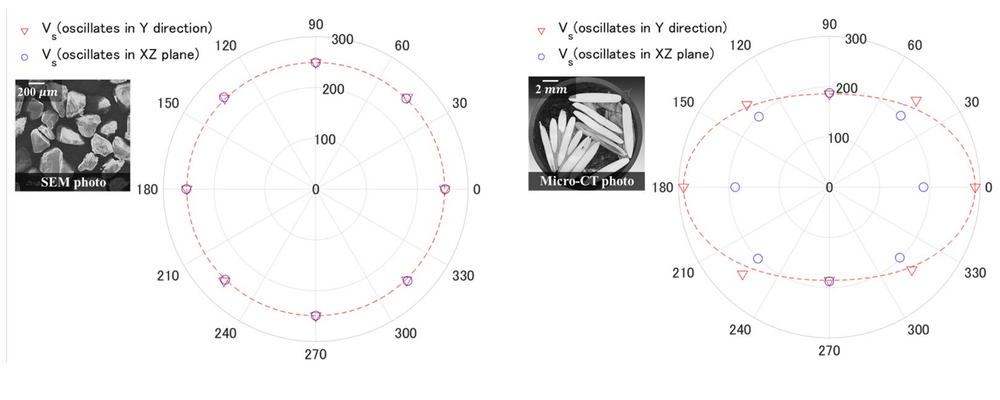
Eight prismatic membrane cell

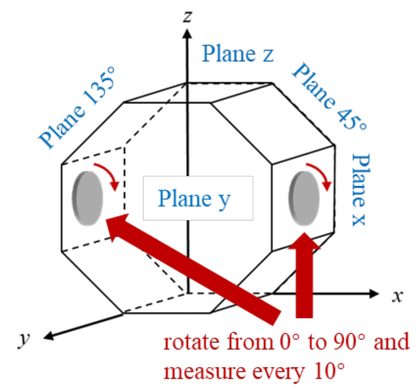
Testing Programs and Results



Variation of S-wave propagation direction

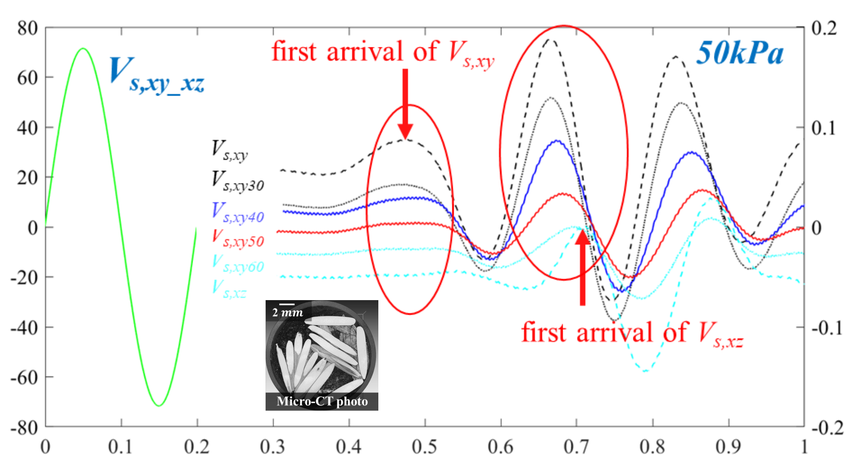
V_s in five directions are measured to evaluate the fabric anisotropy of soil specimens under isotropic confinement.





Variation of S-wave oscillation direction

V_s of S-waves propagating in the same direction but oscillating differently are measured under isotropic confinement. .



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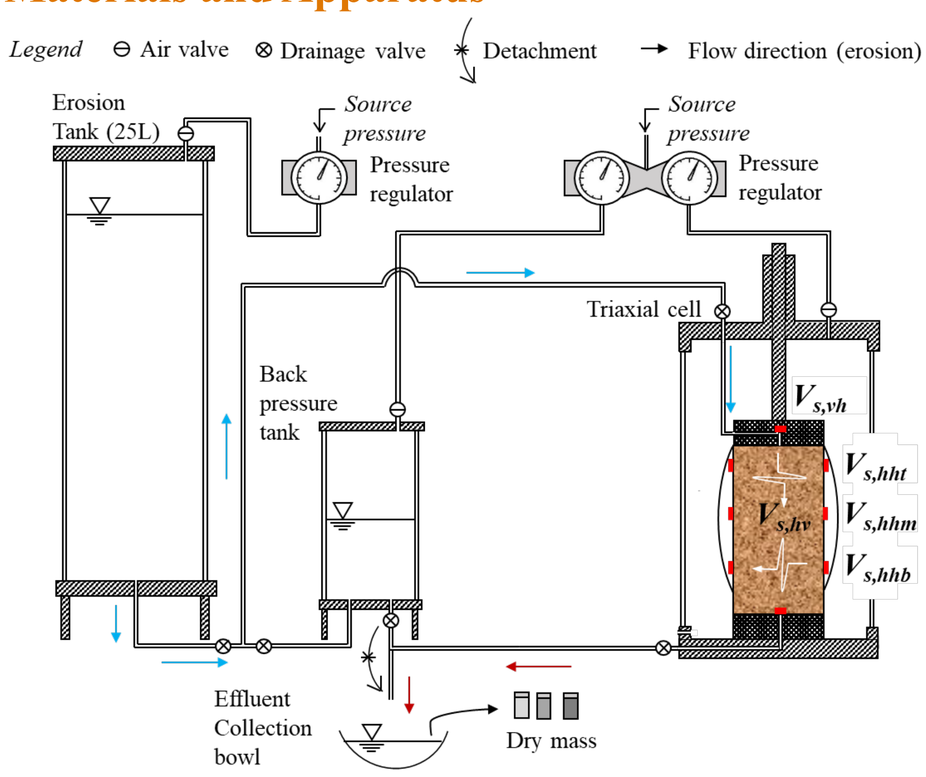
Shear Wave measurement for Real-time Monitoring of Soil Fabric Changes Due to Suffusion

せん断波を用いた内部侵食のリアルタイムモニタリング

Internal erosion, caused by water-induced soil displacement and transportation, poses a significant risk to the stability of earthen structures. Advancing our scientific understanding and crafting tools for early-stage internal erosion detection is crucial because prompt intervention could help avert catastrophic structural damage and the ensuing costly repairs. The shear (S-) wave's sensitivity to changes in soil structure makes it an ideal instrument for non-destructive monitoring of internal erosion in soils. Our study has innovatively modified a conventional triaxial device to measure S-wave propagation from multiple directions during internal erosion. This advancement successfully tracks the structural changes in internally unstable, gap-graded soils.

土の内部侵食は、水流により地盤内部で土粒子が移動・流出する現象で、これにより、地盤や土構造物の強度が低下する恐れがあります。せん断波（S波）は、土の構造の変化に対する感度が高いため、土の内部侵食の非破壊モニタリングに適しています。本研究では、従来の三軸試験装置を改良し、内部侵食を受けている際の地盤材料のS波の伝播を多方向から測定できるようにしました。この改良により、内部侵食を受けたギャップグレード材料の構造の変化を追跡することができました。

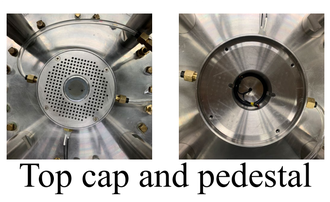
Materials and Apparatus



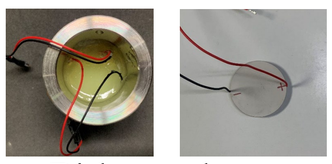
Schematic testing system



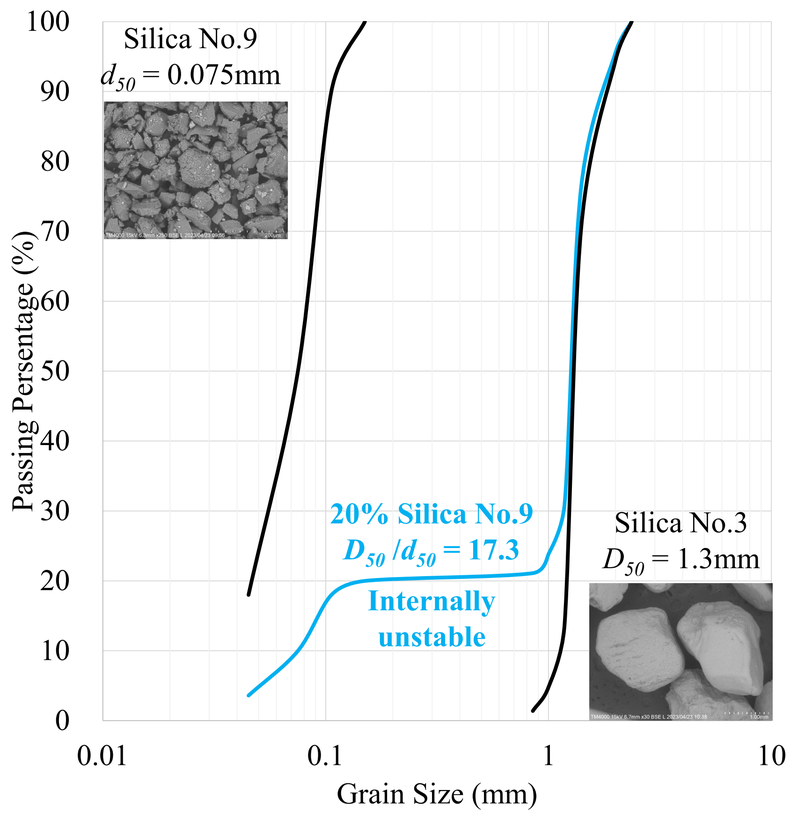
Specimen after preparation



Top cap and pedestal

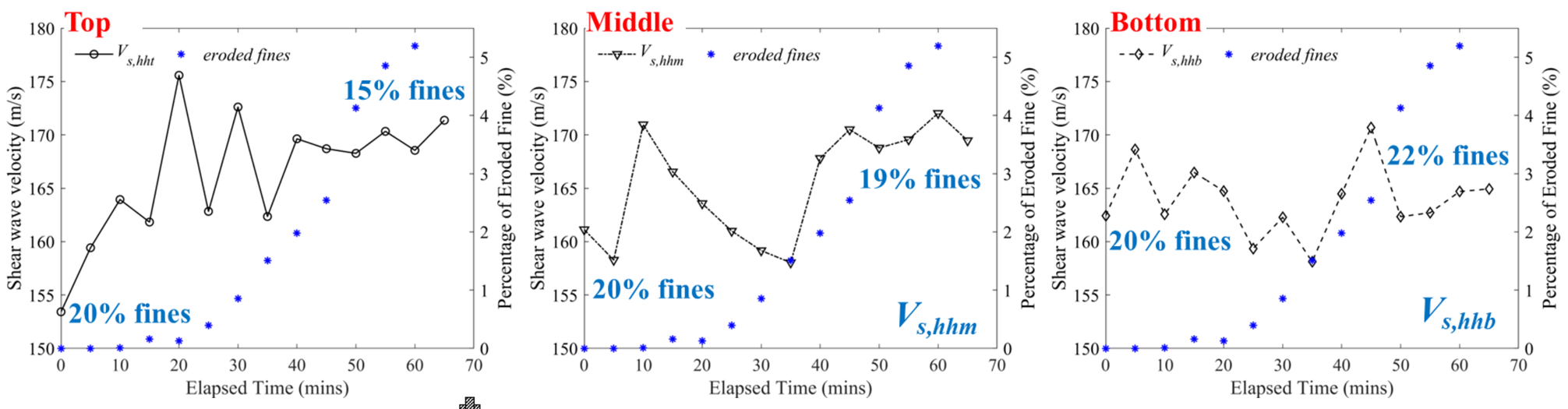


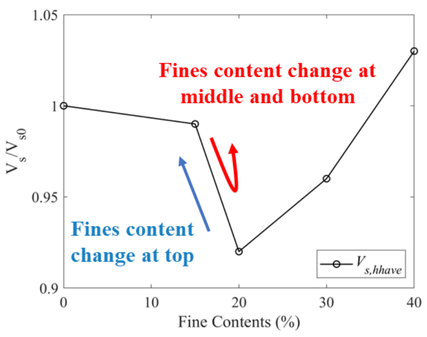
Disk transducers

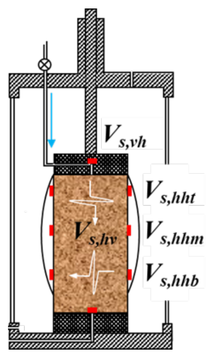


Particle size distribution curve

Results







- V_s transitions occur as fines content increases, resulting from the disruption of force chains by coarse particles and the inactivity of the filled fines.
- The transitional point of the horizontal component ($V_{s,hh}$) occurs later than that of the vertical component ($V_{s,vh}$), likely due to particle orientation favoring the horizontal plane during deposition, leading to more force chains horizontally.

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Development of Multi-Directional Elastic Wave Measurement System Using Disk-Shaped Piezoelectric Transducers

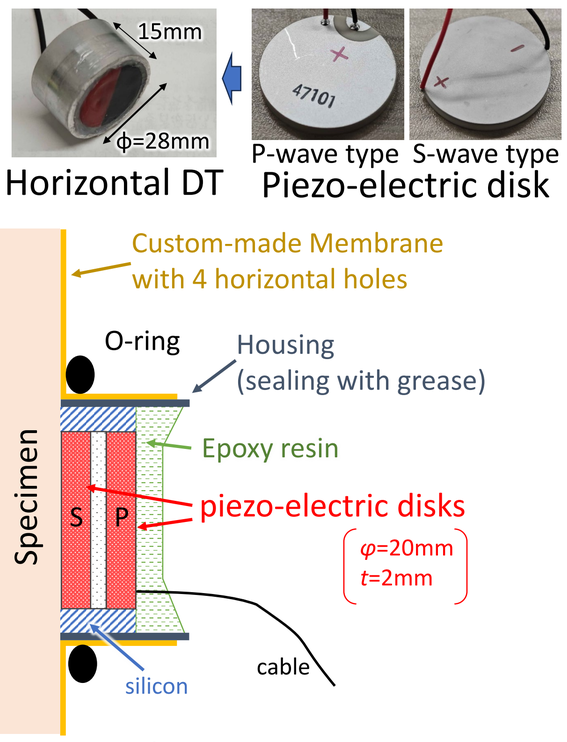
ディスクトランスデューサーを用いた多方向弾性波計測システムの開発

Overview

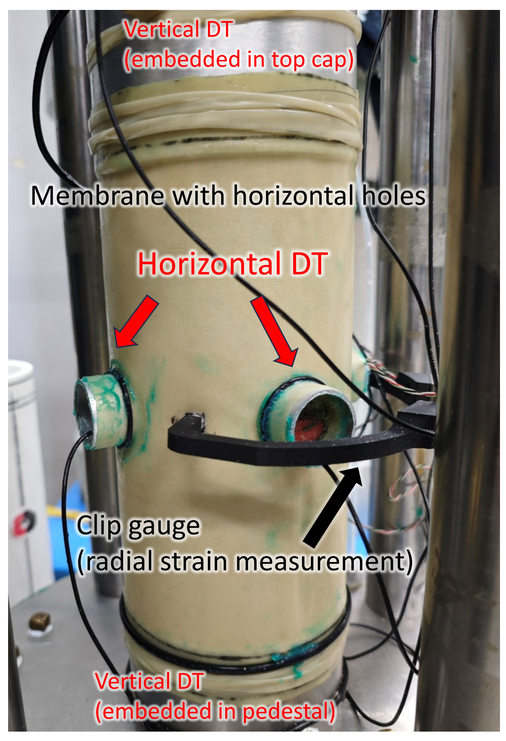
The elastic wave velocities and small strain stiffnesses of soils are essential parameters that are used in the design of foundations, tunnels, etc. Disk-shaped piezoelectric transducers (DTs) developed at IIS have been used for measuring elastic waves propagating through geomaterials. In this study, these transducers were modified to develop a system capable of automatic multi-directional elastic wave measurements in triaxial specimens. Changes in multi-directional elastic wave velocity of dry Toyoura sand during triaxial compression are presented.

桑野研究室では、ディスクトランスデューサー(DT)を用いて地盤材料を伝わる弾性波速度の計測が行われている。本研究では、DTを用いて、三軸供試体で弾性波の多方向自動計測を行うシステムを開発した。このシステムを用いて、乾燥豊浦砂の三軸圧縮中の弾性波速度の計測を行った結果を示す。

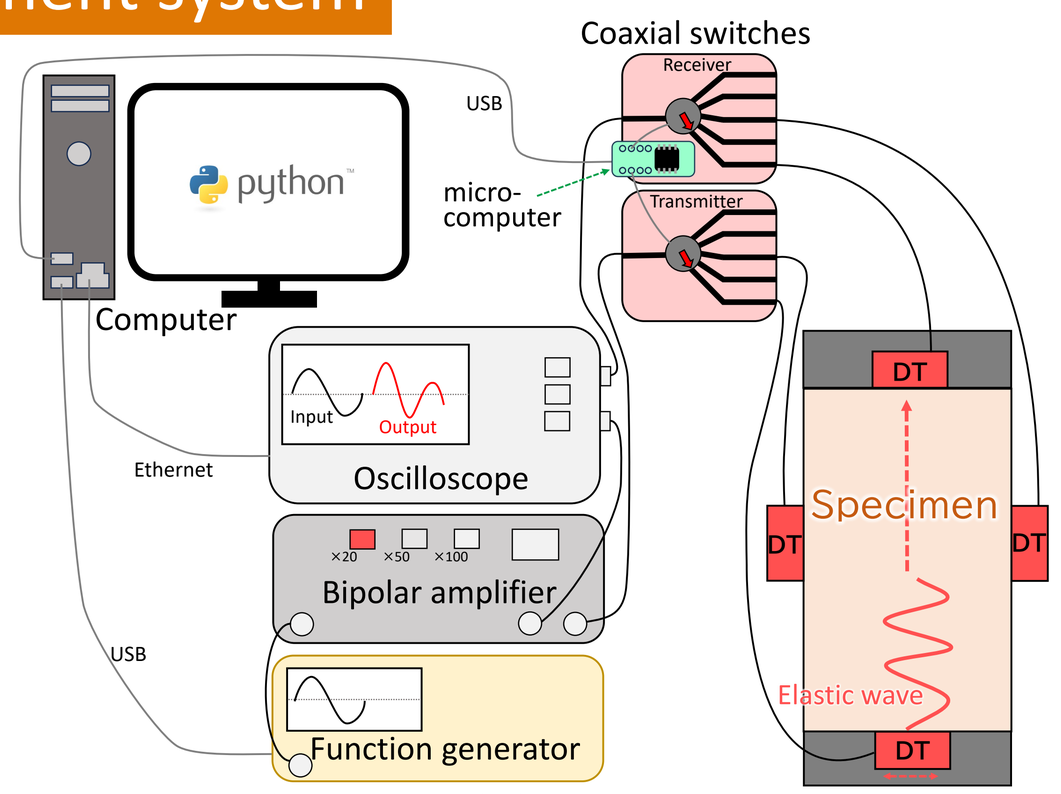
Multi-directional elastic wave measurement system



Vertical cross section



Appearance of the specimen

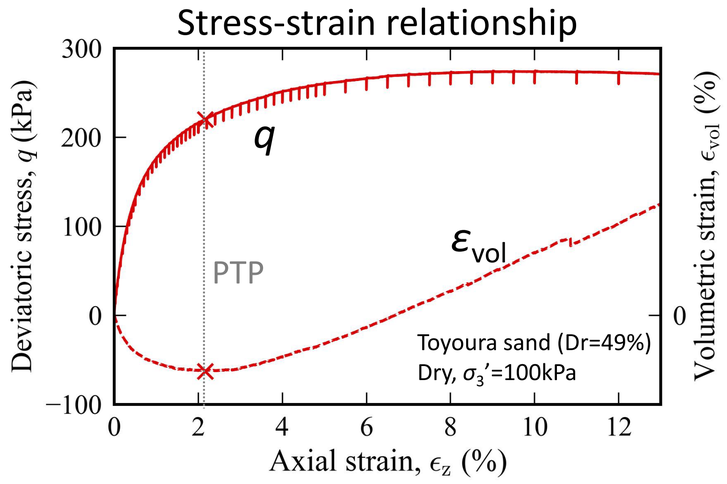


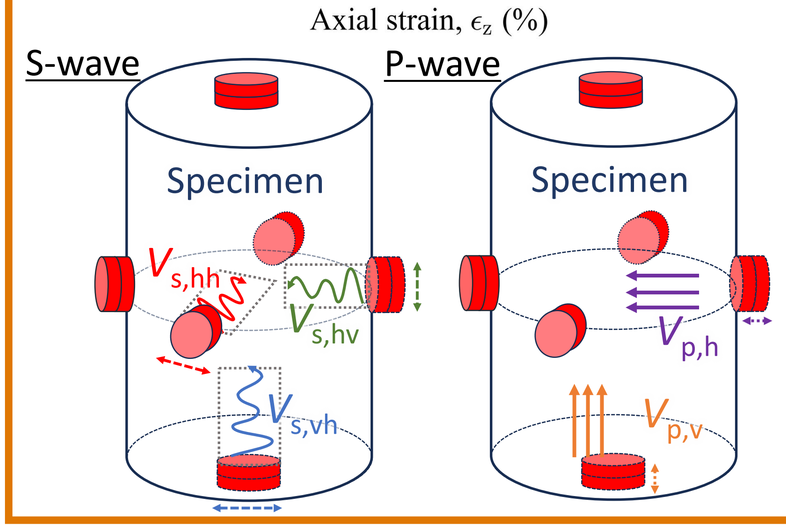
Automatic multi-directional elastic wave measurement system

✓ non-inversive ✓ easy to seal ✓ Automated measurement of 3 S-waves and 2 P-waves in 10 seconds

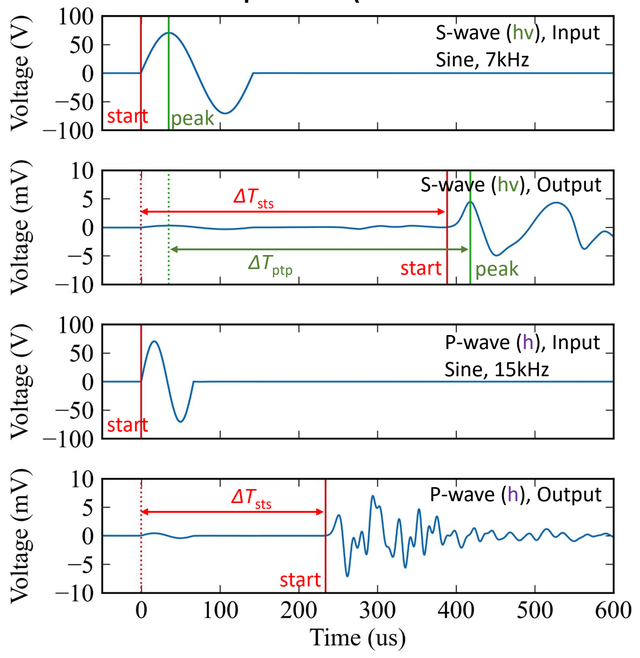
Results

Stress-strain relationship

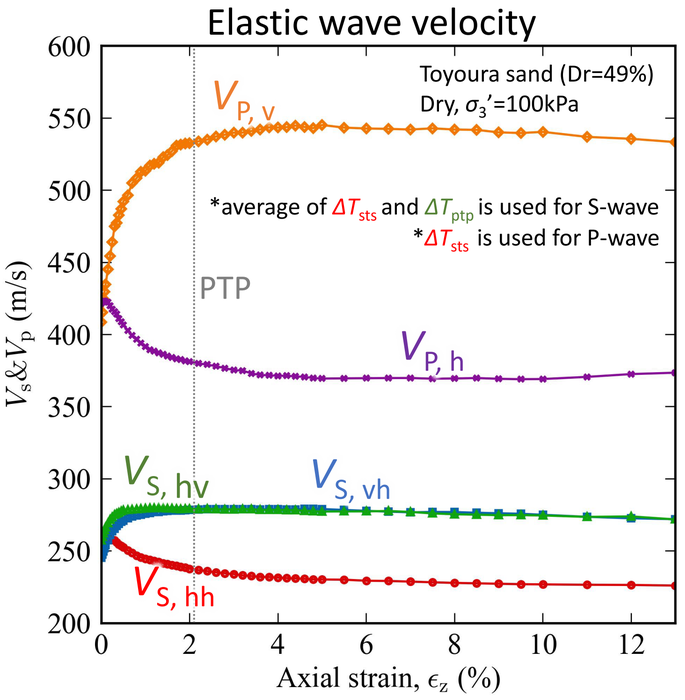




Time-domain response (after consolidation)



Elastic wave velocity



✓ $V_{s,hh}$ and $V_{p,h}$ decreased with increasing axial strain.

✓ $V_{s,hv}$ and $V_{S,vh}$ exhibited peaks at phase transformation point (PTP) and subsequently decreased.

✓ $V_{p,v}$ increased until around the peak of q, followed by a slight decrease with strain softening.

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Shear Wave measurement for Real-time Monitoring of Soil Fabric Changes due to shear

せん断に伴う粒子配向変化の弾性波を用いたモニタリング

Granular materials often demonstrate macro-scale anisotropic behavior. Traditional methods of assessing small strain stiffness through elastic wave propagation, typically applied vertically in triaxial tests, fall short in capturing the particle orientation and anisotropic characteristics of soils under dynamic shear conditions. This study presents a novel approach by modifying a conventional triaxial apparatus to include planar piezoelectric transducers capable of measuring elastic wave propagation (P-waves and S-waves) in both vertical and horizontal directions. The apparatus was used to test three granular materials under monotonic compression with multi-direction P&S wave measurement.

砂などの粒状材料は、マクロスケールで異方性を示すことが多い。従来の弾性波伝播を用いた微小ひずみ剛性評価法は、三軸試験で垂直方向に適用されることが一般的である。本研究では、従来の三軸装置に平面型圧電トランスデューサーを追加し、垂直および水平方向の弾性波伝播（P波およびS波）を測定できるよう改良した。この装置を用いて、3種類の異なる粒状材料をせん断し、鉛直・水平方向のP波およびS波を調べた。

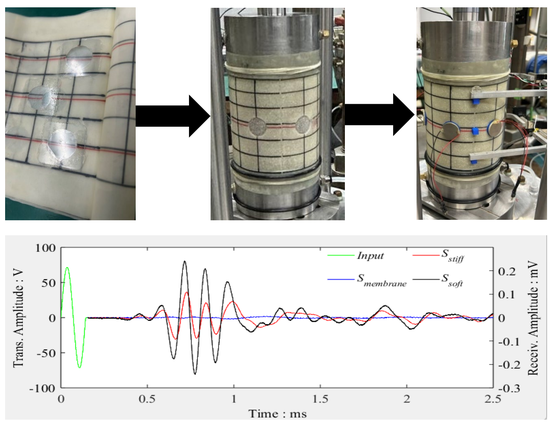
(1) Introduction

The design of safe and resilient structures necessitates thorough geotechnical investigation, where elastic wave velocity and small strain stiffness play crucial roles. Previous studies focused on vertically propagating waves using planar piezoelectric transducers, there is limited research on horizontally propagating waves research, which is not conducive to explaining the anisotropic characteristics of soil during dynamic shear processes. Therefore, the objective of this research is as follows:

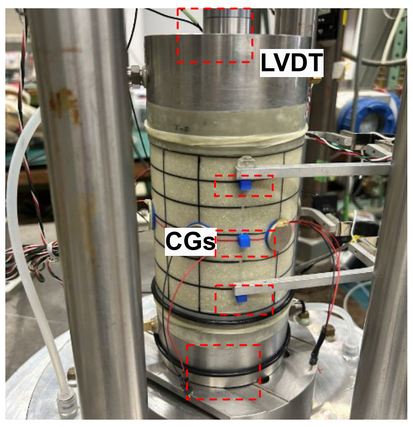
a) Evolution of stress wave velocity of two directions (vertical and horizontal) during triaxial compression
b) Influence of grain characteristics on the mechanical behavior of granular materials
c) Try to reflect the principle of particle orientation change and anisotropy from the relationship between vertical and horizontal waves in dynamic shear processes

(2) Experimental Procedure-Membrane Setup&Experimental Setup

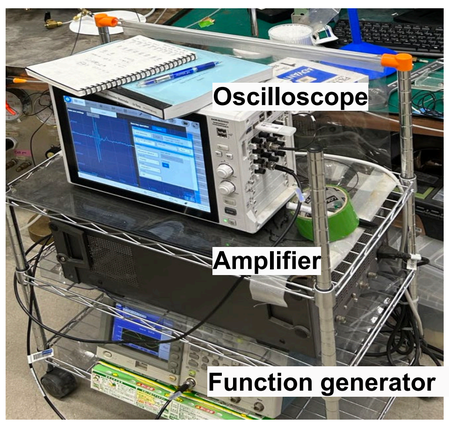
New methodology for testing horizontal wave



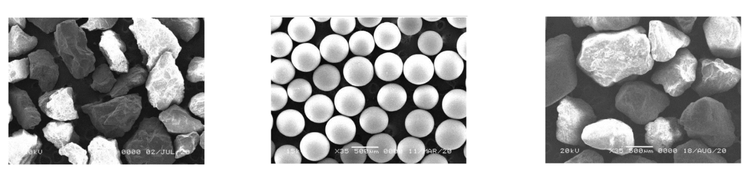
Sensor installation



Wave measurement

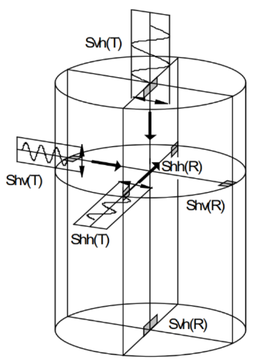


Testing materials

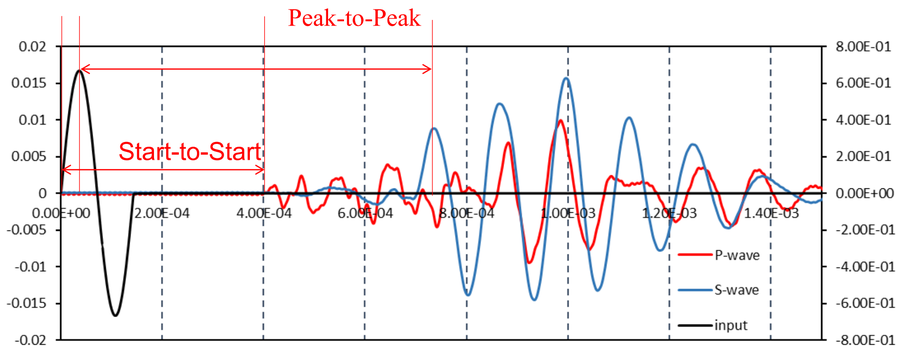


Materials	Silica Sand No.5 (SS5)	Smooth Spherical Glass Beads (SSGB)	Natural River Sand (NRVS)
G_s	2.64	2.5	2.66
e_{min}	0.699	0.589	0.622
e_{max}	1.067	0.694	0.882
D_r	14%,60%,80%	14%,60%,80%	14%,60%,80%

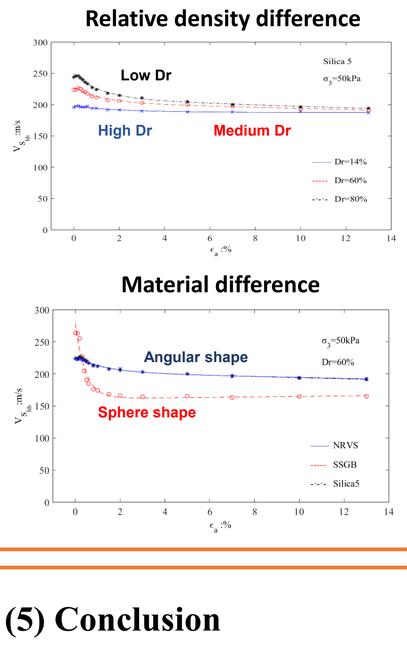
(3) Dynamic Wave Propagation Tests

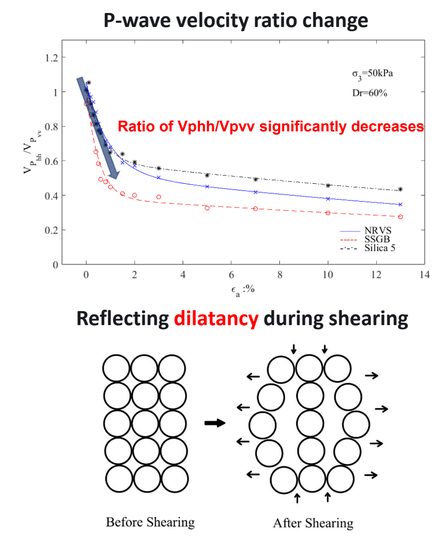


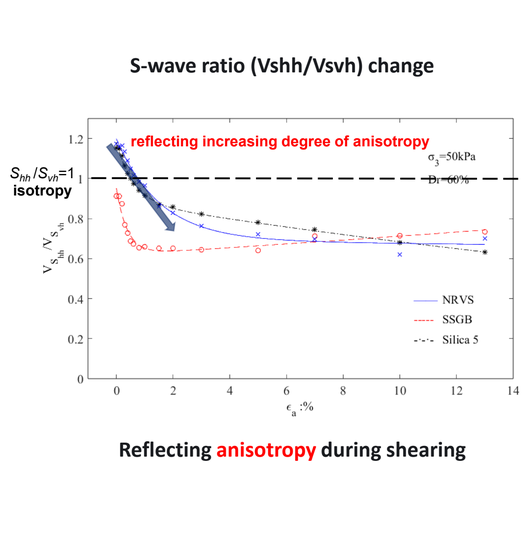
- ✓ Considering both P- and S-waves, there are six types of elastic wave components as illustrated the left hand.(e.g. Svh means Shearing Wave which spreads vertically but vibrates horizontally)
- ✓ When calculating the velocity of elastic waves, the time interval for P-waves is measured using the Start-to-Start reading, while the time interval for S-waves is measured using the Peak-to-Peak reading (P-waves travel faster, thus using the Start-to-Start reading for S-waves would be affected by the interference from P-waves).



(4) Experimental Results







(5) Conclusion

- ✓ The relative density of granular samples significantly affects the small-strain stiffness at the initial stage of shearing, while different materials exhibit various elastic wave development trends due to changes in particle orientation during the shearing process.
- ✓ The decrease in the ratio of horizontal P-waves to vertical P-waves during shearing reflects the dilative characteristics of granular materials, with particle shape and orientation changes influencing this shearing behavior.
- ✓ The variations in horizontal S-waves and vertical S-waves indicate anisotropy in small-strain stiffness during dynamic shearing, with vertical stiffness typically being greater than horizontal stiffness.

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Effects of Particle Shape of Granular Materials in Triaxial Tests

三軸試験における粒状材料の粒子形状の影響

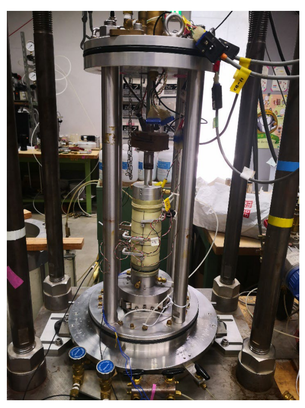
Effects of particle shape of granular materials on dynamic responses of their assembly are significant and thus worth being studied. Different shapes would affect their microstructure such as contact fabric or orientation of particles, and lead to different dynamic behaviours, which have not been fully understood. Consequently, triaxial compression experiments were carried out by considering different particle shapes. Stress responses and wave propagation in the process of monotonic loading were investigated. To eliminate the influence of packing density, specimens consisting of different particle shapes were prepared at a similar relative density.

動的応答に対する粒状材料の形状の影響は大きい。粒子形状が異なることで、粒子の接触モードおよび配向性などの微視構造に影響を与え、異なる力学的挙動を示すと考えられるが、まだ完全には解明されていない。そこで形状が異なる粒状体の三軸圧縮試験を行い、単調載荷の過程における変形強度特性と波動伝播特性を調べた。充填密度の影響を排除するために、異なる粒子形状からなる供試体を同様の相対密度で作製した。

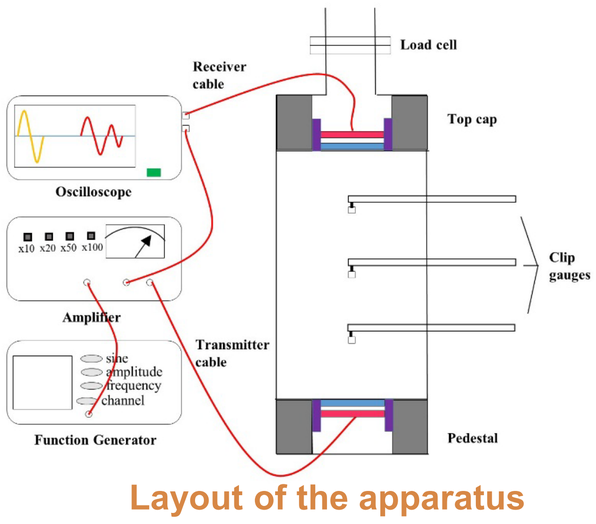
Experiment Apparatus



Wave measurement



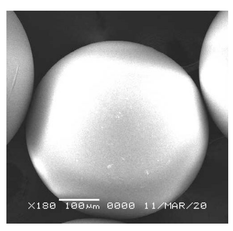
Triaxial apparatus



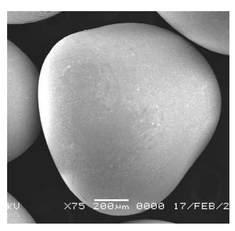
Layout of the apparatus

Tested Materials

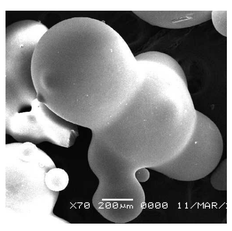
SEM photos



Spherical



Deformed

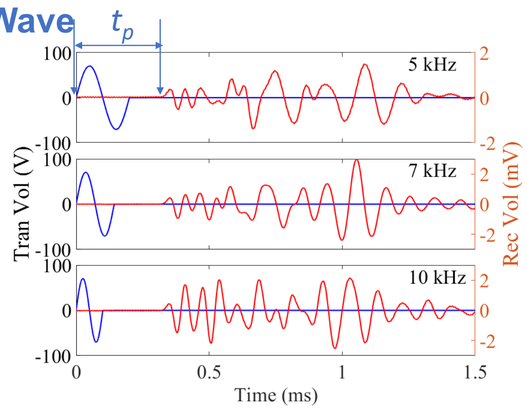


Clumped

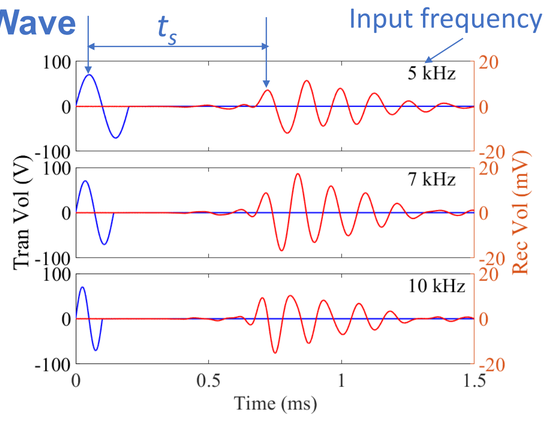
	SSGB	SDGB	SCGB
G_s	2.5		
D_{50}(mm)	0.5	1.0	0.6
e_{min}	0.589	0.494	0.694
e_{max}	0.694	0.666	0.961

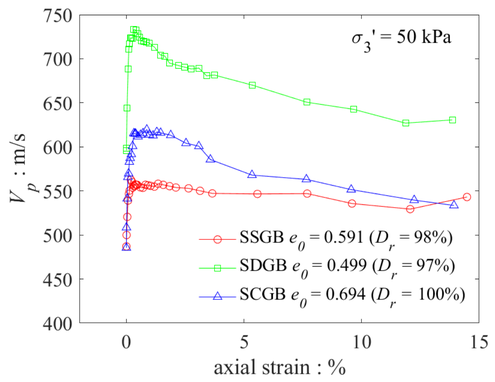
Wave Propagation

P-Wave t_p

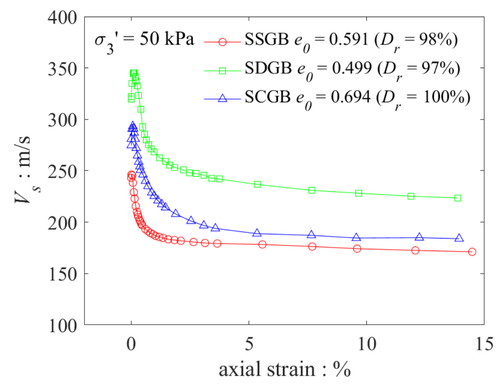


S-Wave t_s Input frequency

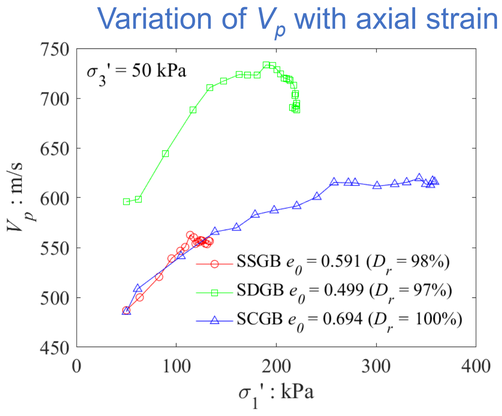




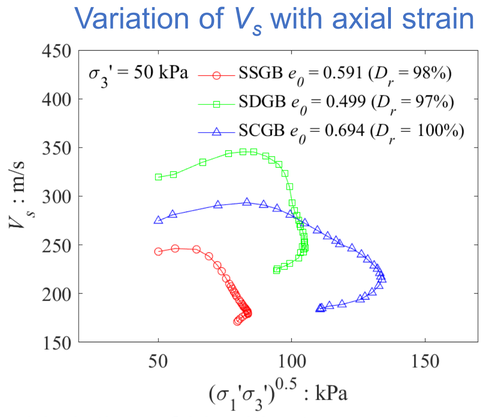
Variation of V_p with axial strain



Variation of V_s with axial strain

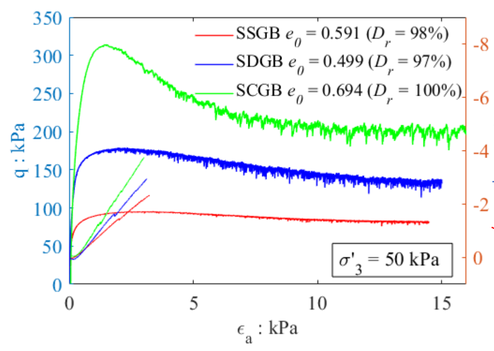


Variation of V_p with normal stress



Variation of V_s with stress components

Stress Response

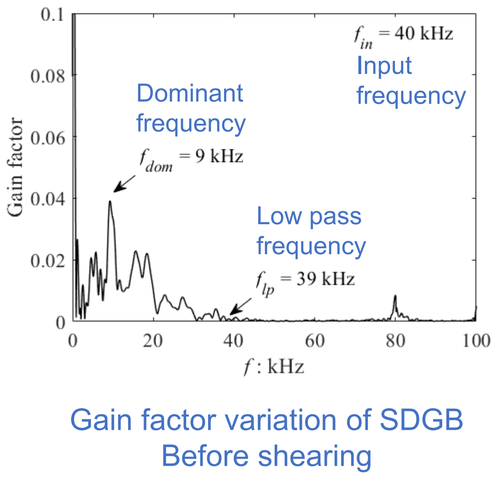




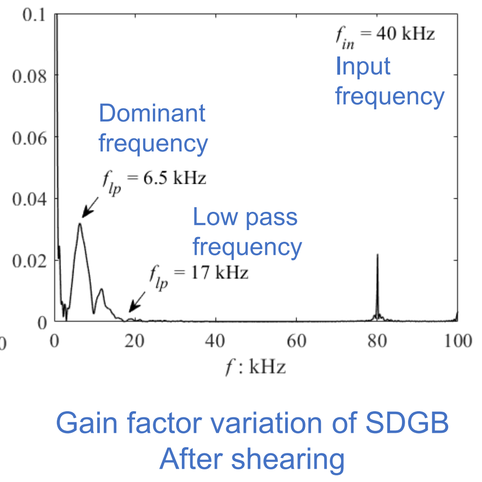
Deviatoric stress and volumetric change with axial strain due to particles with different shapes

Frequency Domain Analysis

Gain factor =FFT_{output}/FFT_{input} FFT = Fast Fourier Transform



Gain factor variation of SDGB Before shearing



Gain factor variation of SDGB After shearing

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DEM analysis on the stress wave responses of spherical particle assemblies in Triaxial Tests

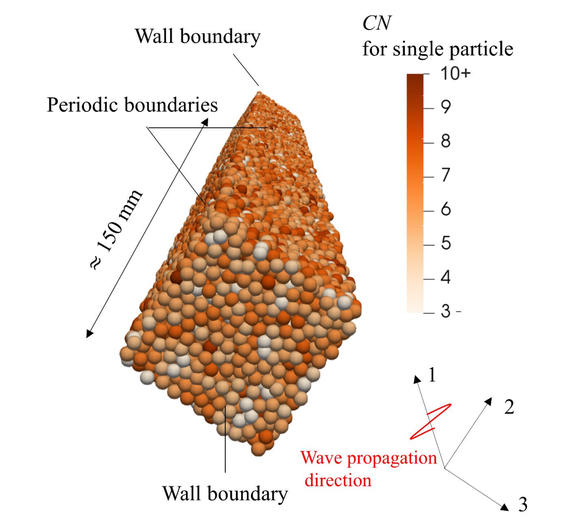
https://doi.org/10.1016/j.compgeo.2021.104043

三軸試験における粒状体の弾性波応答のDEM解析

It is challenging to understand the stress wave responses of cohesionless particle assemblies including compression (P-) and shear (S-) wave velocities (V_p and V_s). Discrete element method (DEM) enables to simulate the wave propagation during triaxial compression using spherical particles. Four samples are isotropically confined at various initial packing densities and then sheared monotonically up to the critical state. Small-amplitude wave propagation simulation is performed during shearing along the axis of loading. V_p and V_s are found to be well correlated with the stress state, as well as the soil fabric.

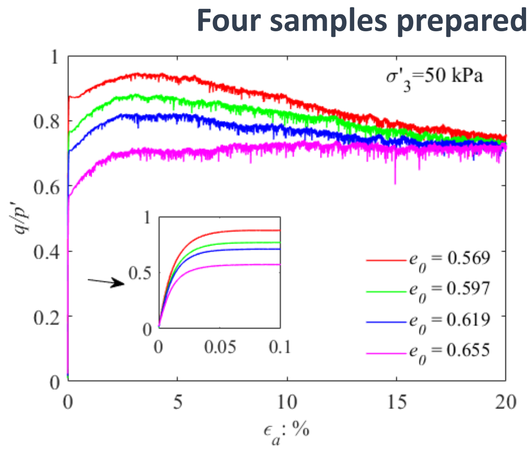
非粘性粒状体の弾性波応答、すなわちP波およびS波の速度（V_p および V_s）を理解することを目的とし、個別要素法（DEM）を用いて、球状粒子供試体の三軸圧縮時の波動伝播のシミュレーションを行った。4種の様々な初期充填密度の供試体を等方的に拘束し，極限状態まで単調せん断した。さらに、せん断時に微小振幅の波動を載荷軸方向に伝播させた。その結果，V_p と V_sは，応力状態や土の堆積構造と高い相関があることがわかった。

Representative random packing sample

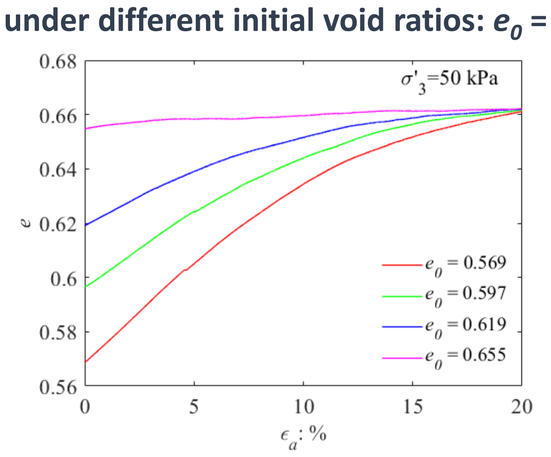


Typical mechanical responses

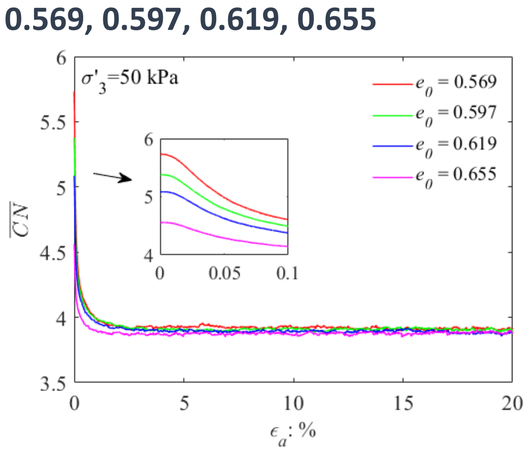
Four samples prepared under different initial void ratios: e_0 = 0.569, 0.597, 0.619, 0.655



Stress-strain response (q/p'-ε_a)



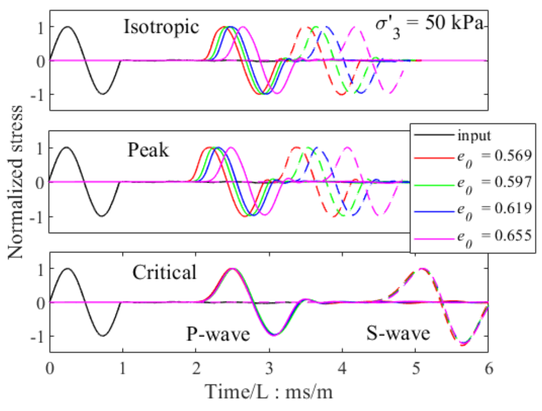
Void ratio (e)



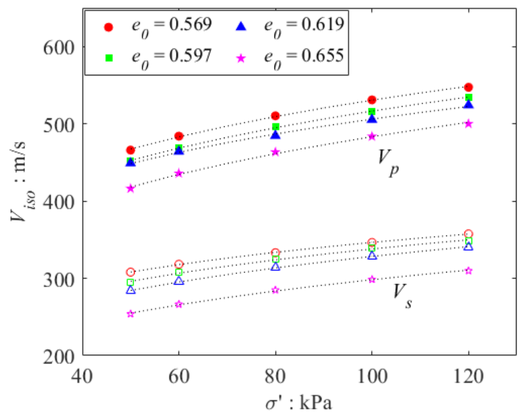
Mean coordination number ($\overline{CN}$)

Stress wave responses — Small amplitude of a sinusoidal pulse is activated to the wall boundaries to generate dynamic waves propagating through 1-axis

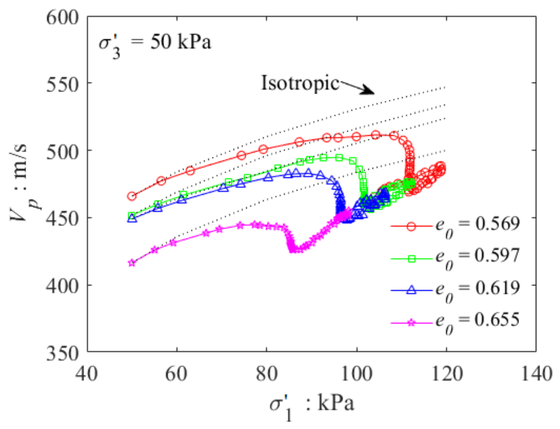
P- and S- wave signals

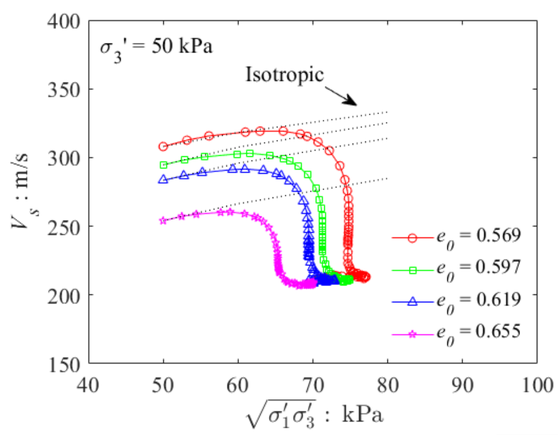


V_p and V_s in the isotropic state



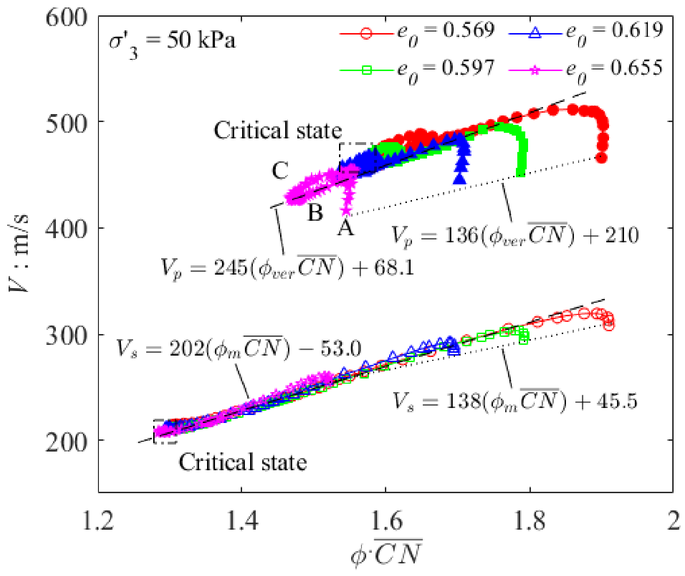
V_p and V_s during triaxial loading



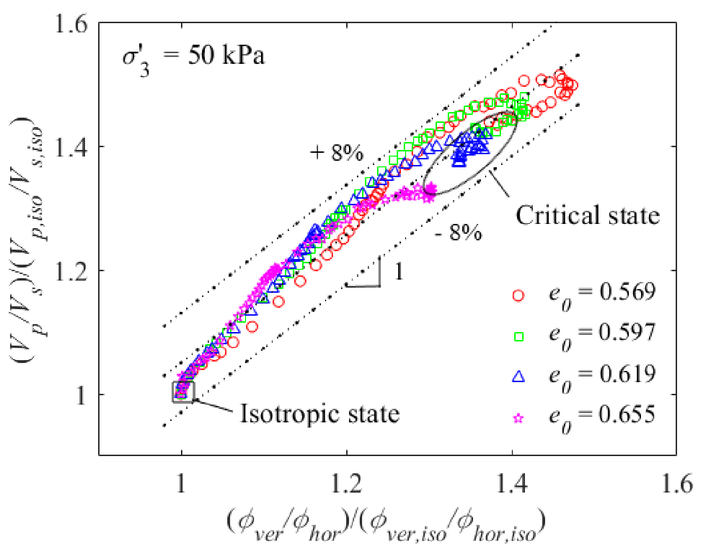


V_p and V_s with isotropic effective stress (σ') V_p with major principal stress (σ'_1) V_s with geometric mean stress ($\sqrt{\sigma'_1\sigma'_3}$)

Relationships between V_p , V_s and the soil fabric ($\Phi_{ij} = \frac{1}{N}\sum_{k=1}^{N} n_i^k n_j^k$)

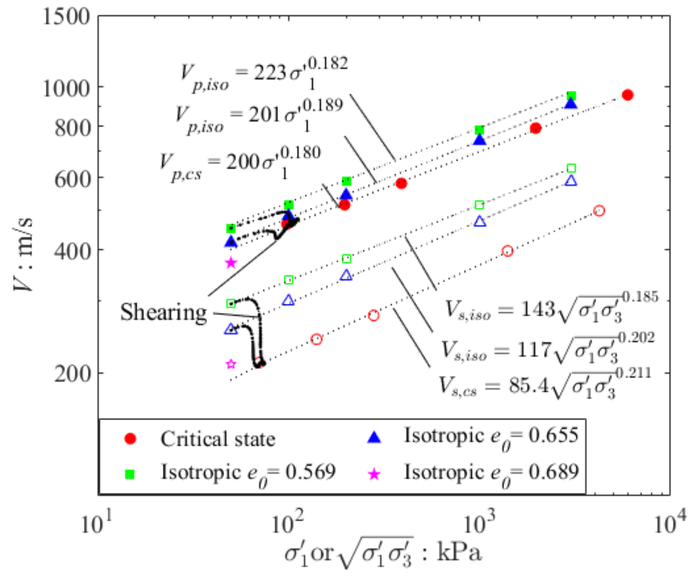


V_p and V_s with soil fabric (Φ) and $\overline{CN}$



Velocity ratio (V_p/V_s) with fabric ratio (Φ_{ver}/Φ_{hor})

V_p and V_s in the critical state



V_p with σ'_1 or V_s with $\sqrt{\sigma'_1\sigma'_3}$

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Effects of particle morphology on mechanical responses of granular materials

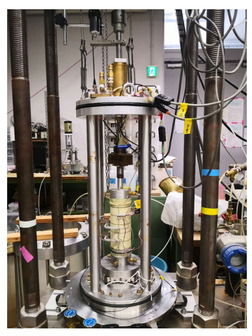
粒状体の力学特性における粒子形態の影響

Sandy soils are generally treated as cohesionless granular particles whose macroscopic responses are determined by particle-scale parameters. It is essential to have a better understanding of the effect of particle morphology on the mechanical response of granular materials. Physical experiments are conducted and discrete element method (DEM) is applied. In the meantime, the effect of particle morphology on the propagation of stress waves is also examined by performing wave measurements throughout the loading process in the laboratory. The evolution of stress waves during loading is investigated using DEM simulations.

砂質土のような粒状材料の力学特性は、個々の粒の状態に影響されると考えられます。粒子の形状や表面粗度などの粒子形態が巨視的な力学応答に及ぼす影響を、室内要素試験と個別要素法（DEM）により検討しました。また、供試体中の応力波の伝播に対する粒子形態の影響も、せん断中に弾性波を測定して調べました。



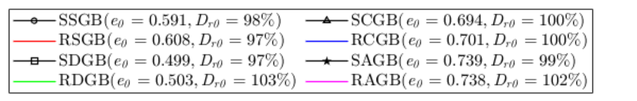
Materials with different particle shapes

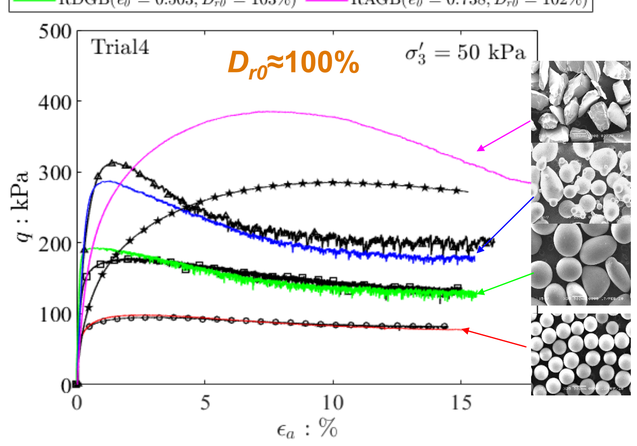


Triaxial apparatus



Wave machines

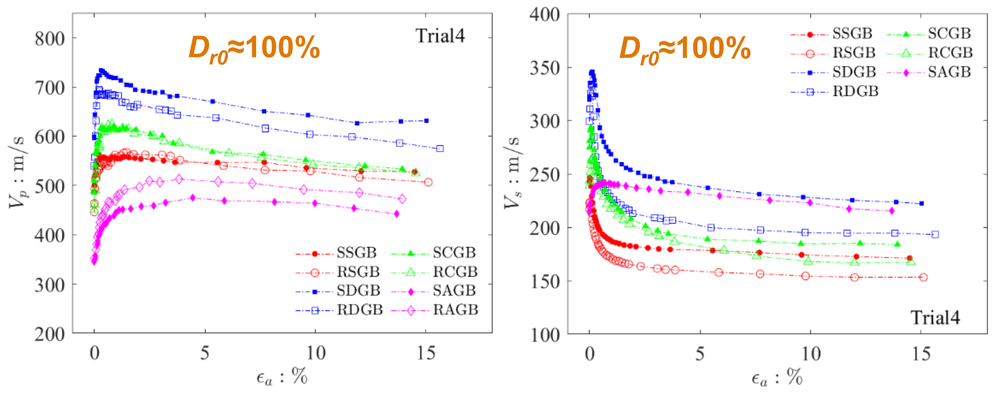




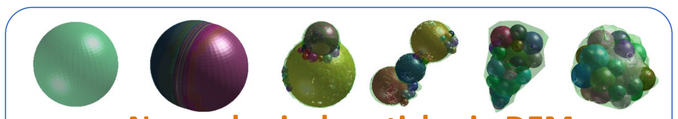
Stress-strain responses during triaxial loading

Compression waves

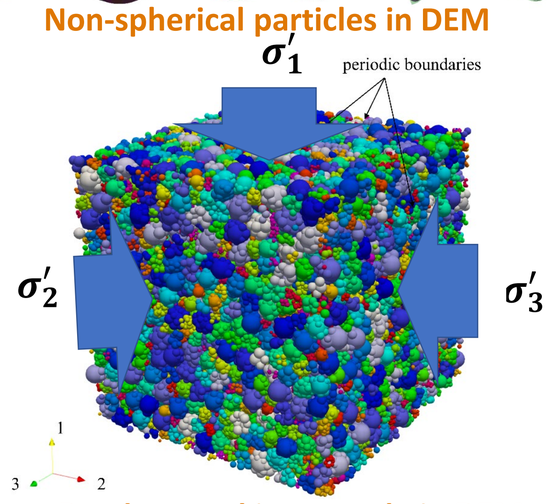
Shear waves



Stress wave responses during triaxial loading

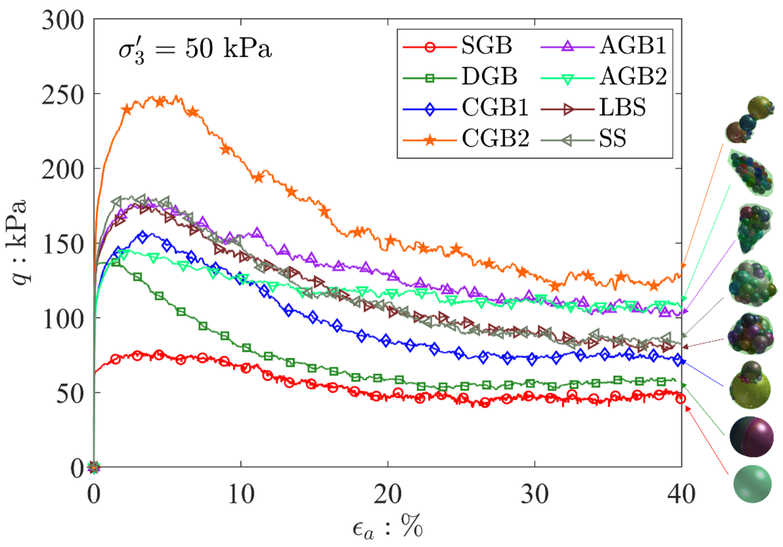


Non-spherical particles in DEM

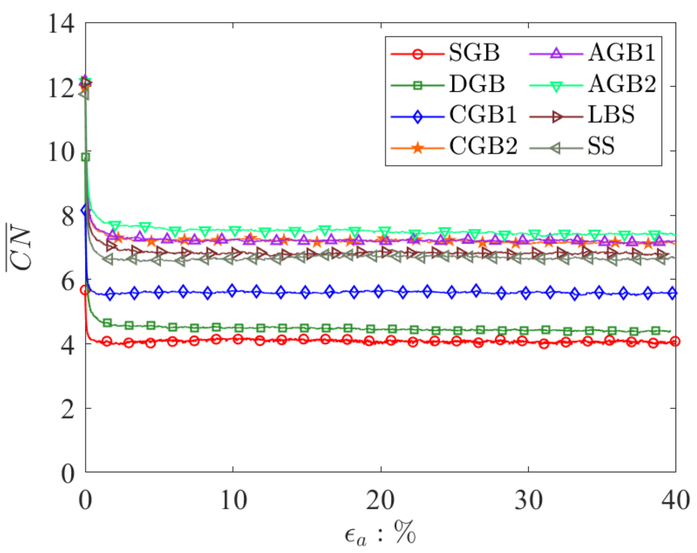


Random packing sample in DEM

Samples were prepared under a densest condition.

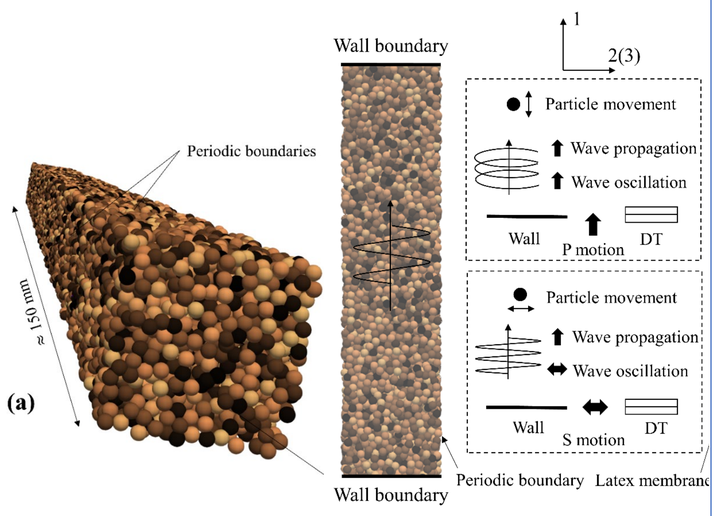


Stress-strain responses during triaxial loading



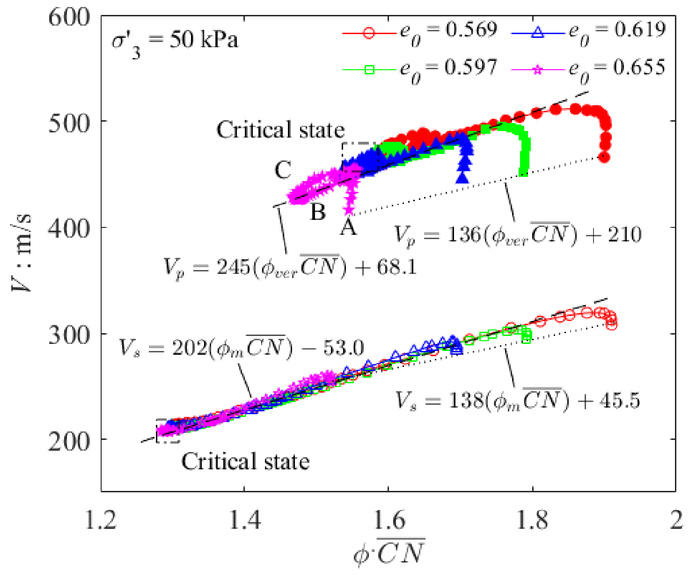
Variation of mean coordination number ($\overline{CN}$)

Wave propagation using wall boundaries

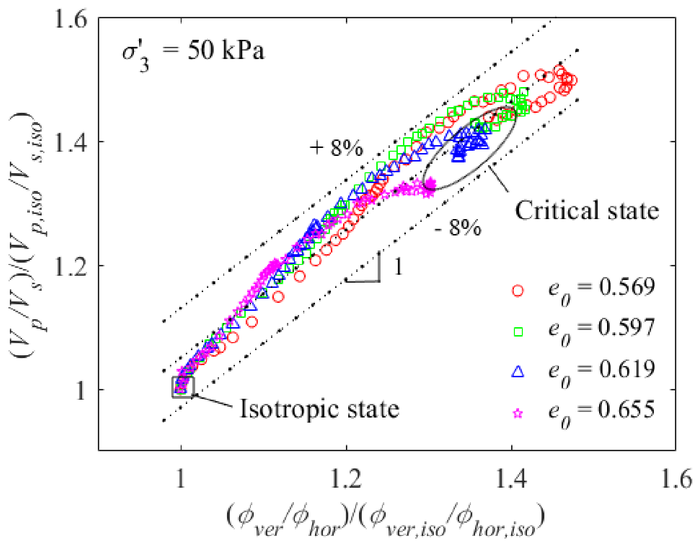


A random packing sample composed of spherical particles

Relationships between V_p , V_s and the soil fabric ($\Phi_{ij} = \frac{1}{N}\sum_{k=1}^{N} n_i^k n_j^k$)



V_p and V_s with soil fabric (Φ) and $\overline{CN}$



Velocity ratio (V_p/V_s) with fabric ratio (Φ_{ver}/Φ_{hor})

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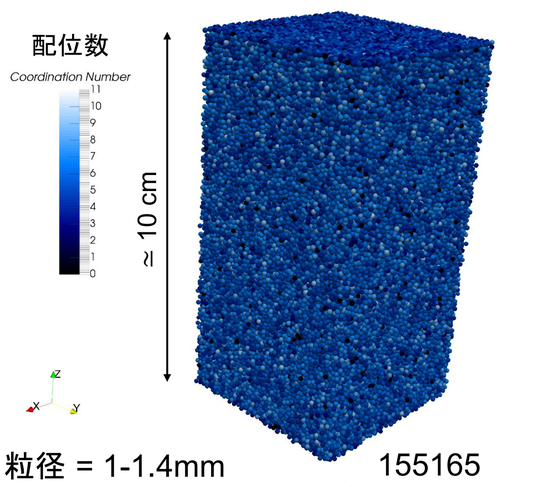
Discrete Element Method Simulation of Elastic Wave Propagation

個別要素法を用いた弾性波伝播解析

The small-strain shear modulus of soil is important to evaluate the deformation characteristics in Geotechnical Engineering. It is not easy to measure the shear modulus accurately in the laboratory partially due to the complex nature of granular materials. Recent development of bender elements or disk-transducers enable measurements of shear wave velocity, leading to the small-strain shear modulus. These dynamic approaches are often favored instead of the static triaxial shearing tests. However, the interpretation of received dynamic signals has not been fully understood. The discrete element method (DEM) simulations were conducted to analyse the nature of elastic wave propagation though granular materials. Visualisation of particle-scale responses led to better understand of how the waves propagate. A good match was observed between DEM simulations and equivalent laboratory dynamic tests using specimens composed of glass beads.

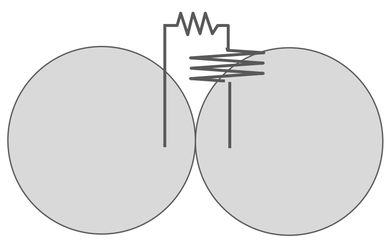
微小ひずみ領域における土のせん断剛性は重要な指標であり，地盤材料の微小変形を予測する際に有用である．金属等の連続体とは異なり粒状体的性質の強い土の剛性を正確に計測することは容易でない．近年では静的三軸圧縮試験に代わり，ベンダーエレメントや圧電振動板による動的計測が頻繁に実施されている．測定したせん断波（横波）速度からせん断剛性を算出することが可能である．しかしながら，計測したデータの解釈方法，あるいは圧縮波（縦波）成分との干渉等による影響に関しては議論の余地がある．本研究では個別要素法を用いて土質室内試験を模擬した弾性波伝播シミュレーションを実施した．実験では観測できない供試体内部の粒子挙動を可視化することができ，弾性波伝播機構の理解を深めることができた．また，個別要素法シミュレーション結果は同物性値を有するガラスビーズ供試体を用いた実験結果とも精度良く一致した．

個別要素法と室内試験供試体
DEM and laboratory specimen

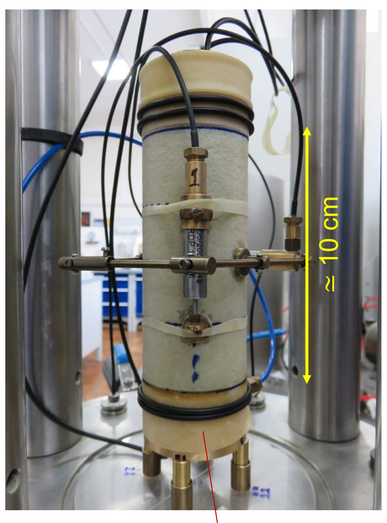


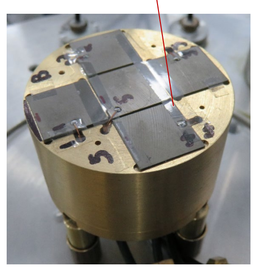
粒径 = 1-1.4mm
particle diameter

155165
粒子 (particles)



供試体と粒子間バネモデル
DEM sample and spring model

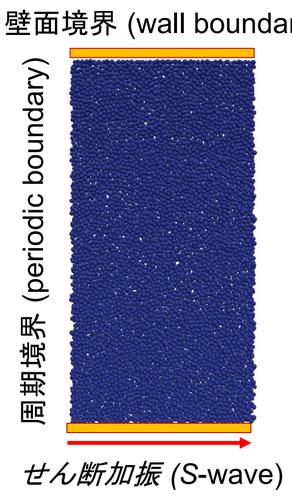




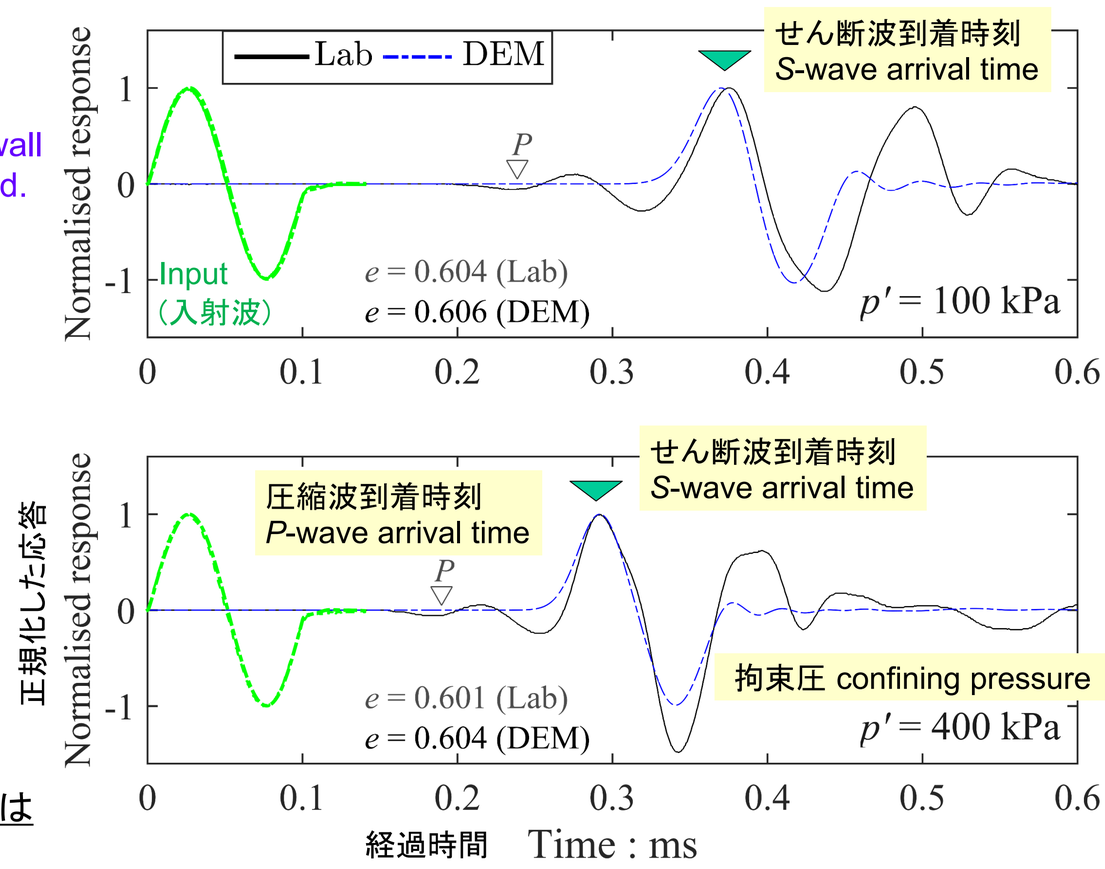
実験供試体と圧電振動板
Laboratory specimen and shear plates

供試体上下端面での計測結果　System responses at boundaries

壁面境界に作用するせん断応力を測定
Shear stresses acted on wall boundaries were recorded.

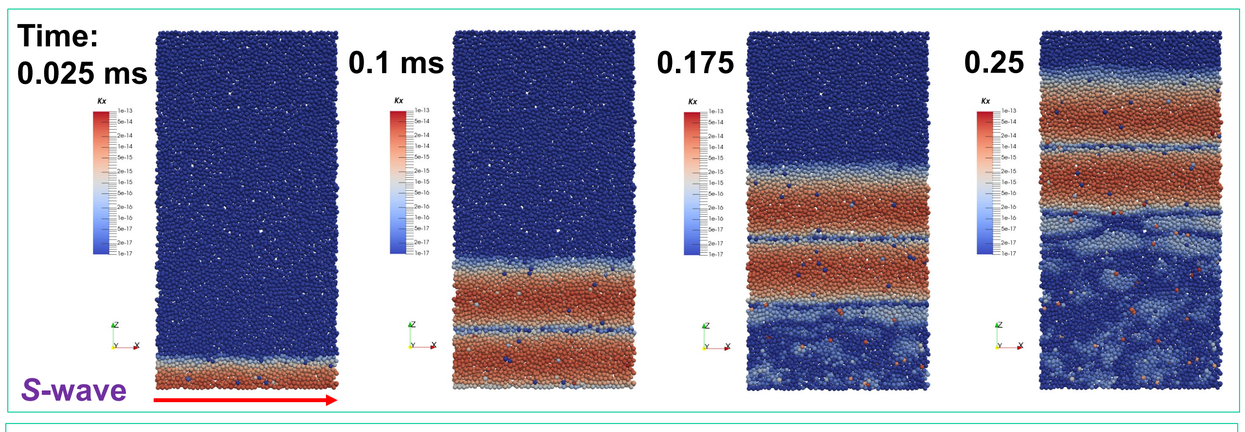


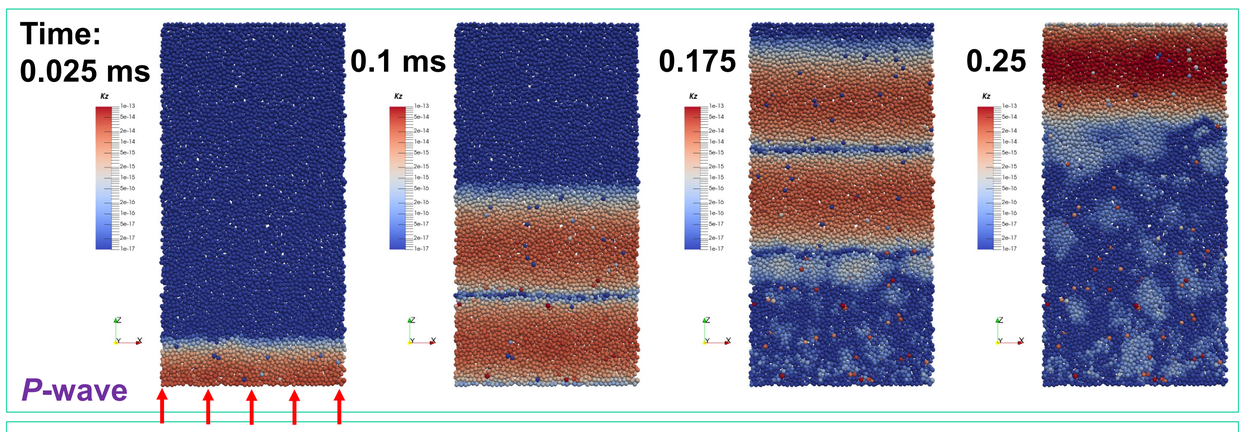
個別要素法と実験結果は精度良く一致

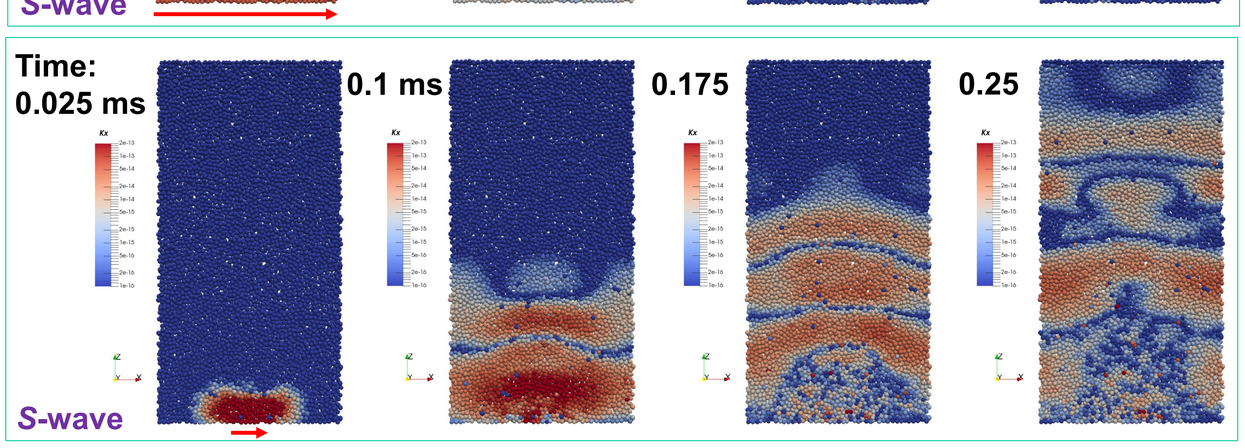


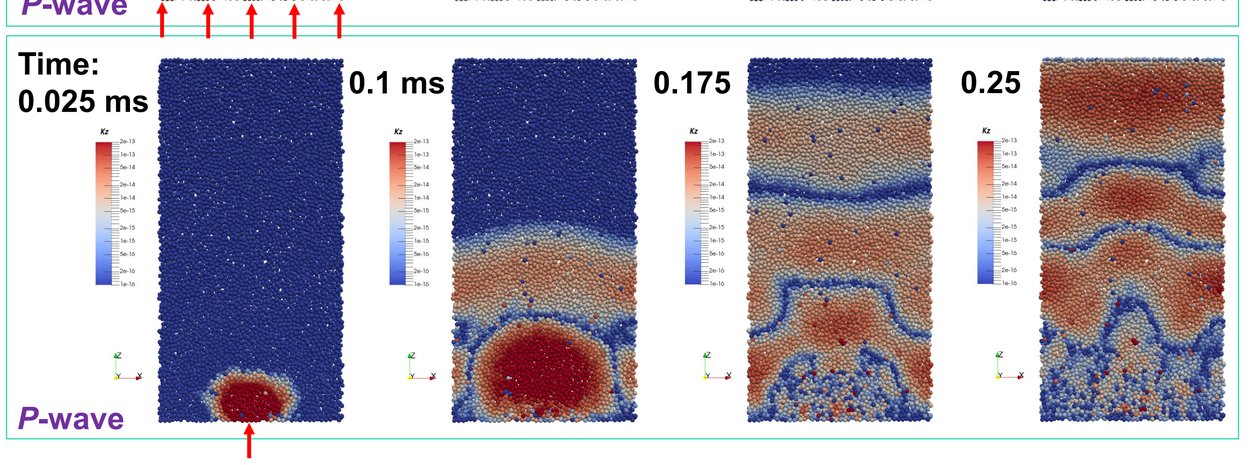
DEM simulations and laboratory tests concurred to show similar wave velocities.

供試体内のせん断波（左図），圧縮波（右図）の伝播様子（粒子運動エネルギーに着目）
S-wave (left), *P*-wave (right) propagation (Kinetic energy of individual particles is illustrated.)









上段：下端全面加振
upper row: excitation of the entire wall

下段：下端中央部加振
lower row: excitation of the centre part only

圧縮波の方が速く伝播する．供試体下端中央部のみ加振した場合，複雑な波紋が観測されるため，弾性波速度の測定が容易ではない．

P-waves propagate faster than *S*-waves. Quantifying wave velocity is easier when exciting the entire wall boundary.

本研究に関する担当研究室は桑野研究室です．部屋は東京大学生産技術研究所B棟3階のBw−304です．
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大坪正英 (2017)

Numerical Study on Shear Wave Propagation through Gap-graded Granular Material

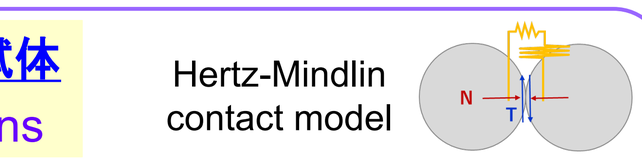
ギャップグレード粒状体のせん断波伝播特性に関する数値解析

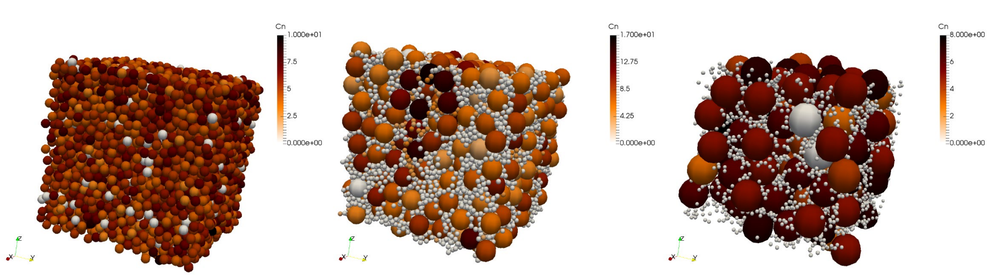
Gap-graded soils, consisting of mixtures of finer and coarser particles are sometimes used to construct the filters and shoulders of dams and embankments. The role of the finer particles on the mechanical response of gap-graded materials depends on both the size ratio between coarse and finer particles, and volumetric fines content (Fc). This study assesses variations of shear wave velocities (Vs) and low-pass frequency filtering effects of gap-graded materials using discrete element method (DEM) simulations considering material properties of glass beads. We found that finer particles do not contribute to both Vs and $f_{lowpass}$ at lower values of Fc (< 20%). The low-pass frequency limit ($f_{lowpass}$) increases with increasing Fc above a threshold value of Fc = 20 - 30%. It is revealed that the proportion of contacts between finer particles determines the variation of $f_{lowpass}$.

ギャップグレード粒状体とは粒径の大小異なる地盤材料の混合物であり，ダムや堤防のフィルタや法面材料として使用されています．既往の研究では，材料の粒径比および細粒分含有率（Fc）はギャップグレード材料の力学特性に影響を及ぼすことが知られています．本研究では，個々の土粒子をモデル化する個別要素法（DEM）を用いることで，このような特殊材料に対するせん断波伝播速度（Vs）および最大通過周波数（$f_{lowpass}$）について検討しました．研究の結果，細粒分含有率が低い場合（Fc ＜ 20%），せん断波伝播速度・最大通過周波数に対する細粒分の影響は小さいことが明らかとなりました．ただし，細粒分含有率が20-30%以上の場合，最大通過周波数が大きく上昇する結果となり，これは細粒分同士の接触点数が急激に増加した結果であることが確認されました．

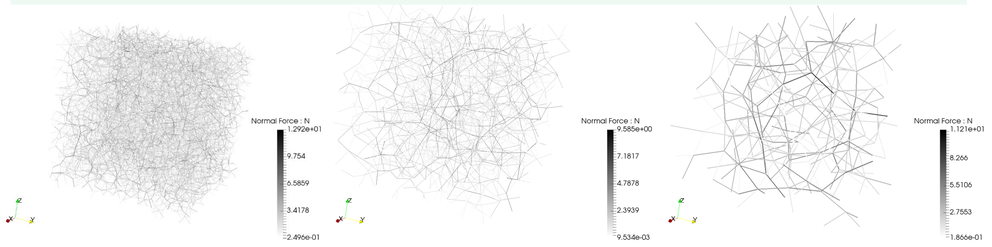
個別要素法供試体 DEM specimens

Hertz-Mindlin contact model



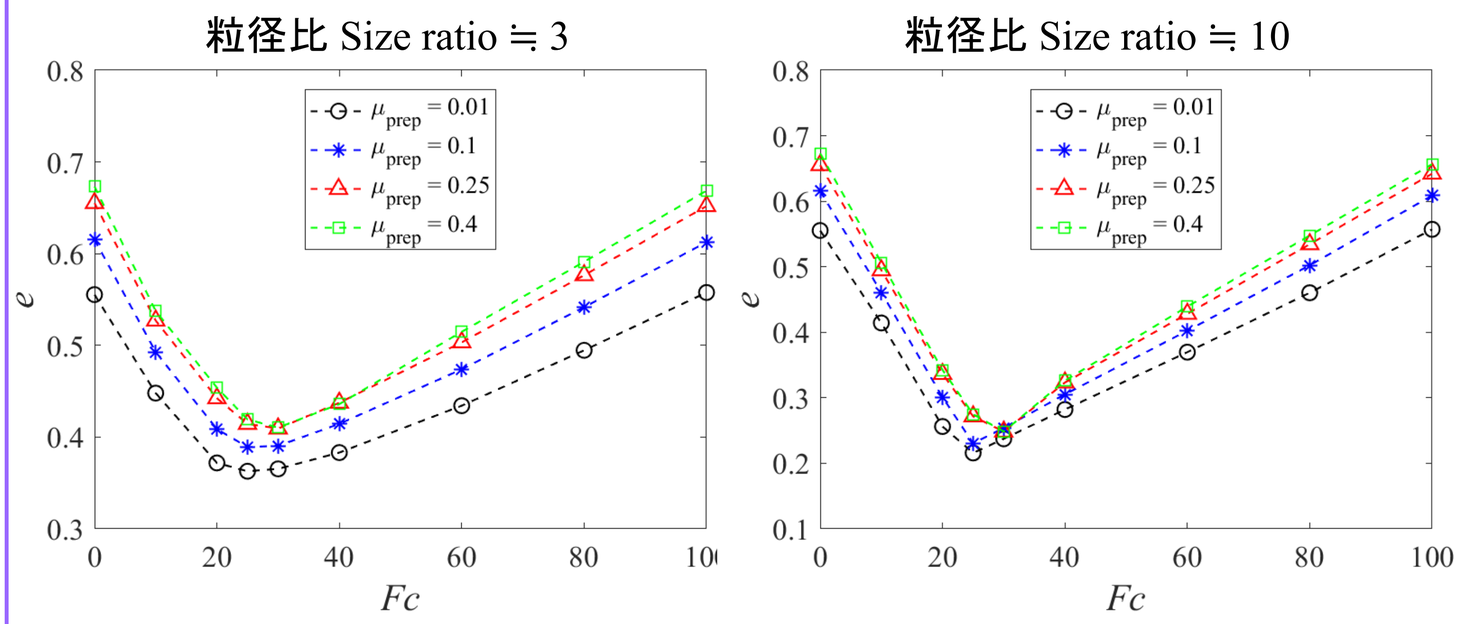


配位数（接触点数） Coordination number



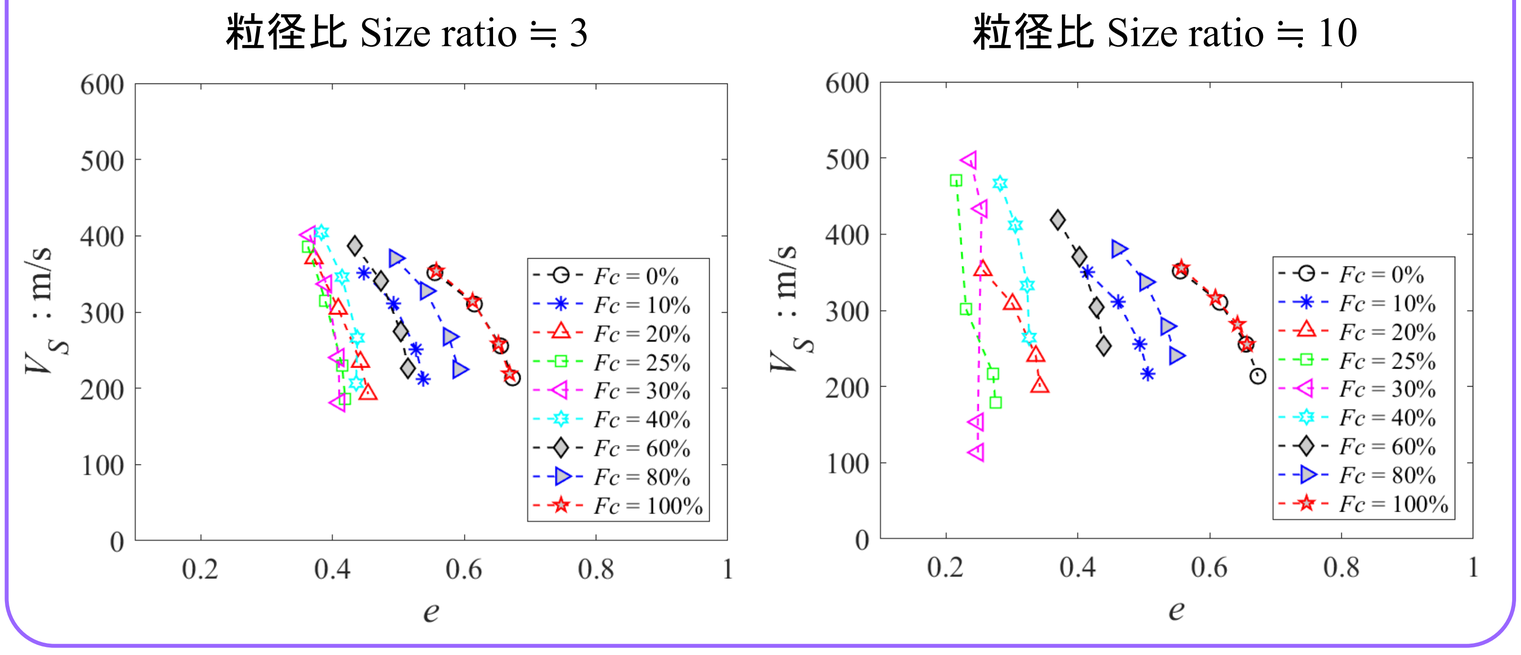
接触力網 Contact force chain

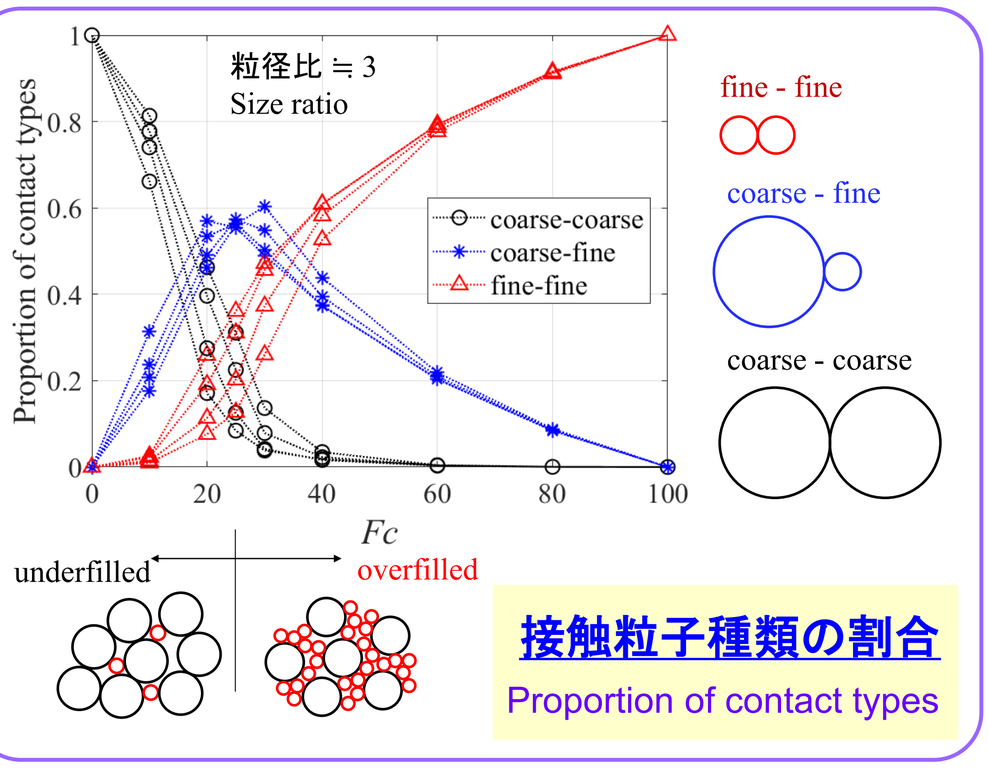
細粒分含有率 Fc と間隙比 e Variation in e with Fc



Inter-particle friction coefficient during sample preparation : μ_{prep} = 0.01, 0.1 0.25, 0.4
during wave propagation : μ_{wave} = 0.5

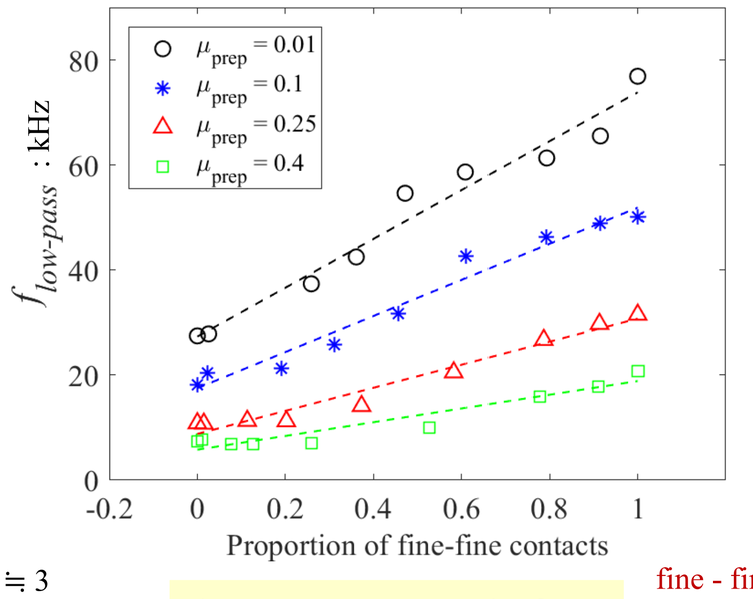
細粒分含有率 Fc とせん断波速度 Vs Variation in Vs with Fc





接触粒子種類の割合 Proportion of contact types

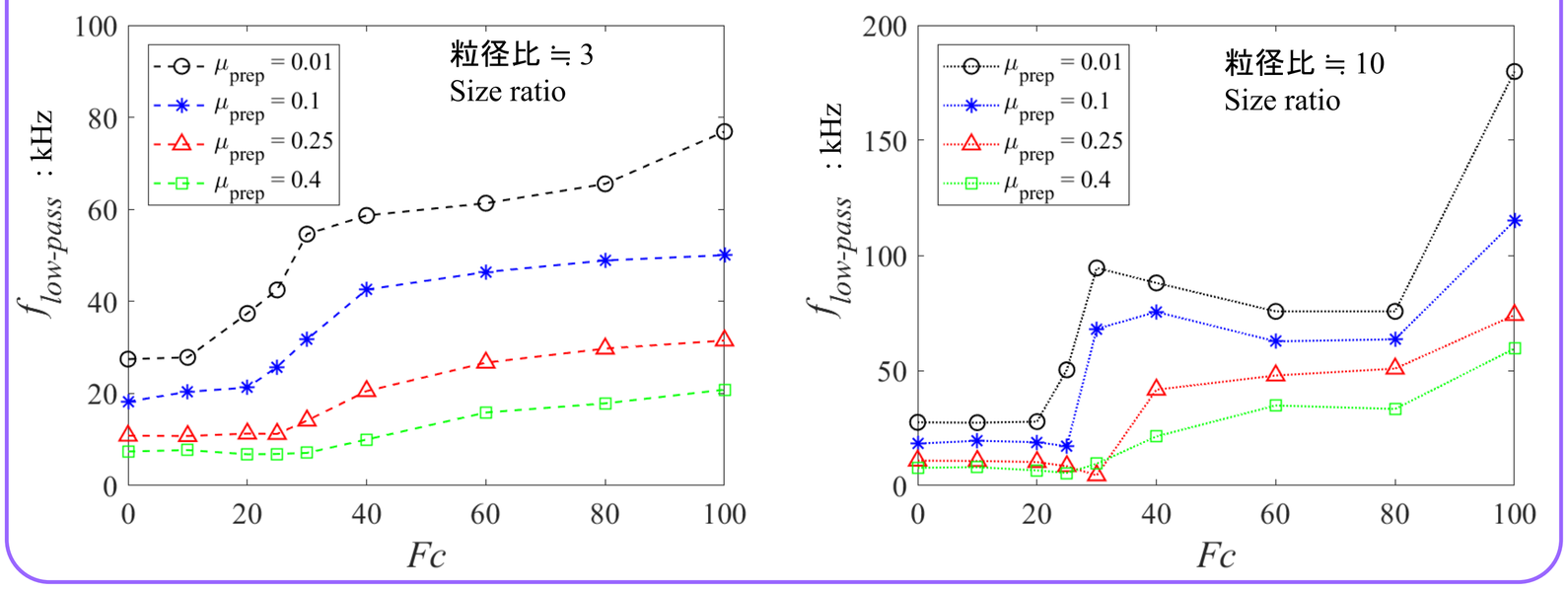
最大通過周波数



粒径比 ≒ 3
Size ratio

細粒分同士の接触割合 fine - fine

細粒分含有率 Fc と最大通過周波数 Variation in Vs with $f_{lowpass}$



本研究に関する担当研究室は桑野研究室です．部屋は東京大学生産技術研究所B棟3階のBw−304です．

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大坪正英 (2018)

Elastic wave propagation through Gap-graded silica sand mixtures

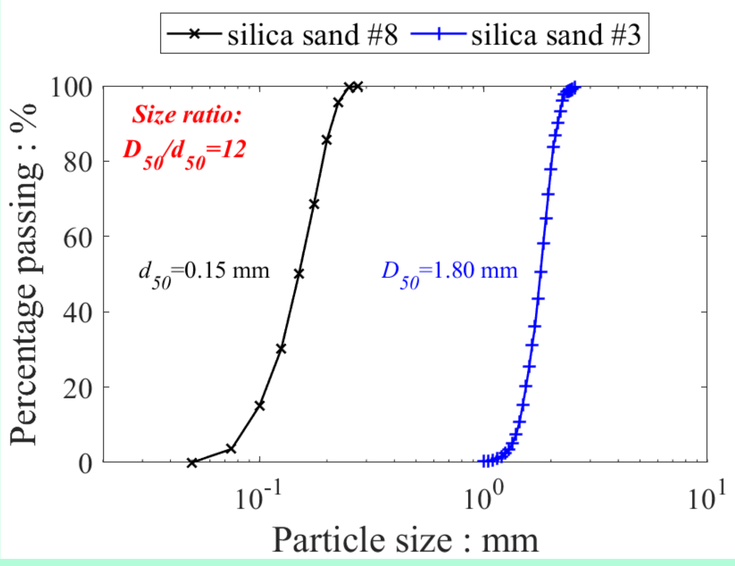
ギャップグレード硅砂の弾性波応答特性に関する基礎的研究

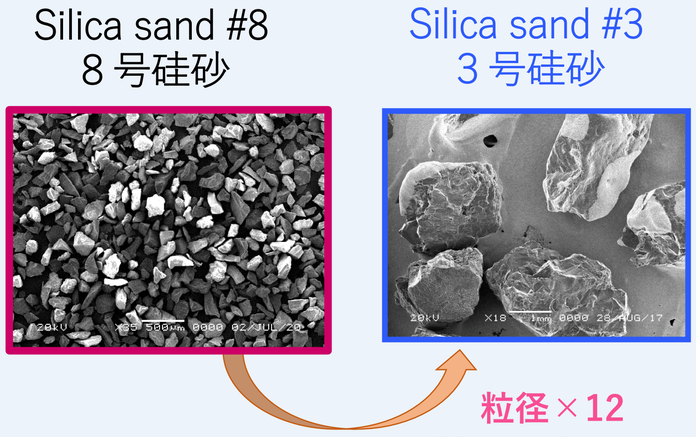
Research Purpose

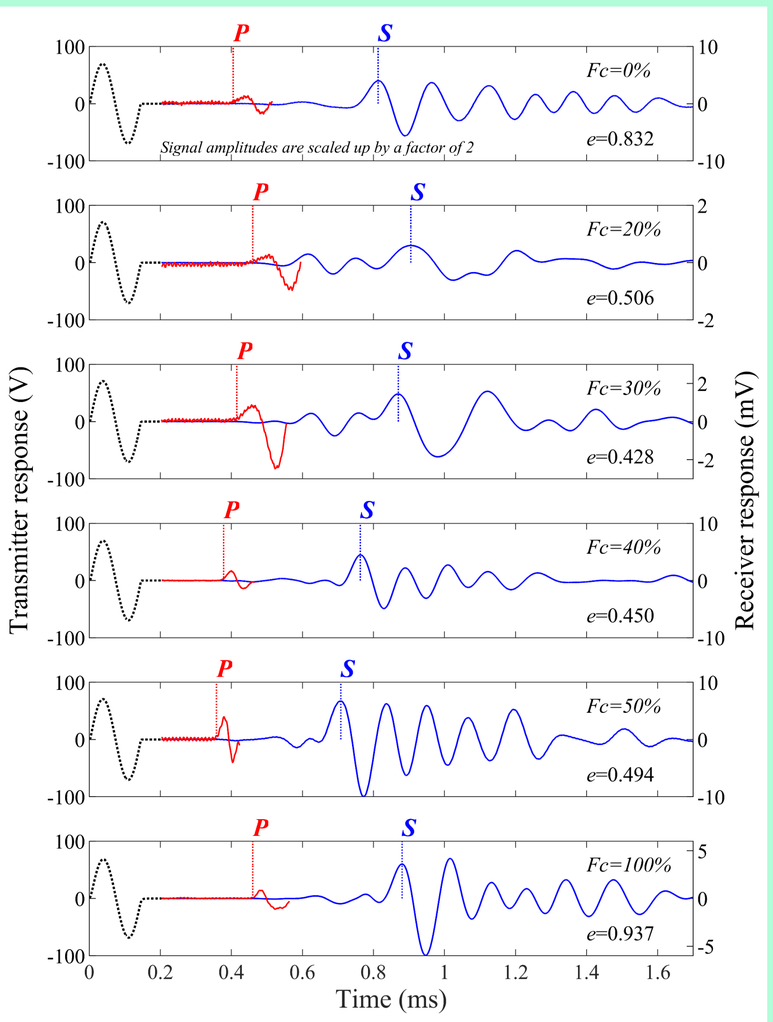
Gap-graded soils are mixtures of finer grains and coarser grains, and they are used in geo-hydro structures such as embankment or fill dam to improve the permeability characteristics. However, the mechanical response of gap-graded soils is complicated, and therefore fundamental study on this topic is essential. This study aims to understand small-strain mechanical properties of gap-graded soils using elastic wave (*P*-wave and *S*-wave) propagation approach where time and frequency responses are analyzed.

研究目的

ギャップグレード材料は粒径の異なる土粒子で構成された材料であり，透水性能調整の目的で堤防やダム等の土・水理構造物に使用されています．しかし，その複雑な力学挙動を理解するためには基礎的な研究が必要です．本研究の目的は，ギャップグレード硅砂に対する弾性波（せん断波，圧縮波）の伝播特性（時刻歴応答および周波数応答）を理解し，微小ひずみ領域における力学挙動の解明することです．



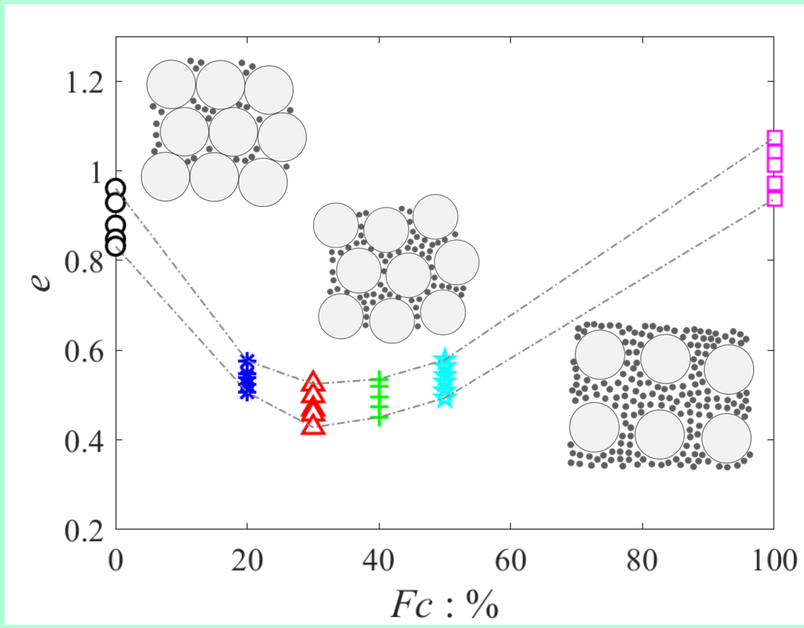




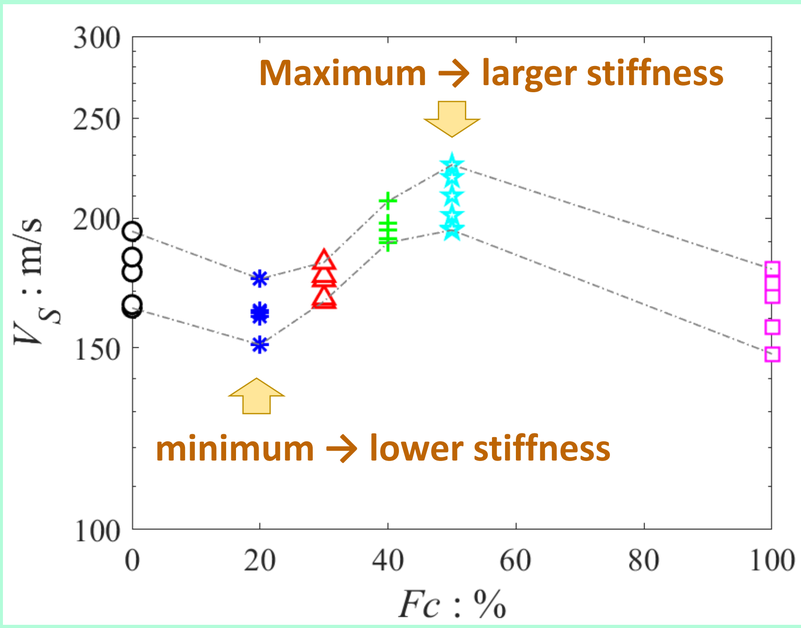
Time-domain responses of gap-graded soils

Coarse silica sand #3 and fine silica sand #8 were mixed to prepare gap-graded soils having various F_C. For each F_C value, specimens with various densities were tested in triaxial apparatus equipped with disk transducers. Considering the densest specimens tested for each F_C value, the arrival times of *P*- and *S*-waves are pointed in the time-domain plot as a function of F_C.

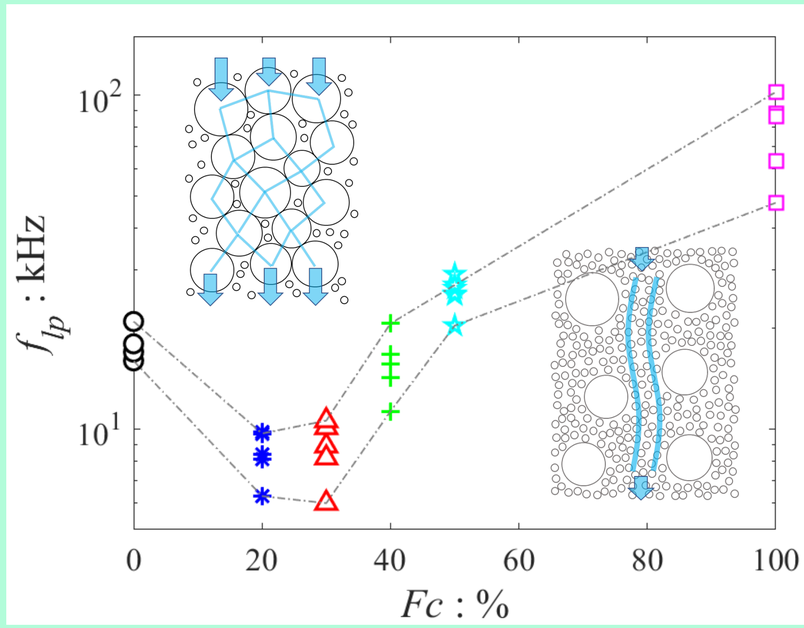
全体積に対する細かい硅砂８号の体積割合（**細砂含有率，F_C**）を変化させながらギャップグレード供試体を作製し，各F_C値における供試体密度の影響を検討しました．圧電素子を取り付けた三軸試験装置内で計測した弾性波の時刻歴応答のうち，各F_C値において最も密詰め供試体の結果を右に示します（圧縮波の最初の立ち上がり時刻を *P*，せん断波の最初の大きなピーク時刻を *S* と示している）．



e : Void ratio 間隙比



V_S : Shear wave velocity せん断波速度



f_{lp} : Low-pass frequency 最大通過周波数

- e, V_S and f_{lp} vary with F_C sensitively. At low F_C values, both V_S and f_{lp} decrease, but f_{lp} increases sharply at large F_C values.
- F_C が小さい場合は V_S および f_{lp} は共に低下しますが，F_C が100%に近づくと f_{lp} は急増することが明らかとなりました．

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Arian Ghaemi (2020)
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Granular Soils as a Low-pass Frequency Filter

地盤材料の高周波フィルタリング機能

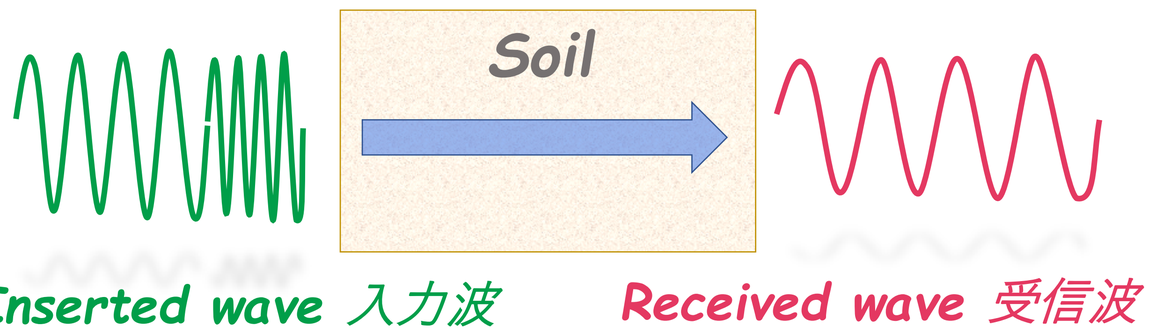
Summary まとめ

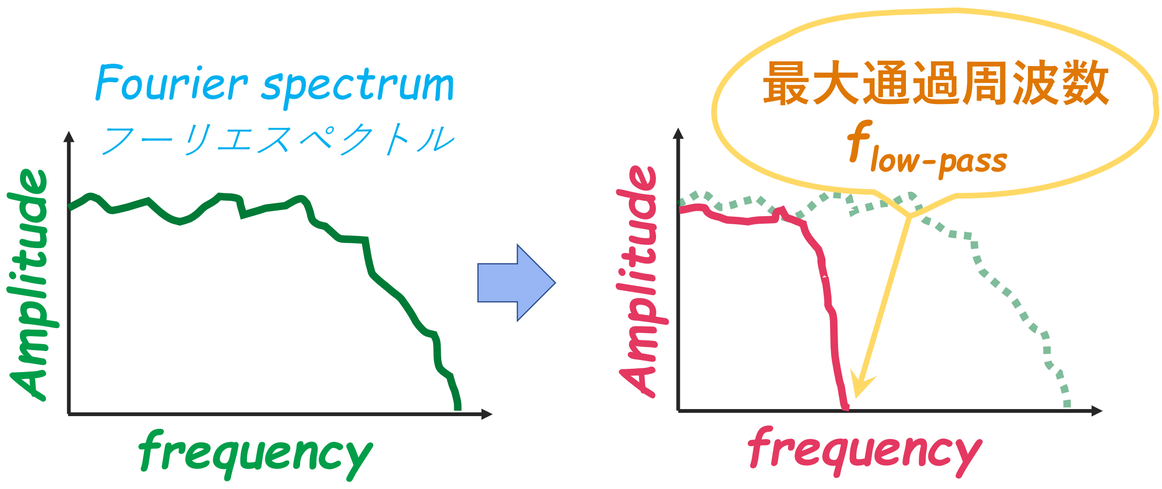
Mechanical properties of granular soils such as sandy or gravelly soils have been studied for many decades and documented in research papers and textbooks. However, it is not well known that soils can act as a low-pass frequency filter against applied stress waves, i.e. frequency contents higher than a threshold frequency cannot pass through the soil media. We newly found that the threshold frequency is a material property, influenced by grain size, confining stress level, and packing density.

砂や礫材のような地盤材料の力学特性については長年研究され、論文や教科書に詳しく記されています。一方、振動などの応力波に対する地盤材料の高周波フィルタリング機能についてはあまり知られていません。地盤材料固有の最大通過周波数が存在し、それよりも高い周波数はその地盤を通過できないという性質があります。当研究室では、その最大通過周波数は、①砂粒の大きさ、②地中応力の大きさ、③土の密度に依存することを明らかにしました。

Low-pass frequency filter 高周波フィルタとは

e.g. vibration, earthquake 例： 振動、地震波





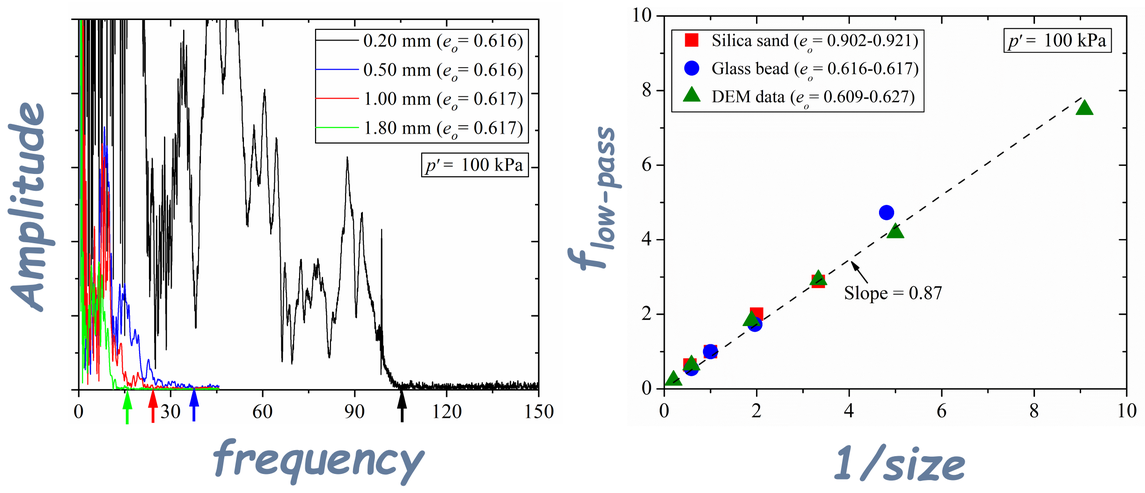
Factors to affect low-pass frequency 最大通過周波数に影響する因子

① Grain size 砂粒の大きさ

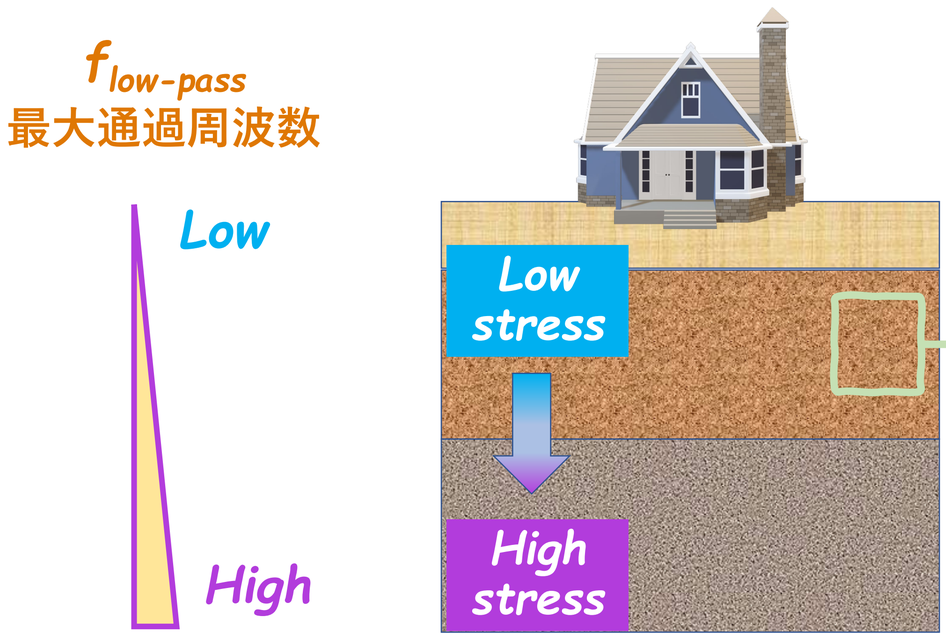


$f_{low\text{-}pass}$ 最大通過周波数

Low ⟶ High



② Confining stress 地中応力



③ Packing density 密度



$f_{low\text{-}pass}$ 最大通過周波数

Low ⟶ High

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EVALUATION OF LOOSED GROUND ASSOCIATED WITH UNDERGROUND CAVITIES BY TRIAXIAL TESTING

地盤内空洞まわりのゆるみ領域の力学特性の評価

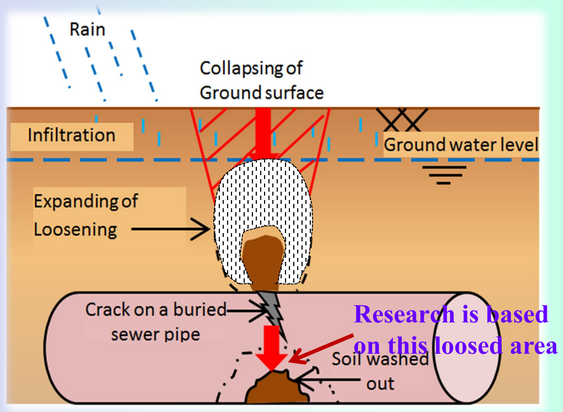
Ground cave-in happens in all over the world, which usually starts from internal erosion and finally leads to underground cavities. Ground loosening is a common phenomenon which is always associated with expansion of such initially formed cavities. The main objective of this research is to analyze the variation of mechanical properties of loosed soil associated with cavities. Small triaxial experiments for uniform fine (Toyoura) sand were conducted with an artificial cavity in the specimen. The loosening was formed by passing water through and the variation of stresses, strains, stiffness and shear strength were evaluated before and after loosening. In addition, one triaxial test was scanned by X-ray Computed Tomography to visualize the loosening formation in 3-dimensional ground.

地盤内の土砂が何らかの理由により流出して空洞ができると、その空洞が成長し進展して地表に到達し地盤陥没が引き起こされる危険性があります。空洞の進展過程においては通常空洞上部に地盤の密度が低下したゆるみ領域が形成される事が知られていますが、実態についてはまだあまりよく分かっていません。本研究ではゆるみの範囲や力学特性を定量的に把握することを目指し、三軸供試体内に人工的に空洞やゆるみを作り、ゆるみが供試体の変形・強度特性に与える影響を明らかにしました。またX線CTスキャナを用いて地盤内部のゆるみ形成を可視化しました。

1. Introduction to ground cave-in





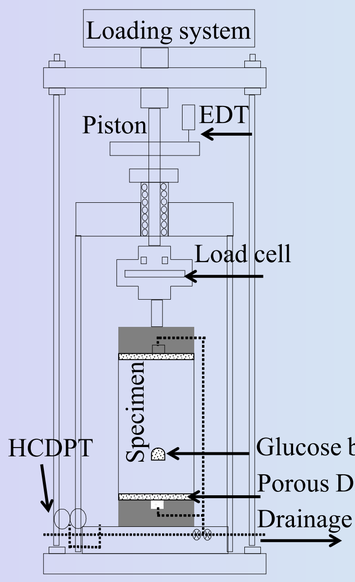


- Damaged sewer pipes cause many cave-ins. In this research, specially attention will be paid on evaluating of mechanical properties of loosed ground above the initial cavity.

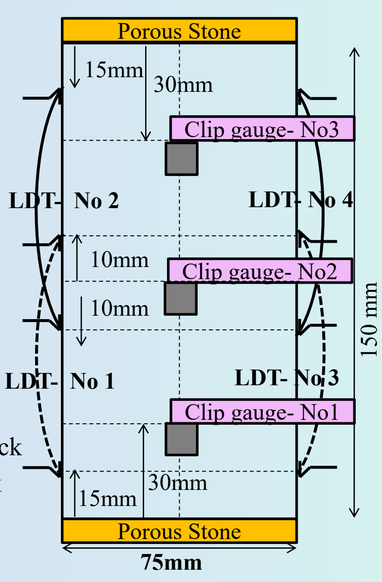
3. Testing procedure

- Toyoura sand was tested at two different relative densities (Dr = 60% and 35%) and sand was placed by air pluviation while inserting the cylindrical glucose block. (Dia.=12mm, height=15mm, void ratio =0.25%)
- Specimens were erected at isotropic state of 25kPa.
- Isotopic stress increment from 25 to 50 kPa was applied and then controlled at 50kPa till starts shearing at the end.(Stress path shown under No.2)
- Small cyclic loadings were applied to evaluate the stiffness and Poisson's ratio before and after ground loosening is formed.
- Special arrangement of sensors allowed to measure radial and axial strains separately at loosed soil closer to cavity and normal soil away from it.
- One specific test was repeated under the same control conditions. Extend of loosening was visualized by capturing series of X-ray images before/after infiltrating, after drainage and at several stages during shearing.

2. Testing apparatus, Stress path and material properties

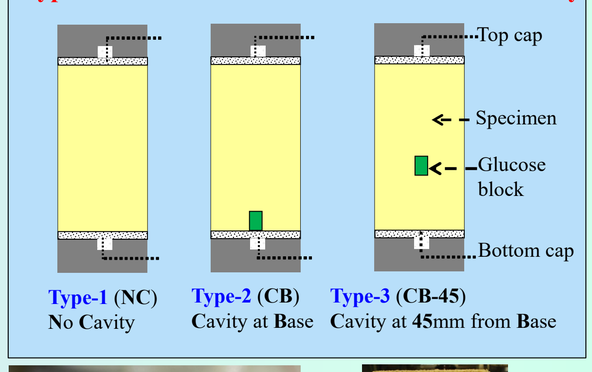


Testing apparatus



Arrangement of sensors

3 types of tests based on location of the initial cavity

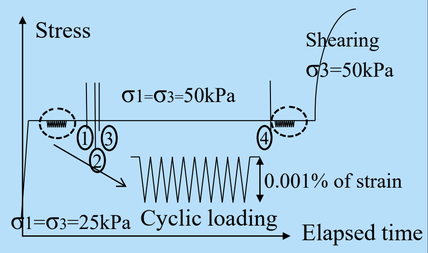


Type-1 (NC) No Cavity | **Type-2 (CB)** Cavity at Base | **Type-3 (CB-45)** Cavity at 45mm from Base



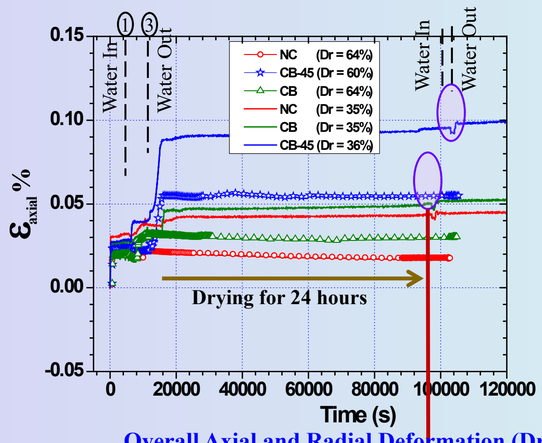
Artificially formed cavities and loosening (after shearing)

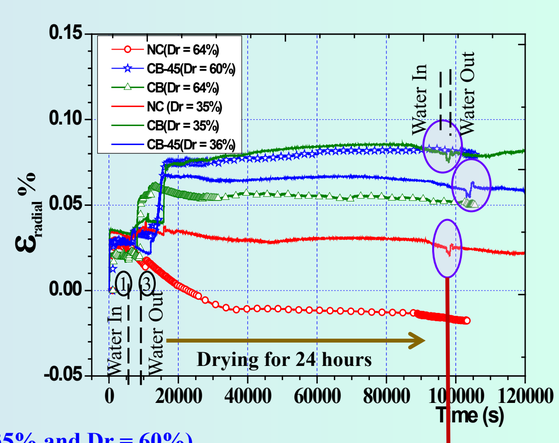
Stress and water movement path



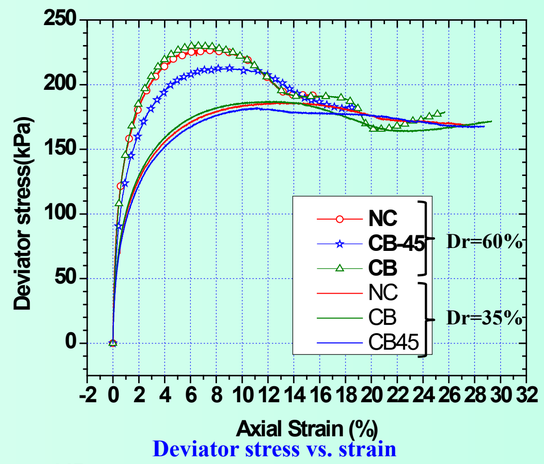
Step 1- Inserting water from bottom cap with rate of 14-16 ml/min and draining from top cap.
Step 2- Once 1500ml of water is passed through; both the bottom and top cap valves are closed and hold the water inside the specimen for a short time. (Nearly 10 mints)
Step 3 to 4- Then the top cap was open to atmosphere while the drainage was started from bottom cap.

4. Results

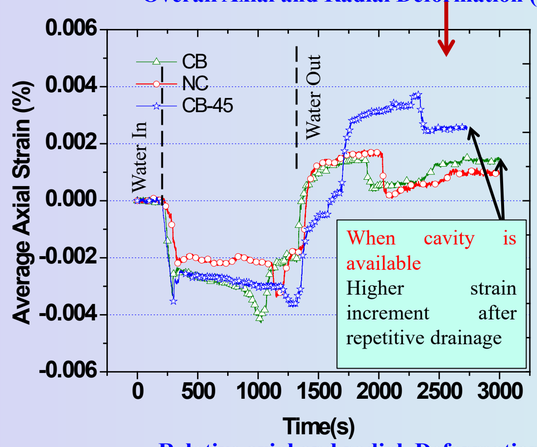


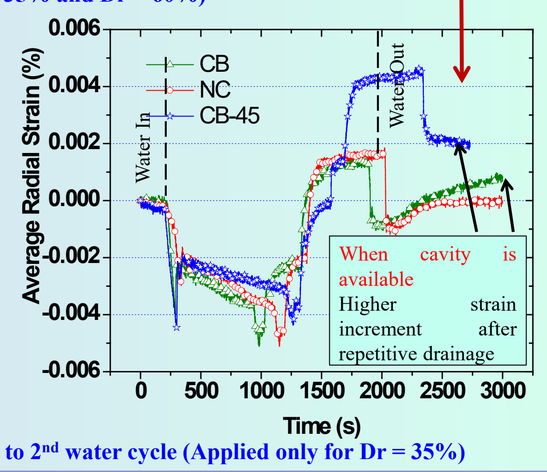


Overall Axial and Radial Deformation (Dr = 35% and Dr = 60%)

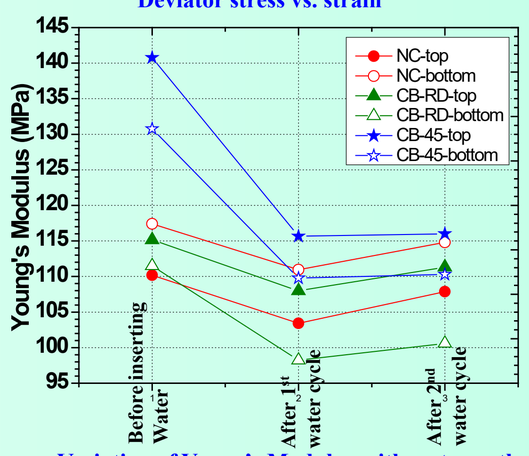


Deviator stress vs. strain



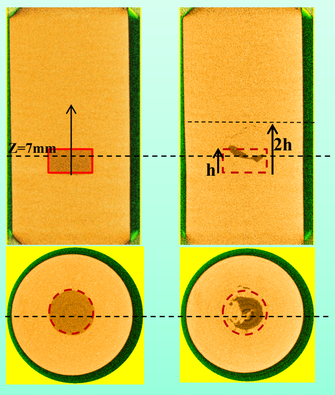


Relative axial and radial Deformation due to 2nd water cycle (Applied only for Dr = 35%)



Variation of Young's Modulus with water path

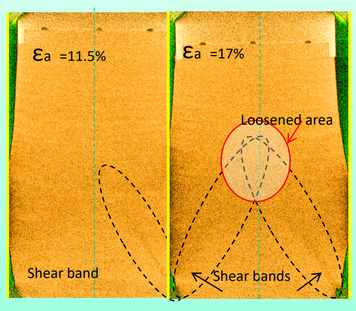
5. Visualization of loosening in triaxial specimen by X-ray CT



Initial

After 2nd infiltration and drainage

- Ground loosening was spread in vertical direction similar to two times of initial cavity.
- No significant deformation in radial direction.
- Shear band formed as crossing through the loosened part.



6. Summary

- When the initial cavity is closer to ground surface, the deformations are increasing significantly and shear strength is also decreasing.
- Repetitive water infiltration is supporting further propagation of ground loosening and increases the radial and axial deformations.
- When the cavity is located more than 10 times of the height of cavity, the effect of cavity on shear strength is negligible.
- When the cavity was located at the bottom part of the specimen, the ground stiffness has reduced at the bottom than the top part. However the scale of reduction is larger when the initial cavity moves towards the surface.
- Stiffness seems slightly increased after 2nd infiltration while strains are increased.

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Samanthi Renuka
Indiketiya Hewage (2012)

Evaluation of mechanical properties of sand loosened due to piping

ソイルパイプを有する土供試体の力学特性

Piping, known as a complex phenomenon of internal erosion, presents a great risk for hydraulic structures. In order to investigate the mechanical properties of sand with internal pipes, artificial piping was created by dissolving glucose column in a hollow-cylindrical specimen of Toyoura sand. In this research, triaxial compression(TC), triaxial extension(TE) and torsional shear(TS) tests were conducted on specimens with vertical pipes before shearing. Piping propagation during water infiltration was observed with Glip Gauges, and gap sensors were used to obtain shear modulus before and after piping effect by conducting small torsional cyclic loadings. Finally, monotonic torsional shear were applied to all the specimens until failure.

盛土や斜面に繰返し雨水が浸透することにより土粒子が流出しパイプ状の水みちができる場合があり、ソイルパイプと呼ばれる。浸透した雨水を速やかに排水する効果が期待されるものの、何らかの理由で水みちが閉塞された場合は一転して危険であるうえ、土構造内に空隙を有することになり構造上の弱点となりうる。本研究では、中空ねじり試験供試体内にグルコースを溶解させることにより人工的なパイプ生成を試み、供試体の変形強度特性に対するパイプの数や拘束圧、土の密度の影響を調べた。

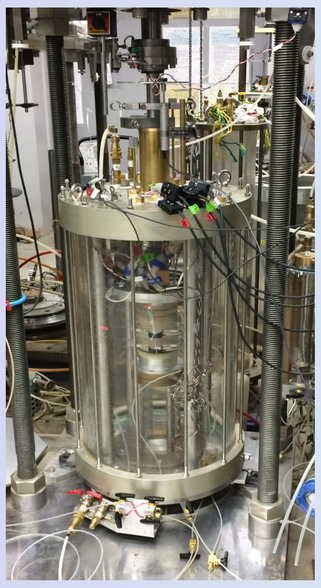
1. Soil pipe



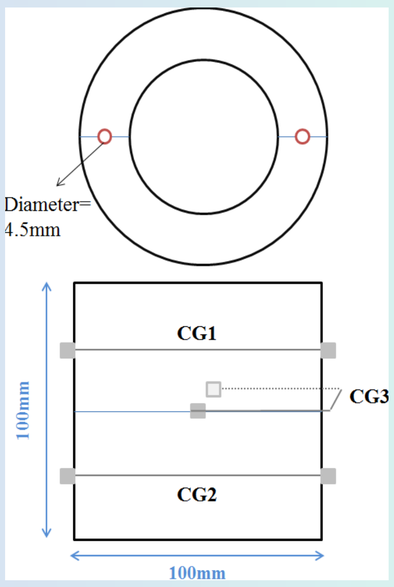


- ❖ Piping, which often occurs in hydraulic works, involving the removal of subsurface soils in a continuous tunnel to a free or escape exit.
- ❖ Landslide caused by piping has drawn much attention recently.

2. Testing apparatus and stress path



Hollow cylindrical torsional shear apparatus

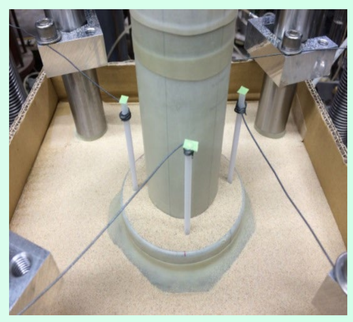


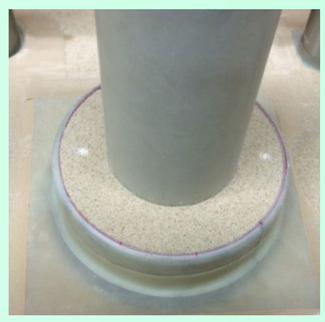
Arrangement of Clip Gauges (Radial strain measurement)



Gap Sensor (Shear modulus measurement during small torsional cyclic loadings)

Specimen with glucose pipe

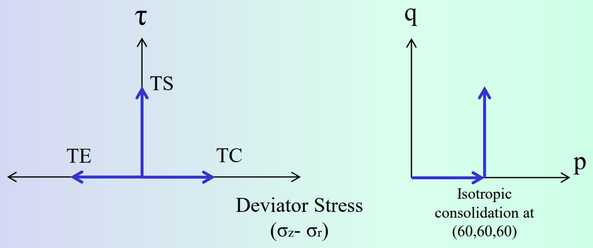






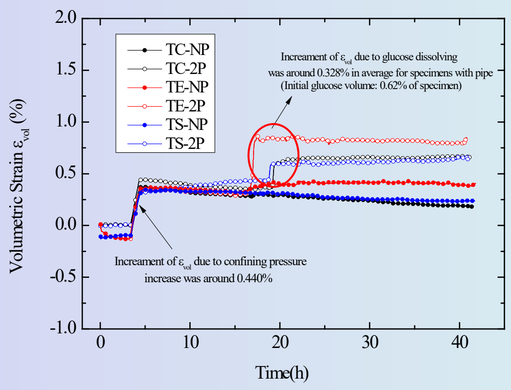
3. Testing procedure

Stress path before shearing

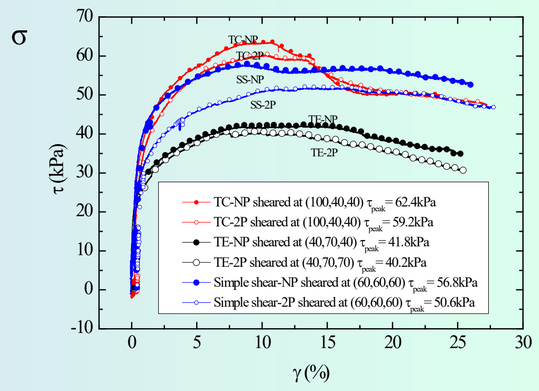


- ❖ Specimen with relative densities around 75% were tested, and the number of internal pipe (Dia.=4.5mm) was 0 and 2.
- ❖ Specimens were erected at isotropic stress of 30kPa and then the confining pressure was increased to 60kPa.
- ❖ After isotropic consolidation around 12 hours, 1300ml water was infiltrated into specimen, with the aim of completely dissolving the glucose pipe.
- ❖ Triaxial compression and triaxial extension was conducted while kept p' constant; for simple shear test, τ was applied at .
- ❖ Small torsional cyclic loading were conducted at the initial dry state, after water infiltrition and during TC (triaxial compression), TE (triaxial extension) and TS(torsional shear) under certain stress state.
- ❖ Monotonic torsional shear test were applied for all the specimens at last.

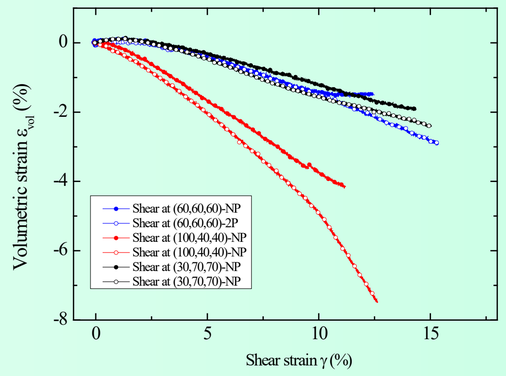
4. Results



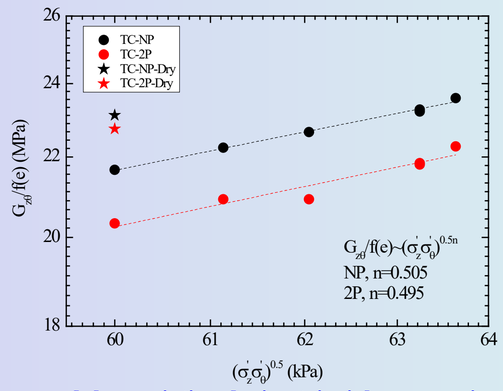
Volumetric strain variation before shearing



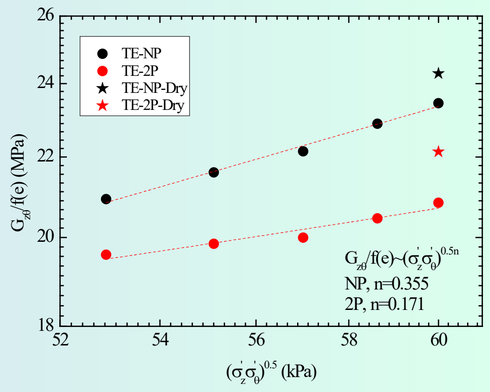
Shear stress vs. shear strain



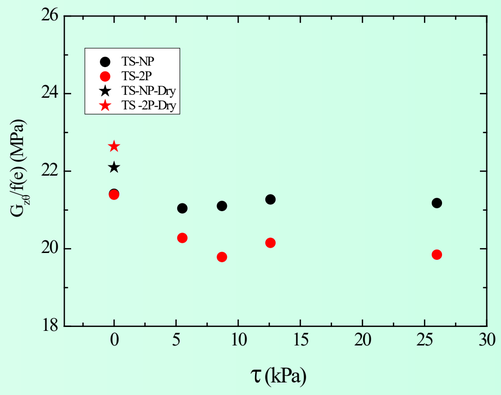
Volumetric strain during shearing



Shear modulus variation during triaxial compression



Shear modulus variation during triaxial extension



Shear modulus vs. Shear Strength

6. Summary

- ❖ Internal erosion in the form of piping was successfully created in sand by glucose power.
- ❖ Decrease of shear modulus G was observed in specimens subjected to piping effect.
- ❖ Shear starting from triaxial compression showed the highest resistance while triaxial extension the lowest. Larger difference of peak shear strength between specimen with and without pipe was found at simple shear test.
- ❖ For G measured during TE, n computed from the function of $G\sim(\sigma_z\sigma_\theta)^{0.5n}$ was not normal possibly due to the limitation of the data number. Still, more degradation was observed in specimen subject to piping effect.

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Yang Yang (2015)

EVALUATION OF INTERNAL EROSION BY THICKNESS OF FLOWED WATER

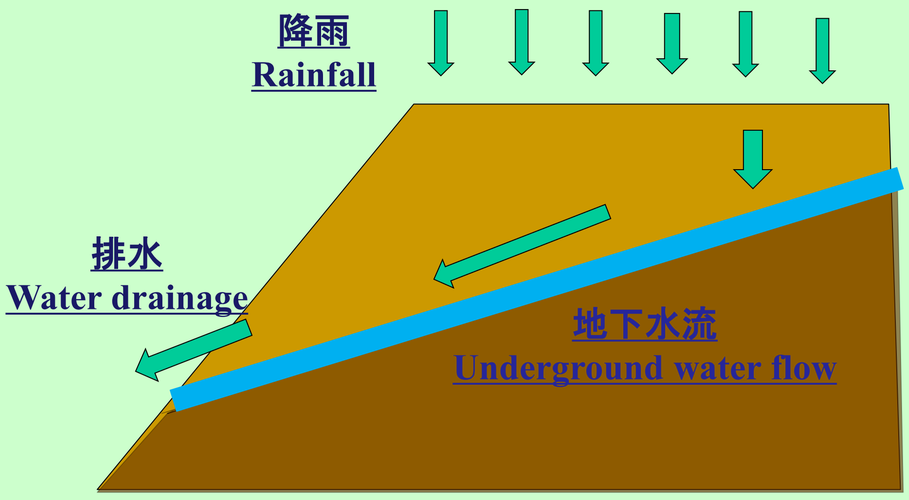
地排水の濁度による土砂流出評価

Internal erosion causes various ground disaster such as a cave-in accident, which is supposed to happen due to water penetration under the ground with rainfall. Especially in fine-graded material, finer particles flow out first and this flow makes drained water turbid, which has been considered as a warning of the ground disaster. However, relationship between turbidity of drained water and internal erosion is not yet clear. In this research, characteristics of internal erosion was evaluated from turbidity of drained soil by one dimensional column test.

地盤内土砂流出は空洞の形成、陥没事故の発生や内部浸食等様々な土砂災害を引き起こします。こうした土砂流出は降雨に伴う地中の水の浸透で発生すると考えられており、粒度の良い地盤においては細粒分が卓越して流出すると予想されます。細粒分の流出は地排水を濁らせ、地排水の濁りは地滑り等の地盤災害の前兆現象とされているもののその実態については殆ど明らかとなっていません。本研究では一次元円筒カラム内に地盤を作成し地中への水の浸透による土砂流出状況を、排水の濁度により評価しました。

水みちと内部浸食
Situation of increasing of air pressure under the ground

沢筋等の水みちへの浸透と排水の繰り返し
Repetition of water flows through



雨水は地盤内の水みちを通り排水され、細粒分流出による排水が濁る時がある
Water is drained through water pathway, and some times drained water is turbid

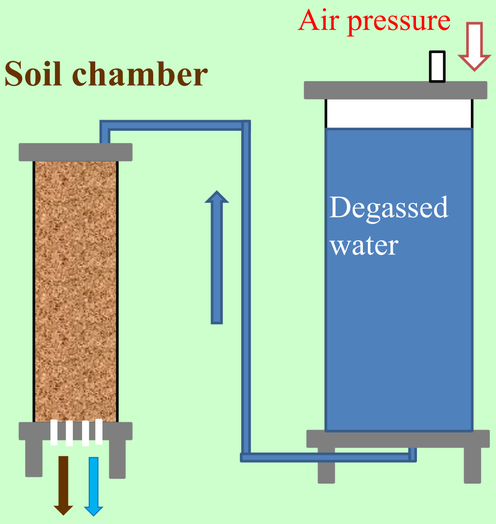
To clear…

- 排水の濁りの起きうる条件
- 細粒分流出による水みちでの強度
- Conditions which cause thickness of drained water
- Influence of internal erosion on stiffness

浸透圧をコントロールしたアクリル円筒実験
Model test simulating soil drainage surrounding an underground structure

アクリル円筒上端部から浸透圧を掛け水を流入させ、底部の穴から土と水の排出を調べる。
Pressurized water flows from the surface ground and investigate .







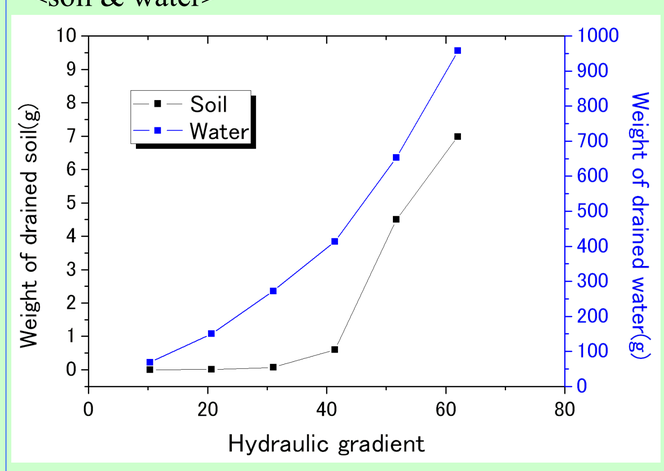
Soil and water is draind → <Turbidimeter>

一定時間ごとに排水の濁度・排水量等を計測
Measuring turbidity of drained water, weight of drained water and so on at certain period

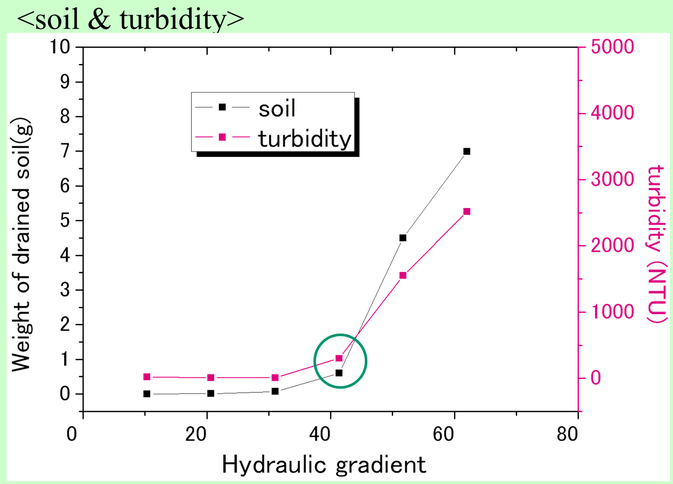
実験結果
Test Result

排水量、排土量と濁度の関係
Relationship between drained soil, drained water and turbidity

<soil & water>

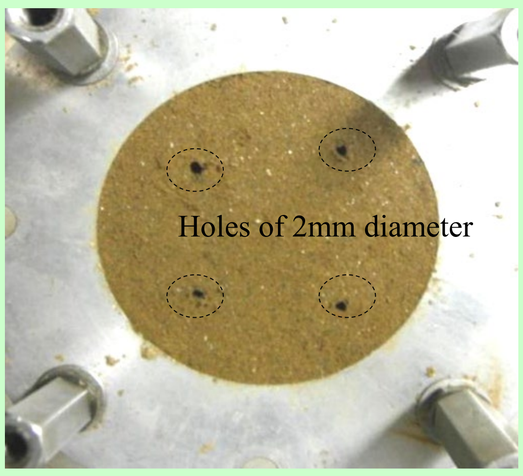


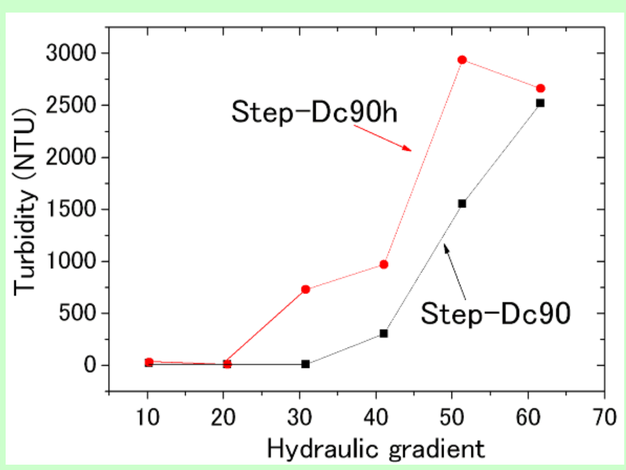
<soil & turbidity>



- Weight of drained water increased acceleratory with rise of seepage pressure.
- Turbidity was relative to weight of drained soil and increased rapidly over the threshold pressure
- 排水、濁度、排土量は動水勾配上昇と共に増加
- 濁度、排土量はある動水勾配を境に増加

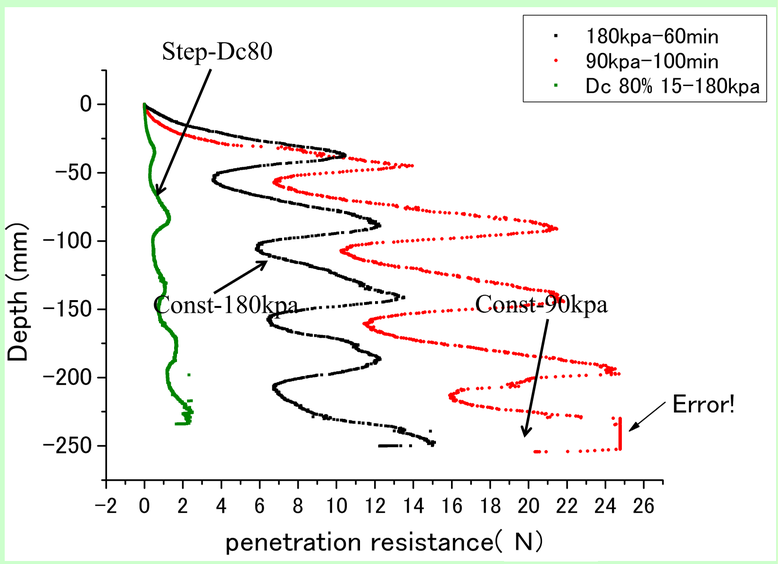
<Effect of soilpipes>





- Small soil pipes accelerated internal erosion.
- 200-300times of water was flown through soil pipes as the ground.
- ソイルパイプを模擬した穴を開けたケースでは排水量、排土量、濁度が穴のないケースに比べ増加、ソイルパイプ内を集中して水が流れている可能性が高い

コーン貫入試験
Cone penetration test



排土量が少ない程貫入抵抗は大きい
(強度低下していない)
Test case with small seepage pressure and small amount of drained soil has larger penetration resistance



Photos of sample cells
Hydraulic gradient: high→low

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佐藤真理 (2013)

Triaxial Test for the Evaluation of Mechanical Properties of Soil with Internal Erosion

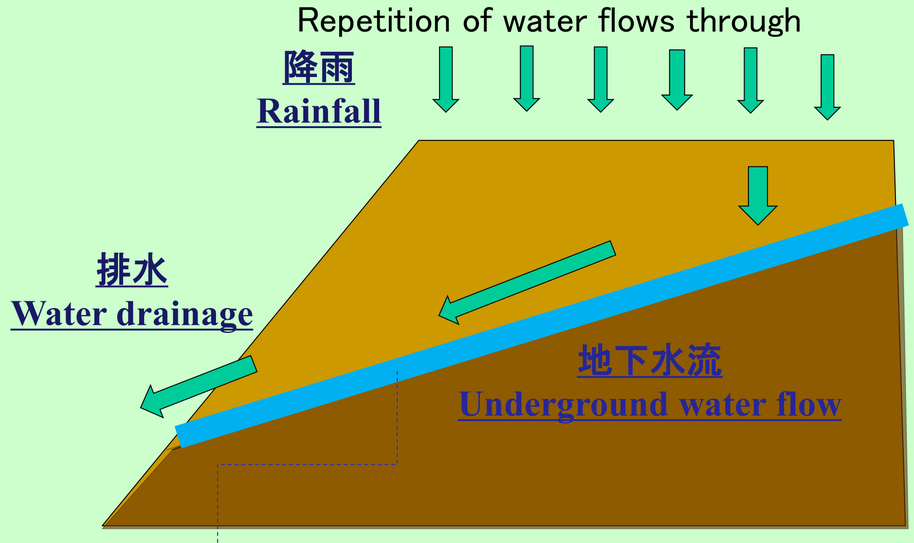
内部侵食を受けた土供試体の三軸試験

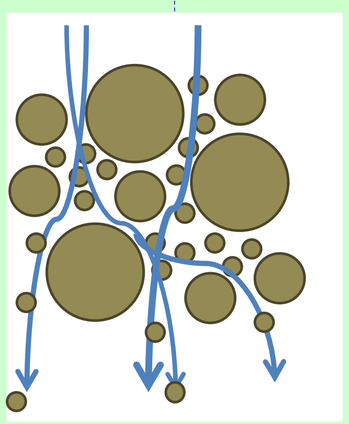
Internal erosion is a phenomenon of fine particles' washing out from the ground, which causes various ground disaster such as a sinkhole accident. It is supposed to happen due to water penetration under the ground with rainfall. In this research, new triaxial test apparatus, which was possible to cause internal erosion inside the specimen was developed. The influence of small degree of internal erosion on mechanical properties was investigated.

地盤内土砂流出（内部侵食）は地中空洞の形成、地盤陥没の発生や地滑り等様々な土砂災害を引き起こす。こうした土砂流出は降雨に伴う地中の水の浸透で発生すると考えられ、粒度の良い地盤においては細粒分が卓越して流出すると思われる。本研究では、供試体内で内部侵食の発生が可能な三軸試験装置を開発し、内部侵食が地盤の強度や変形に与える影響について定量的な評価を行った。

内部侵食について
Internal Erosion

沢筋等の水みちへの浸透と排水の繰り返し
Repetition of water flows through



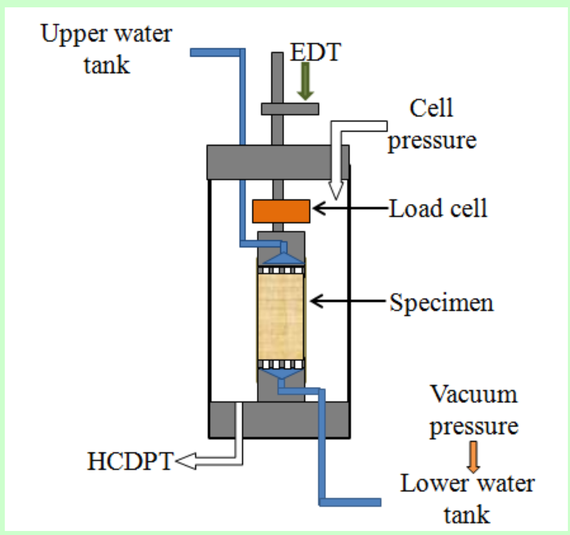


- Water seepage was concentrated at the certain areas such as boundary of fills→internal erosion
- Influence of small degree of erosion was not clarified.
- 浸透流は盛り土境界など特定の箇所で集中し、"水みち"となる。→内部侵食発生の恐れ
- 少量の内部侵食が地盤に及ぼす影響は明らかになっていない

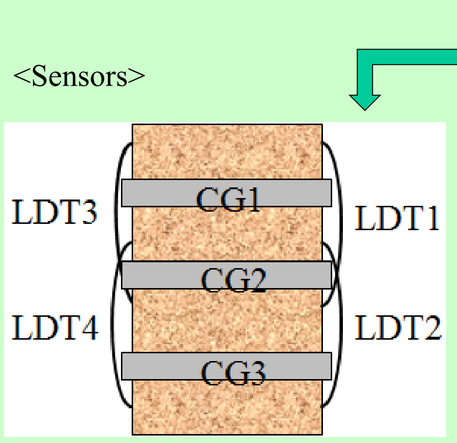
供試体内部で侵食を発生させる三軸圧縮試験装置
Triaxial test apparatus causing internal erosion inside the specimen

三軸圧縮試験装置内で浸透流を発生させ、侵食を発生させる。侵食終了後排水せん断を実施。
Internal erosion was made in the specimen
and then the specimen was sheared with drained condition.

<Test apparatus>



<Sensors>



LDT



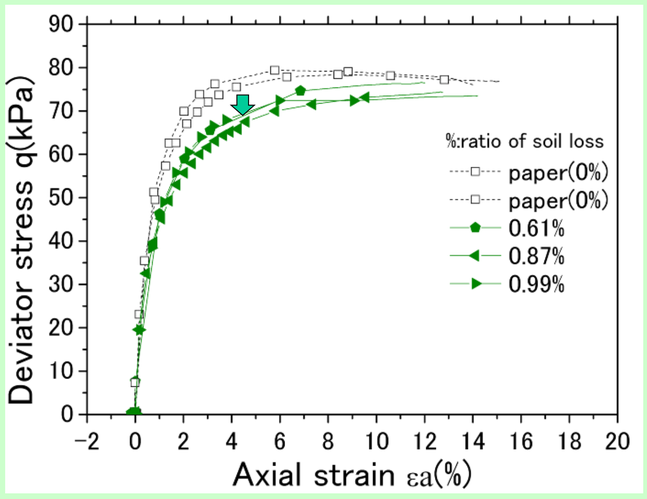
ClipGage



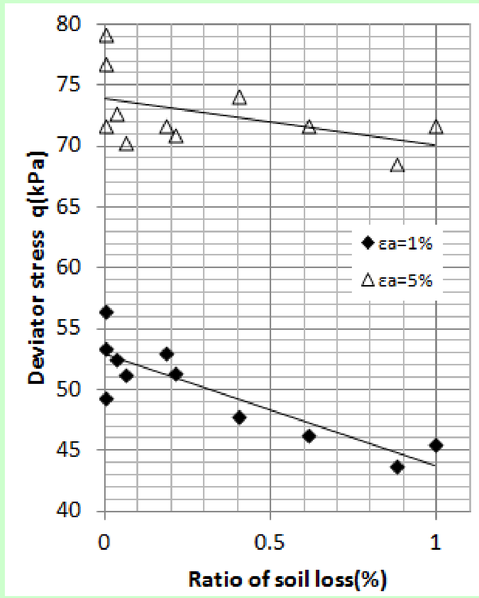
センサーを設置し水平ひずみ(CG)と鉛直ひずみ(LDT)を測定
微小ひずみ繰り返しにより実験中のヤング率とポアソン比を算出
ClipGages are for horizontal strain and LDTs are for vertical strain
Young's Modulus and Poisson's Ratio were estimated from these sensors by applying the cyclic loadings.

地盤の力学特性に与える影響
Effects of internal erosion on the strength and stiffness of soil

<stress-strain curve>



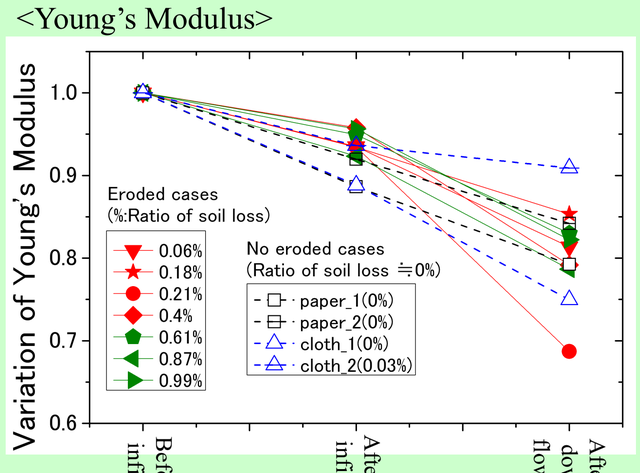
<Deviator stress at εa=1% and 5%>



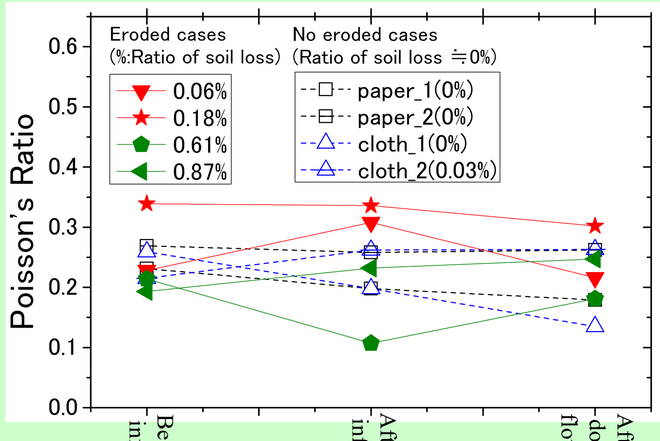
- Deviator stress decreased due to less than 1% amount of erosion in the whole specimen.
- The decreasing ratio was larger at small strains, and was relative to the amount of eroded soil.

- 偏差応力は少量の侵食（全体の1%以下）でも低下がみられた
- この減少程度は特にひずみの小さな範囲で大きく、侵食量に比例した。

<Young's Modulus>



<Poisson's Ratio>

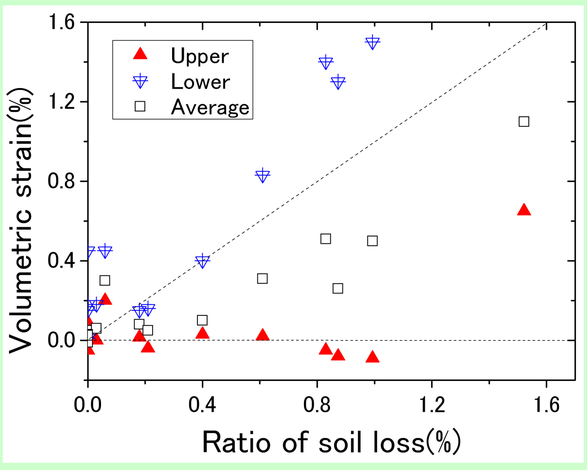


- Young's Modulus decreased due to internal erosion but Poisson's ratios were not affected by erosion.

- ヤング率は侵食が発生したケースで減少したが、ポアソン比にはほとんど影響がみられなかった。

侵食による変形
Deformation

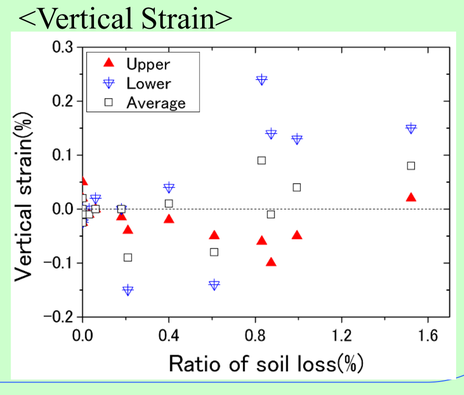
<Volumetric Strain>



- 下部においては侵食量以上に圧縮されたが上部においてはほとんど変形がみられなかった。
- 鉛直ひずみはほとんど発生せず。異方性がある。

- Lower part was compressed more than the amount of erosion but upper part was not deformed so much.
- Vertical strain was not so large, which suggested anisotropic behavior.

<Vertical Strain>



本研究に関する担当研究室は桑野研究室です.
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佐藤真理 (2014)

Effect of water flow in internal erosion of sandy soils

流水がもたらす砂質土の内部侵食

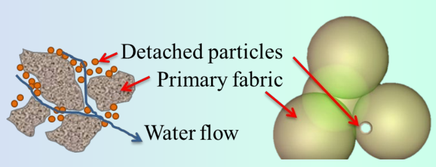
The phenomenon of internal erosion refers to the detachment of soil particles from the main structure due to the action of a fluid flow; both suffusion and piping are result of internal erosion in the ground, and can cause disasters in hydraulic structures due to heavy rainfalls. In order to know the influence of water penetration into the ground, a series of permeability tests had been performed in a highly erodible soil, applying water with various hydraulic gradients from the top part of specimens with different densities, and letting fine particles drain out, leaving the coarse skeleton behind.

豪雨時などに、土中に水が浸透しパイピング（漏水）を起こすことで河川構造物を中心に大きな被害が出ています。その原因として地盤内の浸透流によって地盤内部の土が流出する内部侵食が挙げられます。
本研究では、内部侵食現象を室内供試体内で再現することを目的として、試料を異なる密度調整に調整し、異なる動水勾配下での透水実験を実施しました。その際、細かい土粒子は水と共に排出を許し、土の流出量と排水の濁度を測定しました。

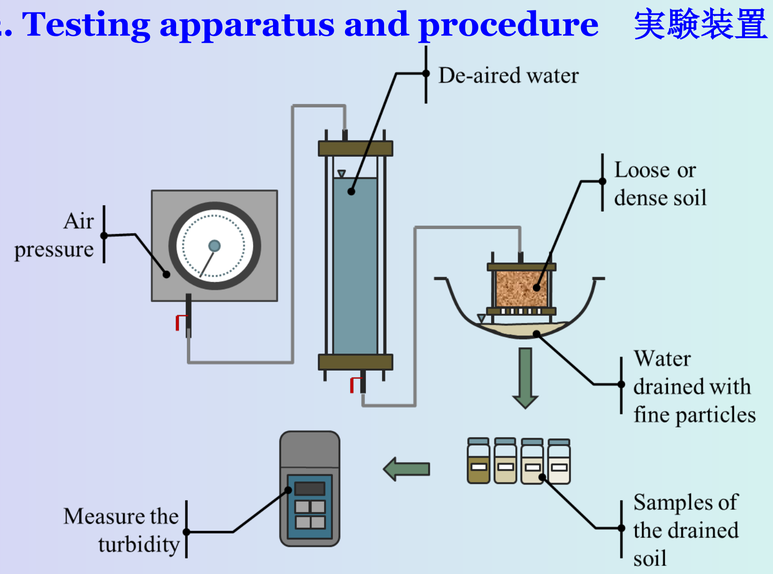
1. Internal erosion　内部侵食とは



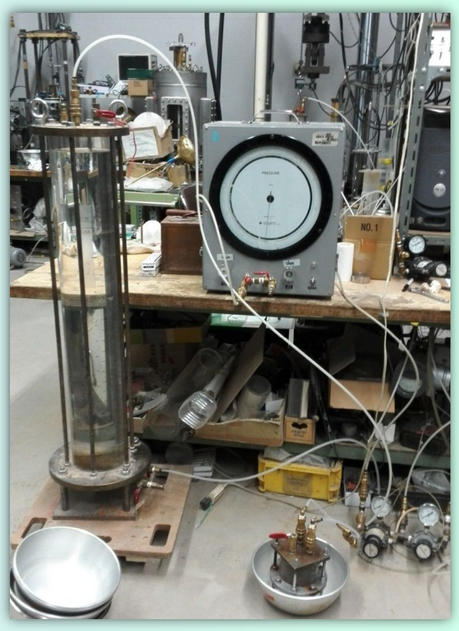
Internal erosion refers to the detachment of soil particles from the main soil structure due to the action of a fluid flow
内部侵食とは水の流れによる土（細粒分）の流出

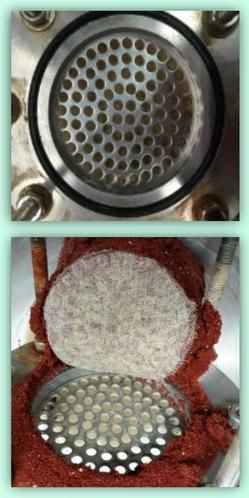


2. Testing apparatus and procedure　実験装置と方法



Water pressure is applied to the top part of the specimen and the water with detached particles is recollected from the bottom. The pressure applied was varied in every test. The weight of particles drained out was measured by drying the water in the oven. Additionally, the turbidity of the water expelled was measured during the experiments.



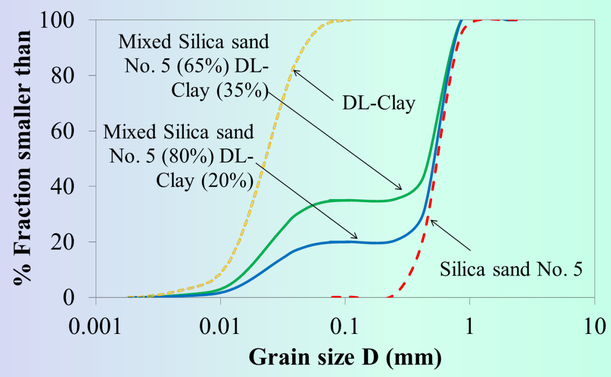


Open bottom and gauze



Turbidimeter

3. Test material　実験材料

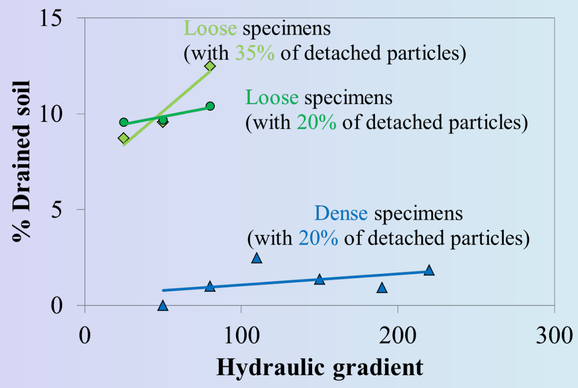


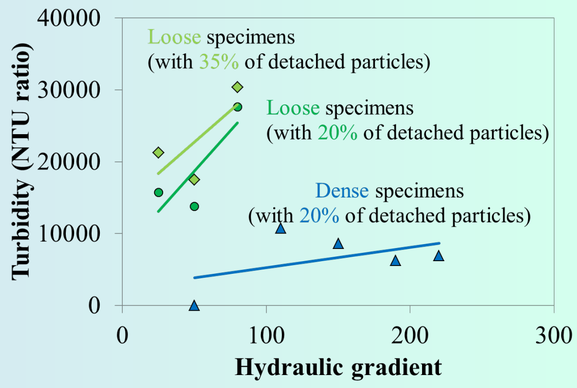
- Mixtures of silica sand number 5 colored red (mean diameter D_{50} of 0.5mm) as primary fabric, and non-plastic yellowish brown silt called DL-Clay (mean diameter D_{50} of 23μm) as detached particles were used

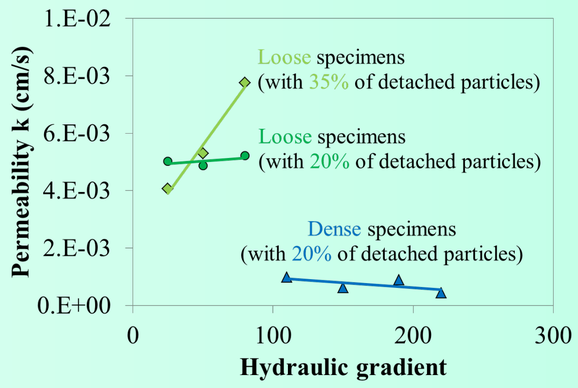
- Three soil conditions were studied:

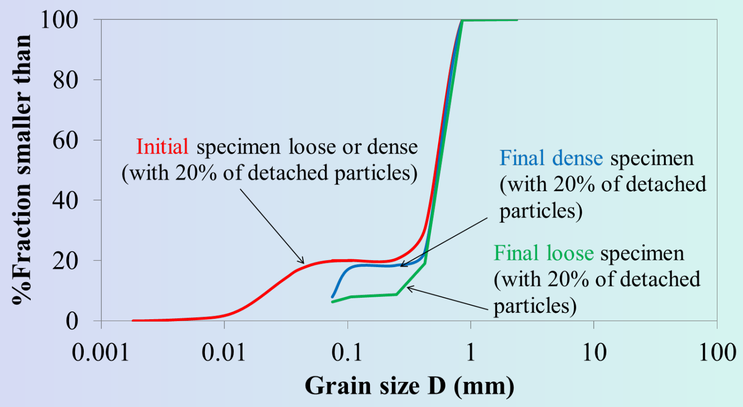
(1) loose soil (Dr= 4~10%) with 65% of primary fabric
(2) (silica sand) and 35% of detached particles (DL-clay) (2) loose soil (Dr= 4~10%) with 80% of primary fabric and 20% of detached particles
(3) dense soil (Dr= 88~90%) with 80% of primary fabric and 20% of detached particles

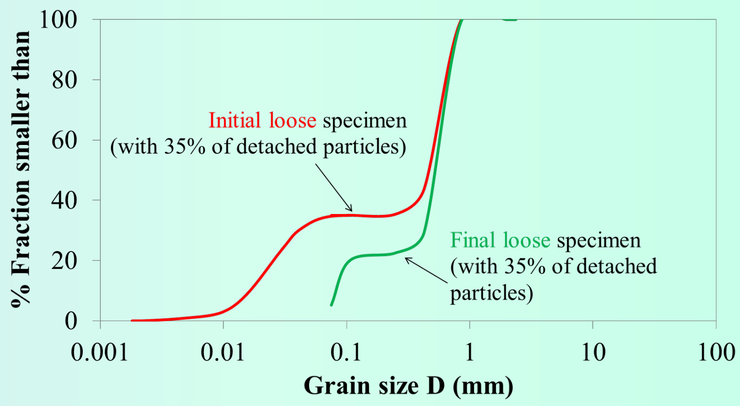
4. Results　実験結果











5. Specimens after the test　試験後供試体



Dense soil



Loose soil

Samples of drained water and fine particles



Dense soil



Loose soil

6. Summary　結論

- The tests in loose specimens were performed for two combinations of soils (20% and 35% of detached particles), however the particles expelled are of the same proportion in both cases, meaning that the amount of detached particles is not as significant as the gradient of water.

- It was found that specimens with relative density around 4 to 10% exhibited a large amount of particles displaced (around 13% of the total), and for the specimens with relative density around 90% the particles drained out represented 3% of the total

- Turbidity can be related to the amount of particles removed, and therefore the measuring of the turbidity can be used in field in order to estimate the grade of internal erosion

本研究に関する担当研究室は桑野研究室です.
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Luisa Fernanda Santa Spitia (2016)

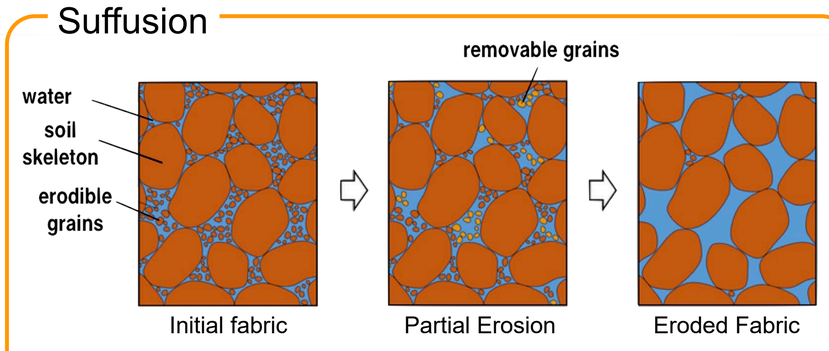
Mechanical Properties of Suffused Gap-graded Soil

細粒分流出したギャップグレード土の力学特性

Suffusion is a type of erosion that has contributed to the failure of several earth-filled water retaining structure. Despite numerous experimental and numerical investigations, our understanding of the effects of changing fabric caused by suffusion on the mechanical properties of the soil remain unclear. A parametric study of density and stress state is conducted using a reconstituted gap graded mix and a modified triaxial cell for the purpose of erosion. The results show that the eroded specimens exhibit different peak strength, small strain stiffness and effective stress path compared with non eroded specimens.

盛土の浸透破壊と細粒分流出との間には関係があると考えられています。既往の研究や調査は数多くありますが、細粒分流出による土の工学的性質の変化は未だに明らかにされていません。試験中に細粒分流出を許した特殊な三軸試験を行い、細粒分流出による力学特性の影響を体系的に調べました。

Suffusion



Suffusion is the removal of fine particles from the soil though mechanical action of a fluid flow, leaving behind the coarse fabric.

Tested material

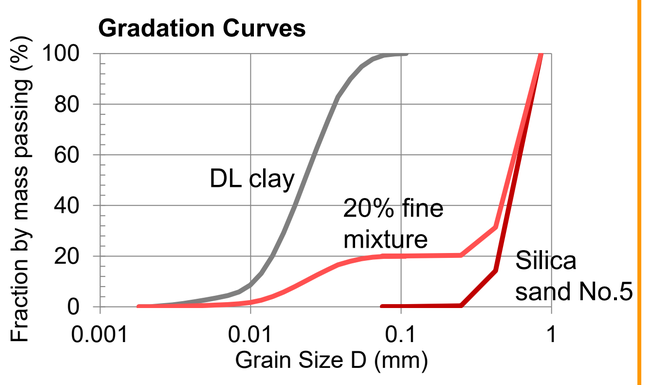
a gap graded mix of **Silica sand & DL Clay (20%)**

Silica sand No.5

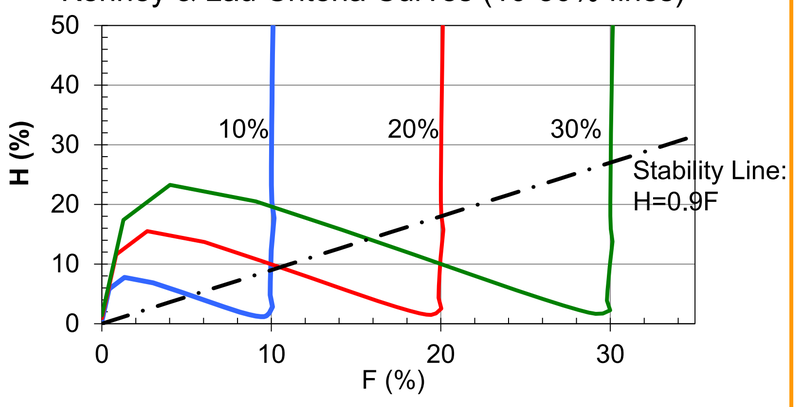


DL clay





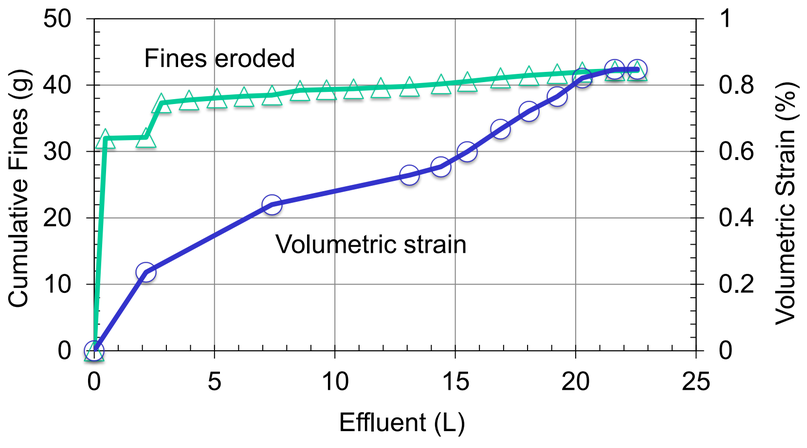
Kenney & Lau Criteria Curves (10-30% fines)



This soil is **internally unstable,** (i.e. unable to filter itself) according to:
Kedzi's, Burenkova's, Kenney & Lau's criteria.

Eroded Fines & Deformation

Eroded Fines & Volumetric Strain vs Effluent

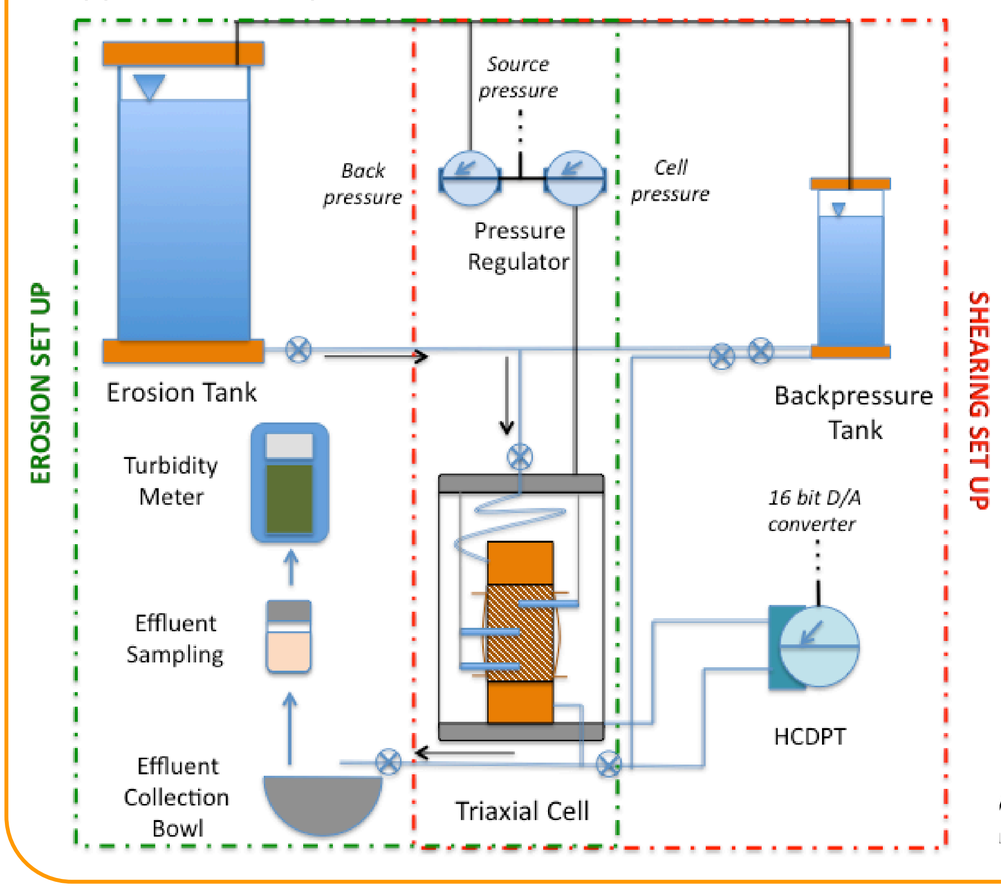


The **erosion rate** is high at first and flattens rapidly, whereas the **volumetric strain** increases almost linearly. This indicate that the fines eroded at the beginning are not a part of the force chains.

Objectives & Methodology

Investigation of the **effects of suffusion** on **mechanical properties** of **gap graded soils** through erosion/non erosion test comparison.

<Apparatus set up>



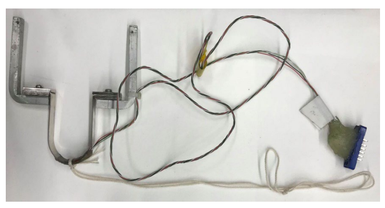
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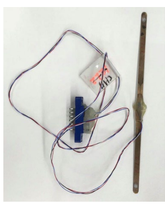
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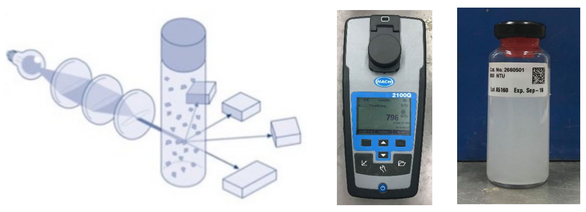
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<LDT>



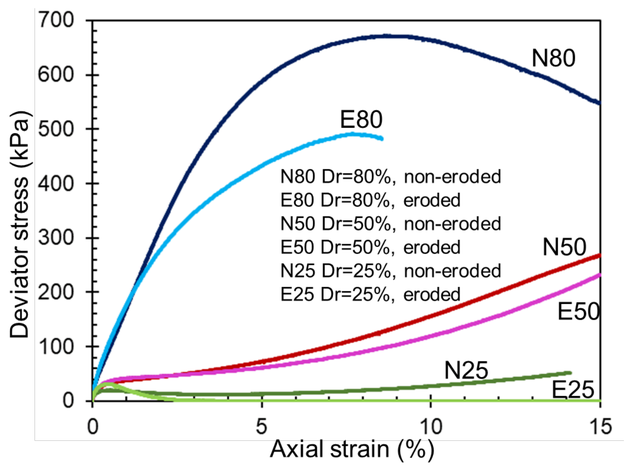
<Turbidity Meter>

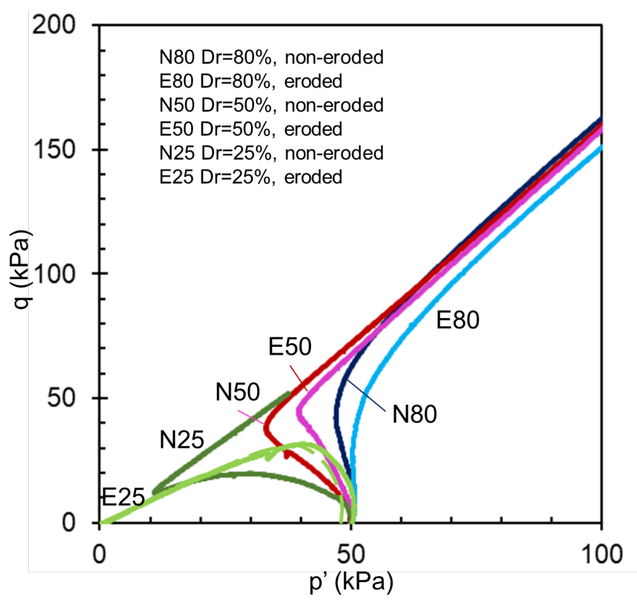


Mechanical properties (peak strength, young's modulus) are obtained through a **modified triaxial cell**.

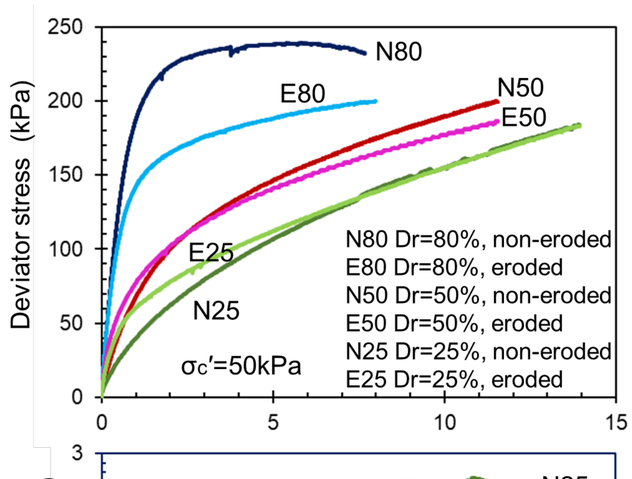
Behaviour in triaxial compression

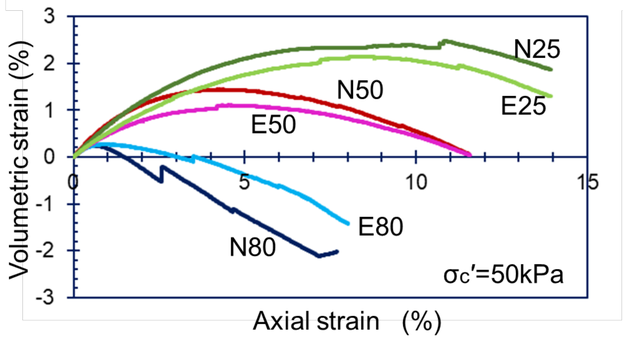
Undrained compression





Drained compression





In drained shear, the stiffness of the eroded specimens in the small strain range are larger in comparison with non-eroded specimens. At medium and large strains, the decrease in strength was highest for eroded soils with high initial density, whereas initially loose specimens showed no change in strength.
Under undrained conditions, suffusion caused an increase in peak strength in the small strain region and a decrease in strength in the medium strain range. These observed effects are also density dependent.

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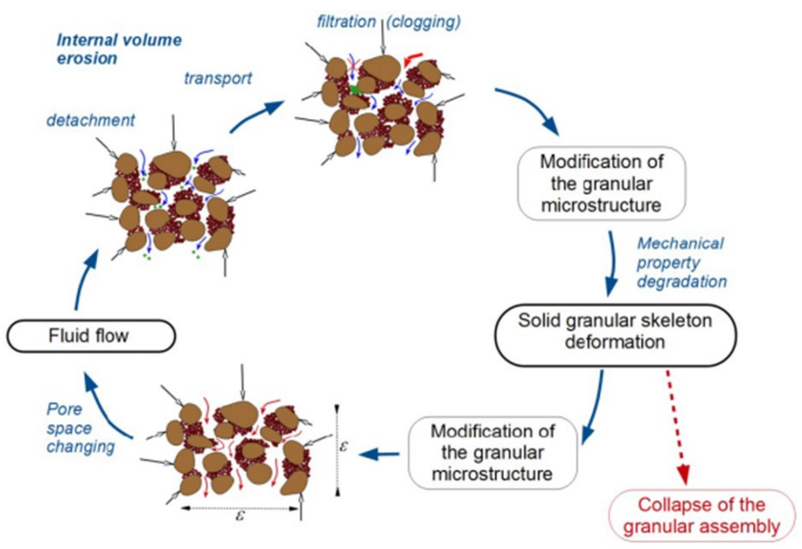
Effects of Suffusion on Mechanical Properties of Volcanic Ash

火山灰質土の力学特性における細粒分流出の影響

Suffusion is a type of internal erosion in which the fine particles migrate through the voids between the coarse particles under seepage flow, leaving behind the coarse skeleton. The degree of migration of fine particles can affect both micro and macro structural behaviour of soil. A few studies have used widely graded soil to explore the effect of suffusion. This study analyses the impacts of suffusion on the mechanical properties of widely graded volcanic ash in triaxial compression. The results show that the eroded specimens exhibit different undrained peak strength, small strain stiffness and effective stress path compared with non eroded specimens.

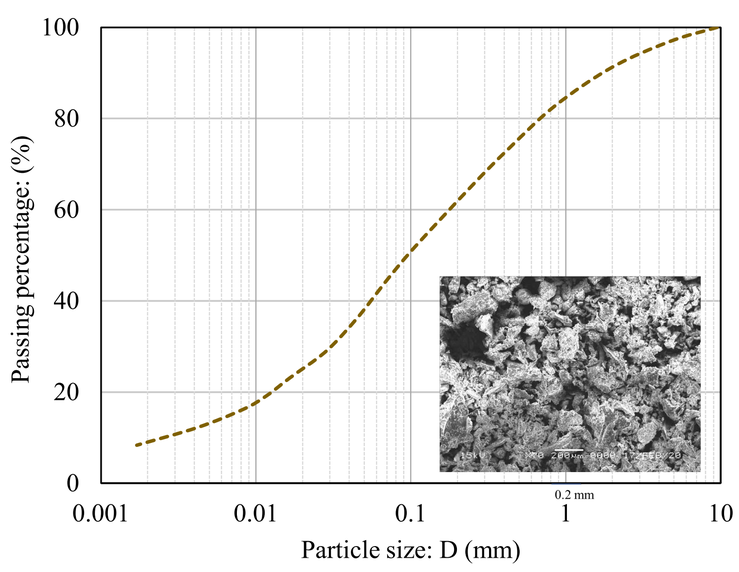
細粒分流出は内部侵食の一つの形態で、細粒分が浸透流のもとで粗粒分骨格を残したまま間隙中を移動する現象である。細粒分の流出の程度によって、土壌の微視的・巨視的構造の両方の挙動に影響が生じる。本研究では粒度のよい火山灰質土の力学特性に対する細粒分流出の影響を三軸圧縮試験にて調べた。侵食を受けた供試体では、侵食を受けていない供試体に比べて異なる非排水ピーク強度、微小ひずみ剛性、有効応力経路を示すことがわかった。

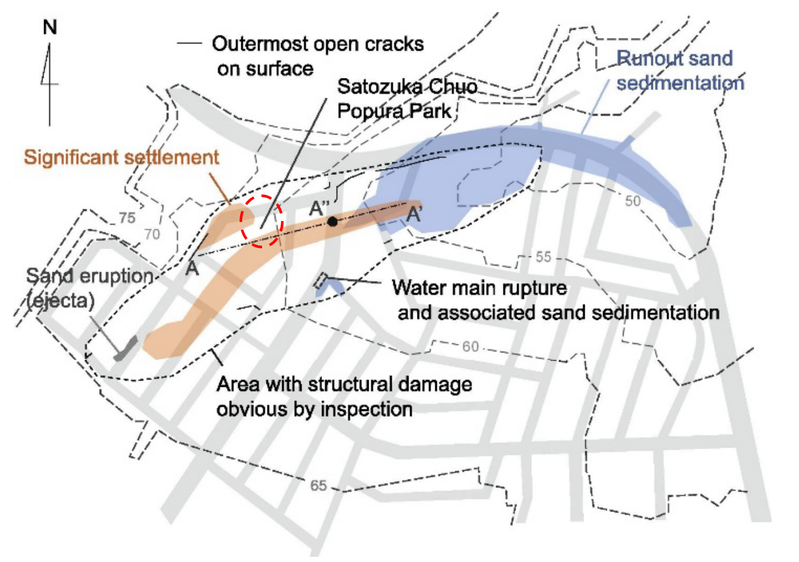
Suffusion



Seepage induced **loss of fine** particles with no change in volume and an increase of hydraulic conductivity

Soil type-Satozuka soil



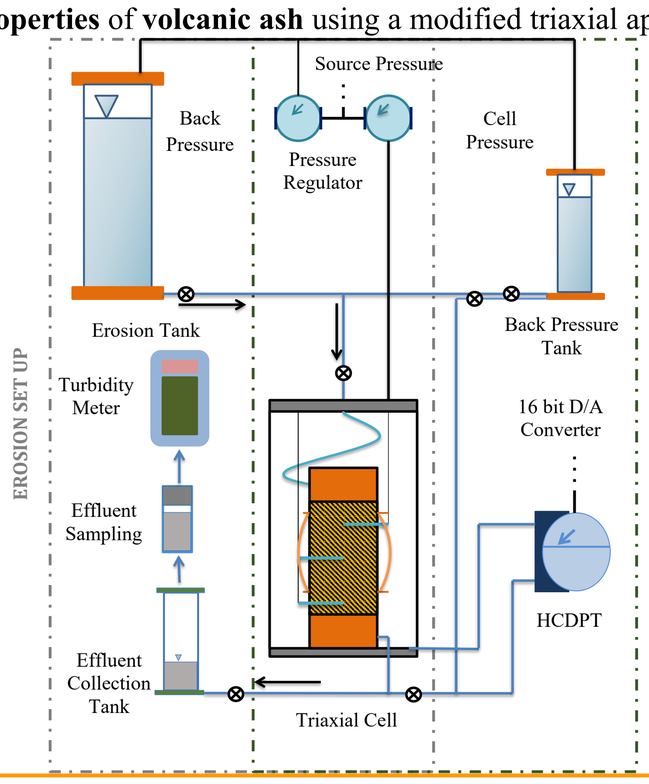


(Watabe and Nishimura, 2020)

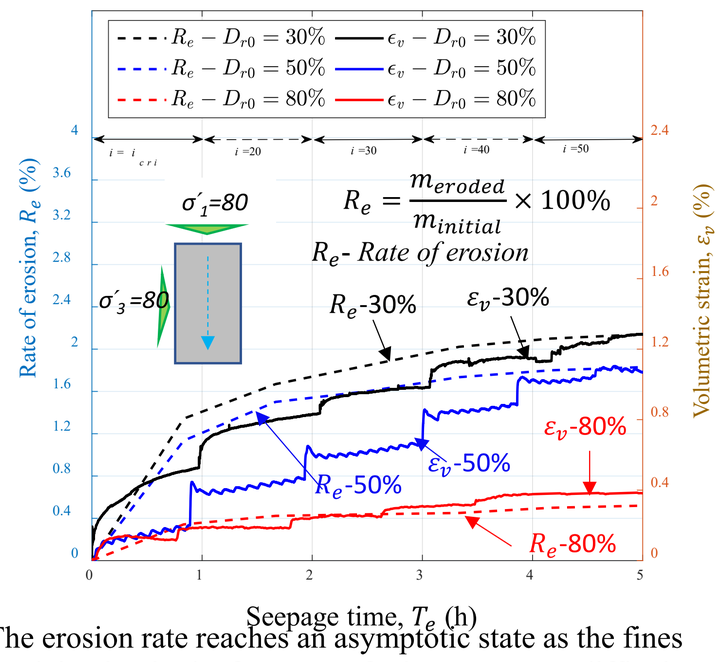
Satozuka soil is **internally unstable** according to the **instability criteria.**

Methodology

Investigation of the **effects of suffusion** on **mechanical properties** of **volcanic ash** using a modified triaxial apparatus.



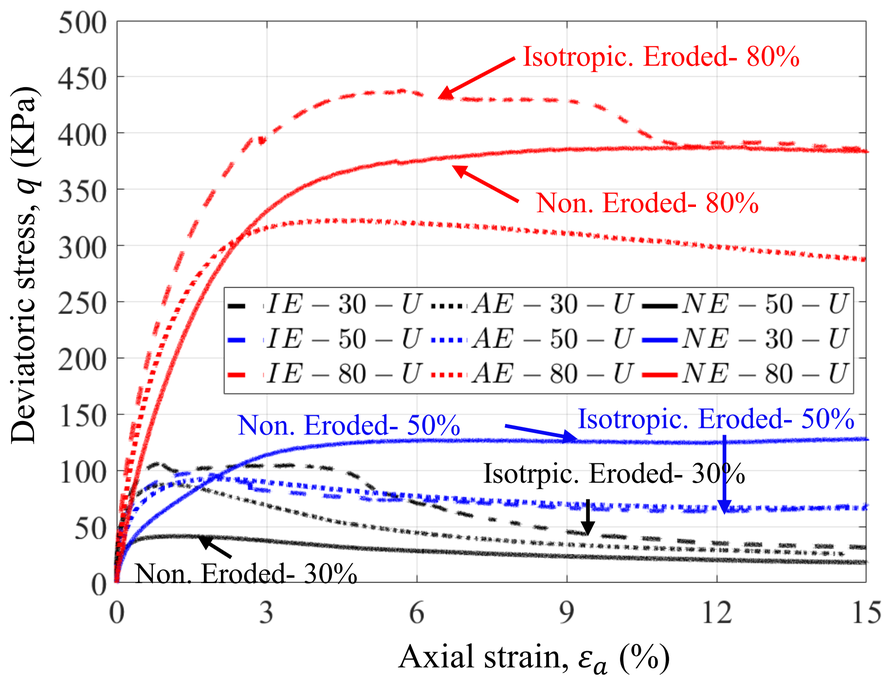
Erosion of soil

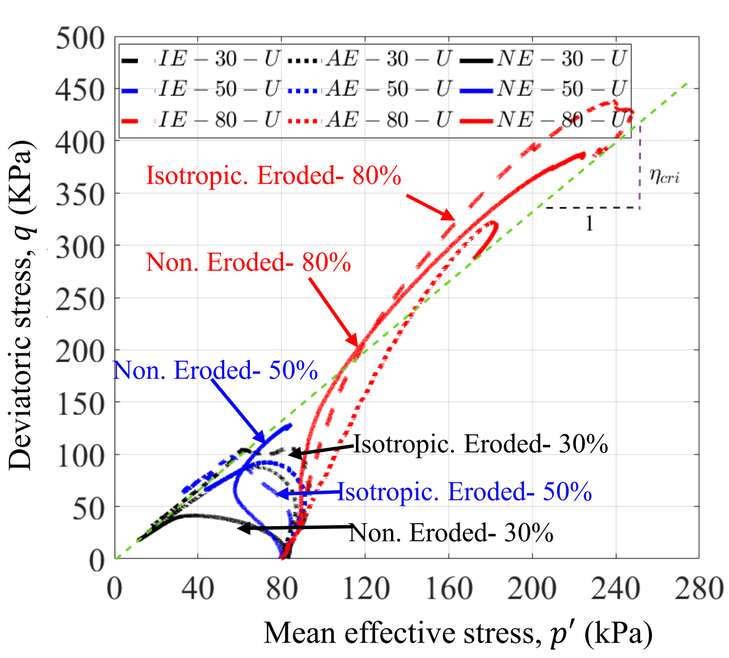


The erosion rate reaches an asymptotic state as the fines participating in the force transfer become more difficult to erode. Rate of erosion is density dependent.

Behaviour in Triaxial Compression

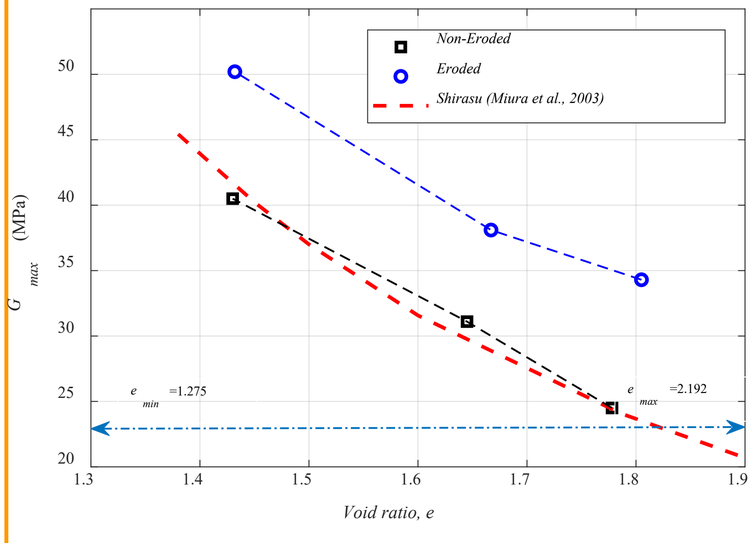
Undrained monotonic compression



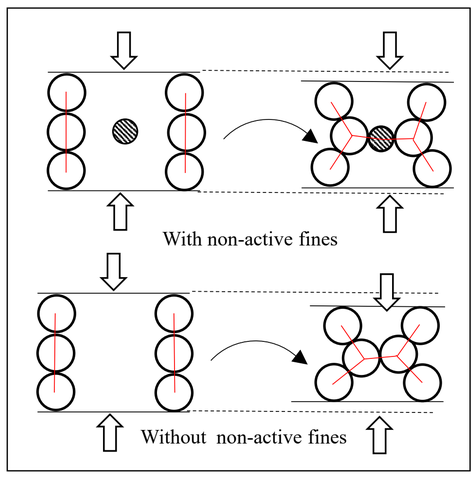


In the undrained triaxial compression tests it was observed that eroded soil shows higher peak strength due to cushioning effect at small strain and becomes more collapsible than uneroded soil at higher strains due to removal of fines and particle rearrangement during the erosion.

Small strain stiffness of non/eroded soil



Network chains of interparticle force



Elastic yield surface seemed to be expanded for eroded soil specimen. It could be due to action of suffusion and fine removal.

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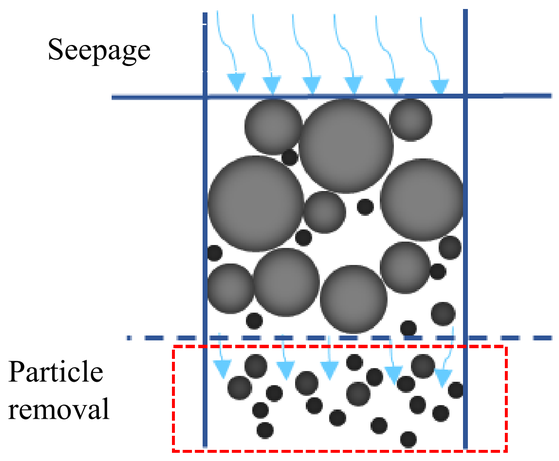
Effects of Internal Erosion on Cyclic Response of Volcanic Ash

火山灰質土の繰返し載荷時応答に対する内部侵食の影響

Internal erosion is defined as detachments of soil particles from the main structure inside the ground due to seepage flow. The degree of migration of fines can affect both micro and macro structural behaviour of soil. The impact of fines content on cyclic resistance and liquefaction potential of soil becomes complicated when the change in fines content is caused by seepage flow leading to internal erosion. This research attempts to investigate the impact of internal erosion on the cyclic behaviour of volcanic ash.

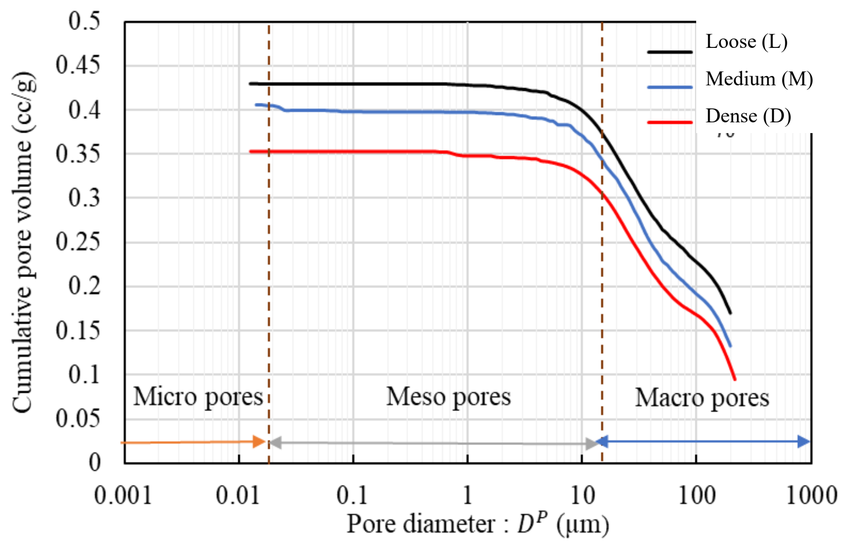
内部侵食とは、浸透流の作用を受け細粒分が地盤内の骨格構造から抜け出す現象です。その抜け出しの程度により、地盤の微視的および巨視的構造は影響を受けます。細粒分含有率は、地盤の繰返し載荷挙動や液状化抵抗に影響しますが、内部侵食によって細粒分含有率の変化が引き起こされる場合にはその影響はさらに複雑になり、十分に解明されていません。本研究では火山灰質土の繰返し載荷挙動に及ぼす内部侵食の影響を明らかにすることを目的としています。

Internal erosion



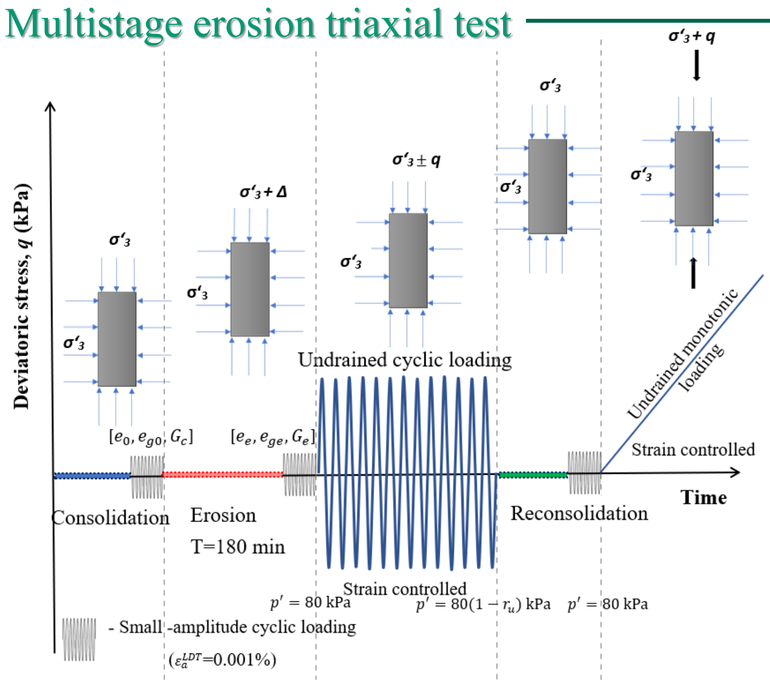
Detachments of soil particles from the **main structure** inside the ground due to mechanical or chemical actions of **seepage flow**

Pore Size Distribution of Satozuka soil



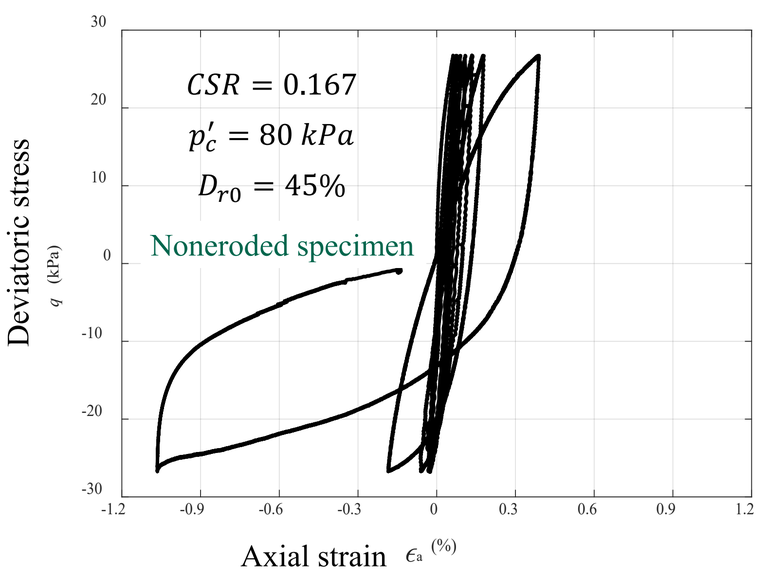
Satozuka soil is **internally unstable** according to the **Kenney & Lau's criteria.**

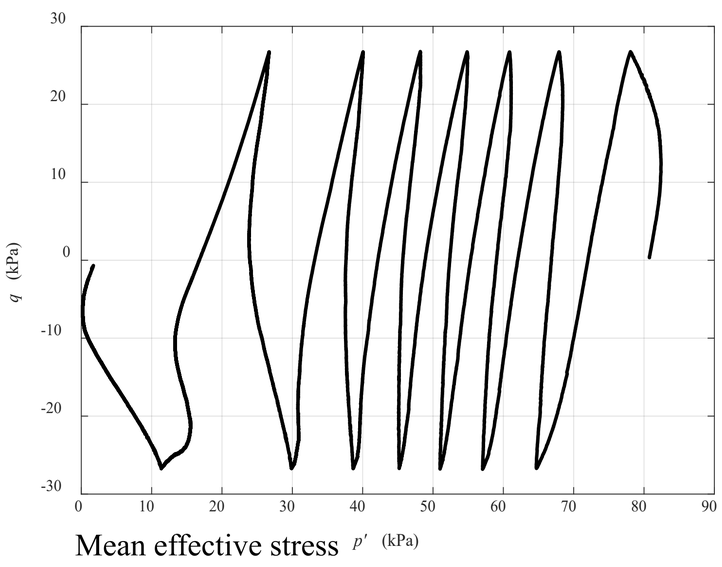
Multistage erosion triaxial test

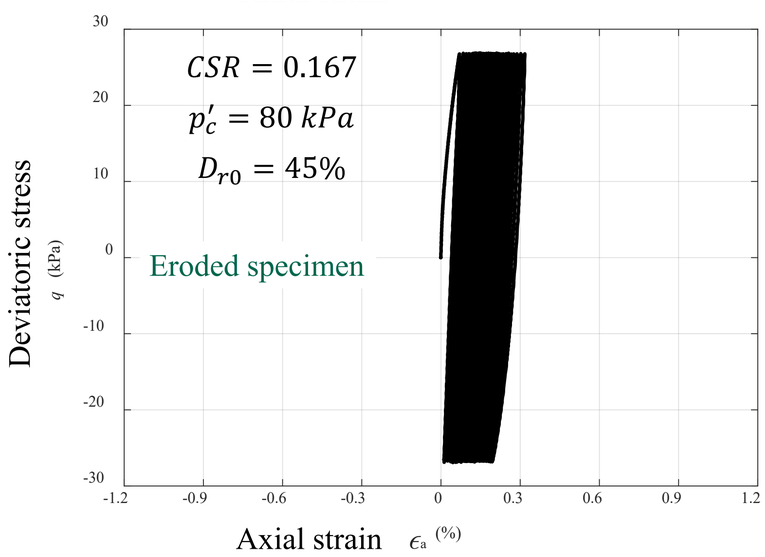


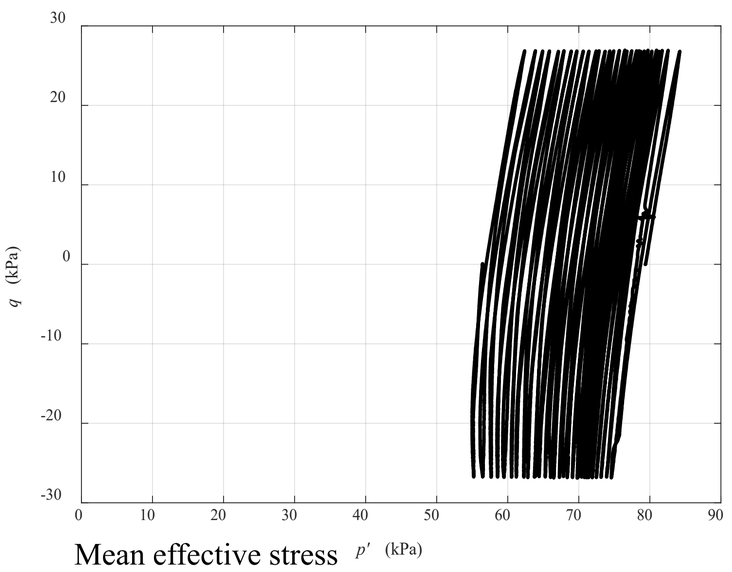
Undrained Cyclic Loading

Undrained Cyclic loading of **loose (L)** specimen (D_{r0} =45%)



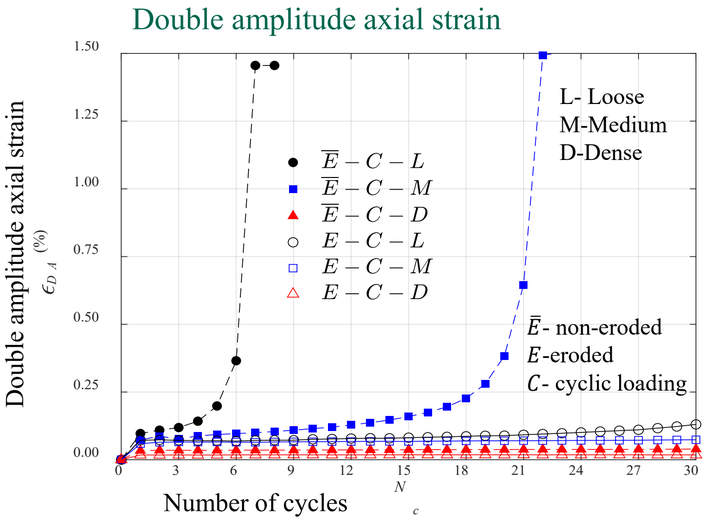




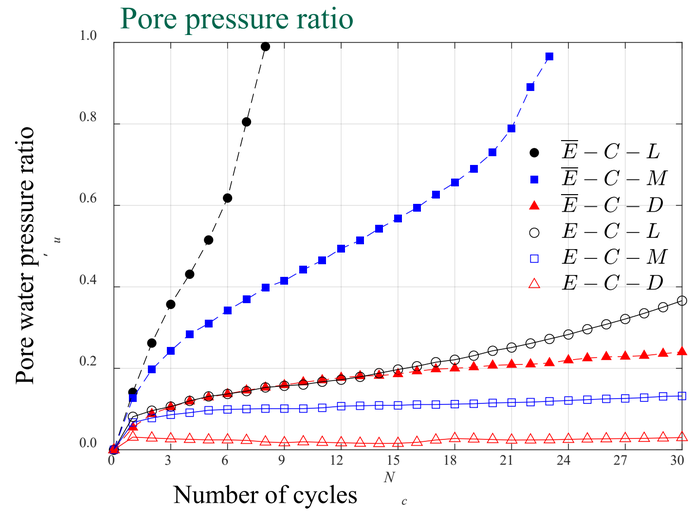


Summary of Results

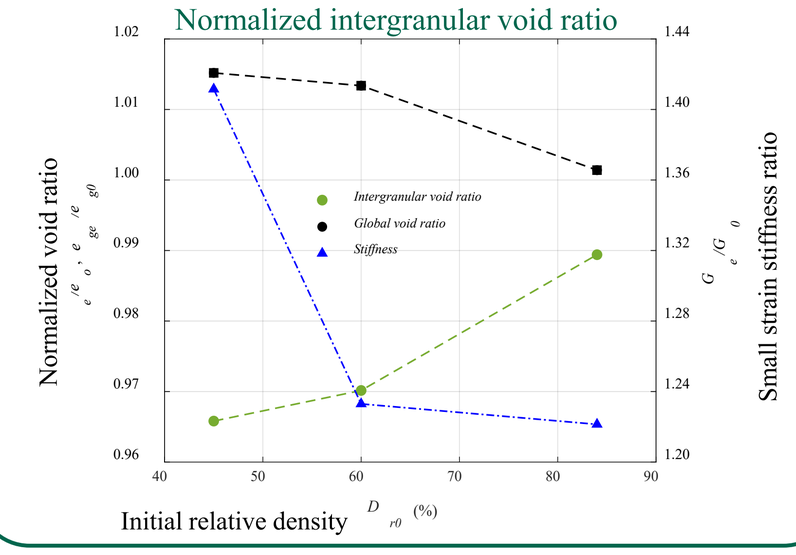
Double amplitude axial strain



Pore pressure ratio



Normalized intergranular void ratio



Summary

This study found that the cyclic resistance of eroded specimens is improved regardless of the percentage of eroded particles and initial relative density (D_{r0}). Moreover, post-erosion cyclic ε_{DA} is less than 0.15% for 30 cycles for any tested density, which confirms that post-erosion stiffness increases significantly. The lower potential of liquefaction for the eroded specimens was found to be due to a decrease in the intergranular void ratio after the erosion of fine.

Notation

(e_e/e_0) - Normalized post erosion global void ratio
(e_{ge}/e_{g0})- Normalised post erosion intergranular void ratio
(G_e/G_0) -small strain stiffness ratio

Intergranular void ratio (e_g) is defined; $e_g = \frac{e+FC}{1-FC}$; where e_g, e and FC are intergranular void ratio, global void ratio and fine content in decimals

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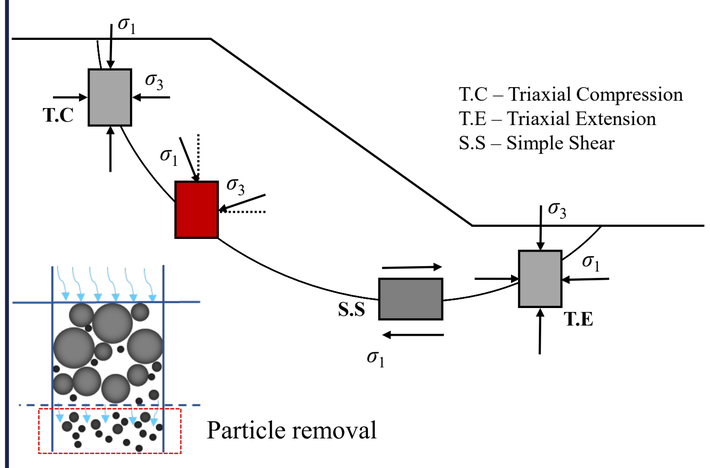
Effects of Suffusion on Simple-Shear Response of Silty-Sand

シルトまじり砂の単純せん断応答に及ぼす細粒分流出の影響

Internal erosion is the transportation of soil particles from within or beneath a water-retaining structure due to the seepage flow, impacting the mechanical and hydraulic behaviour of soil. The impact of fines removal on post-erosion response under different loading direction with respect to the seepage direction is crucial since it is hypothesized vertical reinforcement is improved due to erosion. This research attempts to investigate the impact of internal erosion on the simple-shear response of gap-graded soil with 20% fine content.

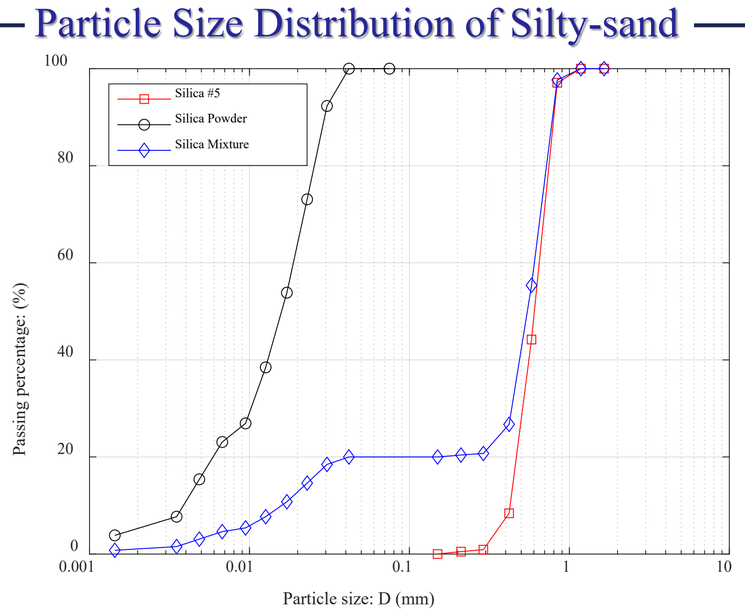
内部侵食は、貯水構造物の内部またはその下からの浸透流による土粒子の流出により起こり、地盤の力学的・水理学的挙動に影響を与えます。上下流浸透に伴う内部侵食により鉛直方向の強度が改善されるという現象が観察され、細粒分流出が、侵食後に浸透方向に対して異なる方向に載荷した際の応答に影響を及ぼすと考えられます。 この研究では、細粒分含有率20%のギャップグレード土の単純せん断応答に対する内部侵食の影響を調べました。

Internal erosion



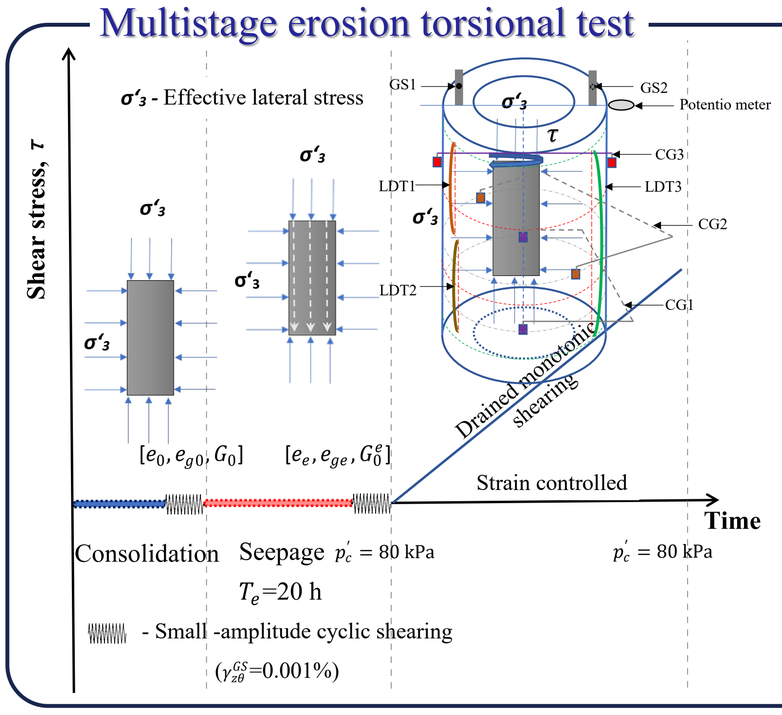
Suffusion is defined as migration of fine particle due to seepage flow without significant volume change.

Particle Size Distribution of Silty-sand

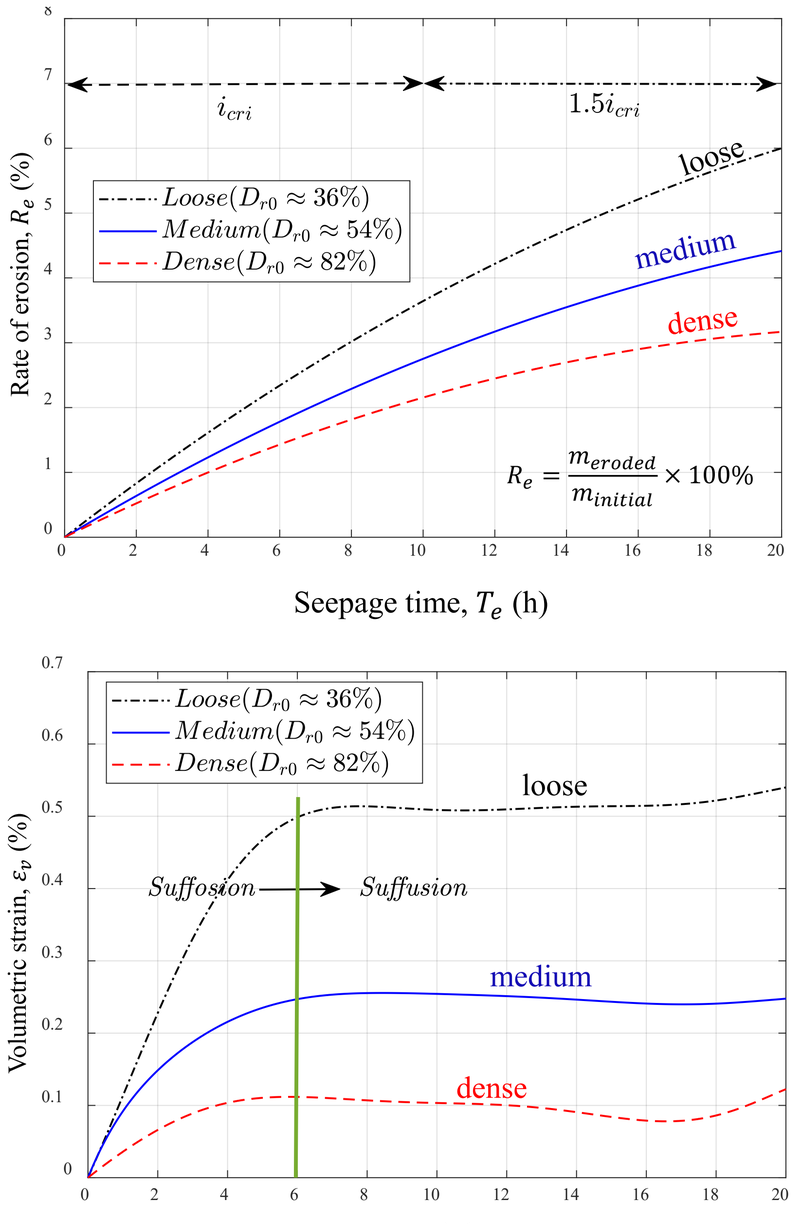


Selected gap-graded soil is **internally unstable** according instability **criteria.**

Multistage erosion torsional test

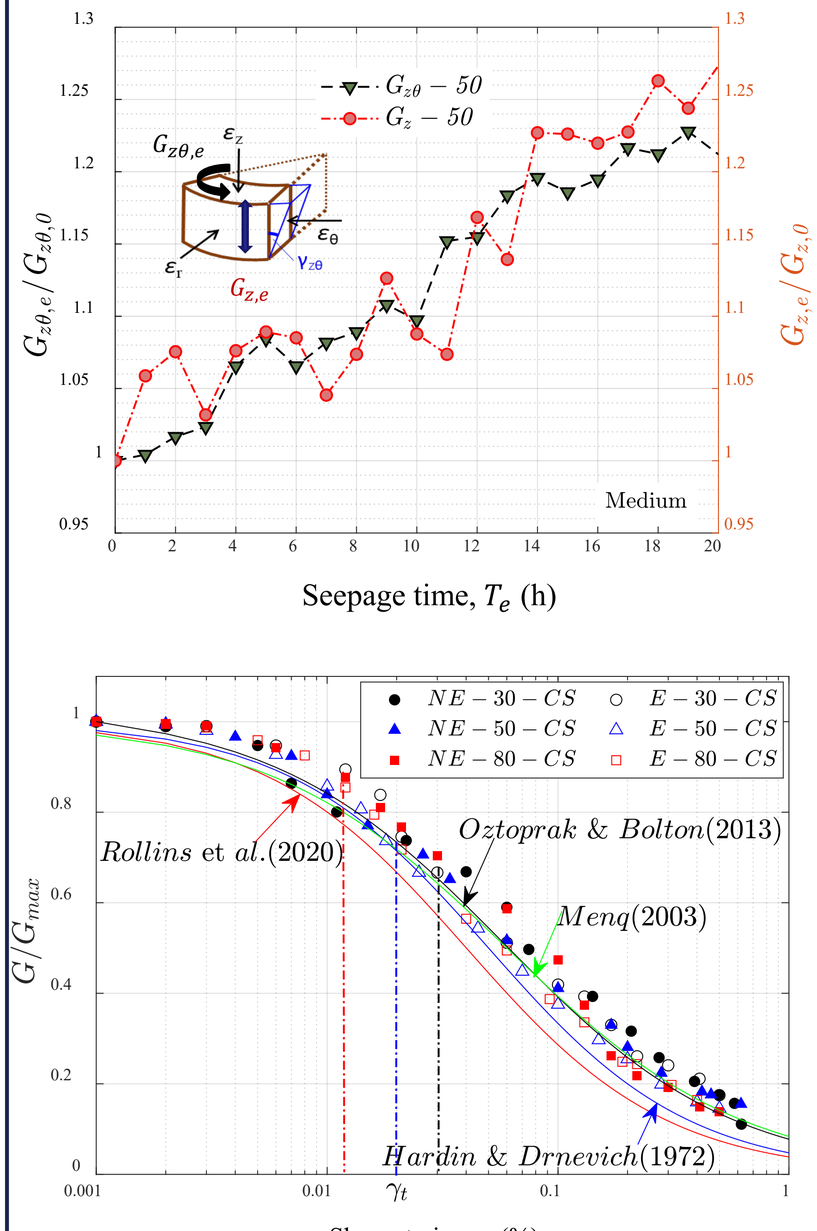


Suffusion response



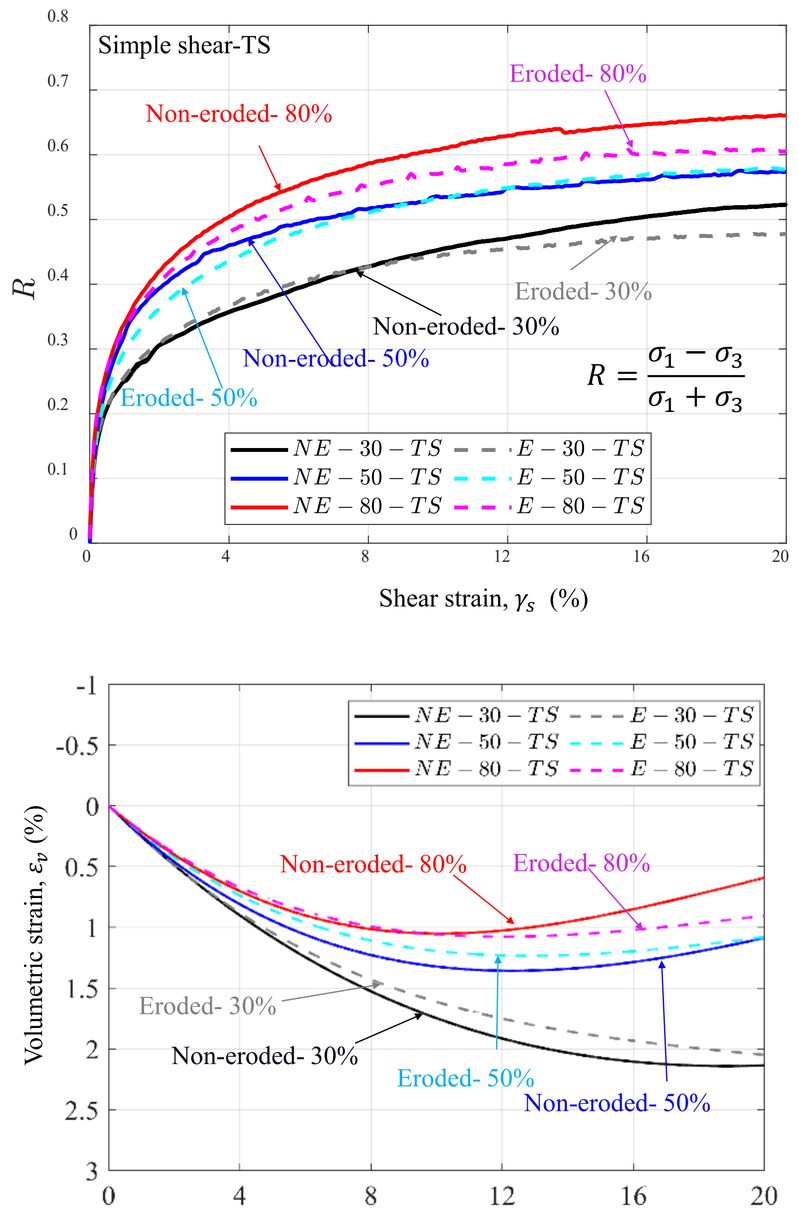
Volumetric strain during seepage increases initially and reaches a steady state.

Shear-modulus



Post-erosion shear modulus increases due to fine removal. Degradation of shear-modulus is rapid for eroded soil

Stress-strain



Post-erosion R_{peak} under decreases while dilatancy of eroded soil is improved.

Summary

This study found that volumetric strain during seepage increases initially and reaches a steady state regardless of initial relative density (D_{r0}). In essence, the limited amount of volume change can be referred to as suffusion. Post-erosion shear modulus increases significantly, however degradation of shear modulus with increasing shear strain is rapid than non-eroded soil. Moreover, Post-erosion R_{peak} under simple-shear depends on the density. This indicates that the horizontal bedding plane becomes weaker.

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Shear Strength of Artificial Pumice Soil Having Extremely Loose Structure

セメンテーションによって保持された超高間隙構造土のせん断特性

Focusing on the fact that the triggering layer of the slope disaster such as mud-flowing and long-distance flowing is a pumice layer with high void ratios, artificial high void ratio structure soil was reproduced and its characteristics were investigated. The high void ratio structure soil with cementation exhibits a large contractancy, and it has high shear strength until cementation breakdown occurs.

泥流化し、長距離流動するような斜面災害の起因層が間隙の大きい軽石層であることに着目し、セメントを付加して人工的に高間隙構造土を再現し、特性を調べた。セメンテーションを持つ高間隙構造土は大きな収縮性を示し、構造を保持しているセメンテーションの破壊が起きるまでは高いせん断強度を持つがひずみ軟化挙動を示す様子が観察された。

セメントを用いて超高間隙構造土を再現

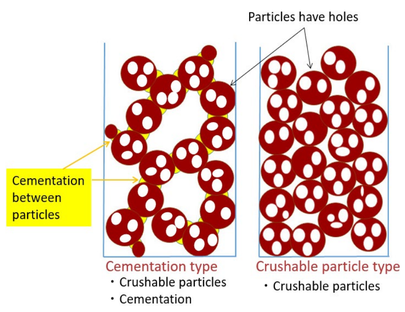
Reproduce high void ratio structure soil using ordinary Portland cement

緩斜面で発生した土砂災害

Mudflowing occurring on gentle slope



非塑性細粒土であるDL-CLAYにセメントを加え、七日間養生することでセメンテーションや破砕性を持つ高間隙の火山性軽石層を再現する。
By cementing DL - CLAY which is non - plastic fine granular soil and curing it for seven days, I reproduced the high void ratio volcanic pumice layer with cementation.



←作成した2タイプの超高間隙構造土のイメージ図
Image of high void ratio structure soil maintained by cementation effect or crushable particles.

DL-CLAY



セメント付加
Adding cement



タイプ	質量比 Dl clay:セメント:水	設計間隙比
A	85:15:25	2.1
B	90:10:25	2.1
C	85:15:25	2.7

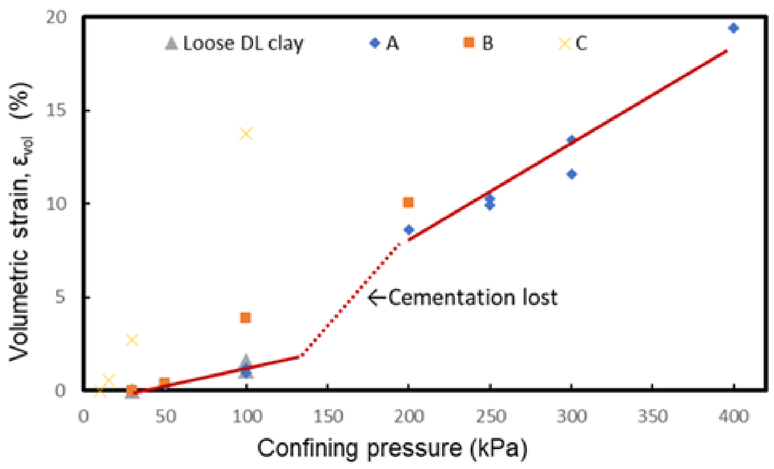
人工供試体の配合
Formulation of artificial specimen

Type	*Specimen*	ρ_s *(g/cm³)*	ρ_d *(g/cm³)*	*e*
Cementation	A	2.69	0.89	2.02
Cementation	B	2.66	0.89	1.99
Cementation	C	2.69	0.75	2.61
Crushable particle	Particle A	2.69	0.86~0.87	2.09~2.14
Crushable paritcle	Particle B	2.66	0.84	2.14~2.16
-	Loose DL clay	2.65	1.03	1.58

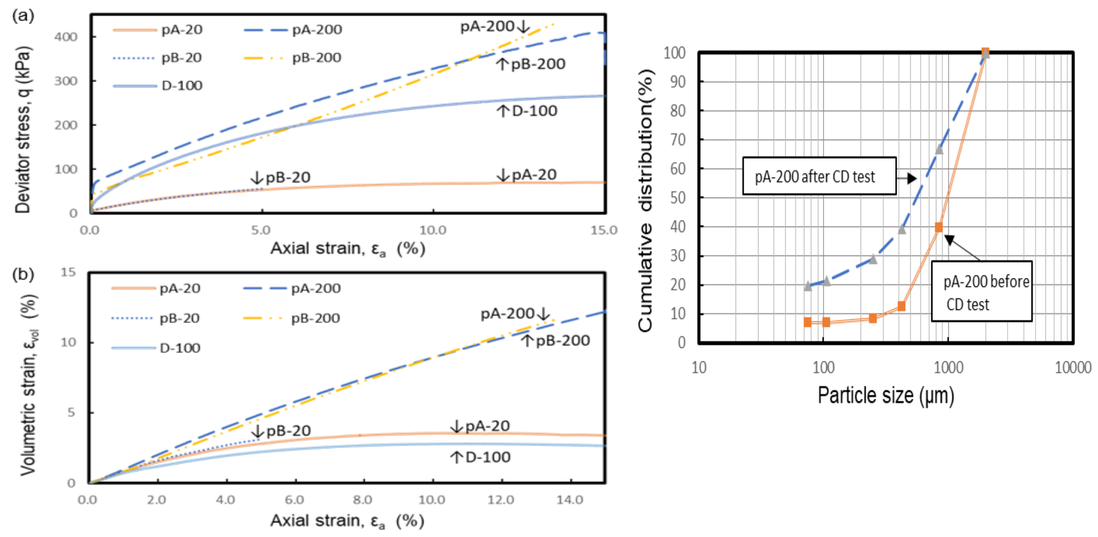
人工供試体の物性値
Properties of artificial specimen

排水三軸圧縮試験結果

Results of CD tests

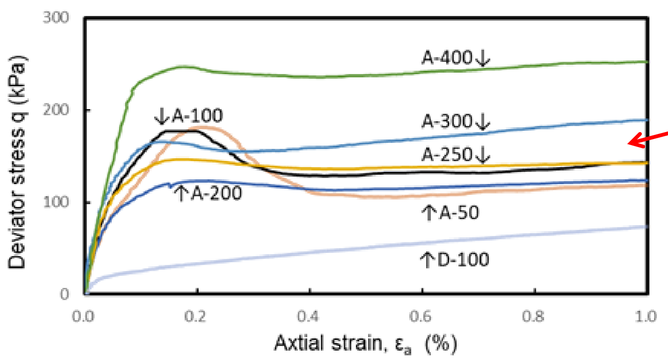


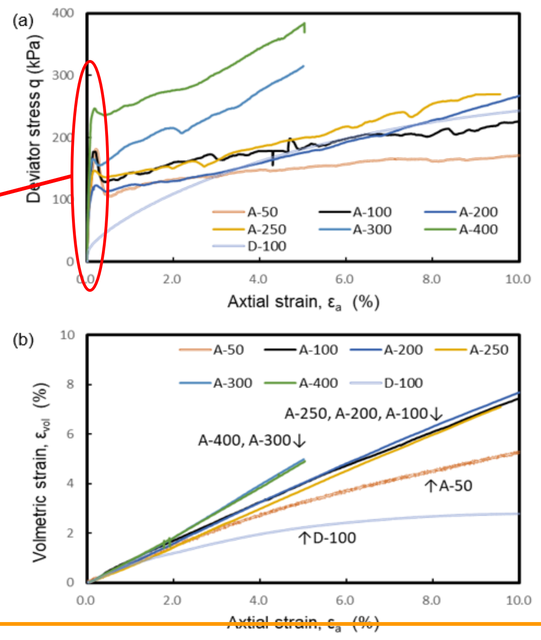
人工供試体Particle AのCD試験結果→
CD test result of Artificial Specimen Particle type
(グラフ上の数字は拘束圧
Numbers on the graph indicate confining pressure)



等方圧密終了時の体積ひずみ

Volume strain at consolidation process





Specimen AのCD試験結果
CD test result of Artificial Specimen A
(グラフ上の数字は拘束圧
Numbers on the graph indicate confining pressure)

結果のイメージ図　Image of the result



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SHEAR CHARACTERISTICS OF EXTREMELY LOOSE VOLCANIC SOIL

多孔質粒子やセメンテーションを持つ火山性超高間隙構造土のせん断特性

Focusing on the fact that the trigger layer of slope disasters (e.g. mud flow and long distance flow) is a pumice layer with high voids, extremely loose soil was artificially reproduced and investigated by CU test. Extremely loose soil has two peak strengths: first peak due to cementation, and second peak due to loose structure maintained by crushable particles. After the peaks, a brittle behavior was observed in which shear strength converges to a residual state, called steady state.

泥流化し長距離流動するような斜面災害の起因層が、粒子間に働くセメンテーションや多孔質粒子によって緩い構造を保持された間隙の大きい軽石層であることに着目し、セメントを付加して人工的に高間隙土を再現しCU試験を行い、その力学特性を調べた。超高間隙土は、軸ひずみ0~20%で、セメンテーション(粒子間固結)に起因するピーク強度と、破砕性を持つ多孔質粒子によって保たれた高間隙構造に起因するピーク強度の二つを示すことがあると分かった。また超高間隙土は軸ひずみが進行しても軸差応力が上昇していかない定常状態に至った。

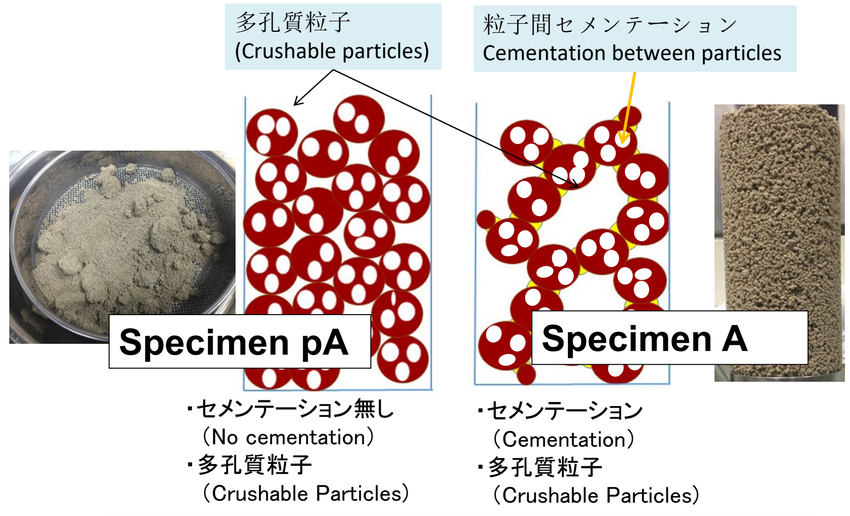
人工的に超高間隙構造土を再現

Reproduction of extremely loose volcanic soil



↑緩斜面で発生した土砂災害 (2016 in Kumamoto)
Mud flow occurring on gentle slope

災害を引き起こす自然の超高間隙土の多くは火山性土であり、その緩い構造は、多孔質粒子やセメンテーションによってもたらされている。今回は人工供試体AとpAの2種類の供試体を準備した。
Extremely loose natural soil is maintained by crushable particles. (Sometimes it also has cementation between particles). Specimen type A and type pA were prepared.



人工供試体の配合と物性値

Formulation and properties of artificial specimen

Type	Specimen	質量比 DL Clay :Cement :Water	設計間隙比Designed void ratio
Crushable particles with cementation	A	85:15:25	2.1
Crushable particles	Particle A	85:15:25	空中落下Air-pluviation

	土粒子密度 ρ_s (g/cm^3)	間隙比e	セメンテーション Cementation	粒子破砕性 Particle crushability
供試体A	2.69	2.02	○	○
供試体pA	2.69	2.15	×	○
緩詰DL clay Loosest DL clay	2.65	1.58	×	×

人工供試体A、pAは、一度構造を崩すと再現できないほどの超高間隙を十分に再現しているといえる。
Artificial specimens have extremely loose structures.

非排水圧縮試験結果

Drained and undrained triaxial compression test

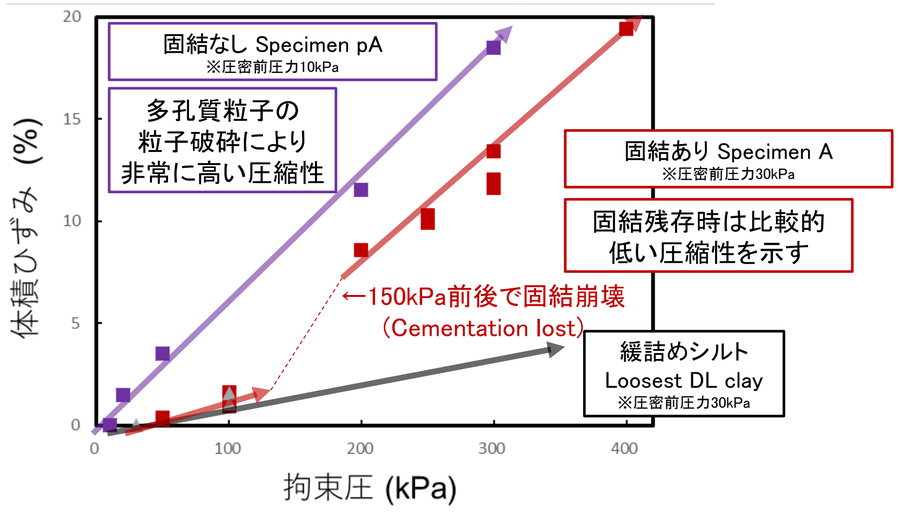
テスト一覧

Experimental cases

Test	Specimen	Type	Consolidation pressure(kPa)	Preconsildation pressure(kPa)	Rate of loading (mm/min)	Consolidation ε_{vol} (%)
A-CU50	供試体A	CU	50	30	v_0=0.239	0.4
A-CU100			100			0.9
A-CU300			300			11.6
pA-CU50	供試体p A		50	20		2.0
pA-CU300			300			17.0

等方圧密終了時の体積ひずみ

Volumetric strain at the end of isotropic consolidation

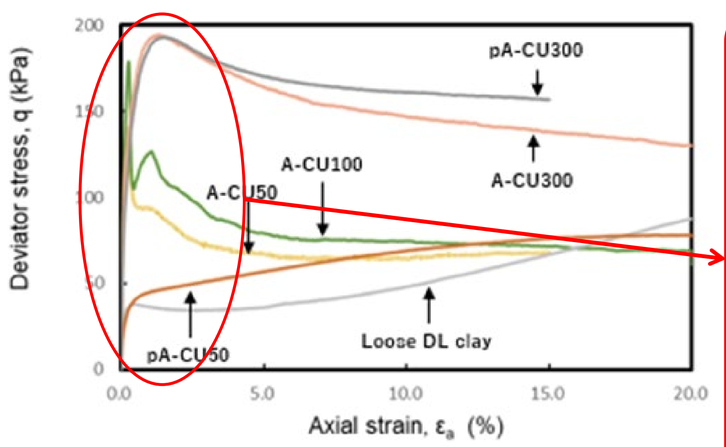


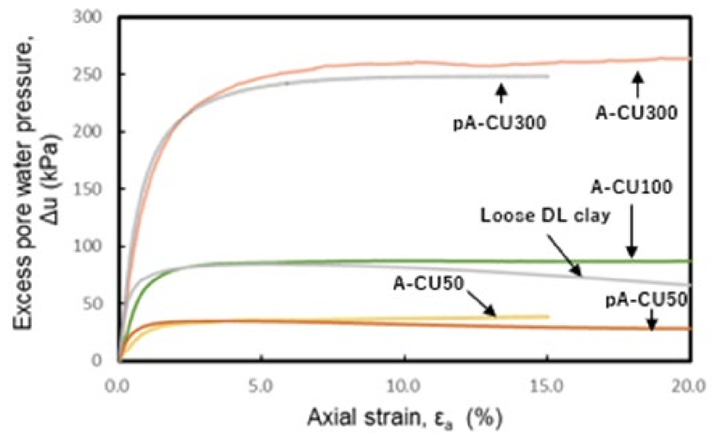
供試体Aはセメンテーションにより粒子間が固結しているため、等方拘束圧100kPa程度までは比較的低い圧縮性を示した。pAと、固結崩壊後のAは、粒子破砕などに起因して非常に高い圧縮性を発揮した。緩詰めシルト（人工供試体の材料として使用）と比べても、超高間隙土は著しく高い圧縮性を持つことがわかる。

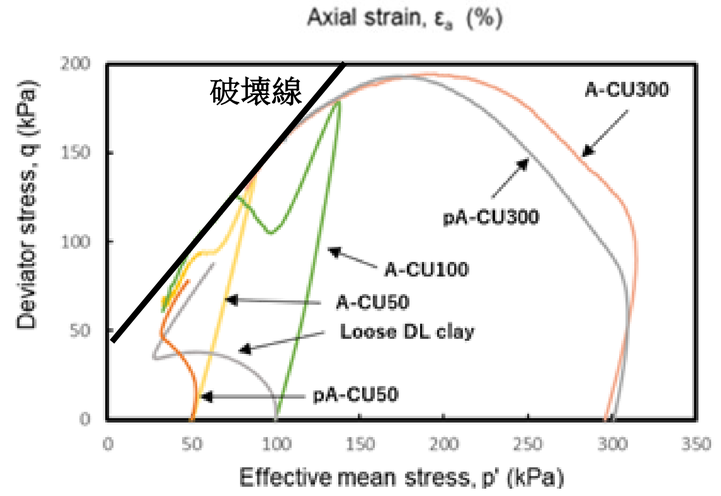
Specimen A showed relatively low compressibility when it has cementation effect between particles. Specimen pA and Specimen A, after cementation loss, had extremely high compressibility.
Extremely loose soil has more compressibility than the loosest DL clay which was used to produce artificial specimen.

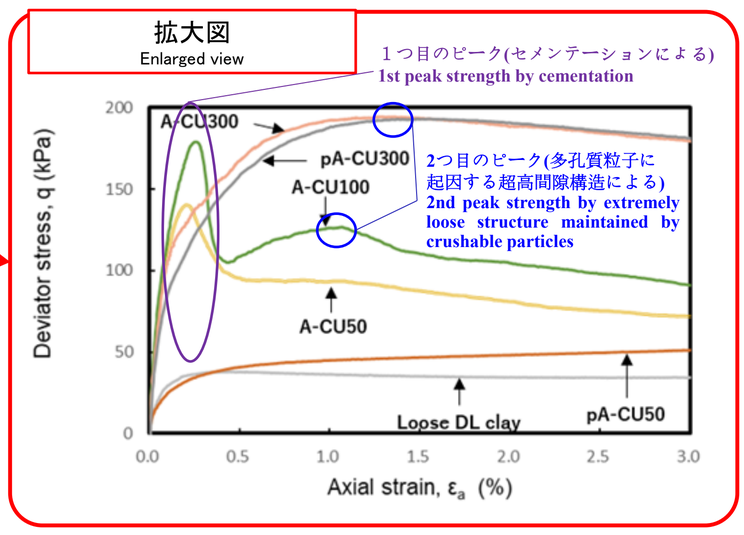
CU試験結果とその解釈

CU test results and Consideration









超高間隙土は、CU試験において2種類のピーク強度を示した。一つ目は圧縮開始時にセメンテーションが崩壊していないケースで、軸ひずみ0.3%付近で観察されたセメンテーションによるピークである。二つ目は、100kPa以上の拘束圧のケースで、軸ひずみ1~1.5%付近で観察された超高間隙構造（多孔質粒子）に起因するピークである。
高間隙土は、全てのケースで同じ破壊線上で、定常状態に収束した。

Extremely loose soil has two peak strengths: first one due to cementation at around 0.3% axial strain in the case that cementation was not lost in consolidation process. The other one is due to loose structure maintained by crushable particles for the cases with confining pressure more than 100kPa. After the peaks, a brittle behavior was observed in which shear strength was converged to a residual state, called steady state.

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佐藤樹 (2019)

Shear Strength of Unsaturated Soil Having Extremely Loose Structure

超高間隙構造土の不飽和せん断特性

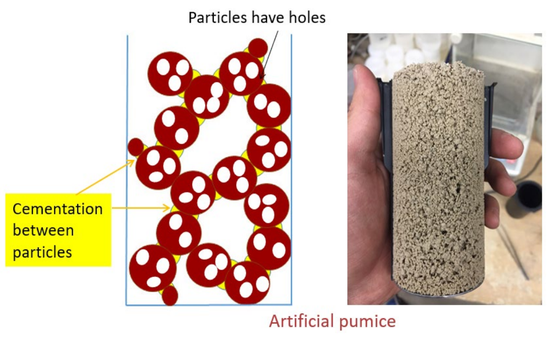
Many slope disasters occur every year all over the world, and a lot of human lives are deprived by them. Sometimes, disasters at gentle slopes and disasters that flow long distance, with destructive energy, are observed in Japan. In such cases, the trigger layer is often volcanic extremely loose soil. Although the cause of destructive long-distance flow has been explained by liquefaction, there are some cases which occurred at unsaturated layer, i.e. liquefaction may not be a major cause. Focusing on those facts, artificial loose soil samples consisting of silt and cement were prepared and a series of triaxial tests with unsaturated condition was performed to discuss how air trapped in voids affects the shear strength properties. It is indicated that extremely loose soil can be vulnerable against risk of landslides even if it is not fully saturated.

日本には火山由来の高間隙構造を有する土が各地に分布し，斜面災害の起因層になっている．事例の中には災害時に起因の軽石層が不飽和状態であったものもある．これらの特殊土のように非常に高い間隙比が不飽和層や緩斜面で起こる災害の被害の大きさに与える影響について，これまでセメンテーションや粒子破砕性を持つ人工供 試体を作製し飽和状態における三軸試験を行った ．その結果，飽和時においては超高間隙土は一定の強度を見せた後 に大変形を起こしうる steady state に至る可能性があることが示唆された．本研究では不飽和排水圧密・非排水非 排気圧縮三軸試験を行い，超高間隙土における不飽和せん断特性について考察した．

セメントを用いて超高間隙構造土を再現

Reproduce high void ratio structure soil using ordinary Portland cement

非塑性細粒土であるDL-CLAYにセメントを加え，七日間養生することでセメンテーションや破砕性を持つ高間隙の火山性軽石層を再現する．
By cementing DL - CLAY which is non - plastic fine granular soil and curing it for seven days, I reproduced the high void ratio volcanic pumice layer with cementation.



Artificial specimen having high void ratio

人工供試体の物性値
Properties of artificial specimen

Specimen	ρ_s *(g/cm³)*	ρ_d *(g/cm³)*	*e*
Specimen A (Artifical pumice)	2.69	0.89	2.02
Loose DL clay	2.65	1.03	1.58

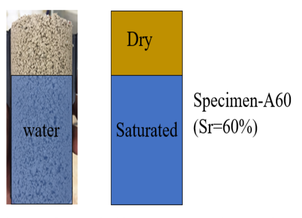


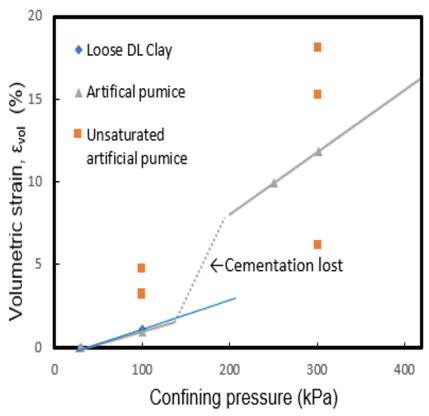
Illustration of partially saturated specimen.

Experimental cases.

Test	Specimen	Type	Degree of saturation before consolidation, Sr(%)	Consolidation pressure(kPa)
A-CU50	Aritifical Pumice	CU	100	50
A-CU100				100
A-CU250				250
A-CU300				300
D-CU100	Loose DI clay	CU	100	100
Ad-100	Aritifical Pumice	Partially saturated CU	0 (oven dried)	100
Ad-300				300
A60-CU100			60	100
A60-CU300				300
A70-CU100			70	100
A70-CU300				300

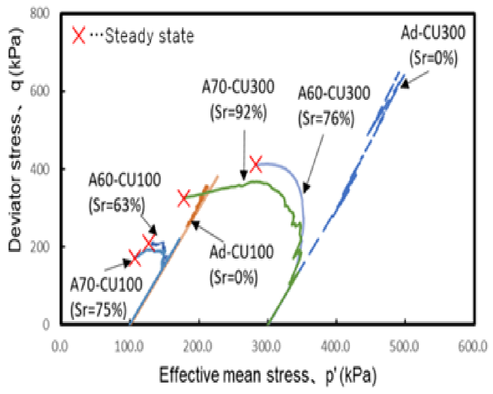
圧密排水・非排気非排水不飽和三軸試験結果

Results of unsaturated CU tests

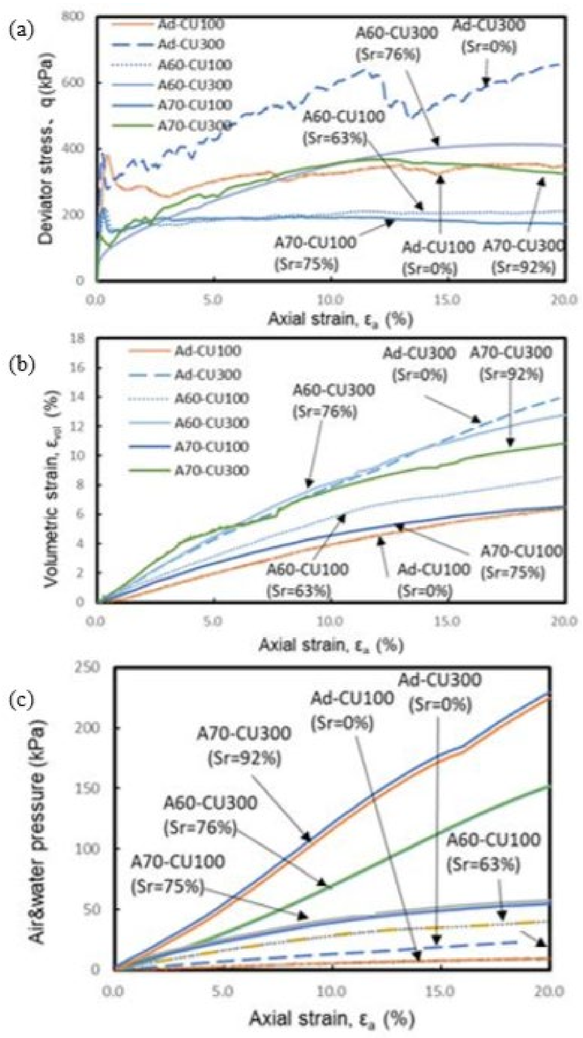


Test	ε_{vol} (%)
A-CU50	0.4
A-CU100	0.9
A-CU250	9.9
A-CU300	11.8
D-CU100	1.0
Ad-100	3.2
Ad-300	6.1
A60-CU100	3.2
A60-CU300	15.2
A70-CU100	4.7
A70-CU300	18.1

Volumetric strain during consolidation stage.



Effective stress path in unsaturated (partially saturated) CU tests.

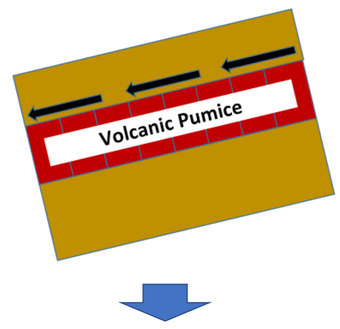


Relationship between
(a) stress and strain, (b) volumetric strain and strain and (c) pore pressure and strain
in unsaturated (partially saturated) CU tests.

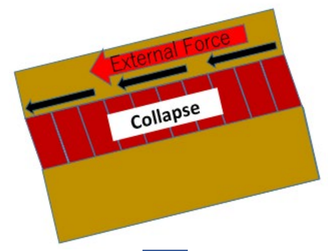
人工的にセメンテーションや粒子破砕性を持つ超高間隙構造土を作製し、三軸非排水試験を行った結果。超高間隙土は、粒子間セメンテーションを持つ場合 は 0.3%程度の軸ひずみでセメンテーションに起因す るピーク強度を示し、さらに粒子破砕を起こす一定 以上の拘束圧では軸ひずみ1～1.5%で粒子破砕に起因 するピークを示した。超高間隙土は、拘束圧によら ず、その非常に緩い構造によって、軸ひずみが進行 しても軸差応力が上昇せず一定に収束する定常状態（脆弱な状態）に至った。
Artificial pumice exhibits a high shear strength and a low compressibility when cementation is maintained. However, once cementation is lost, a high compressibility is observed. In some cases, even if the specimen is not fully saturated, after the shear strength reached its peak and the cementation was lost, a brittle behavior was observed in which the shear strength converges to a residual state, called steady state.

崩壊のイメージ
Illustration of the collapse mechanism

Extremely loose structure is kept in natural condition.

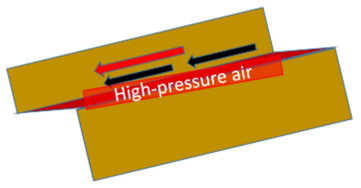


Earthquake breaks soils structure and reaches peak strength



Rapid decrease of strength & Large deformation

→It can occur even if it is unsaturated.
→Compressed high-pressure air can cause local destruction in the ground.



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Strain localization during drained torsional shear tests in crushable artificial pumice soil

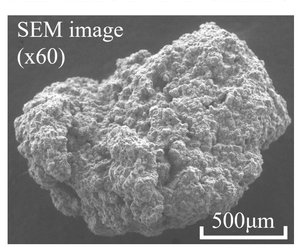
破砕性人工軽石の排水ねじりせん断時のひずみの局所化

Volcanic pumice soils are widely distributed in Japan, causing serious slope disasters. Pumice soils are characterized by its porous and highly crushable particles and its high contractancy during consolidation and shear. In this study, hollow cylindrical torsional shear tests were conducted using a crushable artificial pumice soil. Effect of particle breakage on shear behavior were discussed by comparing the results with those of silica sand. In addition, image analysis was performed on the specimens during shearing to examine the effects of particle breakage on strain localization and shear band formation.

日本には火山由来の高間隙構造を有する軽石が各地に分布し、斜面災害を引き起こしている。軽石の特徴として、多孔質で破砕性を有し、圧密やせん断に伴って高い収縮性を示すことが挙げられる。本研究では、破砕性を有する人工軽石を用いて平均有効主応力一定条件のもとで中空ねじりせん断試験を実施し、珪砂（非破砕性土）の試験と比較することで、粒子の破砕性がせん断挙動に及ぼす影響について考察した。さらに、せん断中の供試体に対して画像解析を行い、破砕がせん断時のひずみの局所化やせん断層の形成に及ぼす影響についても検討した。

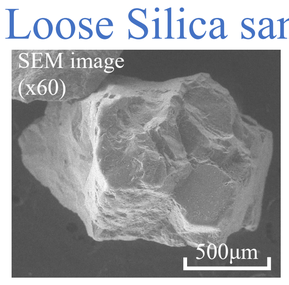
1. Material & Test procedures

Artificial Pumice soil (AP)



- Mixture of DL clay, cement and water, cured for 7 days
- Porous & Crushable
- High void ratio (e_{ini}=2.27-2.31)

Loose Silica sand (LS)



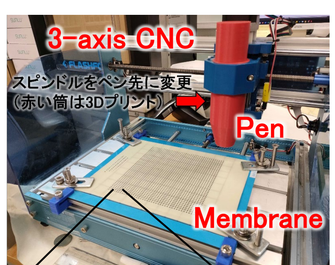
- Normal sand (for comparison)
- Same PSD as artificial pumice
- e_{ini}=0.85
- Dr=36% (loose)

Test Procedure:

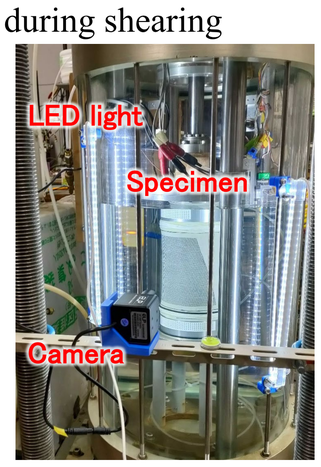
Prepare Specimen (reconstituted) → Saturation → Consolidation 20→100kPa → Drained Monotonic Torsional Shear until shear strain γ=30% → Sieving

2. Image Analysis

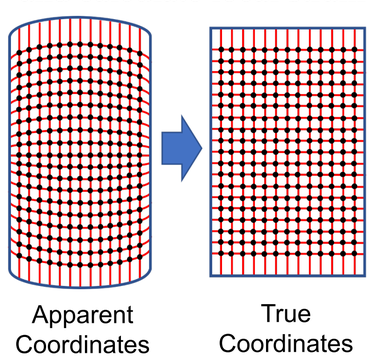
1. Plot grid points on an outer membrane



2. Shoot and track dots during shearing

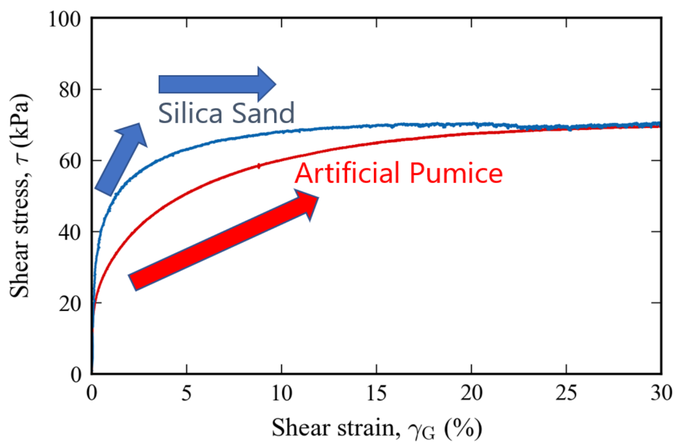


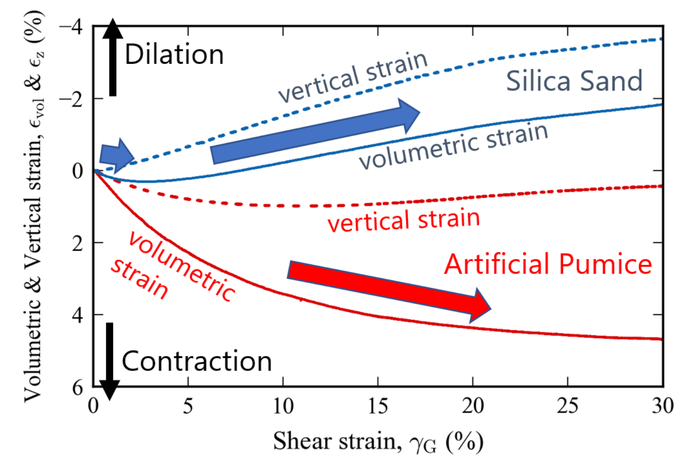
3. Convert coordinates and calculate local strain

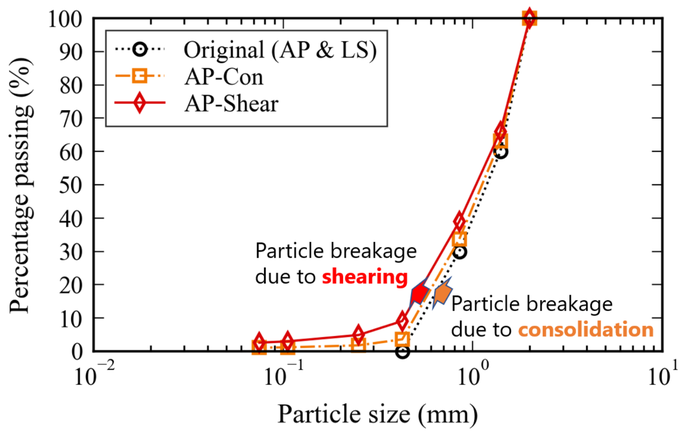


↑Following the method proposed by Zhao & Koseki (2020)

3. Results of tests

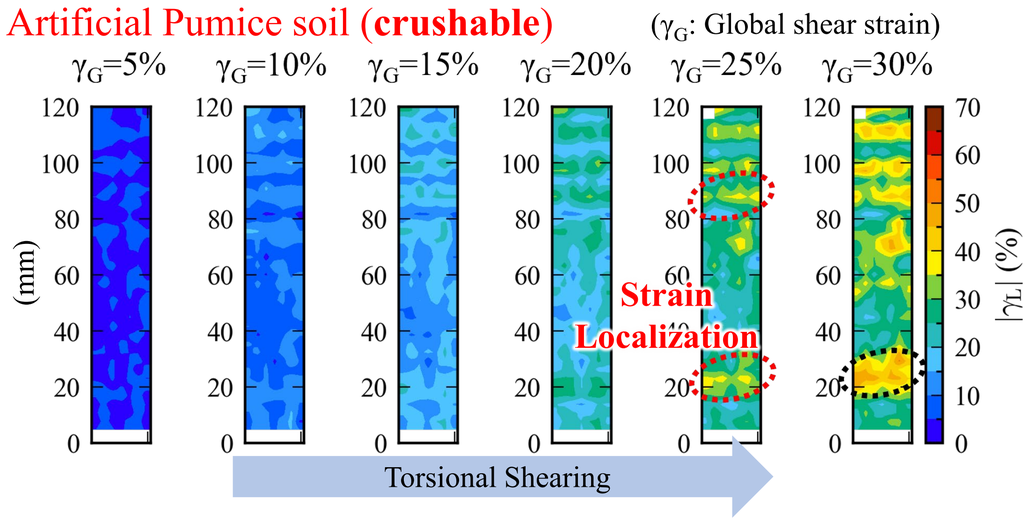


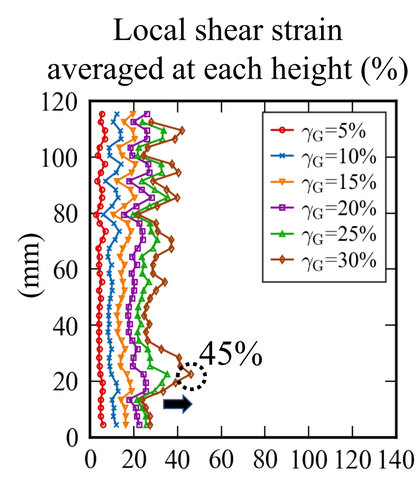




4. Results of image analysis

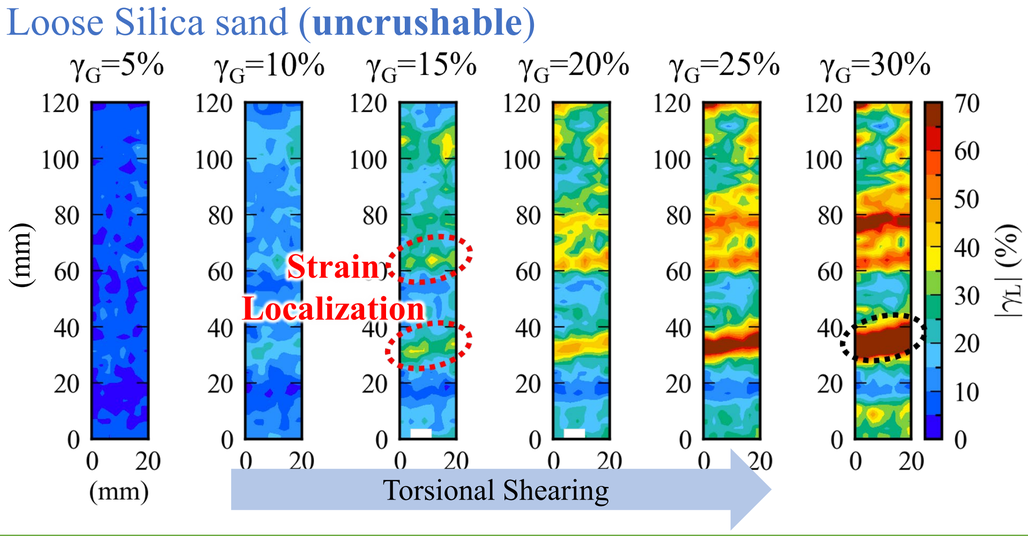
Artificial Pumice soil (**crushable**) (γG: Global shear strain)

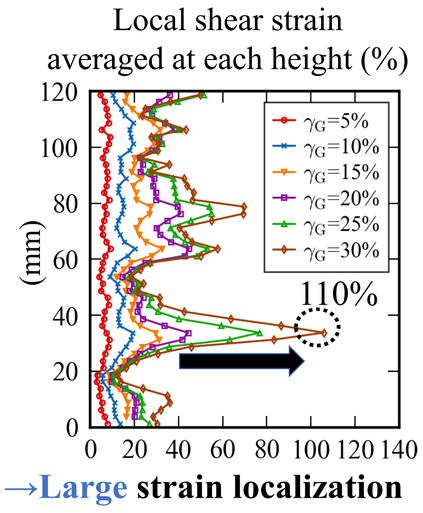




→**Small strain localization**

Loose Silica sand (**uncrushable**)





→**Large strain localization**

5. Conclusion

- ✓ The artificial pumice soil showed slower increase in shear stress and strong contractancy, compared to the loosely packed silica sand. Significant particle breakage was observed during consolidation and shearing.
- ✓ Image analysis revealed that strain localization occurred more slowly in the artificial pumice soil than in the loosely packed silica sand because of particle breakage.

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Evaluation of particle morphology of artificial pumice soil subjected to torsional shear

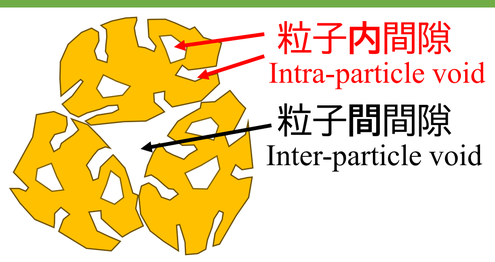
ねじりせん断を受けた人工軽石の粒子内間隙比と粒子形態の評価

A series of torsional shear tests were performed using a porous and crushable artificial pumice soil. X-ray CT images of pumice particles before and after the tests were obtained to quantitatively assess changes in the intra-particle void ratio and particle morphology. It was found that contractancy of pumice specimens was primarily due to the decrease in the inter-particle void ratio, rather than the decrease in the intra-particle void ratio. The pumice particles after tests had transformed into more compact shapes with fewer local irregularities due to particle breakage.

本研究では、破砕性を持つ人工軽石を用いて中空ねじりせん断試験を実施した。試験前後の試料から採取した軽石粒子のX線CT画像を取得して、圧密・せん断を受けた軽石粒子の内間隙比や粒子形態の変化を定量的に評価した。

人工軽石の圧密・せん断に伴う体積収縮（＝間隙比の減少）は、粒子内間隙比の減少よりも、破砕により生じた小さな粒子が粒子間間隙を埋めることによる粒子間間隙比の減少の方が支配的な要因であることがわかった。試験後の粒子は、粒子破砕によって、よりコンパクトで局所的な凹凸が少ない形状に変化していた。

Background



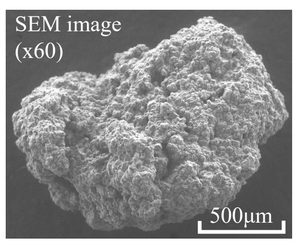
Characteristic of pumice soils :

- Existence of intra-particle voids
- High crushability and contractancy

Research Objective:
Quantification of the intra-particle void ratio (e_{intra}) and particle morphology using 3D images of pumice particles.

Material & Test Procedure

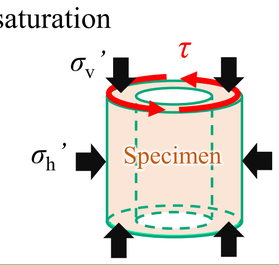
Material: Artificial Pumice soil



- Mixture of DL clay, cement and water
- Porous & Crushable
- High void ratio (e = 2.28 at Dr = 70%)

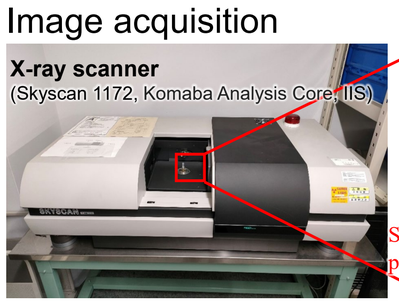
Torsional shear test

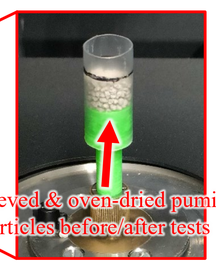
1. Specimen preparation & saturation
2. Isotropic Consolidation (20→500kPa)
3. Drained torsional shear under constant p' until shear strain γ=15 or 30%
4. Sieving



X-ray CT analysis

Image acquisition

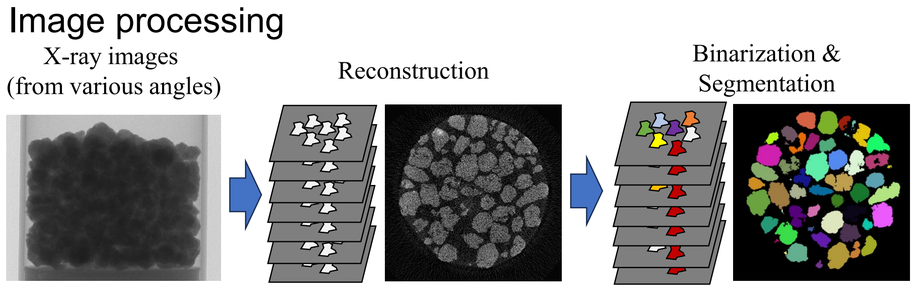




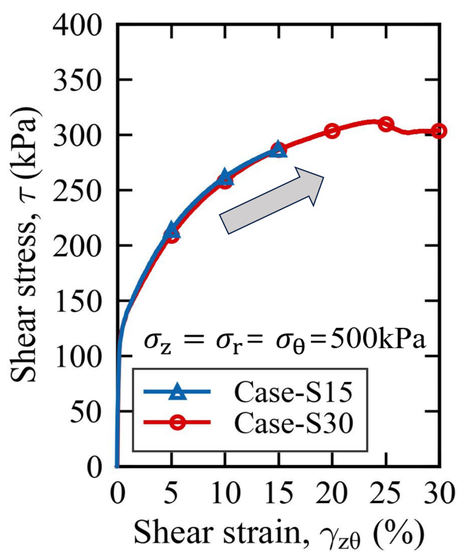
voxel size (μm)	particle size (mm)
5.0	0.106-0.25
	0.25-0.425
7.5	0.425-0.85
	0.85-1.18
14.8	1.18-2.00

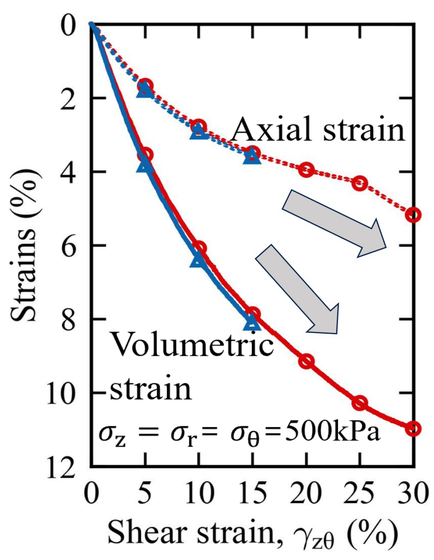
Resolution of 3D images

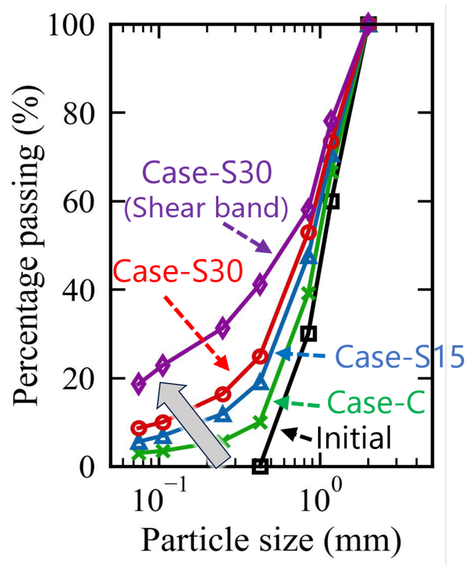
Image processing



Results of torsional shear





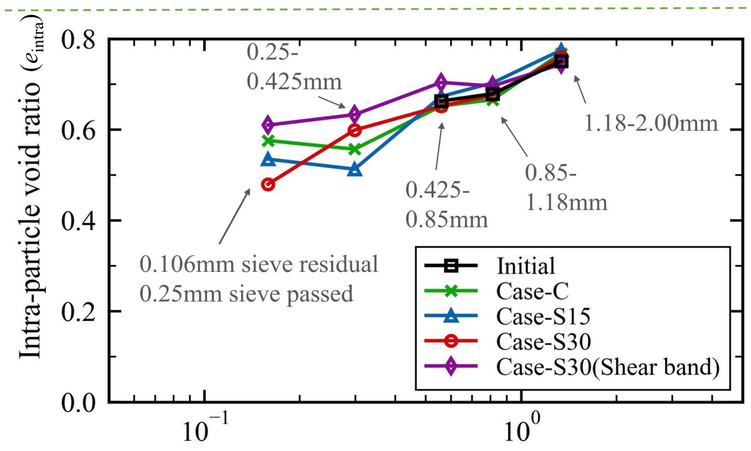


- Shear stress gradually increased, and strain softening was not observed.
- Significant contractancy and particle breakage was observed.

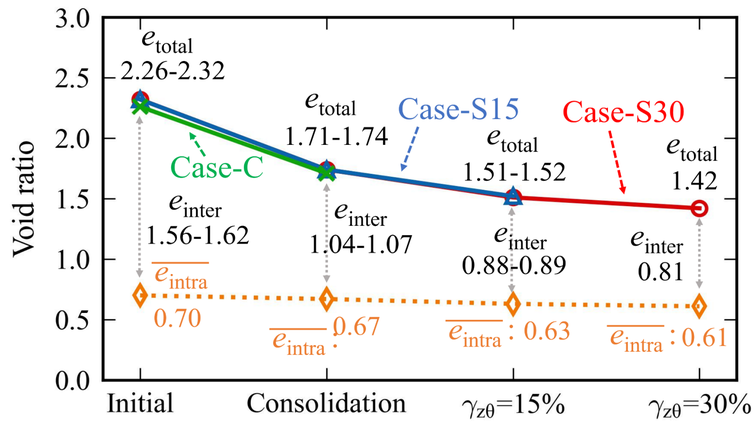
Evolution of void ratios

$$e_{intra} = (V_{app} - V_{solid})/V_{solid} = (V_{app} - M/\rho_s)/(M/\rho_s)$$

(V_{app}: Apparent volume of particles, V_{solid}: Solid volume of particles, M: Dry mass of particles, ρ_s: Solid density of particles)

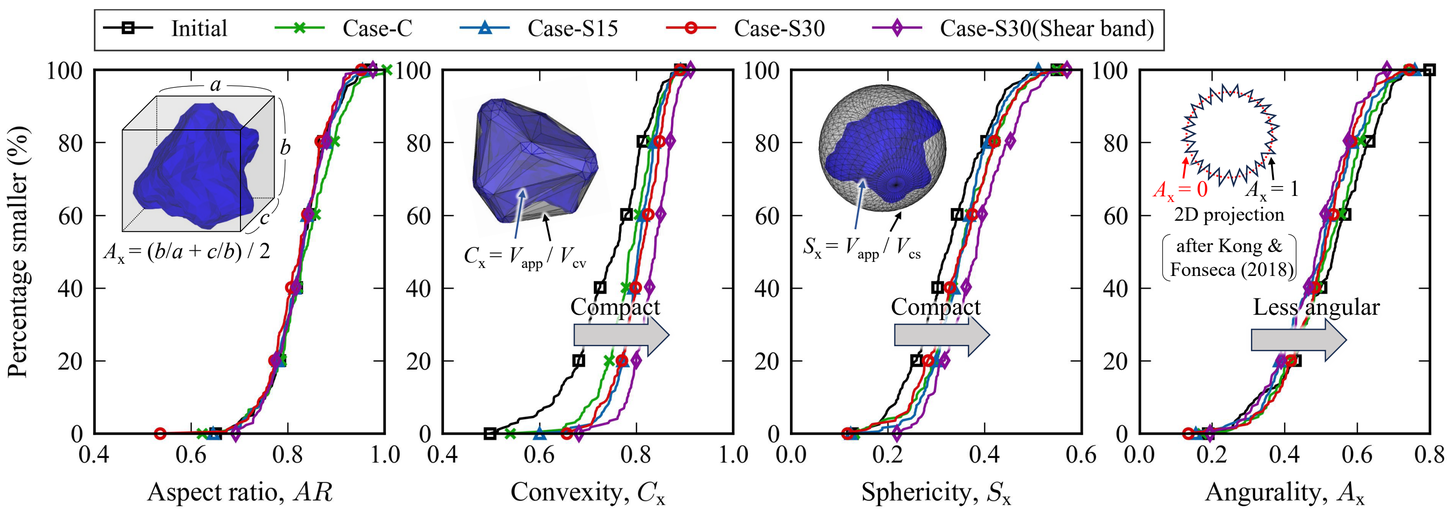


- Smaller particles showed lower e_{intra} values.
- No significant differences were observed before and after the test when comparing particles of the same size.



- Decrease of $\overline{e_{intra}}$ was larger than that of inter-particle void ratio (e_{inter}).
- Filling of inter-particle voids by particle fragments generated by particle breakage was the primary factor in the contractancy of the pumice soil.

Evolution of particle morphology



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Experimentally Obtained Outline of State-boundary Surface of Artificial Pumice

実験により導出された人工軽石の state-boundary surface の概形

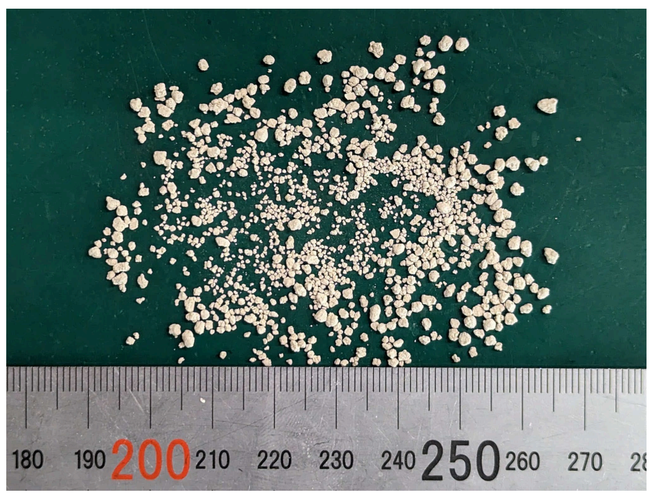
軽石は、斜面崩壊などの地盤災害の原因としてしばしば指摘される材料です。土の力学挙動を考えるとき、多くの場合で平均有効応力p'・軸差応力q・間隙比eをパラメーターにとります。ここで、 p'-q-e空間上にて、土の応力状態(p', q, e)の存在範囲をその内部に制限する曲面のことをstate-boundary surface (SBS) と呼びます。本研究では、人工的に作製した軽石の SBS の概形を、排水・非排水条件での三軸圧縮試験により求めました。得られた状態径路は互いに交差し、網目状となりました。これを包み込む曲面を構成し、排水・非排水いずれの状態径路も妥当に抑え込むことが確認できました。

Pumice soil is often an important factor in ground disasters such as slope failures. When we think about mechanical behaviour of soil, we usually take three parameters: mean effective stress p', deviator stress q, void ratio e. In three-dimensional space p'-q-e, state-boundary surface is a surface to which stress state (p', q, e) is confined. This study obtained an outline of SBS of artificial pumice by drained and undrained triaxial compression tests. The state paths crossed each other, which formed a mesh. We composed a surface which covers the mesh and confirmed that it reasonably keeps drained and undrained state paths inside itself.

Experiment

Test procedure

1. Specimen preparation
   - $e \approx 2.25$
2. Saturation
3. Normal consolidation
   - Creep for 60 min
4. Monotonic shearing
   - To 20 % of axial strain
5. Sieving

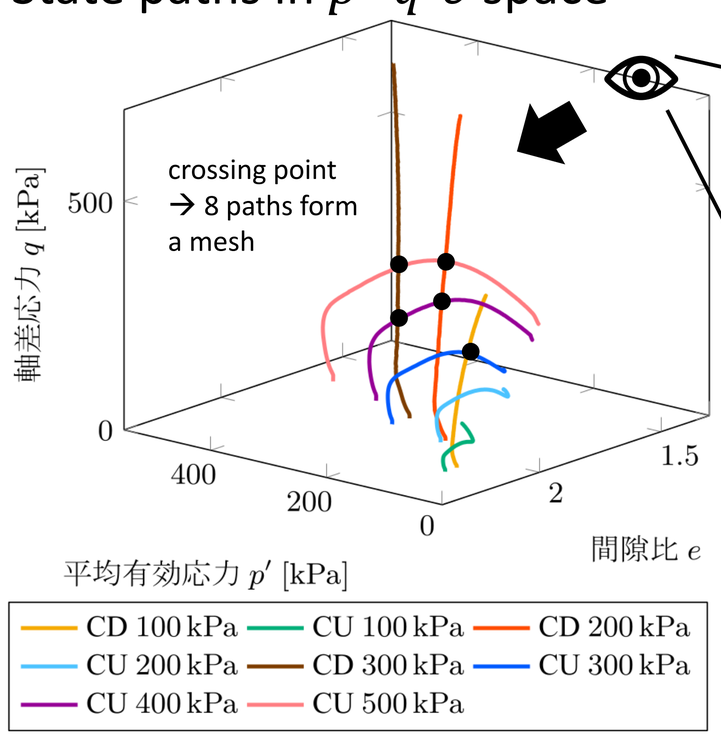


Artificial Pumice ($D_{50} = 1.1$ mm)

No.	Condition	Confining pressure	Hardin's relative breakage
1	CD	100	0.129
2	CU	100	0.050
3	CD	200	0.169
4	CU	200	0.086
5	CD	300	0.191
6	CU	300	0.118
7	CU	400	0.130
8	CU	500	0.128

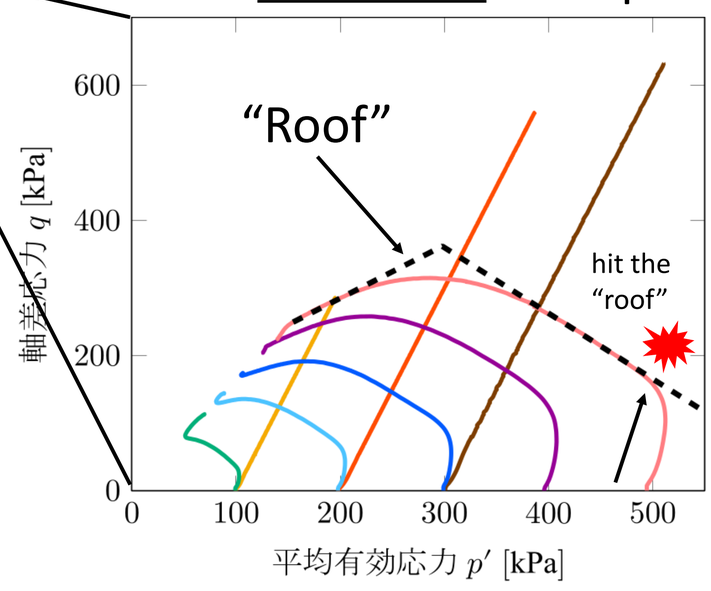
Results

State paths in p'-q-e space

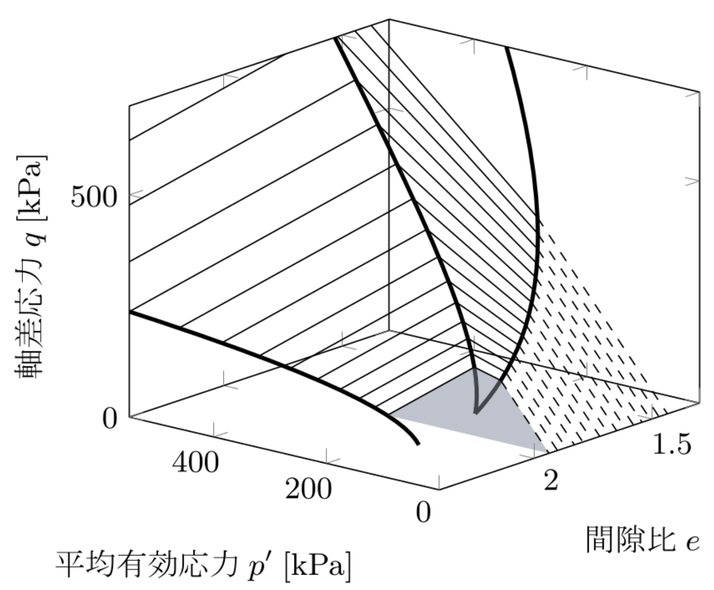


A mesh formed by 8 state paths indicates an SBS, on which every state path moves

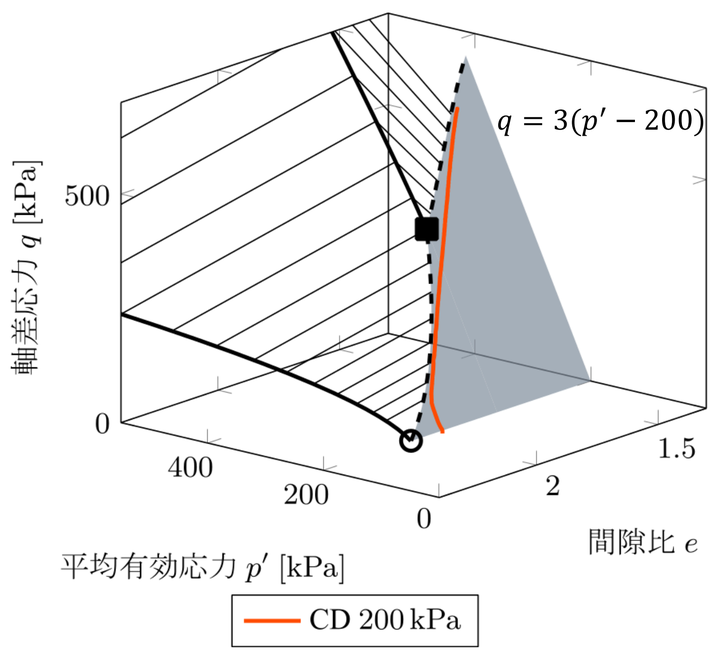
Set a polyline "roof" on each undrained state path



An undrained state path cannot increase q endlessly because p'changes → it hits the "roof"



Obtain a surface by fitting the undrained "roofs"
→ Any undrained state path cannot go out of it



Cut the "roof" surface with a plane which binds a drained state path
→ drained state path also goes beneath the "roof" surface

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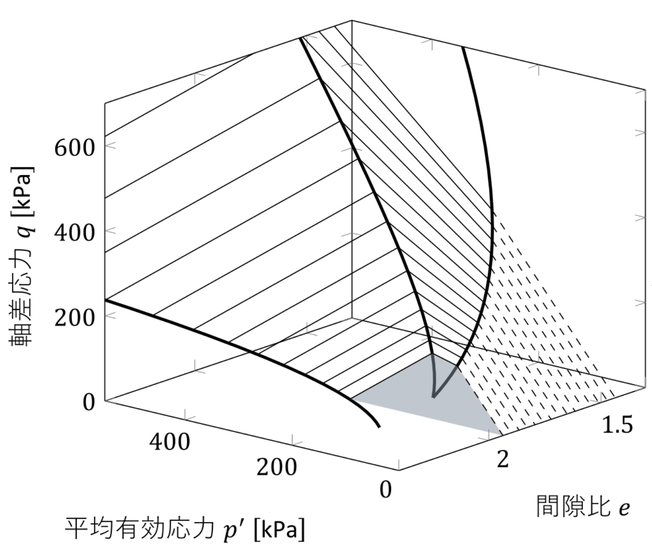
Difference in slope on state-boundary surface between artificial pumice and Ta-d

人工軽石とTa-d のstate-boundary surface の傾きにおける差異

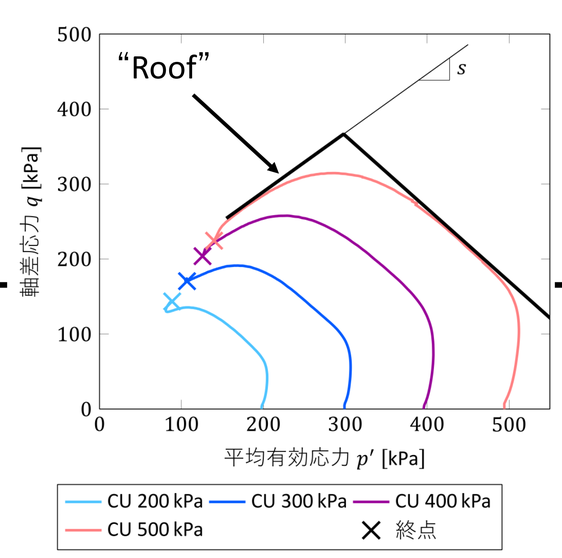
軽石は，斜面崩壊などの地盤災害の原因としてしばしば指摘される材料です．一方，土の力学挙動の議論の多くで，平均有効応力p'・軸差応力q・間隙比eがパラメーターとして用いられます．ここで，p'–q–e空間で，土の応力状態(p', q, e)の存在範囲を制限する曲面のことをstate-boundary surface (SBS) と呼びます．既往研究では，軽石の破砕性とSBSの形状との関係について，人工軽石のみが議論されていました．本研究では天然の軽石Ta-dについて同様に議論し，次の仮説を得ることができました．つまり，間隙比が大きい領域では人工軽石と同様の破砕性土的挙動を示し，小さい領域では非破砕性土的挙動を示す，というものです．

Pumice soil is often a significant factor in ground disasters such as slope failures. The mechanical behaviour of soil is typically expressed using three parameters: mean effective stress p', deviator stress q, and void ratio e. In three-dimensional p'–q–e space, the state-boundary surface (SBS) defines the limit within which the soil's stress state (p', q, e) is confined. Previous research focused on artificial pumice and discussed the relationship between its crushability and the shape of its SBS. This research focuses on natural pumice, Ta-d, and hypothesises that Ta-d behaves like crushable soil, as observed in artificial pumice, when the void ratio is large, and behaves like uncrushable soil when the void ratio is small.

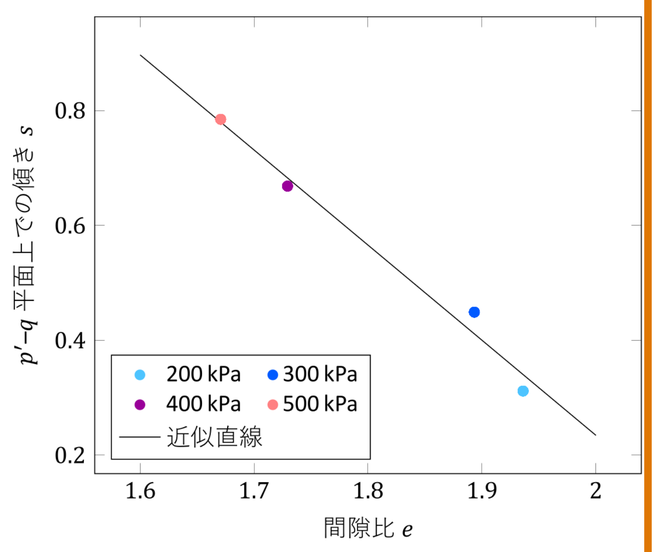
Artificial Pumice (Previous Study)



Obtain an SBS by fitting the undrained ‘roofs’
→ Any undrained state path cannot deviate from it

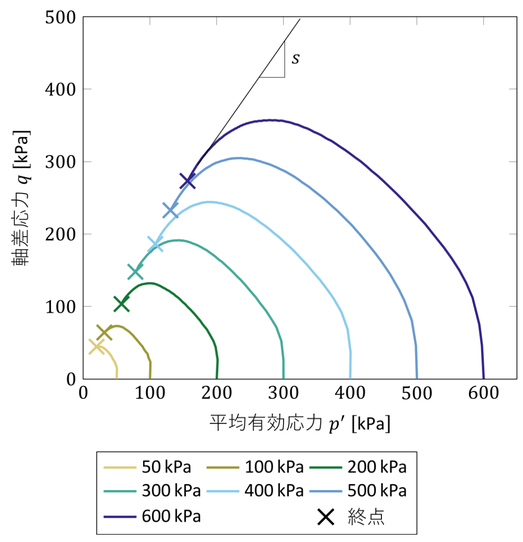


An undrained stress path cannot increase q endlessly because p'changes → it hits the ‘roof’

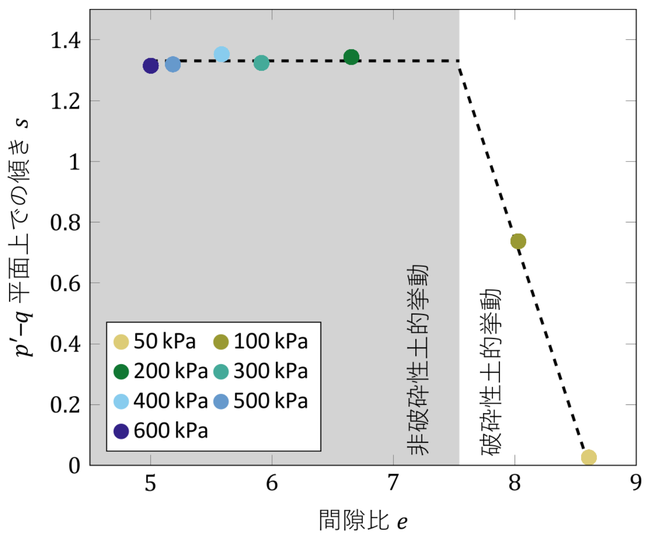


The relationship between the slope (of the stress path [i.e., SBS]) s and e is linear

Natural Pumice – Ta-d



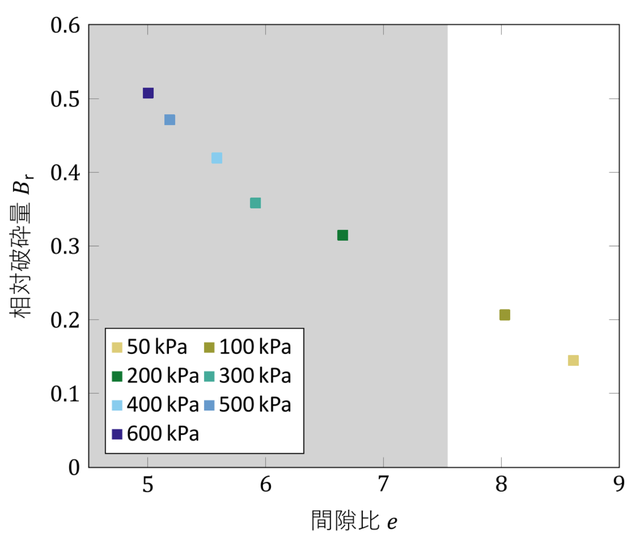
No.	拘束圧 [kPa]	e_{BC}	B_r	$e_{a_{end}}$ [%]
1	50	9.25	0.145	10
2	100	9.33	0.207	10
3	200	8.68	0.315	11
4	300	8.56	0.358	11
5	400	8.60	0.419	11
6	500	8.61	0.471	11
7	600	8.81	0.508	11



The relationship between slope s and e can be interpreted as a combination of two linear relationships, which can be described by the following hypothesis:

1. $e > 7.5$: behaviour like crushable soil, as observed in artificial pumice
2. $e < 7.5$: behaviour like **un**crushable soil

Particle breakage saturates around $e = 7.5$ and does not increase for $e < 7.5$?



* B_r: an index for particle breakage
Particle breakage (in the last phase of the shearing) does NOT change around $e = 7.5$.
→ B_r cannot support the hypothesis
→ Can other parameters support it?
like particle size distribution:
- Just before shearing
- When q reaches its peak

(in future research…)

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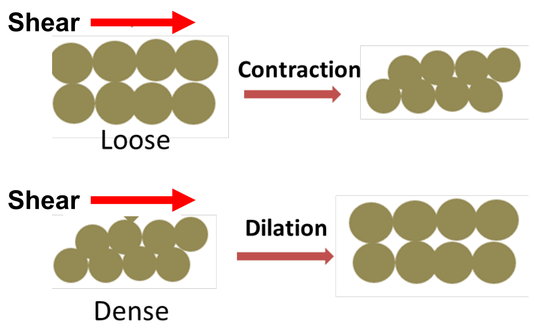
Effect of Strong Contraction on the Shear Behavior of Volcanic Soil

火山性土のせん断挙動における強い収縮傾向

Volcanic soil are often referred as problematic materials, these material exhibit strong contraction upon shear deformation. Due to different source of volcanic origin, weathering formation and aging, the underlying mechanism of these soils is not well understood. The monotonic undrained and drained triaxial tests under varying confining pressures and void ratios were conducted in this study. The results show that the crushability nature of volcanic soil results in contractive behaviour and the effect of contraction depends much on the initial relative density.

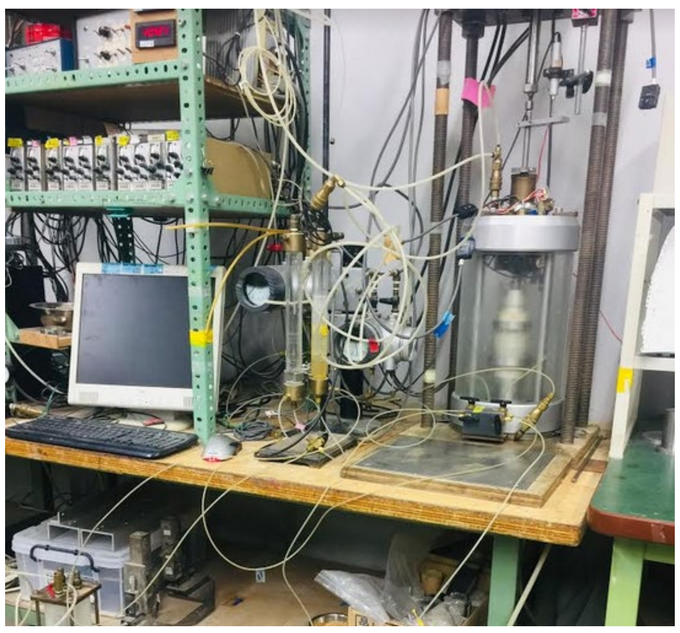
火山性土は災害の起因となることが多く特異な挙動を示します。特にせん断時に強い収縮傾向を持ち、火山起源、風化の形成、年代効果等が多様で、その力学特性は未だ解明されていません。本研究では、異なる拘束圧と密度条件で火山性土の非排水および排水三軸圧縮試験を実施しました。火山性土の破砕性がせん断時の収縮挙動をもたらすこと、またそれは供試体の密度に大きく依存することがわかりました。

Dilatancy

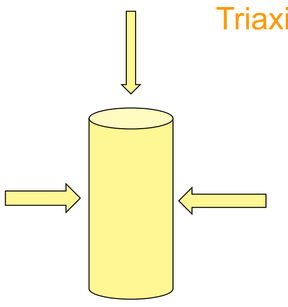


Dilatancy is the volumetric deformation of soil under the action of shear stress. Contraction (negative dilation) occurs in term of volume decrease.

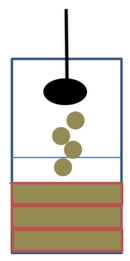
Experimental Apparatus



Triaxial Apparatus

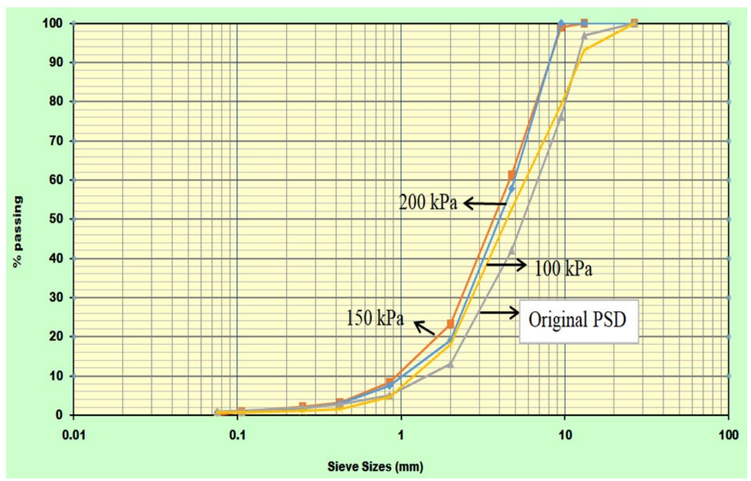


Specimen size:100mm
height:50mm diameter



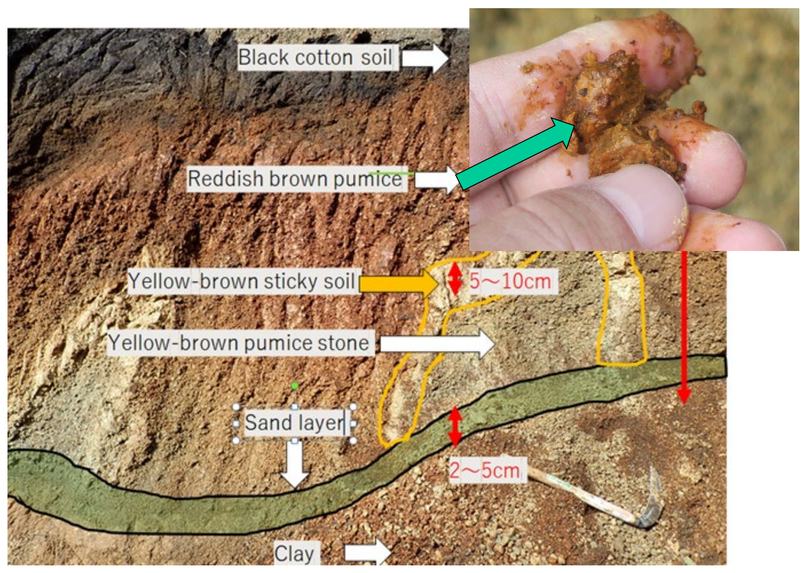
Sample preparation:
Moist Tamping

Particle size distribution after shearing

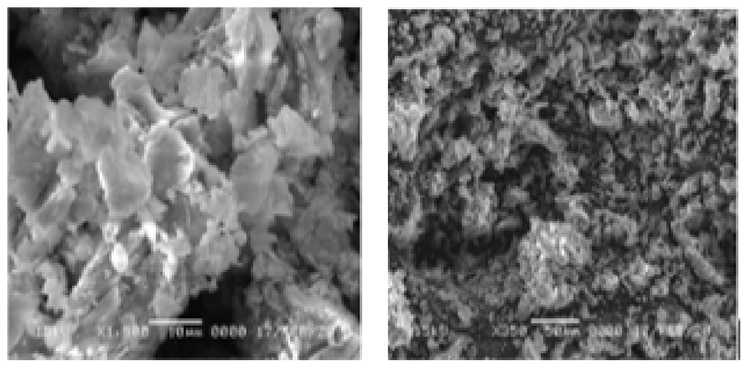


The **particle breakage rate** increases with the increase in confining pressure. This indicate that particle crushability during shearing induces more contractive response.

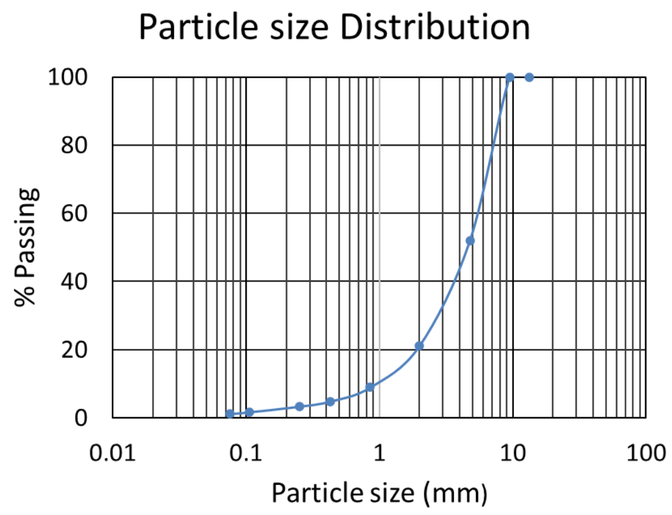
Tested Material



Soil profile from the location site



Microscopic electronic Images

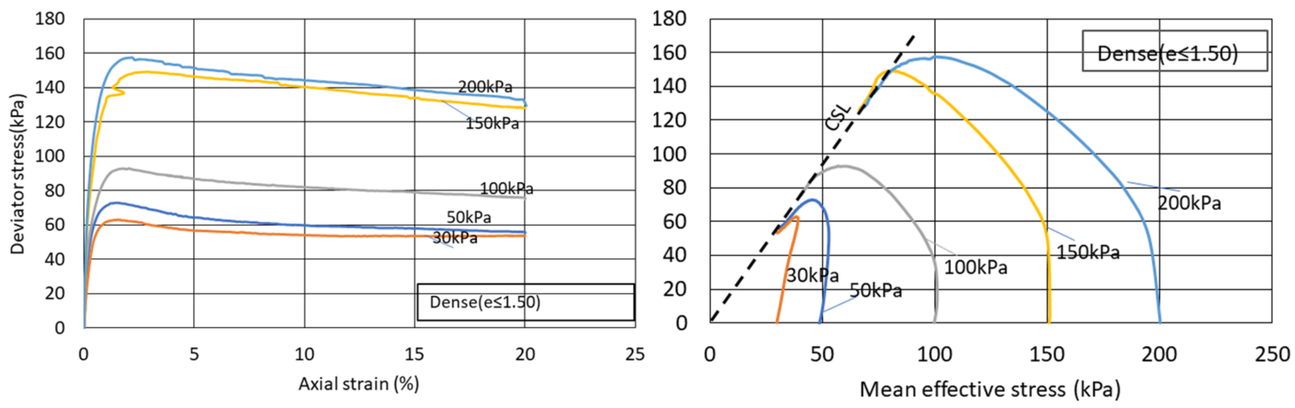


Physical Properties

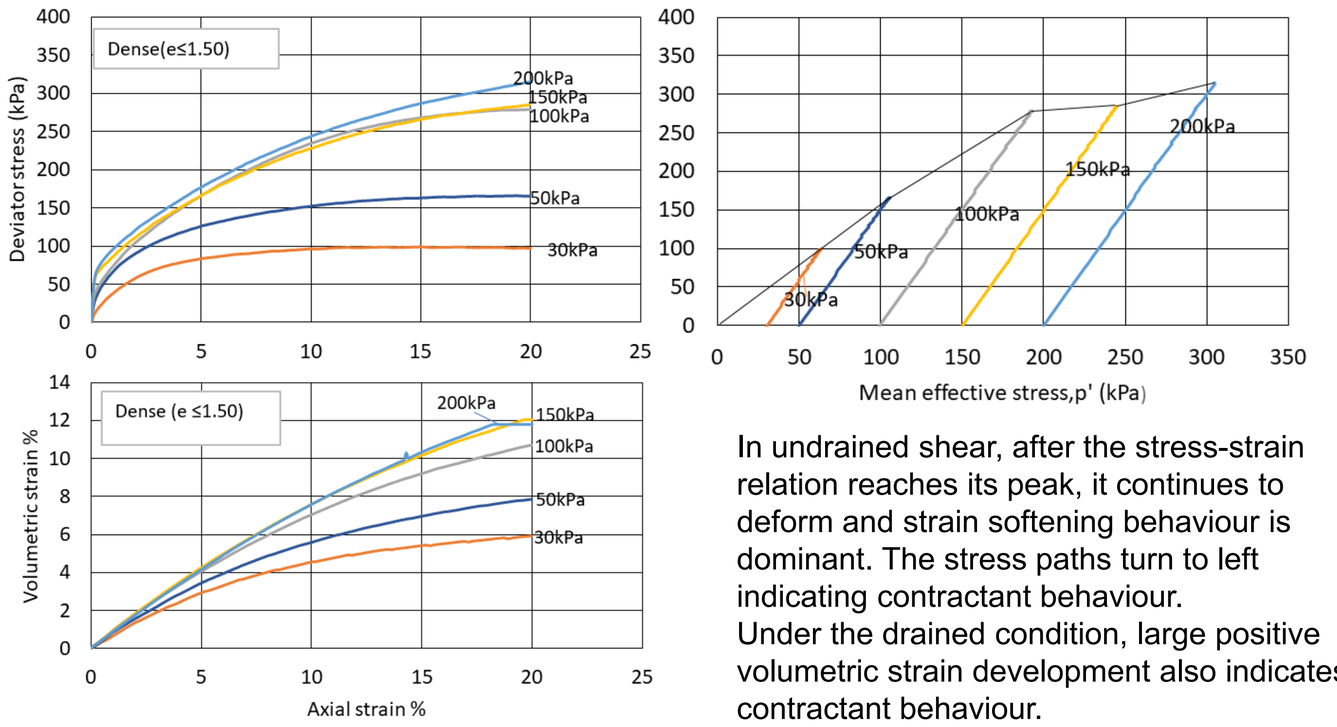
Specific Gravity, Gs	2.56
In-situ Dry Density (g/cm^3)	0.42
Water Content (%)	195
In-situ Void Ratio, e	2.75
Reconstituted specimen void ratio, e (Particle size < 6.7mm)	1.50

Behavior in triaxial compression

Undrained compression of dense state specimen



Drained compression of dense state specimen



In undrained shear, after the stress-strain relation reaches its peak, it continues to deform and strain softening behaviour is dominant. The stress paths turn to left indicating contractant behaviour.
Under the drained condition, large positive volumetric strain development also indicates contractant behaviour.

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Beatrice Magombana, (2020)
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Effects of water content on the behaviour of volcanic pumice in the direct shear box test

火山性軽石の一面せん断挙動における含水比の影響

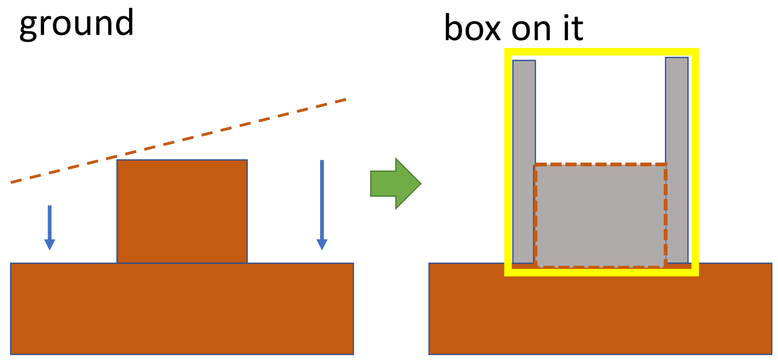
平成30年9月6日の北海道胆振東部地震では大規模な斜面崩壊が発生しましたが、その現場には多量の水の存在を示す痕跡が残されていました。そこで本研究では、現場に広く分布する火山性軽石（Ta-d）の含水比がせん断特性にもたらした影響を調べるため、現場で不攪乱試料を採取し、再構成試料と比較しつつ、浸水および非浸水条件での一面せん断試験を実施しました。

2018 Hokkaido Eastern Iburi earthquake caused a wide-area slope failure, and the site indicated the presence of plenty of soil water. This research investigated how the water content affects the shear strength in the volcanic pumice (Ta-d) which is distributed at the site. We collected undisturbed samples and conducted direct shear box test with samples soaked and non-soaked.

Undisturbed sampling

1. Dig and shape the ground

2. Put the shear box on it



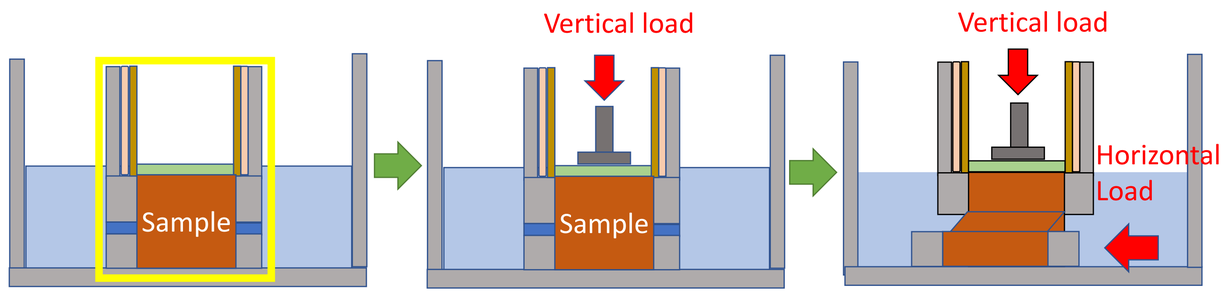


Direct shear box test

1. Soaking

2. consolidation

3. shear deformation

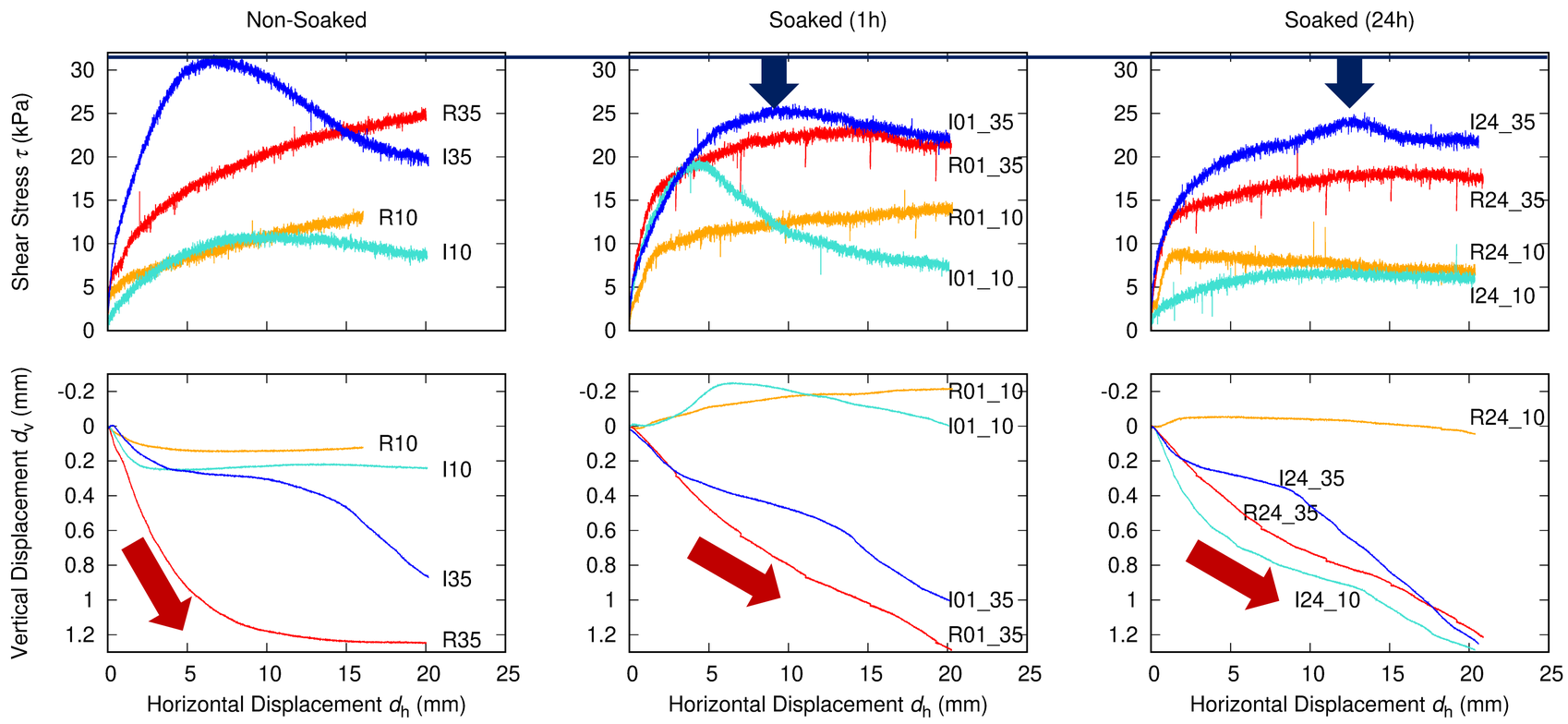


Test conditions

	No.	Type	Soaking time T_{sink} (h)	Vertical stress σ (kPa)	Initial water content W_{ini} (%)	Final water content W_{fin}(%)	Initial void ratio e_i	Void ratio after consoli-dation e_c
Soaked	R24_10	Disturbed	24	11	138	148	4.29	4.19
	R01_10	Disturbed	1	11	125	149	4.24	4.18
	R24_35	Disturbed	24	34	131	154	4.55	4.40
	R01_35	Disturbed	1	34	127	144	4.30	4.12
	I24_10	Undisturbed	24	10	80	131	4.24	3.74
	I01_10	Undisturbed	1	11	109	150	4.65	4.50
	I24_35	Undisturbed	24	35	116	153	5.12	4.46
	I01_35	Undisturbed	1	34	97	129	4.21	3.73
Non-soaked	R10	Disturbed	N/A	10	113	N/A	4.58	4.43
	R35	Disturbed	N/A	35	131	N/A	4.97	4.58
	I10	Undisturbed	N/A	11	112	N/A	4.77	4.64
	I35	Undisturbed	N/A	35	105	N/A	4.63	4.23



Result



- Greater peak shear stress in non-soaked tests
  → the result does not contradict the hypothesis that water content had weakened the soil strength
- Moderate contractancy in soaked tests
  → soaking have some effect on dilatancy/contractancy

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Development of a portable in-situ direct shear box test apparatus and its application to residual strength estimation of volcanic soils

可搬式原位置繰返し一面せん断試験装置の開発とその適用による火山性土の残留強度の推定

概要　Overview

日本には火山性土が広く分布し、大規模な斜面災害を引き起こすことが指摘されている。火山性土は、多孔質な粒子がセメンテーションによる弱い結合によって保持された非常に脆い構造を有することが多い。一般的な室内試験は、土の採取、運搬等の過程で構造が乱れるため、原位置で土粒子構造を保持したまま試験を行うことが望ましい。残留強度を測定するための試験手法として繰返し一面せん断試験があるものの、変位振幅の値や打ち切りのタイミングが一般化されてない。
本研究では、火山性土の残留強度を測定するための繰返し一面せん断試験手法の検討と、既往の研究によって開発された試験装置を改良し繰返し機構を追加することによって新たな可搬式原位置試験装置の開発を行った。さらに、検討した試験手法と開発した装置を用いて、原位置にて火山性土を対象とした残留強度の推定を行った。

Volcanic soils are widely distributed in Japan and have been noted to cause large-scale slope disasters. Volcanic soils are characterized by a very fragile structure of porous particles held together by weak bonds. Since common laboratory tests to determine strength properties disturb the structure during soil sampling, transportation, and other processes, it is desirable to conduct tests while the soil particle structure is retained in situ. A cyclic direct shear test can measure residual stresses but has not been generalized in terms of displacement amplitude values and timing of termination.
In this study, we investigated a cyclic direct shear test method for measuring the residual strength of volcanic soils and developed a new portable in-situ test apparatus by modifying the previously developed device. In addition, the residual strength of volcanic soils was estimated in-situ using the developed apparatus and the test method studied.

繰り返し一面せん断試験手法の検討
Examination of cyclic direct shear testing methods

対象とした土試料
Targeted soil sample

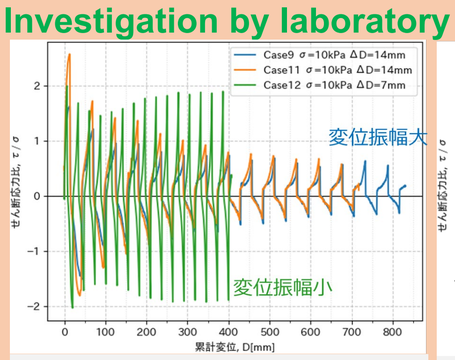


Ta-dの様子

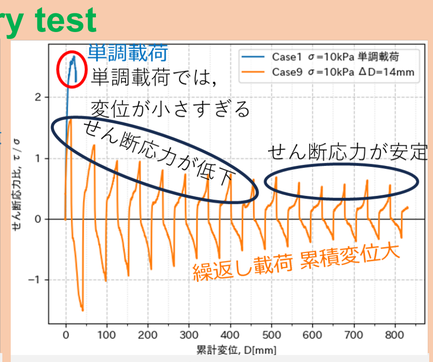

不かく乱試料採取の様子

- 北海道胆振東部地震により大規模な斜面崩壊が発生
  Large-scale slope collapse caused by the Hokkaido Eastern Iburi Earthquake.
- 斜面崩壊の原因とされるのは火山性軽石土（Ta-d）
  Volcanic pumice soils (Ta-d) are the most common cause of slope failure.
- 自然含水比が液性限界より高いという特徴がある
  Characterized by a natural moisture content ratio higher than the liquid limit.

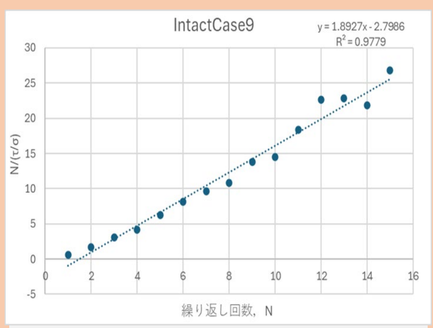
室内試験による検討
Investigation by laboratory test



変位振幅の比較



累積変位の検討



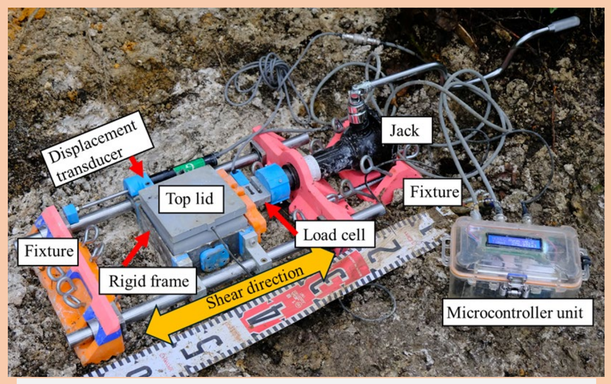
累積変位の検討

原位置試験にて行うべき繰返し一面せん断試験の手法は以下のとおり
In-situ cyclic direct shear test technique to be performed is as follows

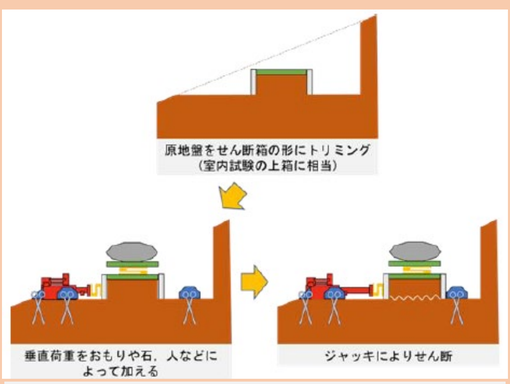
- ピーク強度となる変位よりも大きな変位振幅が必要である
A displacement amplitude must be larger than the displacement of peak stress.
- 残留強度の測定には累積変位500mm以上が必要である
Cumulative displacement of 500 mm is required to measure residual strength.
- 粘土の残留強度を測定する際に用いられる双曲線近似法を火山性土にも適用できる
The hyperbolic approximation method used to determine the residual strength of clay can be applied to volcanic soils..

原位置試験装置の開発
Development of in-situ test apparatus

可搬式原位置試験装置のアップデート
Update of portable in-situ test apparatus



開発した原位置試験装置



原位置試験の試験手順

既往の試験装置の問題点
Problems with existing test apparatus

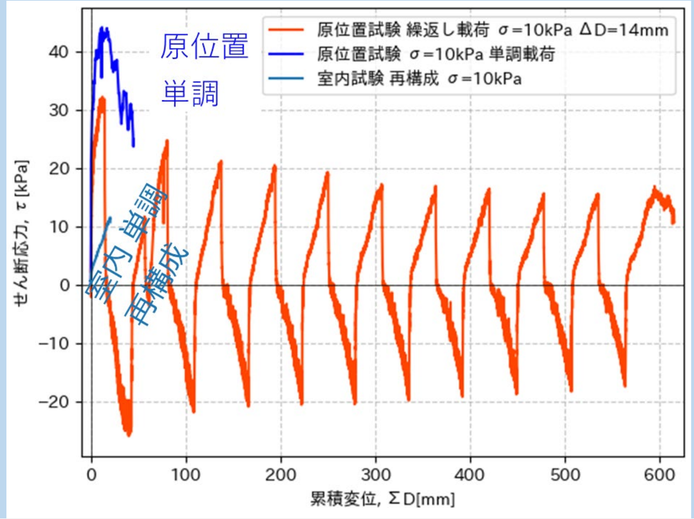
①油圧ジャッキによる非連続な載荷によってピーク強度の不正確な測定
Discontinuous loading by hydraulic jacks
②限られた変位量により残留強度が測定不能
Range of displacement is limited.

主要な変更点
Major changes in test apparatus

①スクリュージャッキにより連続的かつ両方向への載荷を可能にした
Screw jacks allow continuous loading in both directions
②複雑な繰り返し機構を3Dプリンタにより実現
Complex cyclic mechanisms are made by 3D printer.
③せん断箱の壁の厚みを12mmから3mmに変更し、供試体の乱れの影響を削減した
Shear box wall thickness was changed from 12mm to 3mm to reduce the effect of specimen disturbance.

総重量約8kgかつ各パーツの取り外しが可能であり、人力での持ち運びが可能
Total weight of approx. 8 kg and removable parts, allowing for human-powered transportation

原位置試験における火山性土の残留強度の推定
Estimation of residual strength of volcanic soils in In-situ Tests



原位置にて実施した繰り返し一面せん断試験の結果

せん断応力と相対変位率の関係
Relationships of shear stress and relative displacement

検討した試験手法と開発した試験装置を用いて、原位置にて一面せん断試験を行った
In-situ direct shear tests were conducted using the test apparatus developed.

装置の改善により、滑らかなグラフが得られるようになり、ピーク強度がより分かりやすくなった
The improved equipment provided smoother graphs, making peak stress more easily recognizable.
繰返し試験では、双曲線近似法を用いて残留強度が推定された
In cyclic tests, the hyperbolic approximation method was used to estimate the residual strength .

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御嶽高原の斜面崩壊地における原位置試験および斜面崩壊起因層の三軸試験

In-situ investigation and triaxial test of the landslide-causing layer at the slope collapse site in Ontake Plateau

概要　Overview

1984年に長野県で発生した長野県西部地震にて木曽郡王滝村で斜面崩壊が発生しました。この原因を探るため、本調査では、すべり面と考えられる火山性土の特性の把握を目的として、土壌硬度試験、簡易動的コーン貫入試験、現地と実験室の両方での一面せん断試験、さらに室内での三軸圧縮試験を実施しました。

In 1984, a landslide occurred in Otaki Village, Kiso County, Nagano Prefecture, due to Naganoken-seibu Earthquake. To investigate the cause of this, this survey aimed to understand the characteristics of the volcanic soil considered to be the slip surface. We conducted soil hardness tests, dynamic cone penetration tests, direct shear tests both in the field and in the laboratory, and triaxial compression tests in the laboratory.

御嶽高原の斜面崩壊



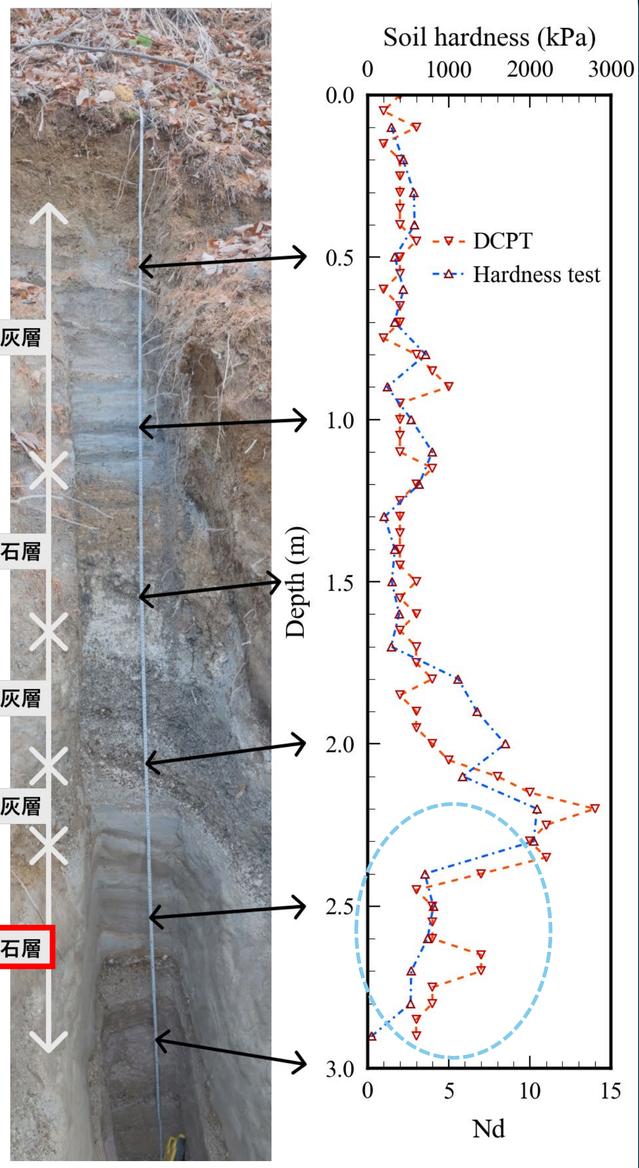
調査地点での崩壊当時の様子

出典：国立防災科学技術センター 編『昭和59年(1984年)長野県西部地震災害調査報告』,国立防災科学技術センター,1985.3.

土砂災害の規模
The scale of the landslide

幅 Width：70m
長さ Length：100m
深さ Depth：10m

各層の土壌硬度とコーン貫入抵抗



土被りの深さを考慮すると、白色軽石層の強度は弱いことが示唆された。
Considering the depth of the soil cover, it is suggested that the strength of the white pumice layer is weak.

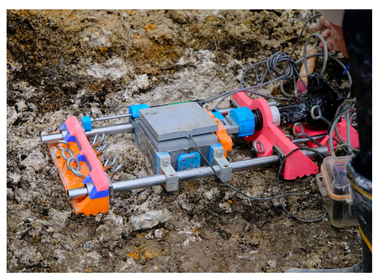
白色軽石の物理特性

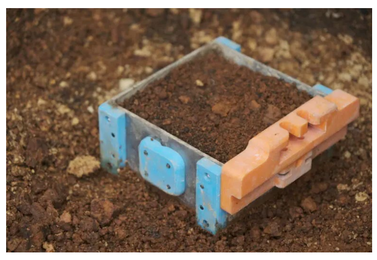
土粒子密度 (g/cm^3)	乾燥密度 (g/cm^3)	含水比 (%)	間隙比	塑性限界 (%)	液性限界 (%)	塑性指数 (%)
2.651	0.549	86.5	3.825	53.2	78.7	25.5

白色軽石は非常に大きな間隙比を持つこと、自然含水比が液性限界を超えていることがわかった。
It was found that the white pumice has a very large void ratio and its natural water content exceeds the liquid limit.

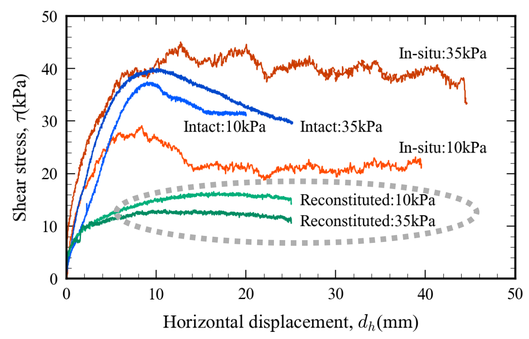
一面せん断試験

原位置・不攪乱・再構成試料を用い一面せん断試験を実施した。
Adirect shear test was conducted using undisturbed and reconstituted samples from the original location.





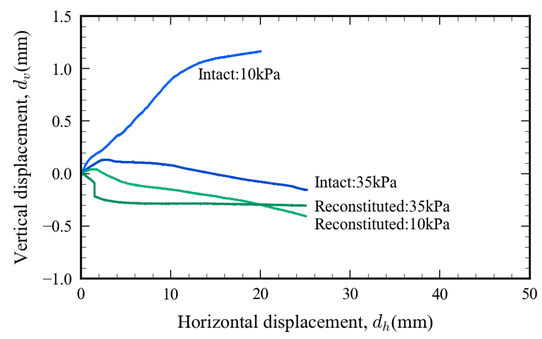
原位置一面せん断試験の様子



原位置・不攪乱・再構成試料の応力ひずみ関係

再構成試料では応力-変位関係が原位置や不攪乱試料とは大きく異なる結果
→白色軽石の力学特性の評価には土粒子構造の影響が無視できないことがわかった。

Comparing the results of in-situ, intact and reconstituted samples, the effect of soil structure seems to be significant on the evaluation of white pumice's mechanical behaviour.



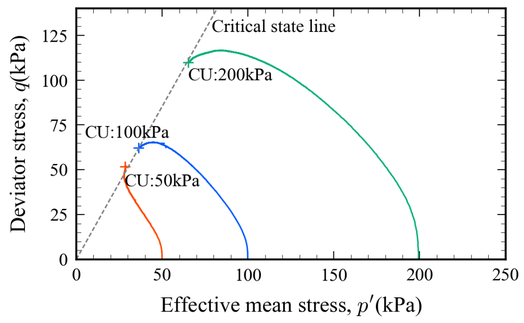
一面せん断試験に伴う鉛直変位
（引張方向が正）

せん断に伴い軽石が破砕し供試体の体積が圧縮される傾向があることが示唆された。

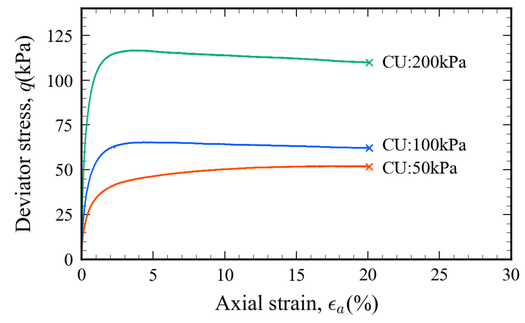
The test specimen tends to be contracted, with particle crushing of pumice.

三軸圧縮試験

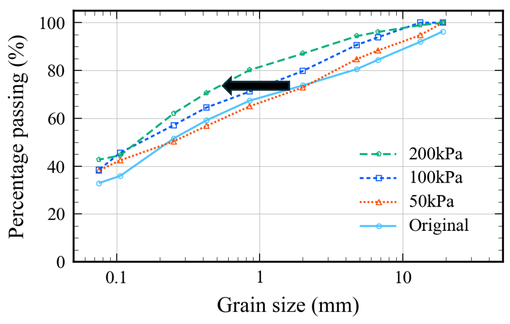
不攪乱白色軽石を試料として用いて、CU試験を行い、試験前後の粒度分布の変化を調べた。
Aseries of CU test was conducted on undisturbed white pumice, and the changes in grain size distribution before and after the test were examined.



軸差応力-軸ひずみ関係



有効応力経路



試験前後の粒径加積曲線

三軸圧縮試験では、圧密およびせん断時に粒子破砕ならびにコントラクタンシーを伴い、限界状態に至る挙動が見られた。
In the triaxial compression test, behavior leading to the critical state was observed, accompanied by particle crushing and contractancy during consolidation and shearing.

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Triaxial compression behaviour of undisturbed and re-constituted volcanic pumice soil taken from Dozo-zawa river

ドゾウ沢火山性軽石の不攪乱・再構成供試体の三軸圧縮挙動

The Iwate-Miyagi Nairiku Earthquake (M7.2) that occurred on June 14, 2008 caused a slope failure in Dozo-zawa River near the summit of Mt. Kurikoma. The debris flow caused by the slope failure flowed for about 10 km and took the lives of 7 people. The mechanisms of the slope failure and long-distance debris flow have not yet been well understood. In this study, undisturbed and re-constituted specimens were prepared using brown pumice soil collected from the collapsed area. Shear behavior and particle breakage were investigated by performing a series of triaxial compression tests.

2008年6月14日に発生した岩手・宮城内陸地震(M7.2)によって栗駒山の山頂付近で大規模な斜面崩壊が起こりました。斜面崩壊に起因する土石流がドゾウ沢を約10kmに渡って流下して死者7名という大きな被害をもたらしたものの、斜面崩壊や長距離流動のメカニズムは未だ解明されていません。本研究では、崩壊地で採取した褐色軽石を用いて不攪乱・再構成供試体を作成し、圧密排水/非排水三軸圧縮試験(CD/CU試験)を行って起因層となった土のせん断挙動と粒子破砕について考察しました。

1. Overview of Dozo-zawa river collapsed area ドゾウ沢崩壊地の概要



現場の写真(2020年10月撮影)



現場の断面図(上)
現場の土の様子(下)

採取土(褐色軽石)の物理特性

含水比 ω_n (%)	湿潤密度 ρ_t (g/cm^3)	乾燥密度 ρ_d (g/cm^3)	土粒子密度 ρ_s (g/cm^3)	間隙比 e
62	1.52	0.93	2.66	1.84

2. Preparation of undisturbed / re-constituted specimens 不攪乱・再構成供試体の作成

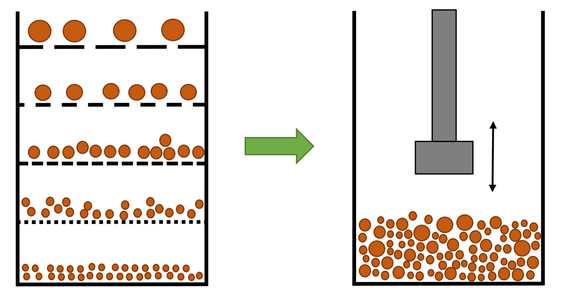
Undisturbed 不攪乱



塩ビ管を用いて採取した乱れの少ない円柱状の試料をそのままペデスタルにセット

Low-disturbance samples collected using PVC tubing are set directly on the pedestal

Re-constituted 再構成



自然乾燥状態で粒子をふるい分け

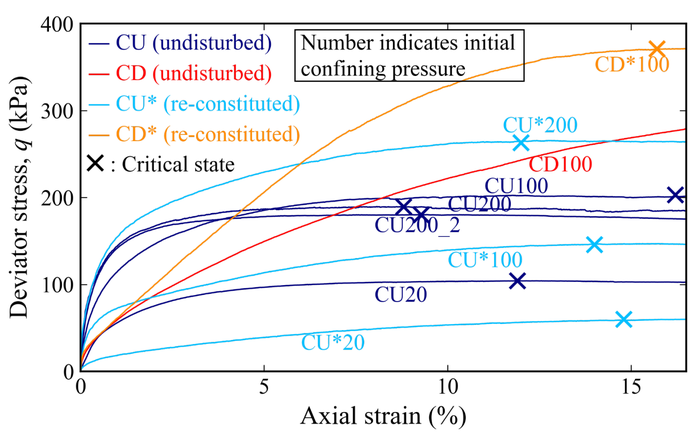
Sieve in natural dry state

原位置と同等の粒度分布・間隙比になるようモールドに詰める

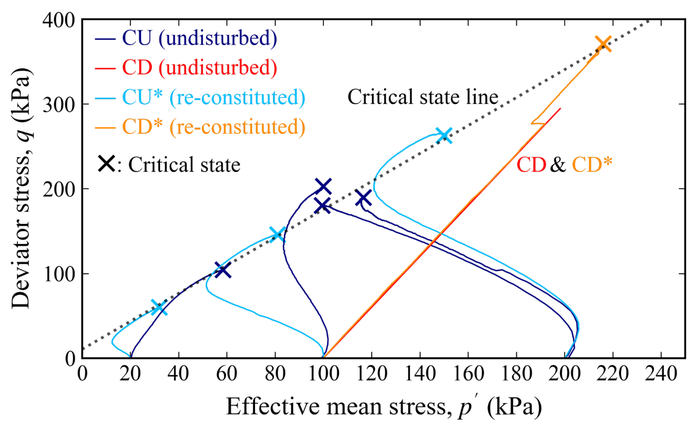
Fill into mold to the same PSD and void ratio as the in-situ condition

3. Results of triaxial compression test 三軸圧縮試験の結果

a)

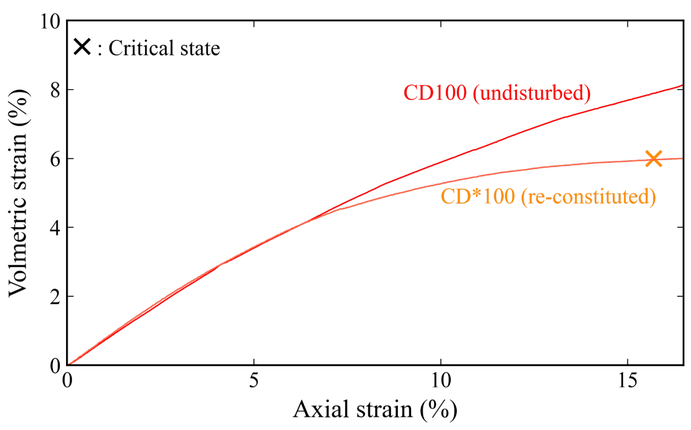


b)

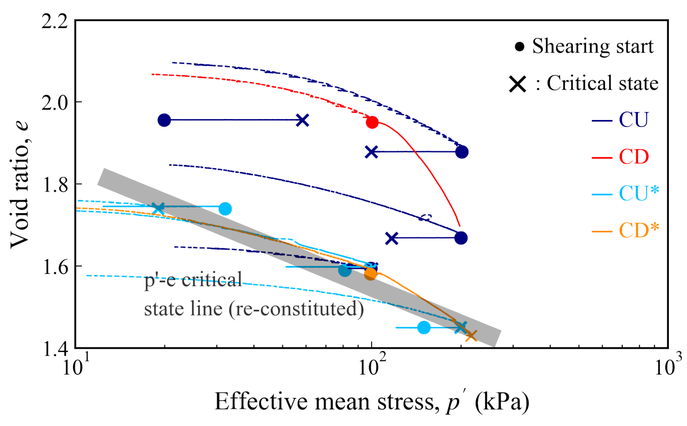


- ✓ In the CU tests, both undisturbed and re-constituted reached steady-state (axial strain increases with no stress state change).
- ✓ CU試験では、不攪乱・再構成ともに限界状態(応力状態が変化せず軸ひずみが増加)に至った。
- ✓ Undisturbed samples, especially in the case of 200 kPa of confining pressure, showed strong contractancy.
- ✓ 不攪乱では特に拘束圧200kPaのケースで強い収縮性を示して限界状態へ至った。

c)

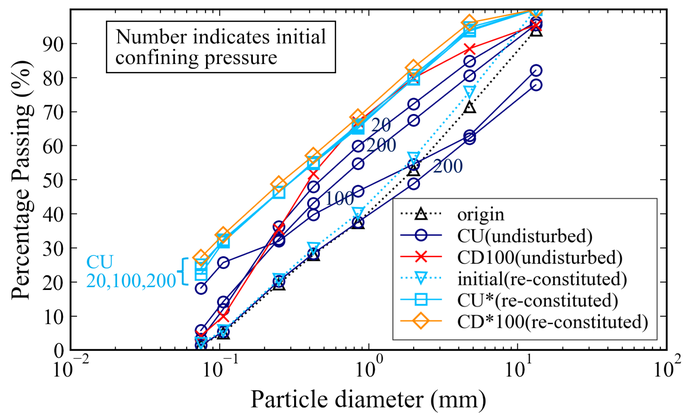


d)



- ✓ Both undisturbed and re-constituted samples showed strong tendency to contract. Stronger contract tendency for undisturbed.
- ✓ 不攪乱・再構成ともに強い収縮傾向。不攪乱の方がより強い収縮傾向を示し、体積一定に至らなかった。
- ✓ In all tests, undisturbed samples had a larger void ratio than re-constituted samples at the same p'.
- ✓ 全ての試験において、不攪乱の方が再構成よりも同じ平均有効応力で間隙比が大きくなった(圧密段階で緩い構造が保持された)。

4. Particle size distribution 試験前後の粒度分布



- ✓ In re-constituted cases, significant particle breakage occurred.
- ✓ No relationship between p' and amount of particle breakage.
- ✓ 再構成のケースでは顕著な粒子破砕が生じた。
- ✓ 拘束圧と破砕量の間に関連性は見られなかった。

5. Conclusions まとめ

- ✓ In all cases except CD100, steady-state was reached.
- ✓ CD100を除く全ケースで限界状態に至った。
- ✓ Undisturbed samples retained their initial structure during consolidation compared to re-constituted samples, and those with greater confining pressure showed stronger contractancy during shearing.
- ✓ 不攪乱試料では、再構成試料よりも圧密時に初期構造が保持され、拘束圧が大きいものほどせん断時に強いコントラクタンシーが見られた。
- ✓ In re-constituted cases, significant particle breakage occurred. No notable relationship was observed between confining pressure and the amount of particle breakage.
- ✓ 再構成のケースでは著しい粒子破砕が生じた。破砕量と拘束圧に顕著な関係性は確認できなかった。

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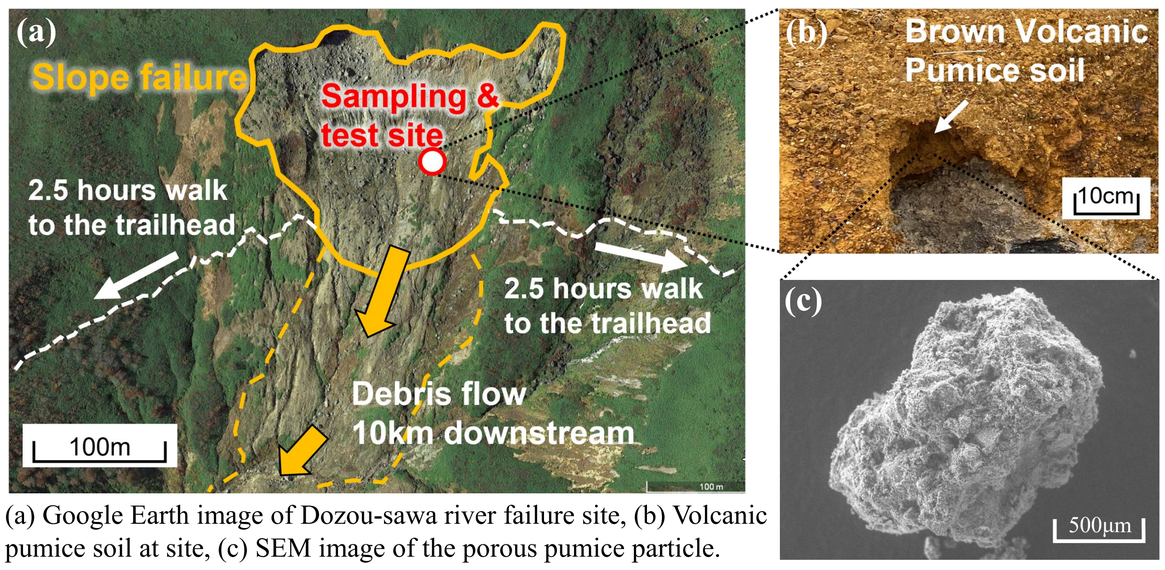
Development of in-situ direct shear test apparatus and its application to Dozou-sawa pumice soil

原位置一面せん断試験装置の開発とドゾウ沢軽石への適用

Volcanic pumice soils are widely distributed in Japan, causing slope disasters. They are susceptible to disturbance during soil sampling, transport, and trimming, so it is desirable to conduct in-situ tests while retaining the soil structure. In addition, when aiming at mountain slopes where vehicles cannot enter, the test apparatus must be transported by hand. In this study, a lightweight and small in-situ direct shear test apparatus was newly developed, and in-situ direct shear tests were conducted on a pumice soil in Dozou-sawa river. Laboratory direct shear tests were also conducted on the same soil to verify the validity of the apparatus.

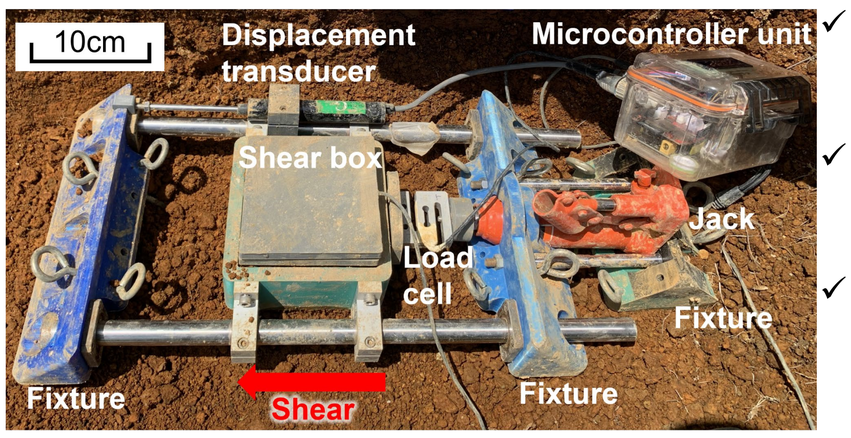
日本には火山性軽石地盤が広く分布し、斜面災害を引き起こしている。軽石地盤は多孔質粒子が緩い構造を保持しており、土の採取や運搬、トリミング時の乱れの影響を受けやすく、原位置で土粒子構造を保持したまま試験を行うことが望ましい。また、車両が入れない山間部の斜面をターゲットとする場合、人力で試験装置を運搬する必要がある。本研究では、軽量・小型の原位置一面せん断試験装置を開発し、岩手宮城内陸地震で大規模な崩壊と流動が発生したドゾウ沢の軽石地盤を対象に原位置一面せん断試験を行った。さらに、同じ試料で室内一面せん断試験を行って装置の有効性を検証した。

1. Dozou-sawa river & its pumice soil



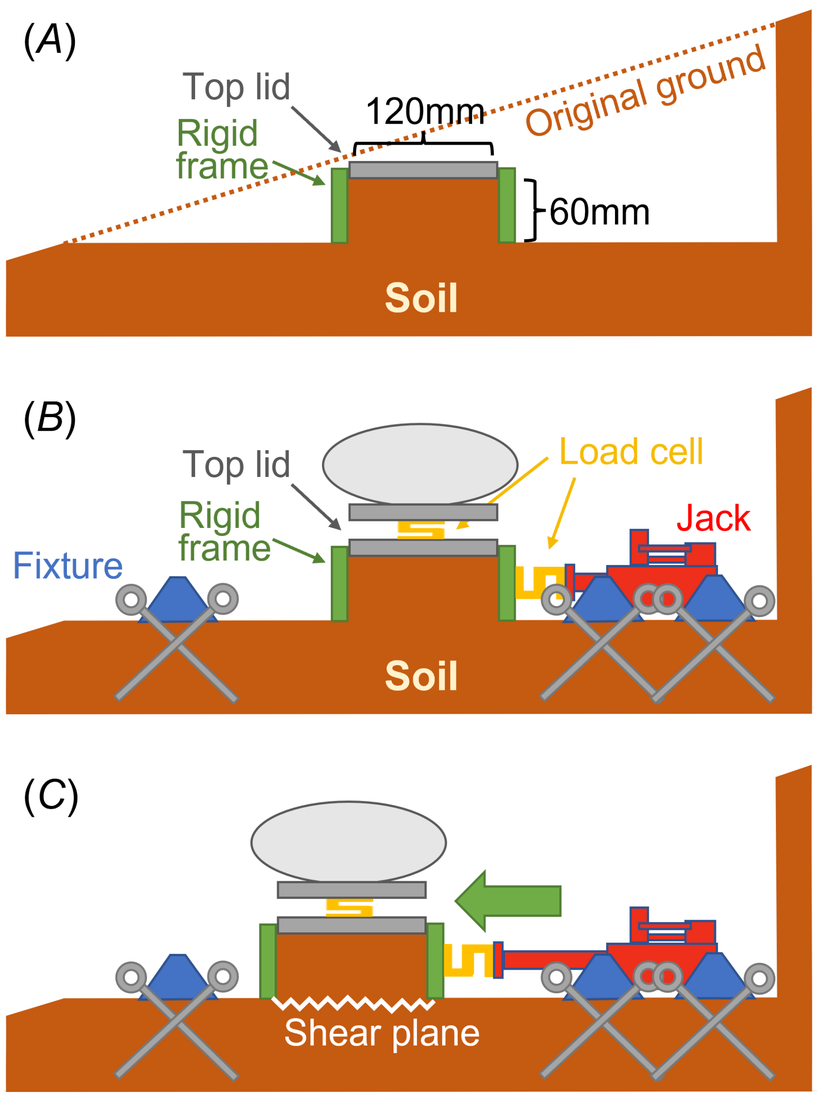
(a) Google Earth image of Dozou-sawa river failure site, (b) Volcanic pumice soil at site, (c) SEM image of the porous pumice particle.

2. In-situ direct shear test apparatus



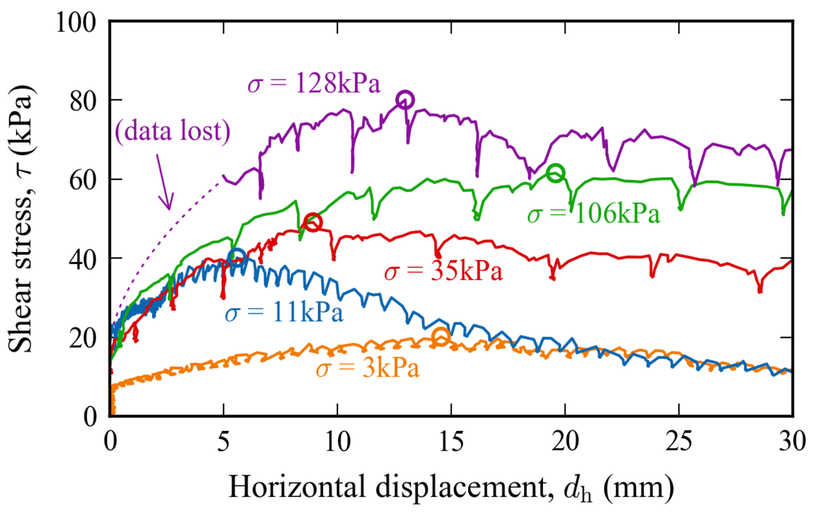
- ✓ About 5 kg in total. (the fixtures, frame & lid were 3D printed.)
- ✓ Maximum allowable vertical load (σ) was 140 kPa.
- ✓ The microcontroller enables data acquisition at a sampling rate of 10 Hz.

3. Procedure of in-situ direct shear tests



1. Excavate the slope horizontally, while preserving the specimen.
2. Place the frame and lid over the specimen.
3. Install fixtures, load cells & displacement transducers.
4. Apply a vertical load by stones or human weight.
5. Start recoding data.
6. Shear the specimen by jacking up.

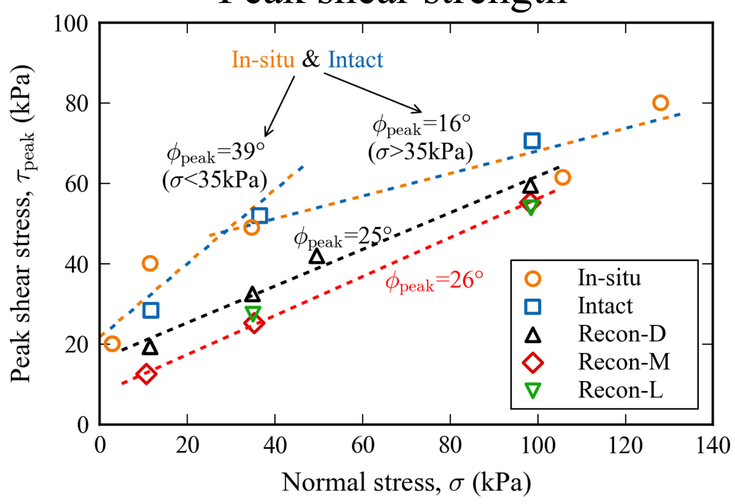
4. Results of in-situ direct shear tests



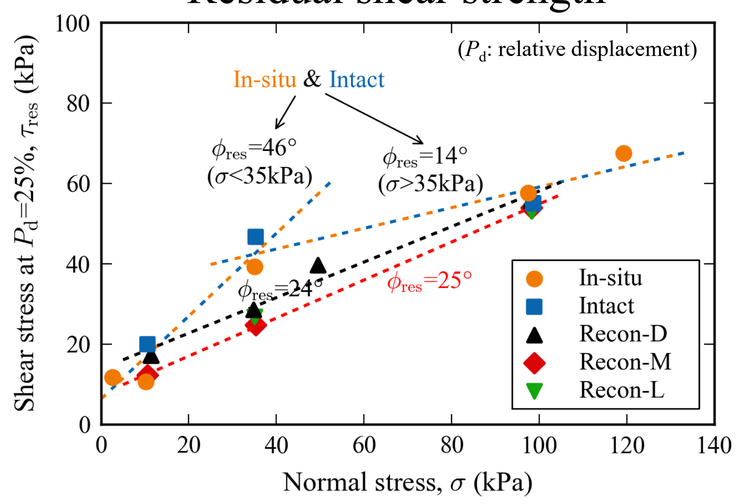
- ✓ Peak strength was observed at a horizontal displacement (d_h) of about 10 mm, followed by strain softening.
- ✓ The strain softening seemed to be due to the breakdown of the in-situ soil structure by shearing.

5. Comparison between laboratory direct shear tests

Peak shear strength



Residual shear strength



- ✓ In-situ direct shear tests and laboratory direct shear tests with intact specimens showed higher shear strength than the laboratory direct shear tests with reconstituted specimens, especially at lower confining pressures.
- ✓ In-situ tests and laboratory tests with intact specimens showed consistent shear strength, indicating that in-situ direct shear test apparatus could validly evaluate the shear strength of the pumice soil.

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Suction of Several Granular Materials and Its Contribution to Arching

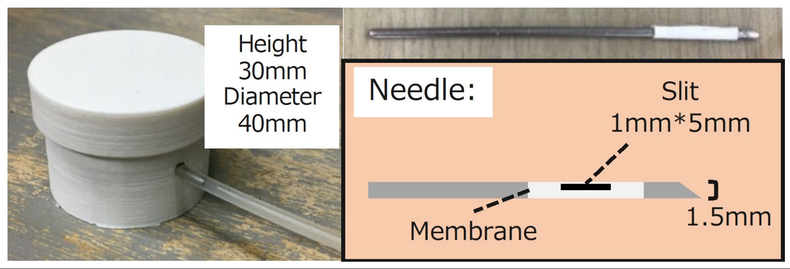
様々な粒子のサクション及びその空洞保持への寄与

Suction between particles plays an important role in the stability of ground. Previous studies mainly focus on small size particles. Suction between larger size particles (>0.2mm) has not been well investigated. In this research, using a simple suction measuring device, small suction of larger particles, which size is categorized as sand, was measured. Effect of several factors on suction was analyzed in microscopic perspective. Then, contribution of suction to the stability of cavity in sandy ground was investigated by a series of simple model tests.

地盤内の粒子間に働くサクションは、地盤の安定性を考える上で重要な役割を果たします。一方、既往のサクションの検討は粘性土から細砂の粒径まで（<0.2mm）が主であり、それ以上の粒径における検討は進んでいません。本研究では、簡易サクション計測装置を作成し、砂の粒径範囲における微小なサクションを計測するとともに、諸因子がサクションに与える影響を微視的観点から考察しました。また、この計測結果に基づき、砂質地盤内の空洞保持におけるサクションの寄与について、簡易的な土層試験をもとに確かめました。

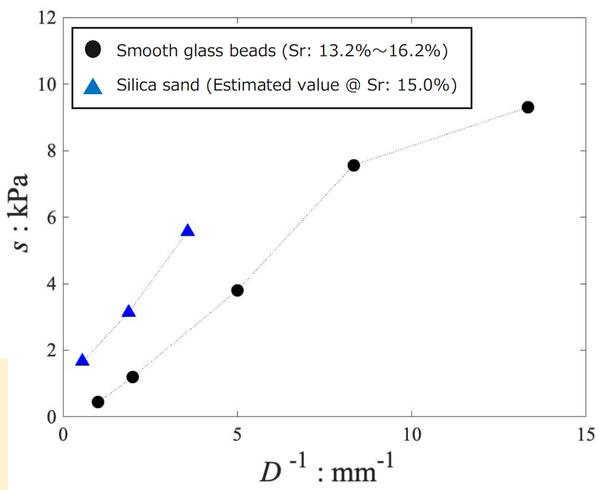
Suction measurement（サクション計測）

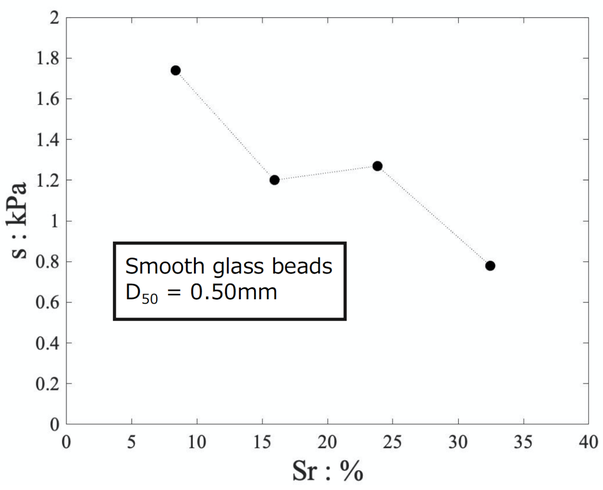
Simple suction measuring device（簡易サクション計測装置）



✓ Capable of measuring small suction between 0.1 kPa to 20 kPa

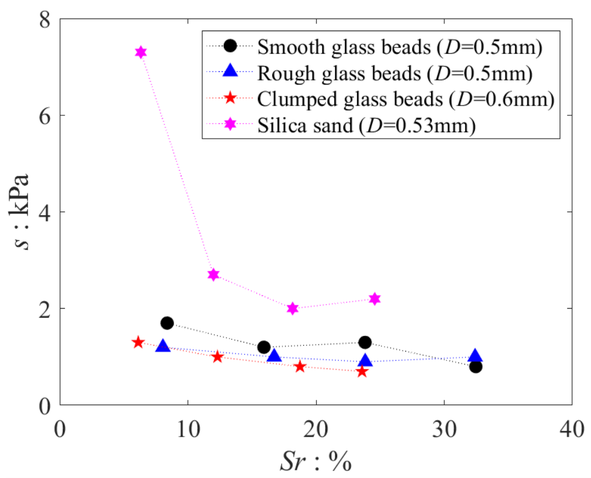
Size & Degree of saturation (Sr)



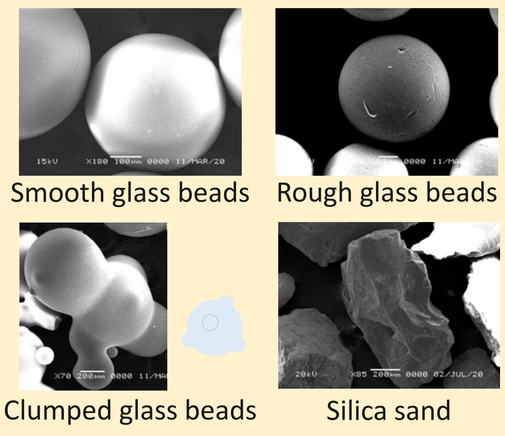


✓Smaller particle size / Lower Sr causes larger suction
✓Inverse of particle size (D^{-1}) and suction have a strong liner relationship
✓Particle size is more dominant

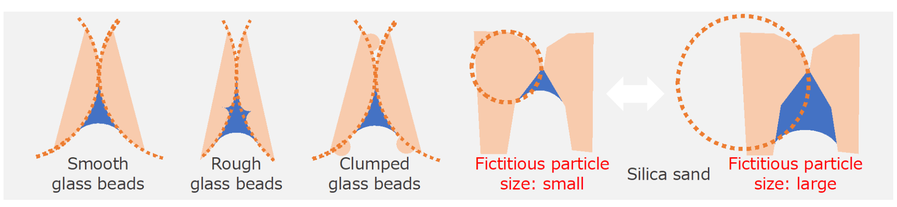
Shape & Roughness



< SEM image >

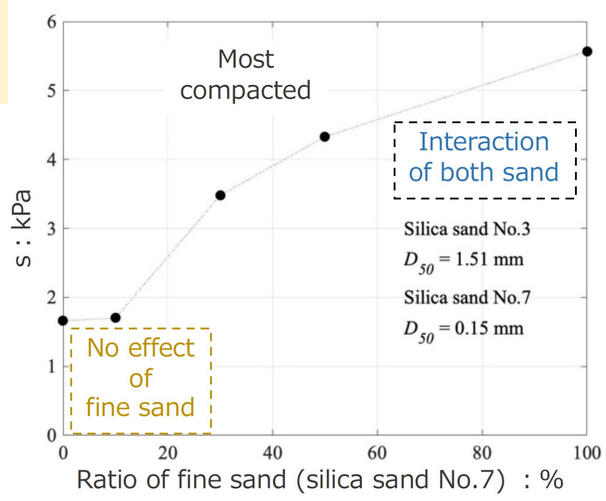


✓ Little difference between smooth glass beads, rough glass beads and clumped glass beads
✓ In silica sand case, suction is stronger when Sr is low
✓ These can be interpreted based on fictitious particle size（見かけの粒径）

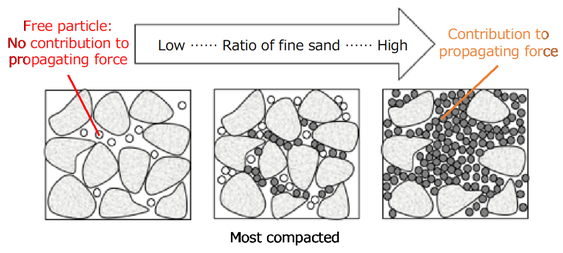


Fictitious particle size（見かけの粒径）

Gap-graded soil (Silica sand No.3 / Silica sand No.7)



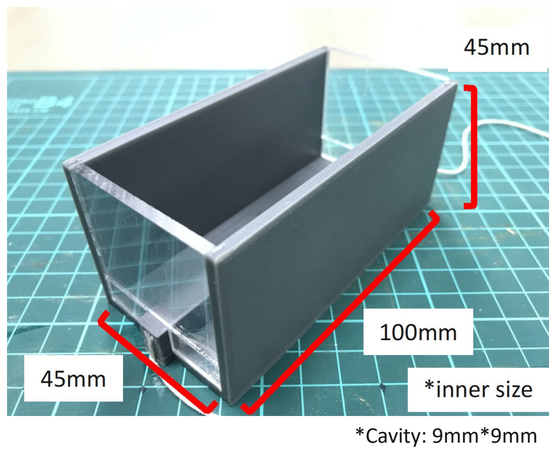
✓Suction increases as ratio of fine sand gets higher
✓Fine sand does not affect suction when ratio of fine sand is low
✓Free particle（自由粒子）, which does not propagate force, may not affect on suction



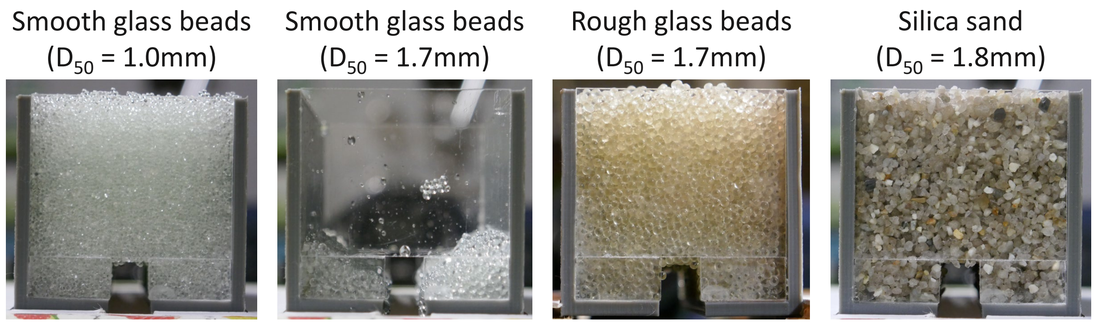
Free particle（自由粒子）

Simple model test（簡易土層試験）

Small simple model（小型簡易土層）



*Cavity: 9mm*9mm



✓ All suction, roughness and shape contribute to the stability of cavity
✓ Not only suction but also other mechanical properties (friction, interlocking, etc.) seem to be related with the formation of arching

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Arch around a cavity in sandy ground based on penetration resistance

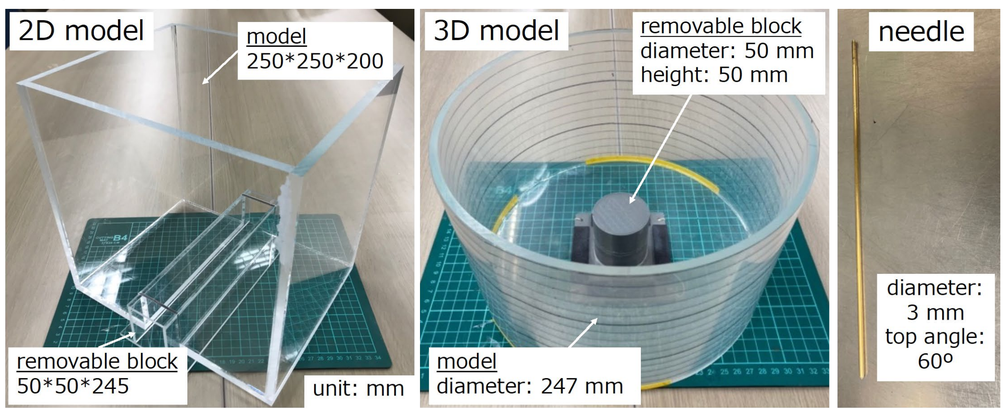
砂質地盤内空洞周辺に生じるアーチングの貫入抵抗に基づく考察

Recently, many cave-in cases have been reported in sandy ground. A cave-in happens when soil above an underground cavity cannot be retained. Arch action formed above/around a cavity is highly related with the stability of cavity. This arch has been analyzed based on strain which can be observed in a trapdoor test. In this research, a series of needle penetration tests was conducted on the sandy model ground with a cavity and arch around a cavity was evaluated based on stress distribution.

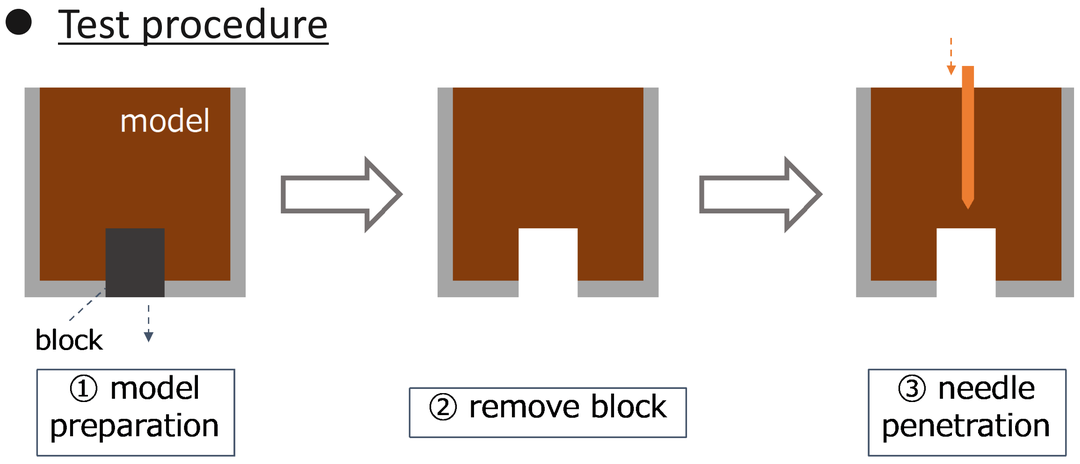
近年各地の砂質地盤で発生する地盤陥没は，地盤内に生じた空洞によってその上部の土塊が支持できなくなることで発生するため，地盤内空洞の安定性が地盤陥没の発生を左右します．地盤内空洞の安定性には空洞周辺に形成されるアーチが重要な役割を果たしますが，そのアーチに関しては主に落とし戸実験から観察されるひずみをもとに考察されてきました．そこで本研究では，砂質地盤を対象に，地盤内に空洞を生成した模型地盤に対し針貫入試験を実施することで，貫入抵抗をもとにアーチングに関する考察を行いました．

Apparatus

- Simple cavity model（小型空洞模型）

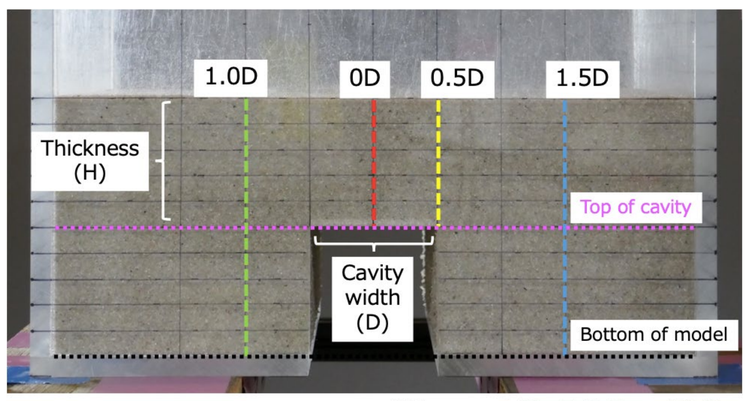


- Test procedure

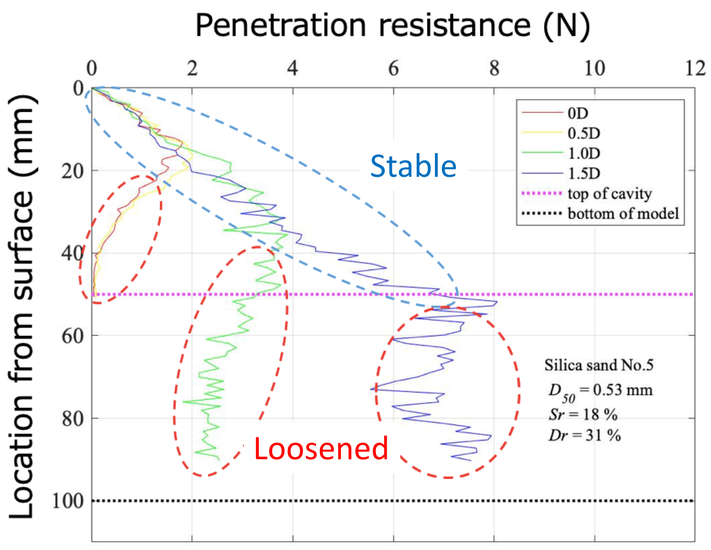


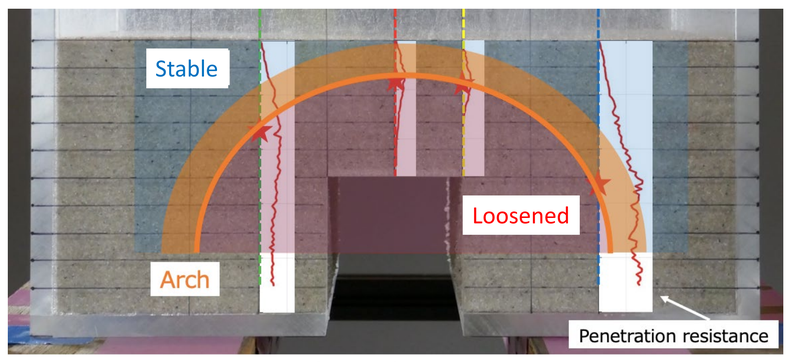
Shape of arch

- Typical shape of arch

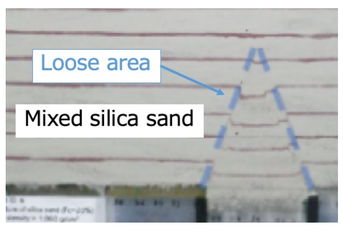


Silica sand No.5 @*Sr* = 18 %





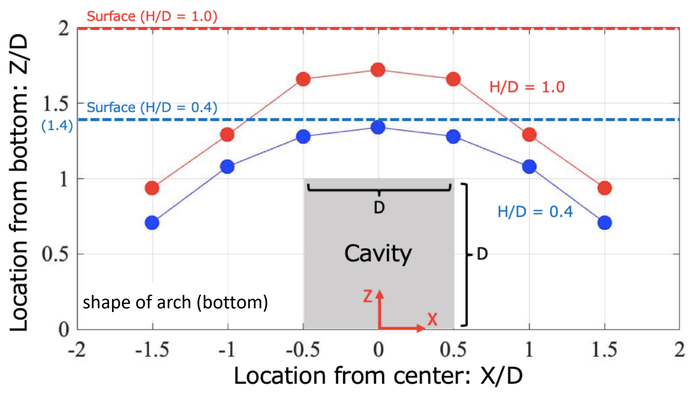
based on penetration resistance



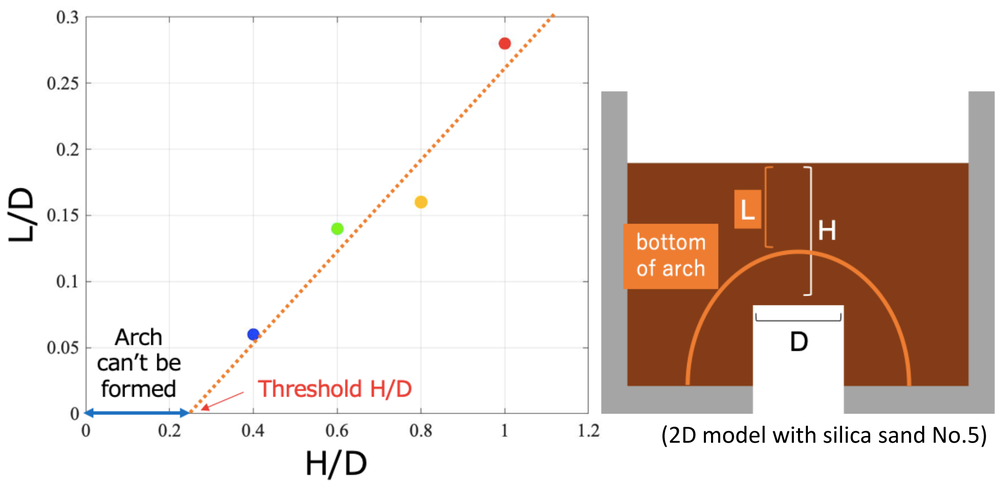
based on strain distribution

- Border between stable area and loosened area indicates shape of arch
- Arch based on penetration resistance is flatter than that indicated in loose area in trapdoor test

Effect of cover soil thickness

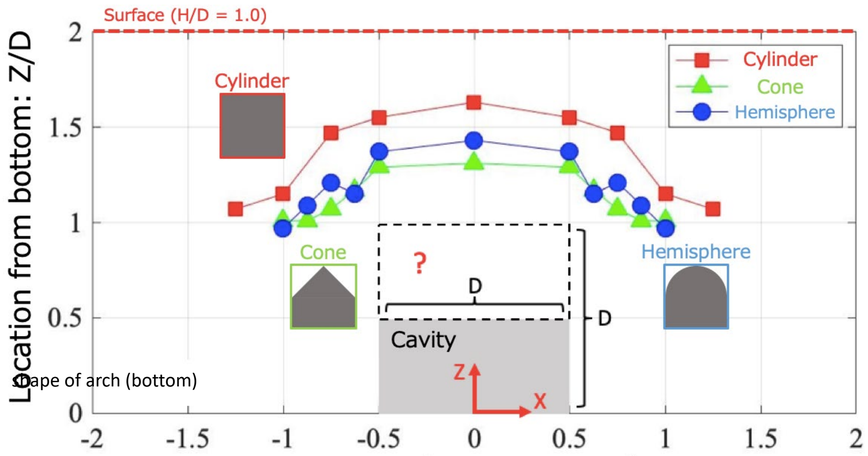


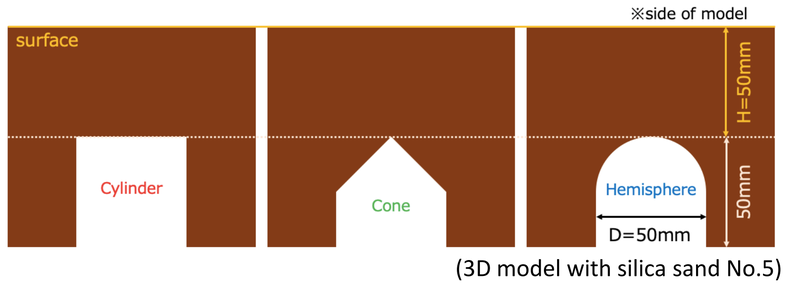
- Lower H/D causes lower L/D
- Arch can't be formed with small H/D



(2D model with silica sand No.5)

Effect of cavity shape





(3D model with silica sand No.5)

- When cavity is cylinder shape, arch is larger compared with cone or hemisphere shape

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TRAPDOOR TESTS FOR THE EVALUATION OF EARTH PRESSURE ON BURIED STRUCTURE

盛土内埋設構造物の作用土圧の評価のための移動床実験

Earth pressures acting on underground structures are highly dependent on the interaction between ground and structure. Increase in the vertical earth pressures acting on a buried structure in high embankment should be, therefore, considered, depending on the size and depth of structure and type of foundation, since differential settlements are often expected in such conditions. However, in practice, the increment of vertical earth pressures on underground structures is estimated in the empirical manner, mainly based on the information of past earth pressure measurements in the limited number of sites. In such estimation, the degree of settlement and/or mechanical properties of backfill materials are not always taken into account.

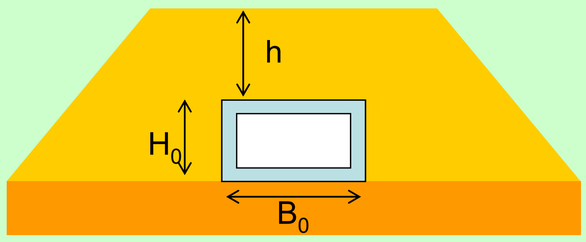
In this study, a trap door test apparatus was developed to evaluate the change in earth pressures acting on a buried structure in an embankment due to differential settlements. Base of a soil chamber consists of five separated blocks, any combination of those can move downward, in order to simulate the uneven settlement.

盛土内に埋設されたカルバートなどの構造物に作用する鉛直土圧は、周辺地盤の沈下が予想される場合は、埋設構造物の規模、土かぶり、基礎の支持条件等に応じて増分を見込む必要があります。しかしながら、鉛直土圧増分の目安については、過去の限られた実績等の経験値に頼っているのが実情で、近年の多様な盛土・埋設状況に合理的に対応できるとは言いがたいところがあります。

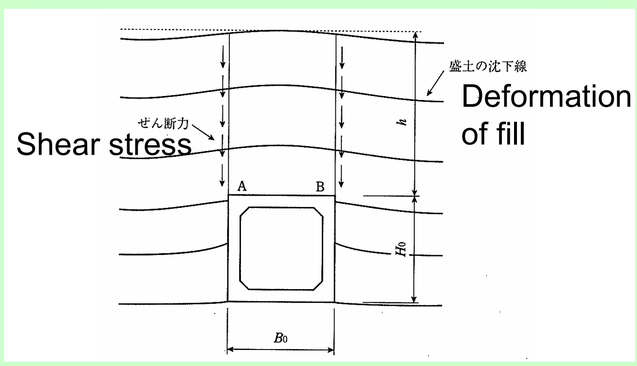
本研究では、盛土の沈下に伴う埋設模型への作用土圧の変化を調べる基礎的検討として、任意の分割底版を昇降できる移動床土槽を製作し、移動・固定床への作用土圧分布を詳細に計測すると共に、その簡易算定手法を提案しました。

盛土の沈下と埋設構造物を想定した移動床実験

Trapdoor test for simulating settlement of embankment and a buried structure



盛土の沈下に伴う埋設構造物の作用土圧の変化を、中央床を固定し両側の床を降下させた移動床実験で計測します。



Vertical earth pressure increases as the filling material settles, caused by downward shear forces.

道路土工指針による鉛直土圧増分の目安

$p=\alpha\gamma h$

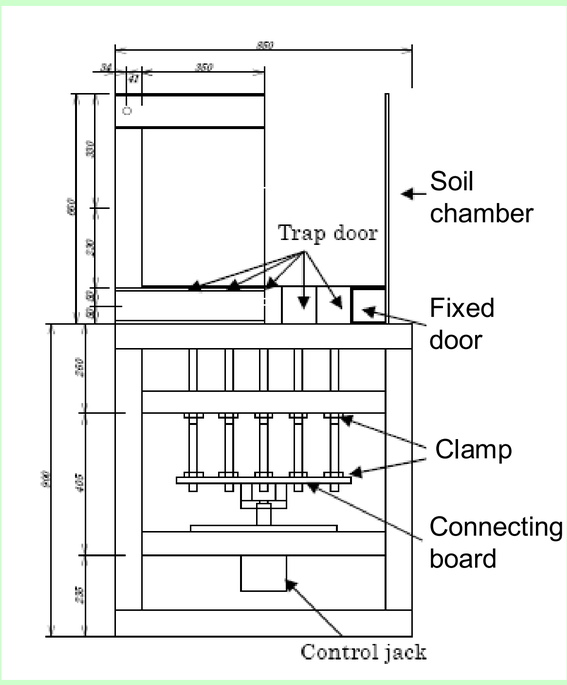
α depends on the width of box, B_0, and burial depth, h

h/B_0	鉛直土圧係数 Vertical earth pressure coefficient
$h/B_0<1$	1.0
$1 \leqq h/B_0<2$	1.2
$2 \leqq h/B_0<3$	1.35
$3 \leqq h/B_0<4$	1.5
$4 \leqq h/B_0$	1.6

移動床実験土槽

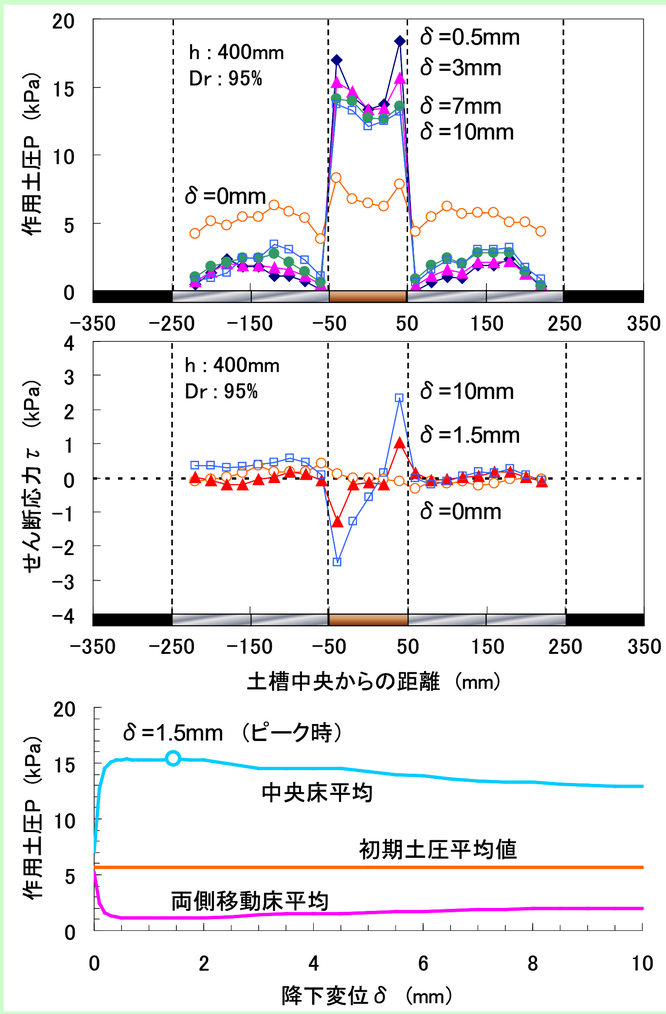
Trapdoor testing chamber





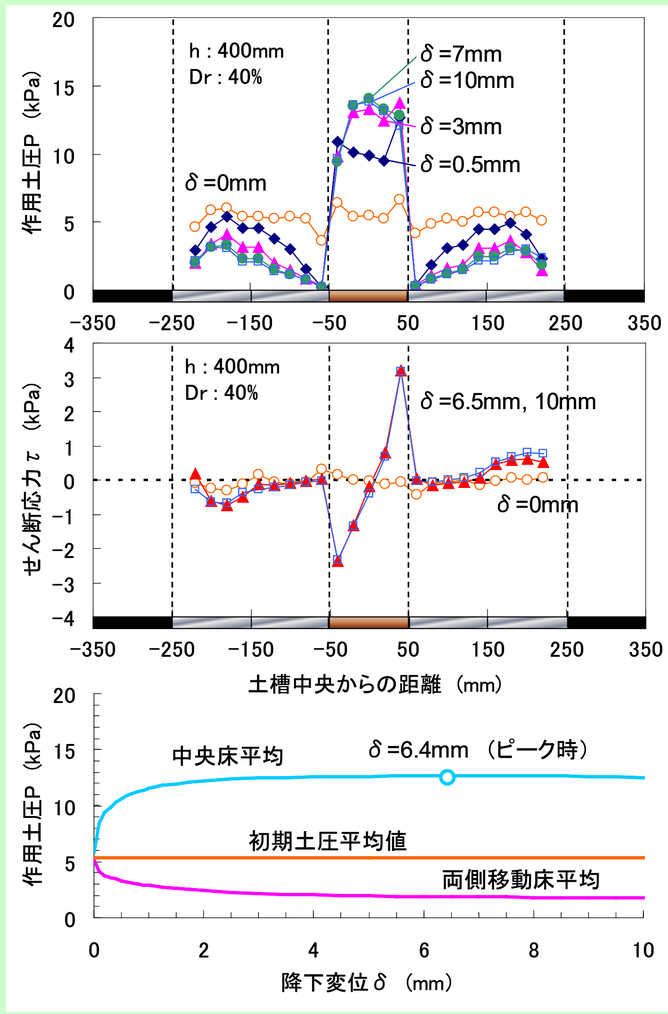
移動床の降下と作用土圧の変化

Displacement of trapdoor and change of earth pressure



密詰地盤（豊浦砂）

Densely compacted Toyoura sand ground

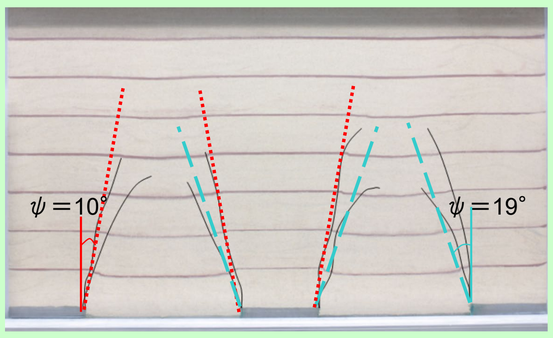


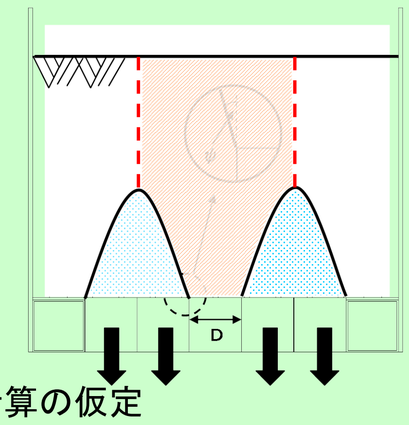
ゆる詰地盤（豊浦砂）

Loosely compacted Toyoura sand ground

作用土圧の簡易計算

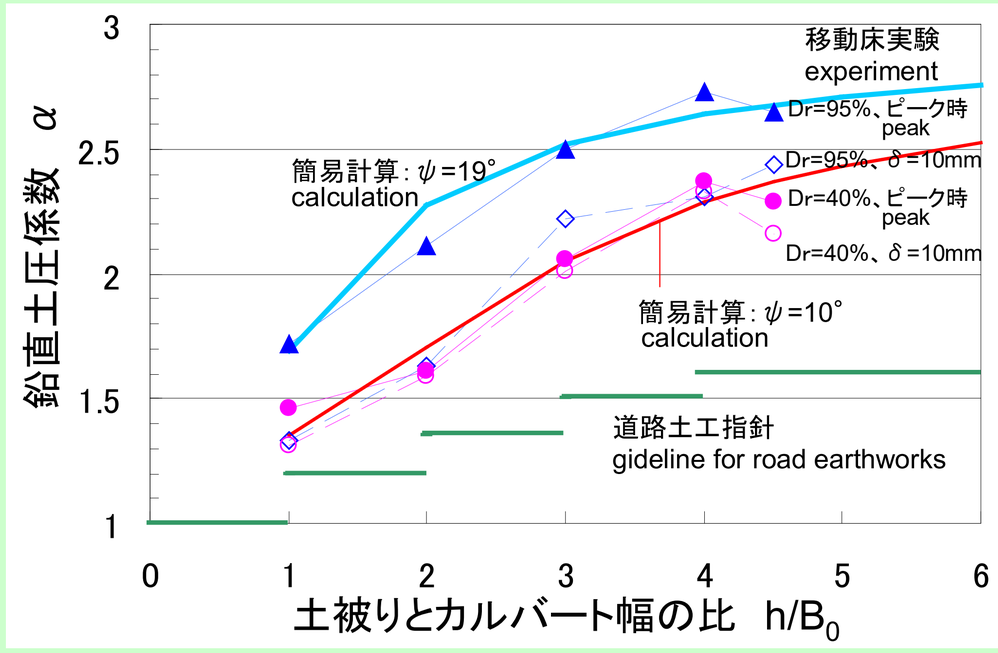
Estimation of earth pressure





実験で観察されたすべり線と簡易計算の仮定

Shear plane observed in experiment and assumption in calculation



鉛直土圧係数の比較

Comparison of vertical earth pressure coefficient

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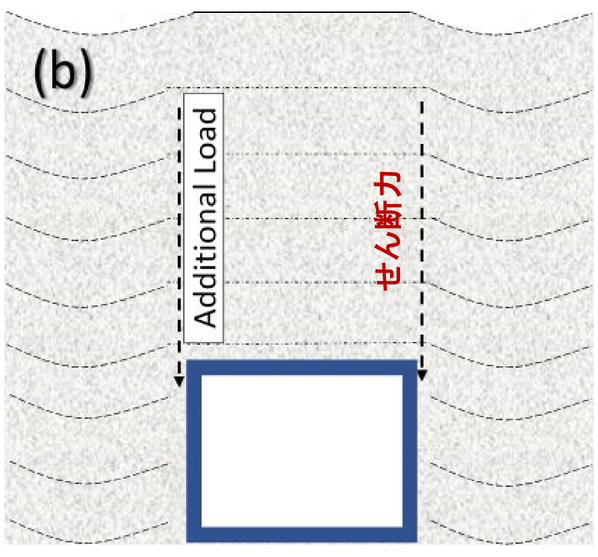
海老塚裕明(2010)

Arching in Trapdoor Model Test & Equivalent DEM Simulations

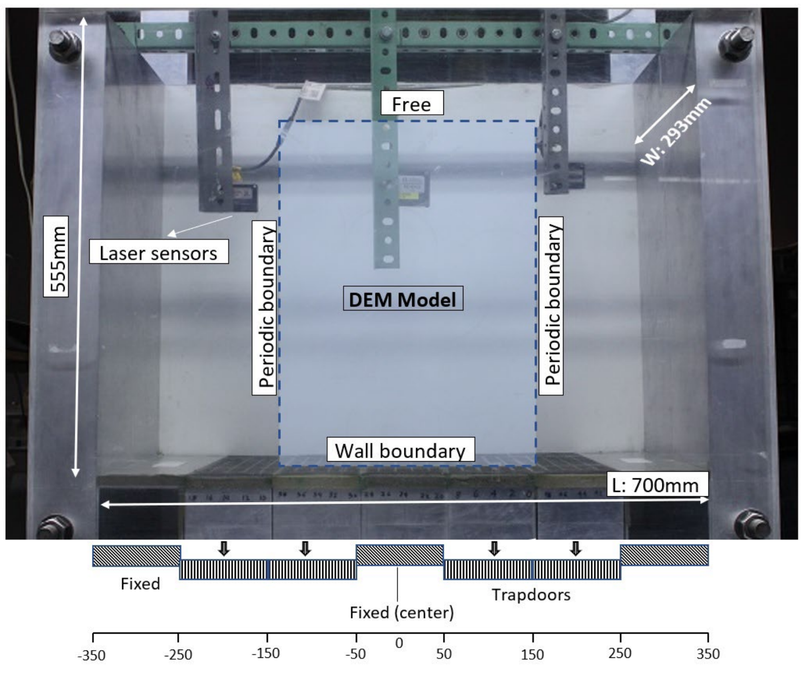
アーチ効果に関する落し戸実験＆個別要素法解析

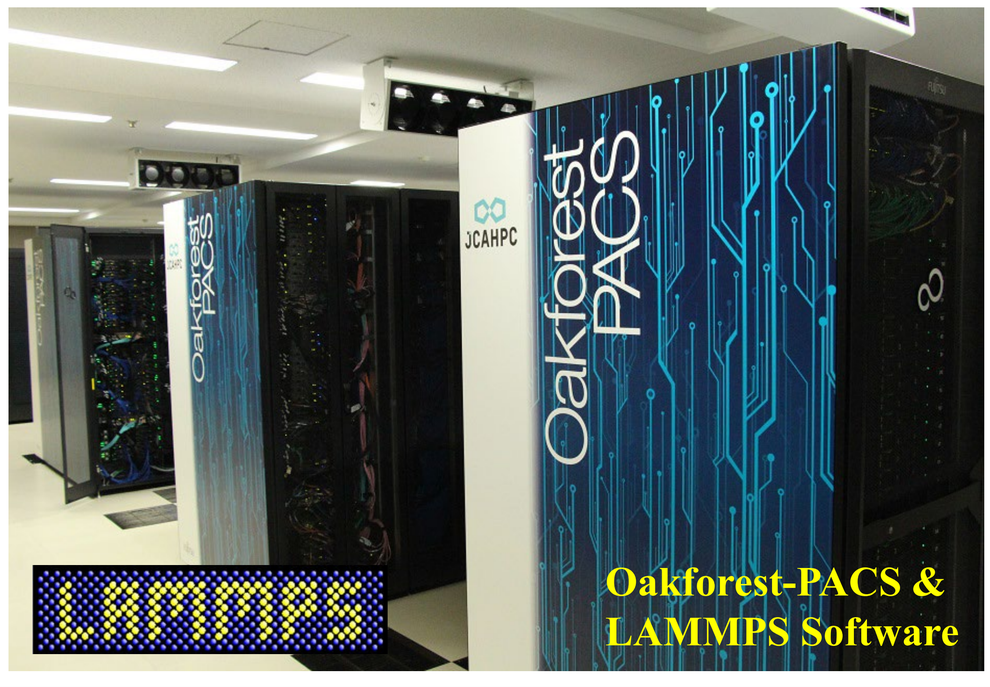
Complex interactions between soil and buried structures have been investigated in this study. A trapdoor test apparatus was used to represent deferential settlement at the base, using Toyoura sand, Kashima river sand and spherical glass beads. Model grounds with different height (H) were prepared, and the side bottom plates were moved downwards to investigate the arch formation. Equivalent numerical simulations using discrete element method (DEM) were performed, and DEM results matched closely with the experimental results. Arching phenomenon was observed with larger ground height for a given width of the lowered plate.

土と埋設構造物の複雑な相互作用に関する理解を深めるため、不同沈下現象を再現する模型実験装置内にガラスビーズ材料地盤を作成し、落し戸実験を実施しました。様々な地盤高（H）に対し，中央部以外の底板を下方に変位させることでアーチ効果の発現について分析しました．球体粒子で構成される地盤をモデル化し，個別要素法（DEM）解析を実施した結果，実験結果と精度良く一致する結果を得ました．特に地盤高の高い地盤において，顕著なアーチ効果が確認されました．



Increased load on buried structure due to settlement of surrounding soil



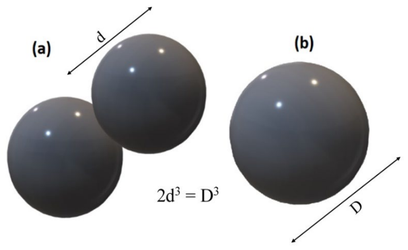


Model Test:
700 mm (X) : 293 mm (Y) : 100-400 mm (H)
Trapdoor width (B): 100 mm
Mean Particle size: 0.203mm (Toyoura)

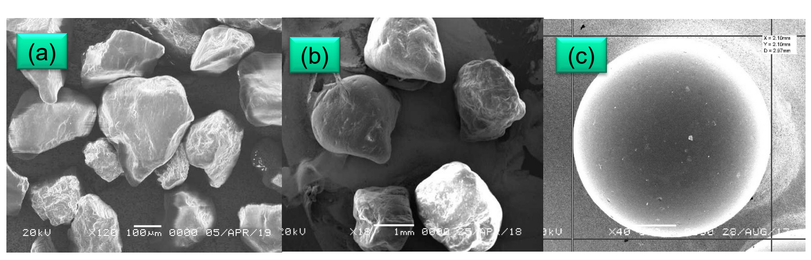
Mean Particle size: 1.72mm (river sand)
1.80mm (glass beads)

DEM Simulations:
300 mm (X) : 40 mm (Y) : 44-521 mm
Trapdoor width (B): 100 mm
Diameter of particle: 1.2 – 2.2 mm

Friction coefficient (μ): 0.35
Young's modulus: 71.6 GPa
Poisson's ratio: 0.23
Specific gravity: 2.5



Spherical and non spherical particles in DEM



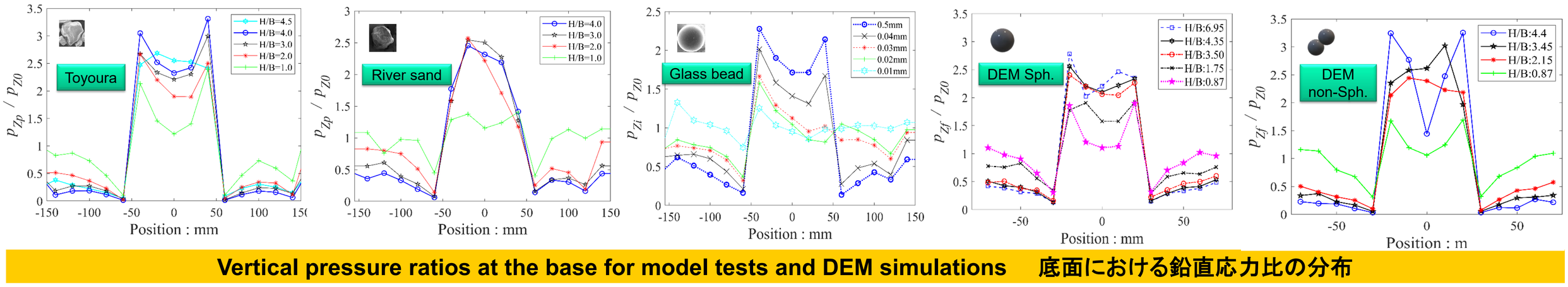
SEM images of (a) Toyoura sand (b) Kashima river sand (c) glass beads

Stress concentration ratio for buried structure

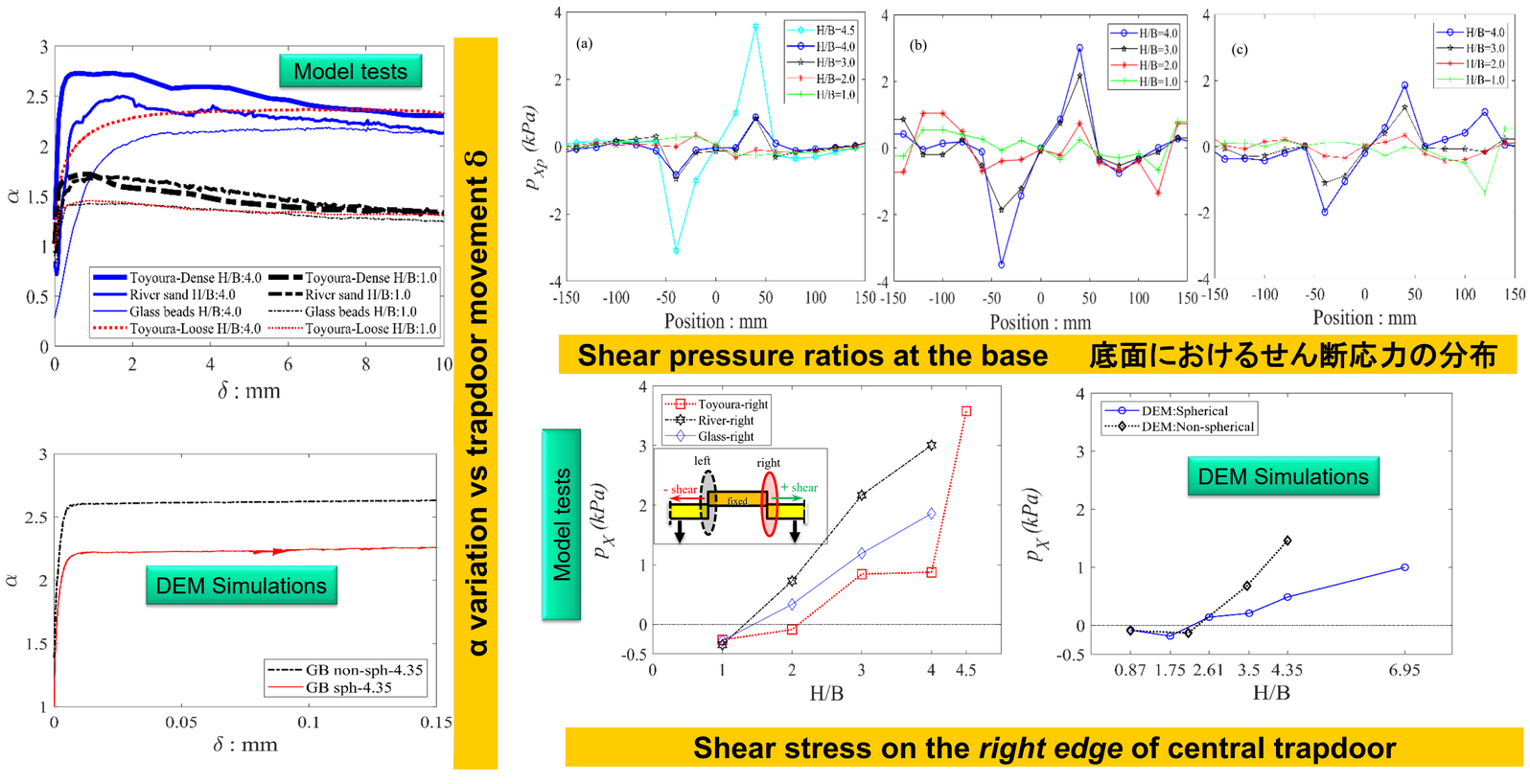
$$\alpha = \frac{P_z c}{P_z o}$$

地中構造物に対する応力集中度

$P_z c$ = Mean vertical pressure on the central plate 中央底板の応力
$P_z o$ = Mean vertical pressure on all the plates 全底板の応力

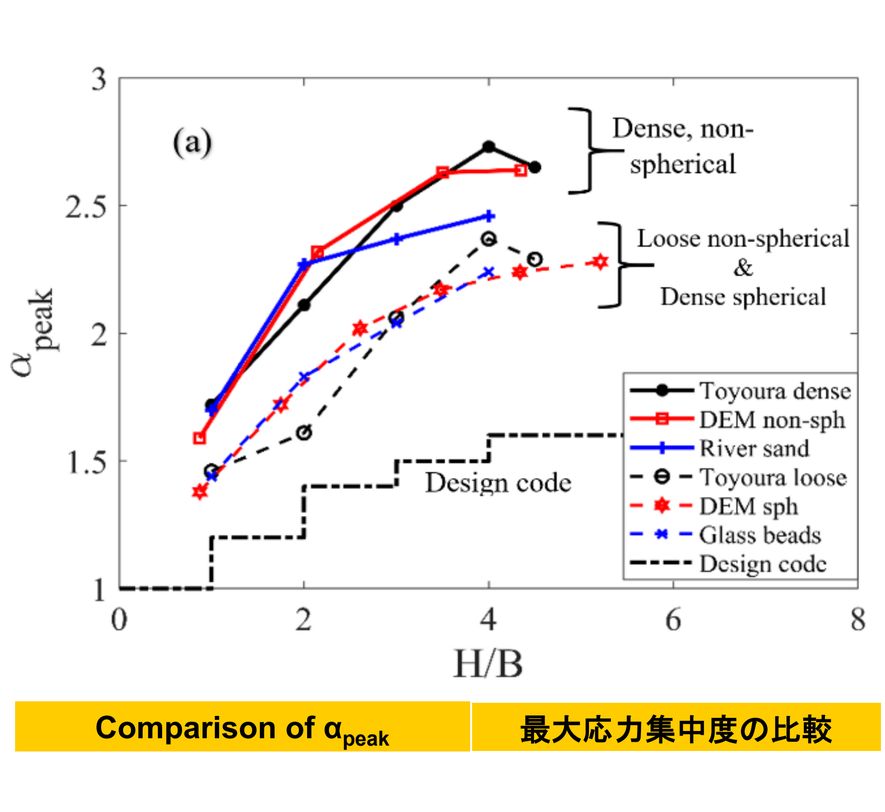


Vertical pressure ratios at the base for model tests and DEM simulations　底面における鉛直応力比の分布



Shear pressure ratios at the base　底面におけるせん断応力の分布

Shear stress on the *right edge* of central trapdoor



Comparison of α_{peak}　**最大応力集中度の比較**

本研究に関する担当研究室は桑野研究室です．
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Syed Umair
Ali Naqvi (2019)

EVALUATION OF STRESS DISTRIBUTION IN MODEL GROUND USING BENDER ELEMENTS

ベンダーエレメント法を用いた弾性波測定による模型地盤内応力の推定

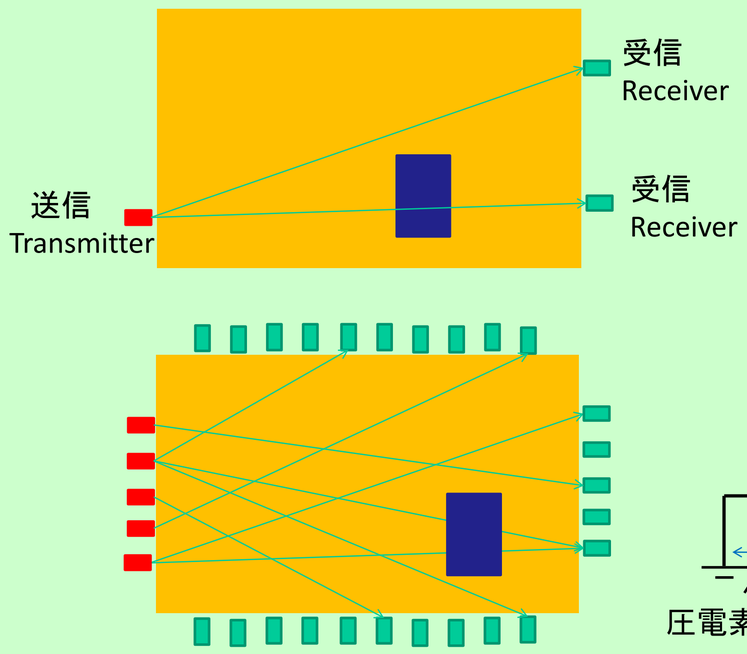
Elastic wave tomography using bender elements was conducted to evaluate stress distribution in a model ground. Bender element method has been widely applied in laboratory soil element testing such as triaxial test, oedmeter test, or direct shear test. When BEs are used in a model test, it was found that the signal processing was essential to obtain clearer waveforms as the amplitude of received signal was not large enough due to generally lower level of confining stress. The effects of chamber side wall should be also taken into account in the arrangement of the elements location.

In a densely compacted model ground in a trapdoor testing soil chamber, the distribution of stress in the ground was estimated using tomography technique and it agreed well with the results of physically measured stresses at the base and shear planes observed.

移動床土槽内でベンダーエレメントを用いた多点送信多点受信のせん断波測定を実施し、トモグラフィ解析を施すことにより内部の応力分布の推定を試みた。ベンダーエレメント法は要素試験装置内への適用は多く報告されている。模型実験に適用する際、一般に応力レベルが低いので受信信号が微弱でノイズの除去などの信号処理が不可欠である。また、素子の配置の仕方によっては土槽壁の拘束の影響を受けるので、配慮が必要であった。移動床実験時の模型地盤内の応力分布をせん断波速度測定のトモグラフィによる逆解析により推定したところ、密詰め地盤において、土槽底版分で測定した境界部の応力とせん断により生成するすべり面と矛盾しない結果が得られた。

弾性波トモグラフィを利用した内部構造の推定

Estimation of internal structure using elastic wave tomography

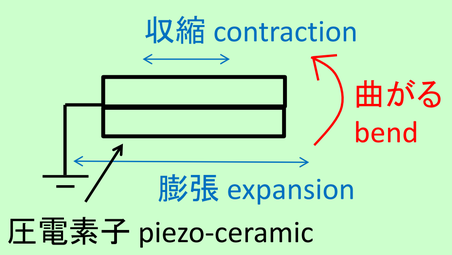


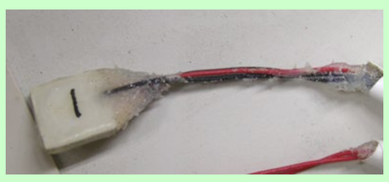
複数の送受信間の伝達時間を計測し，
逆解析により内部の速度分布を求める.

Shear wave velocities between multiple transmitters and receivers are measured. The distribution of wave velocities are then estimated using tomography analysis.

せん断波の送受信にベンダーエレメントを使用

Bender elements are used for the shear wave measurement.

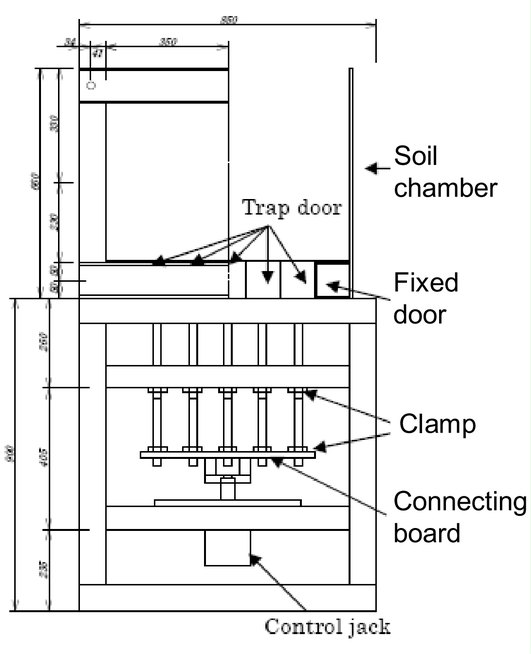




移動床実験土槽

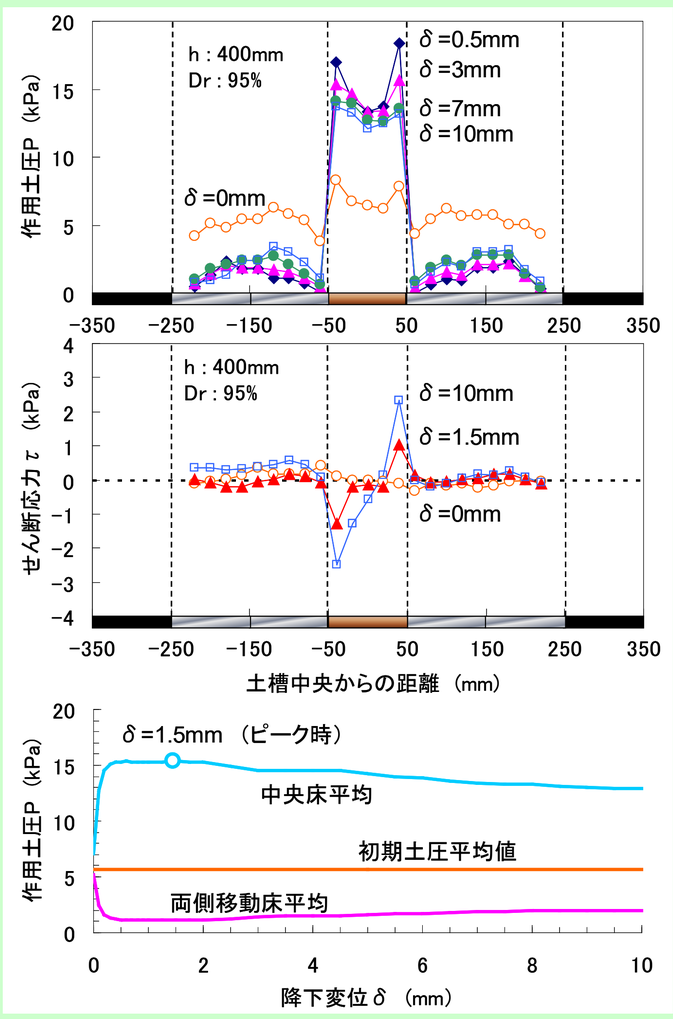
Trapdoor testing chamber





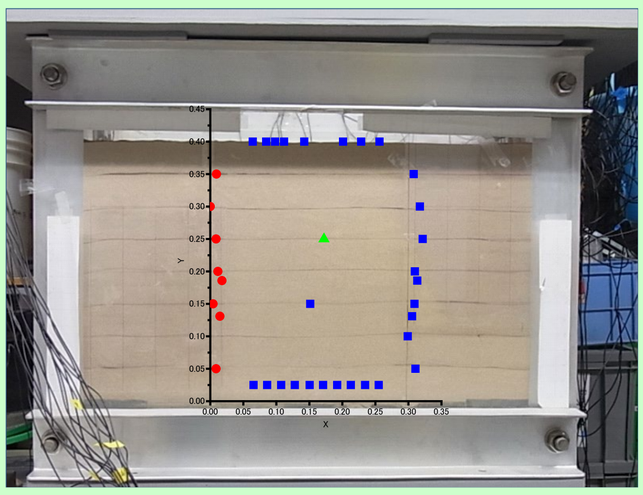
移動床実験における弾性波トモグラフィの適用

Application of elastic wave tomography in trapdoor test



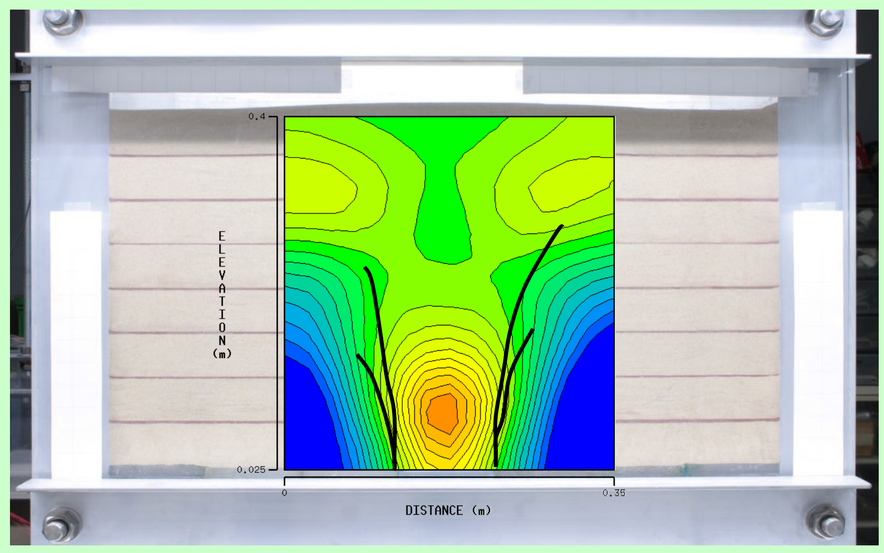
移動床実験における底版の作用土圧（豊浦砂密詰）

Trapdoor test results on densely compacted Toyoura sand



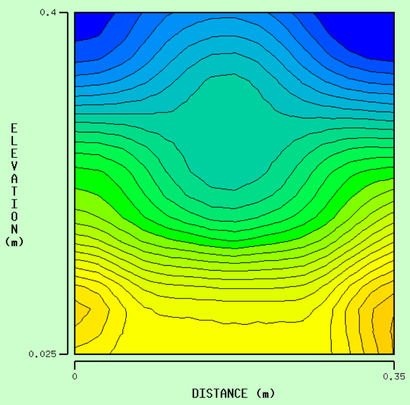
ベンダーエレメントの配置

Arrangement of bender elements

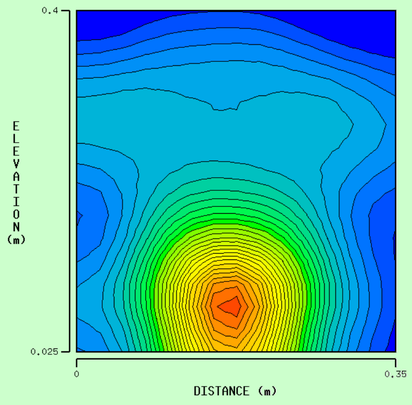


移動前後の速度差分布と地盤のすべり線

Distribution of difference of wave velocities between before and after trapdoor test, shear planes observed in the model ground are also shown



移動前
before trapdoor test



移動後
after trapdoor test

本研究に関する担当研究室は桑野研究室です.
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福王翔 (2012)

Change in Ground Arch Shape and Earth Pressures due to V-Shaped Descent in Trapdoor Tests

落とし戸試験のV字状降下における アーチング形状と作用土圧の変化

概要　Overview

In the hold of bulk carriers, an arching mechanism can be formed by granular dry cargoes such as coal and iron ore based on bottom plate deflection, resulting in redistribution of load on the bottom plate. Using the improved trapdoor apparatus that allows five moving floors to move independently, we measured load on the bottom plate and on the side walls as the bottom plate descend in a V-shape to simulate bottom plate deflection.

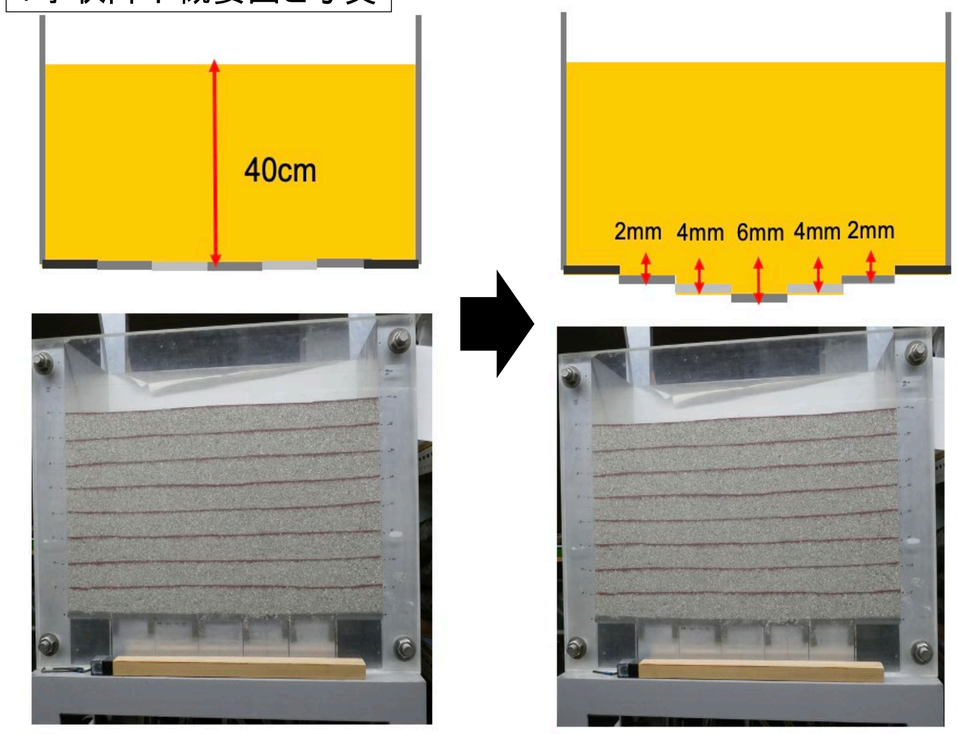
ばら積み貨物船の船倉では、底板のたわみに基づいて石炭や鉄鉱石などの粒状乾貨物でアーチング機構が形成され、底板作用荷重の再分配が起こる可能性があります。モーターが独立して動くことができるように改良した落とし戸試験装置を用い、底板のたわみを模擬したV字状の降下に伴う底板作用荷重、また側面に作用する荷重を計測しました。

底板のたわみを模擬したV字状の降下実験

模型地盤
Sample：Silica sand No.3
Relative density $D_r = 70\%$
Soil Height 40cm

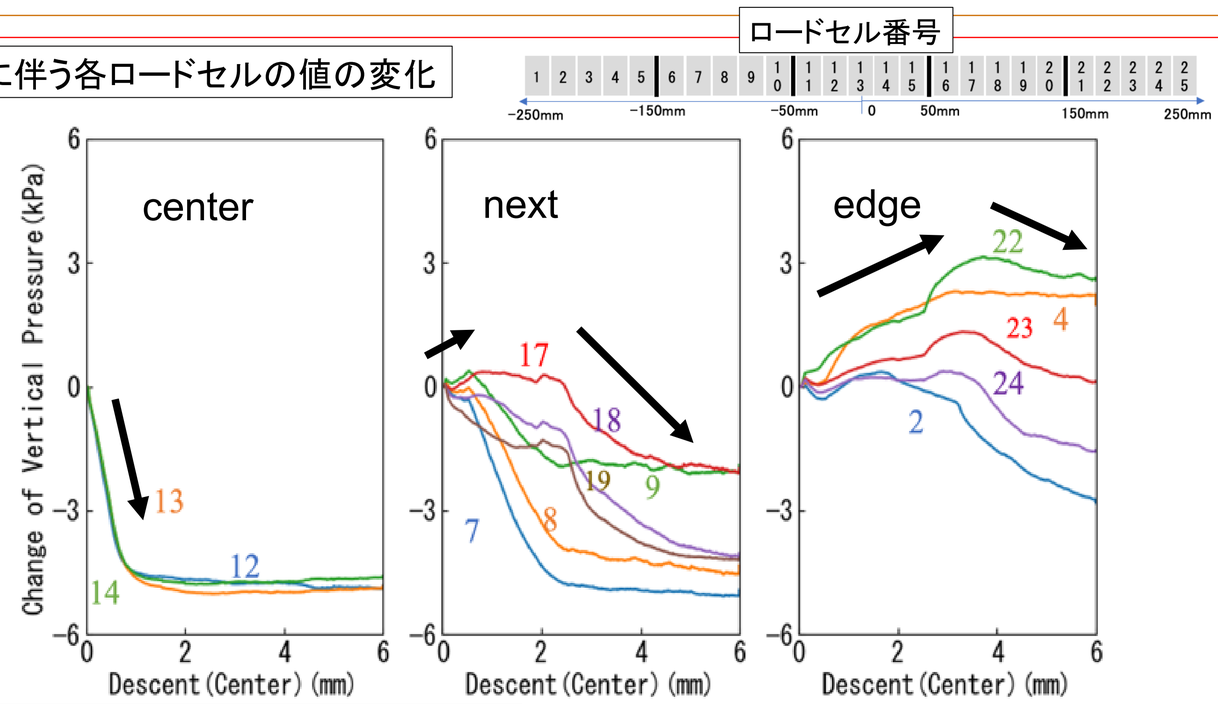
降下速度
center 0.3mm/min
next 0.2mm/min
edge 0.1mm/min

V字状降下概要図と写真

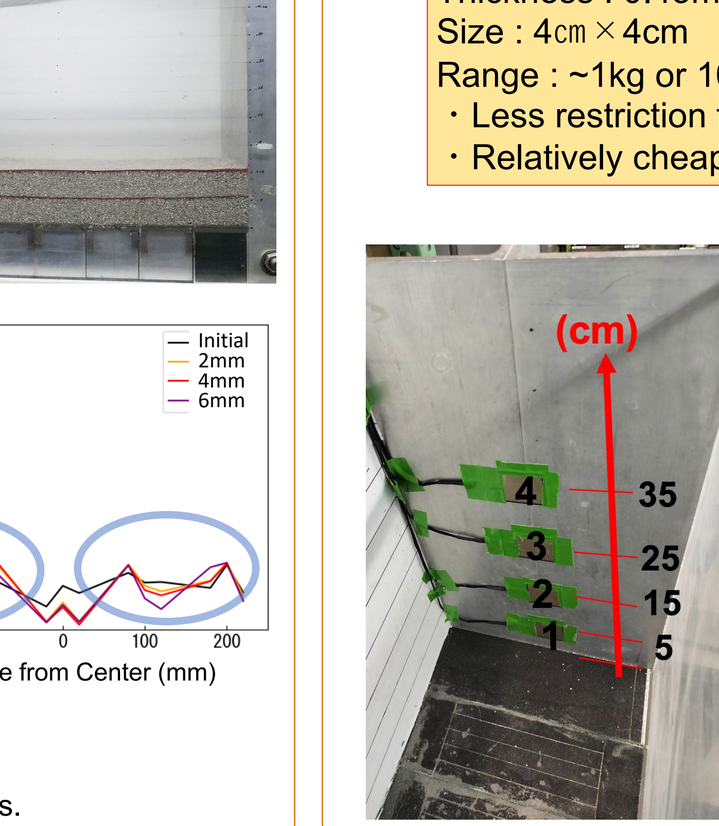


底板の変形は小さいため、目でわかる変化はない
No visible displacement due to relatively small deformation

降下に伴う各ロードセルの値の変化

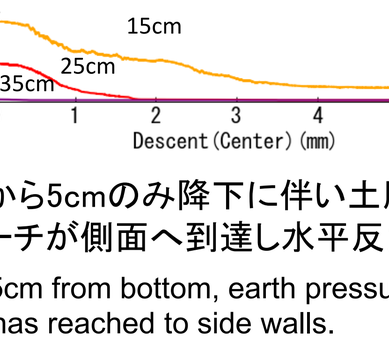


各降下状況における底板作用土圧分布



中央で大きく土圧が減少
→アーチングの形成
土圧の増加する箇所が外側へ移動
→降下に伴いアーチが外側へ

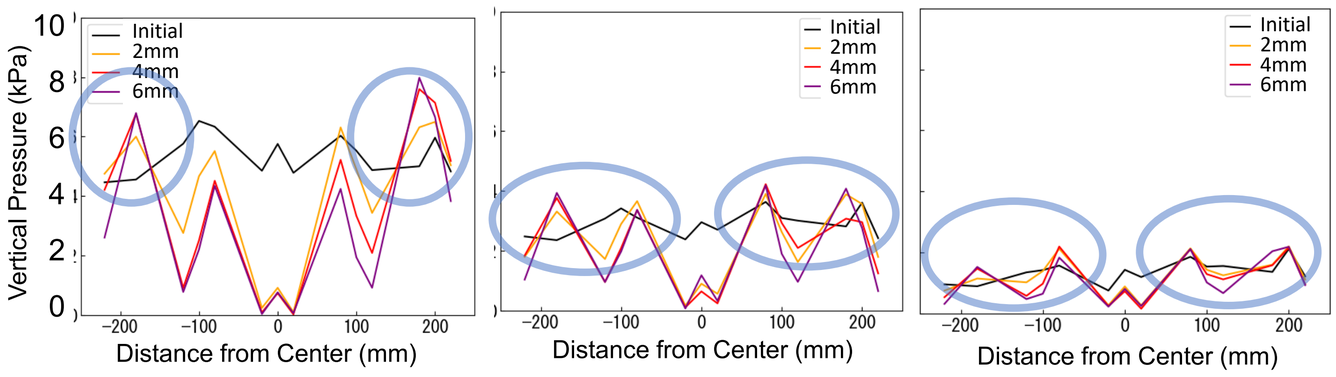
- Vertical load on the center block decreases significantly.
- Load increasing point moves outside
- ➢ Arching extends outward as descending



地盤高の影響

地盤高 40cm　　地盤高 20cm　　地盤高 10cm



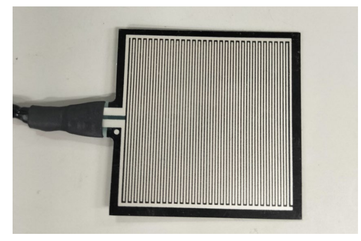


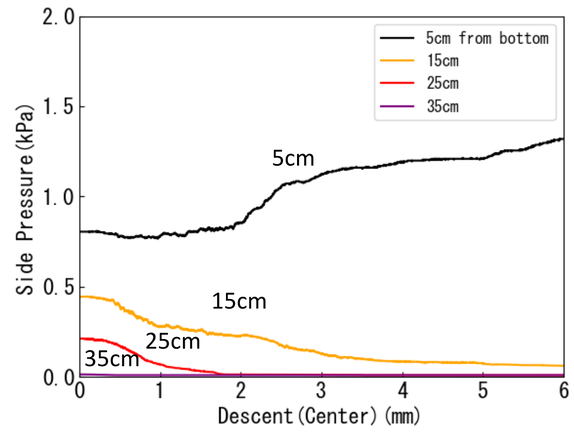
地盤高が高いほど外側での土圧の増大が大きい
→地盤高はアーチの幅に影響

the higher the ground height, the more outside the arching foot is.
➢ Ground height can affect the width of arch

薄膜センサーを用いた側面作用土圧の測定

Thickness : 0.45mm
Size : 4cm × 4cm
Range : ~1kg or 10kg
・Less restriction for measurement
・Relatively cheap





底板から5cmのみ降下に伴い土圧が増大
→アーチが側面へ到達し水平反力を発揮

At only 5cm from bottom, earth pressure increased.
➢ Arch has reached to side walls.

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鉛直揺動に伴う船体底板粒状貨物圧の検討

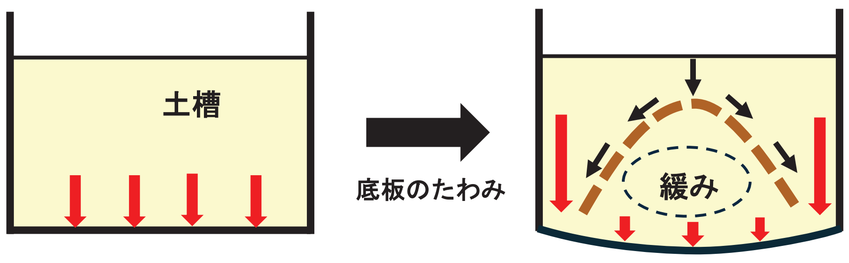
Investigation of granular cargo pressure on the ship's bottom due to vertical vibration

概要 Overview

In the hold of a bulk carrier, an arching mechanism is formed with granular cargo such as coal and iron ore as a result of the deflection of the bottom plate, and there is a possibility of redistribution of earth pressure acting on the bottom plate. We created a vertical vibration model experiment device with a square bottom plate that deforms elastically, and observed the trend of soil pressure changes before and during vibration.

ばら積み貨物船の船倉では、底板のたわみに基づいて石炭や鉄鉱石などの粒状乾貨物でアーチング機構が形成され、底板作用荷重の再分配が起こる可能性があります。弾性変形する正方形底板を持つ鉛直揺動模型実験装置を作成し、揺動前後・揺動中の土圧変化の傾向を観察しました。

アーチングとは



土の局所的な構成が変化し、荷重の伝達経路がアーチのように変化することで荷重が再分配

The local composition of the soil changes, and the load is redistributed as the load transmission path changes like an arch.

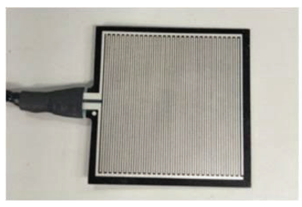
振動装置



コイルばねにて鉛直方向に加振
振動数：約5Hz
加速度：0.5 ～ 1.0G



ギャップセンサ：
底板の変位を測定

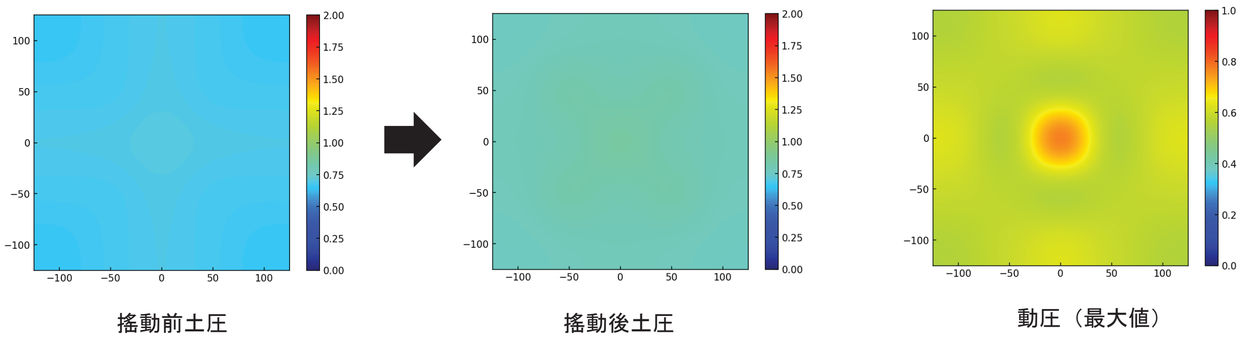


薄膜センサ：
土圧を測定

底板変形の影響

実験条件：珪砂5号, 地盤高25cm, 相対密度40%

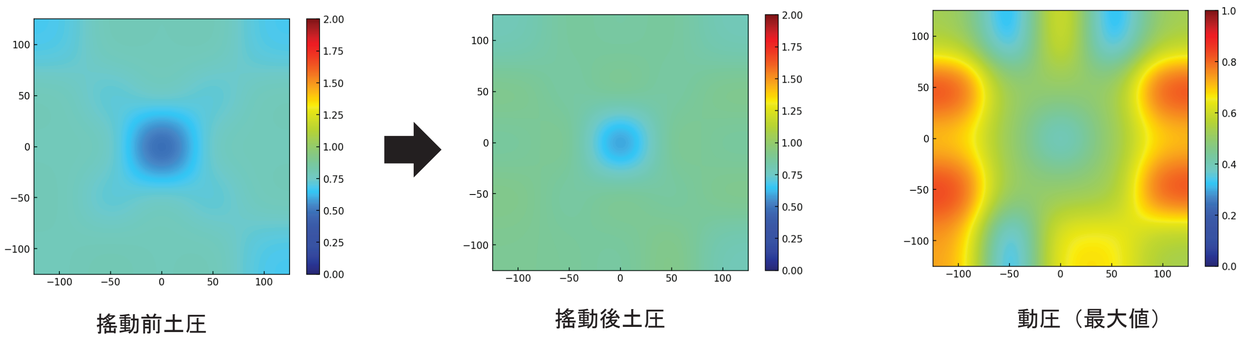
底板変形なし　No base plate deformation



搖動前土圧　搖動後土圧　動圧（最大値）

・静的状態の土圧分布は概ね均一　The distribution of earth pressure in a static state is generally uniform.
・動圧は中央部が大きい　The dynamic pressure is larger in the central part.

底板変形あり　Presence of base plate deformation



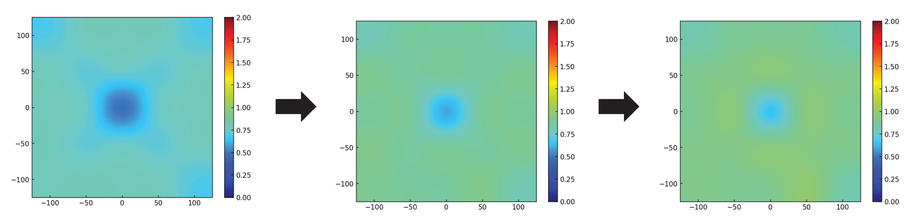
搖動前土圧　搖動後土圧　動圧（最大値）

・自重による底板のたわみに伴い、揺動前から底板中央で土圧が小さい（アーチング形成）
Due to the deflection of the base plate caused by soil weight, the earth pressure at the center of the base plate is small before shaking (arching formation).

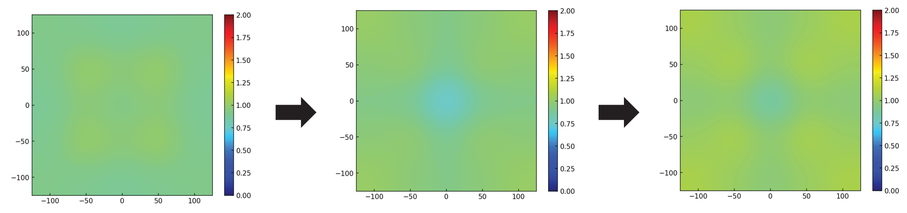
・揺動後にもアーチングは維持され、アーチ形状が変化することもない
Even after shaking, the arching is maintained, and the arch shape does not change.

地盤高の影響

地盤高：25cm



地盤高：15cm



初期状態　1回揺動後　2回揺動後

地盤高はアーチ構造の安定性に寄与し、地盤高が十分であればアーチは鉛直揺動によって崩壊しない
The elevation of the ground contributes to the stability of the arch structure, and if the ground elevation is sufficient, the arch will not collapse due to vertical vibration.

加速度と動圧増分の関係

加速度に対する土圧増分を実験結果からプロット

設計式と比較して小さな傾きの直線関係が得られる
→動的荷重の設計式の過大評価の可能性

A smaller slope linear relationship was obtained compared to the design formula, indicating the possibility of overestimation in the design formula for dynamic loads.

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底板変形及び鉛直揺動に伴う粒状体内のアーチング効果の検討

Investigation of arching effect in granular materials with bottom deformation and vertical oscillations

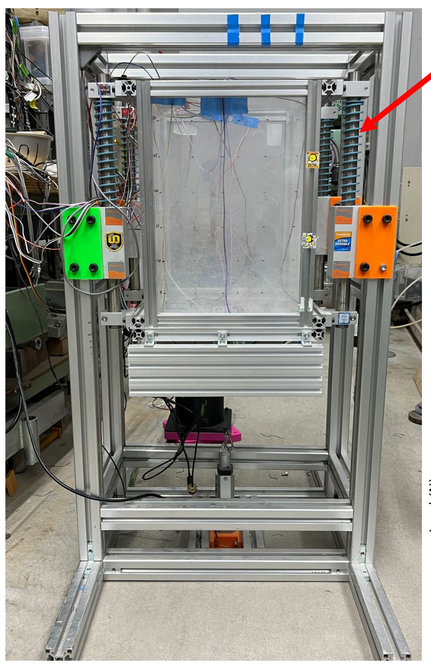
概要　Overview

In the cargo hold of a bulk carrier, the arching effect occurs in granular dry cargo such as coal and iron ore due to the deflection of the bottom plates, leading to a redistribution of the bottom plate load. A vertical oscillation model experimental device with elastically deformable bottom plates was used to examine the trends in dynamic pressure during oscillation. Additionally, observations of soil arches and ground loosening were made by analyzing the depth distribution of penetration resistance within the model ground.

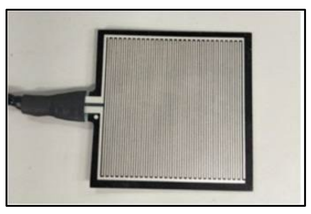
ばら積み貨物船の船倉では、底板のたわみに起因して石炭や鉄鉱石などの粒状乾貨物でアーチング効果が発揮され、底板作用荷重の再分配が起こります。弾性変形する底板を持つ鉛直揺動模型実験装置を用いて揺動中の動的圧力の傾向を検討するとともに、模型地盤内の貫入抵抗の深度分布から地盤内アーチおよび地盤のゆるみを観察しました。

Oscillation Tests

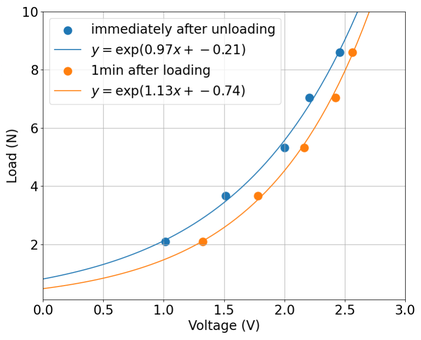
Vertical oscillation using coil springs
Frequency ： 2.5 – 5.0 Hz



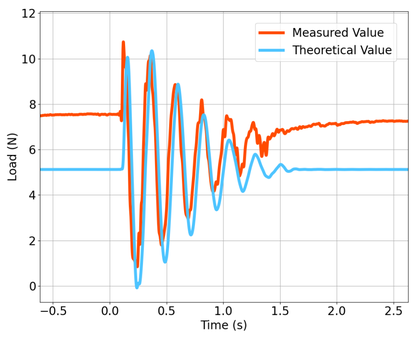
Apparatus



Thin-Film FSR Sensors ：
Measuring vertical load acted on the bottom plate

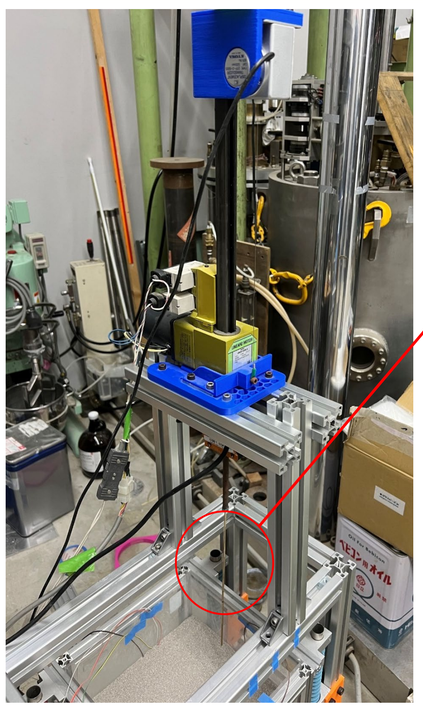


Characteristics of FSR sensors

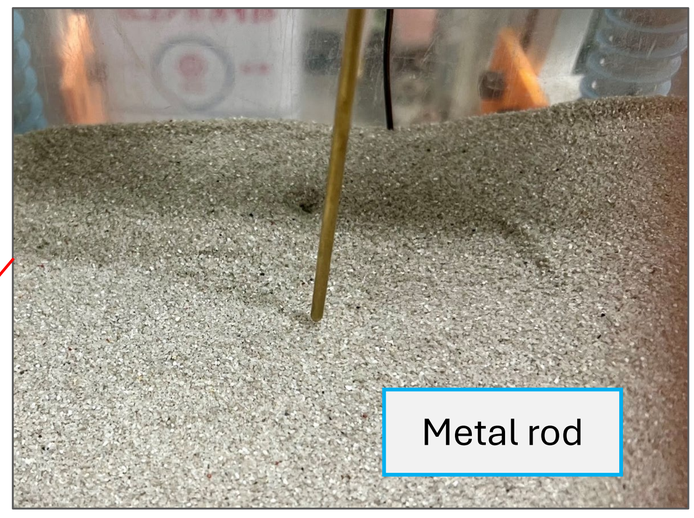


Checking dynamic reactions

Penetration Tests

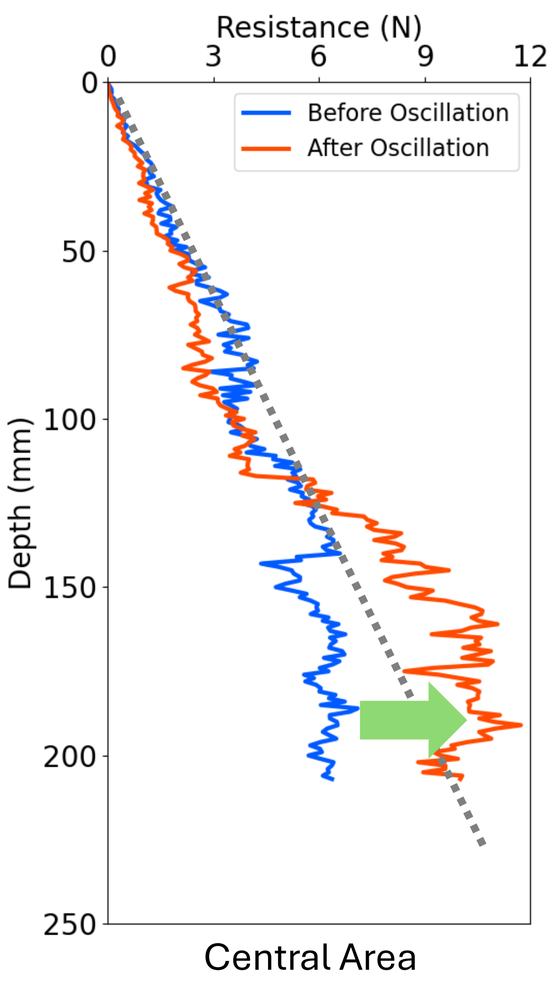


Apparatus

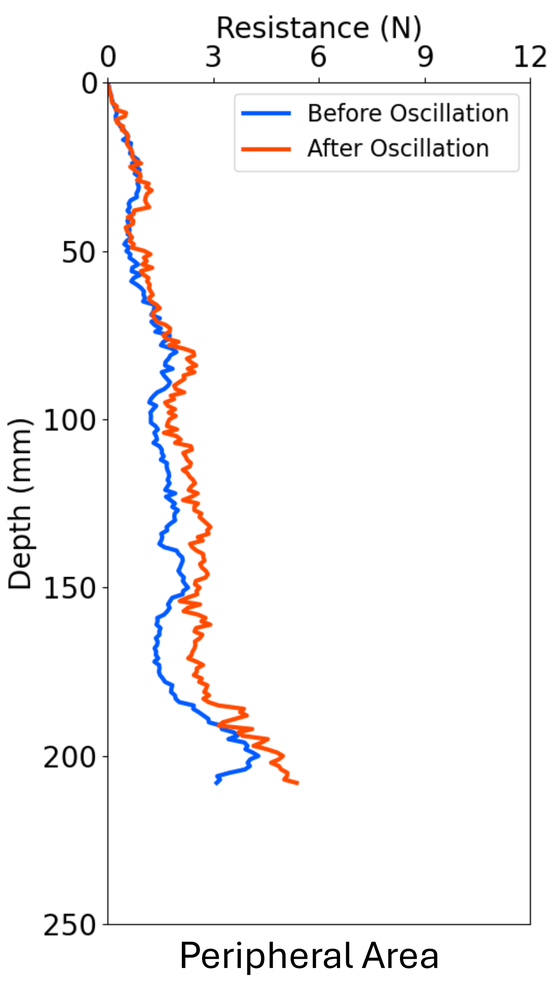


A metal rod with a diameter of 2 mm was penetrated into the ground, and the distribution of resistance values in the depth direction was obtained.

Arch and Looseness



Central Area

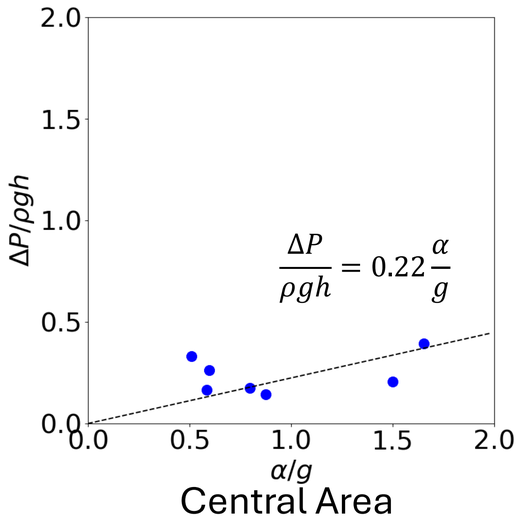


Peripheral Area

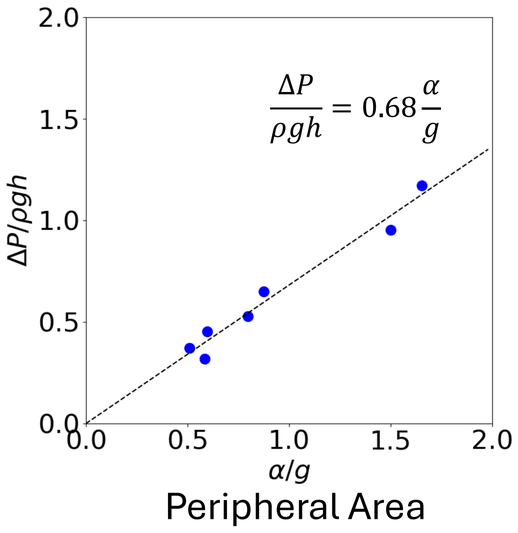
- Before oscillation, the penetration resistance showed no further increase below a depth of approximately 120 mm,
  → Suggesting the presence of an arch at this depth.
- At the center of the bottom plate, the penetration resistance below 120 mm increased significantly after oscillation,
  → Indicating that the loosened zone beneath the arch is particularly compacted by the oscillations.

Dynamic Load

At first oscillations

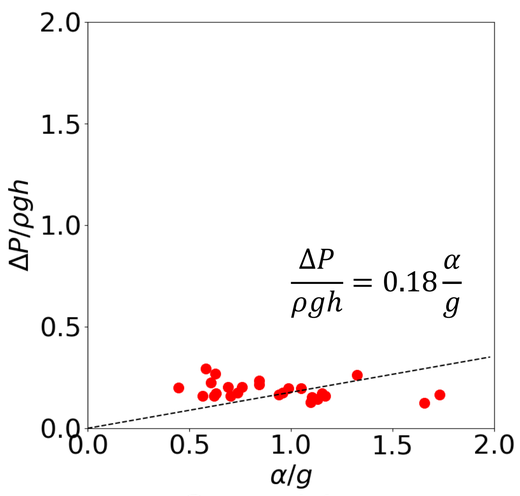


Central Area

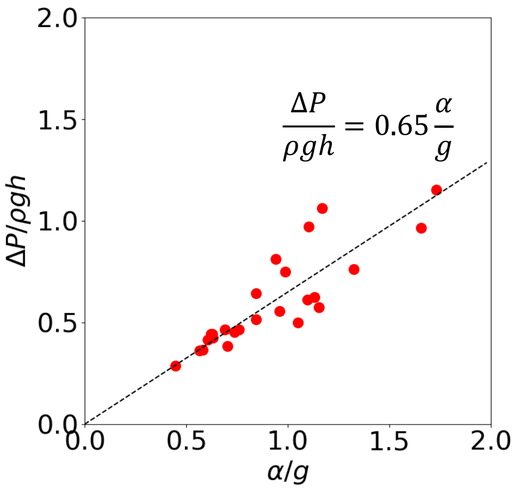


Peripheral Area

At after second oscillations



Central Area



Peripheral Area

- Multiple oscillations were applied to the same model ground, and variations in dynamic pressure were observed across different areas of the base surface.
  →Repeated vertical oscillations result in a reduction of dynamic loads in response to acceleration.

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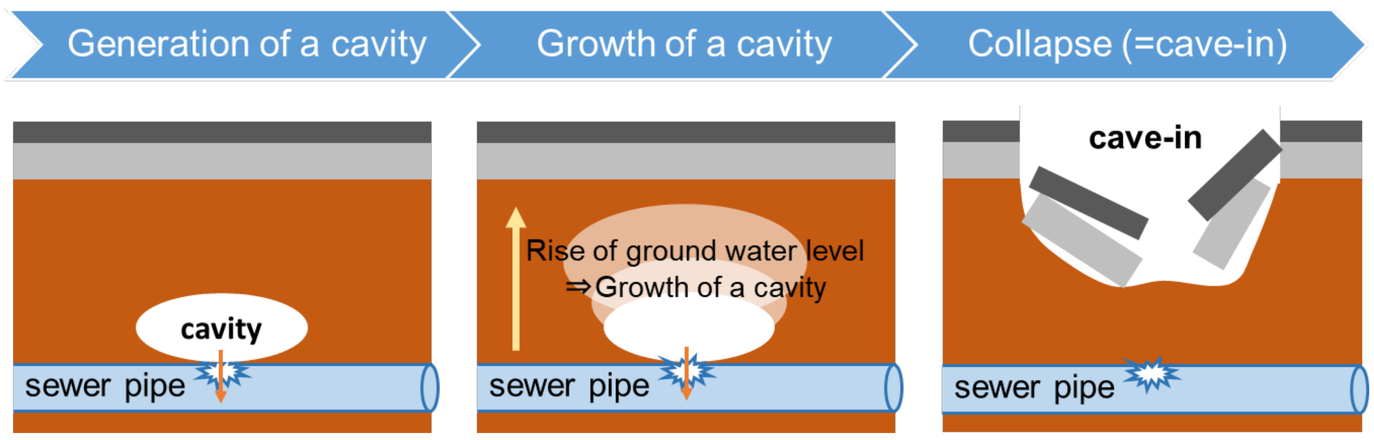
Investigation of Initial and Collapsing Subsurface Cavity with Model Tests

初期から崩壊に至る地盤内空洞の進展プロセス

A road cave-in is one of serious problems in the management and maintenance of road. In this study, series of model tests simulating cave-in formation were conducted to investigate its mechanism.

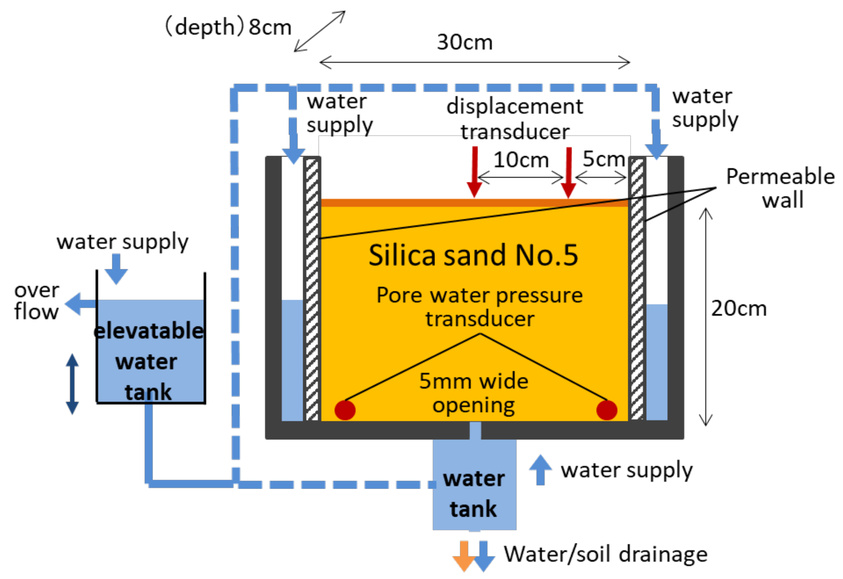
道路陥没は道路保全の観点で重要な問題であり、道路の効率的な維持管理のために路面下空洞の生成・拡大メカニズムの解明が求められています。本研究では、模型実験により地盤陥没の生成過程メカニズム、および陥没危険度評価についての考察を行っています。

Road cave in caused by a subsurface cavity



- Ground cave-ins are initiated by cavities in the ground.
- One of typical causes for the formation of cavities in urban area is old sewer pipes.
- In rural area, underground cavities may be formed by the underground water pathway.
- Rise of ground water level seems to be one of important factors of the growth of cavities.

Model test apparatus and test procedure

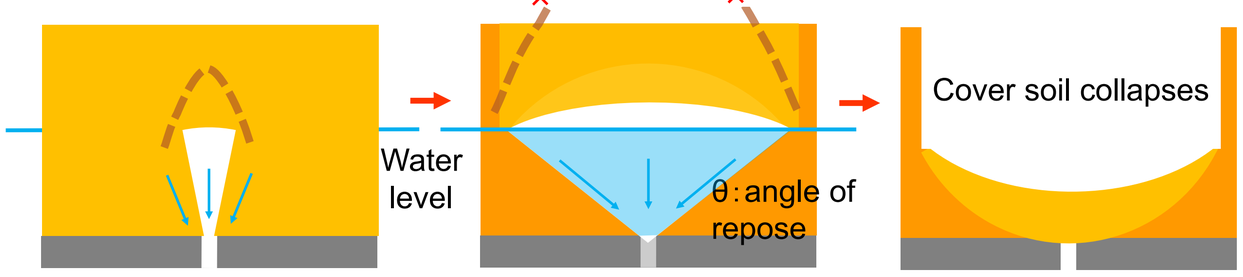


1. Model ground was made in the soil chamber using uniform sand.
2. Water was supplied through side walls or bottom.
3. A plug at the bottom opening was taken out. Water with soil around the opening was drained and a cavity was formed.

Process of cavity formation/expansion

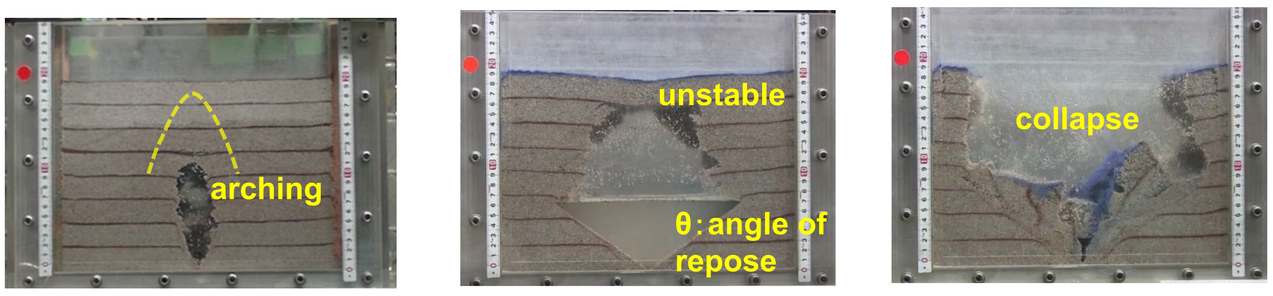
When a narrow cavity is formed deep in the ground, the arch action works

When a wide cavity developed in shallow ground, there is no room for the arch action



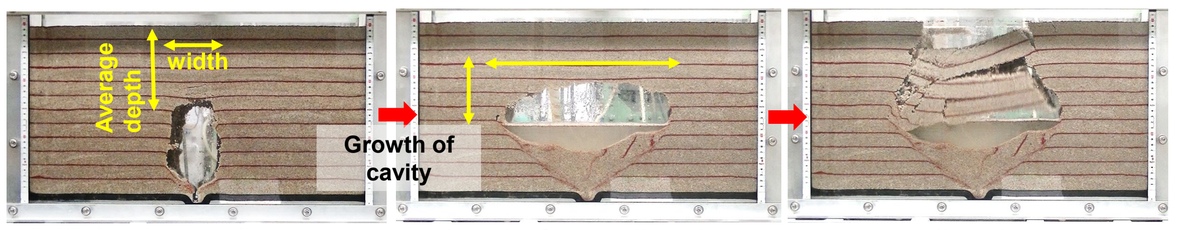
When water drains quickly, a chimney-like narrow cavity forms

When water stays in the cavity, fan-shape cavity develops

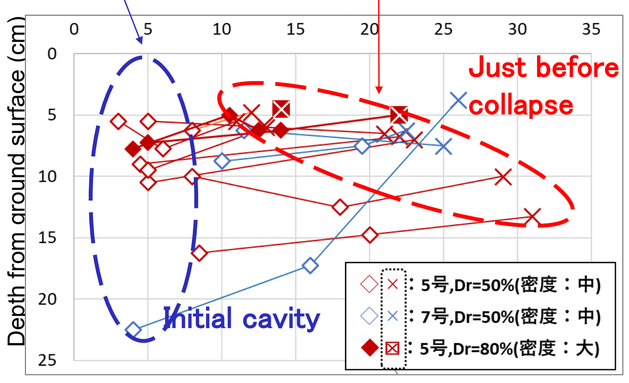


Change of water level, or high water level are one of main factors for cavity expansion

From initial cavity to collapsing cavity



Initial chimney-like cavity | Just before collapsing | collapsing



Chimney-like vertically elongated initial cavity

↓

Width of cavity under the groundwater increase

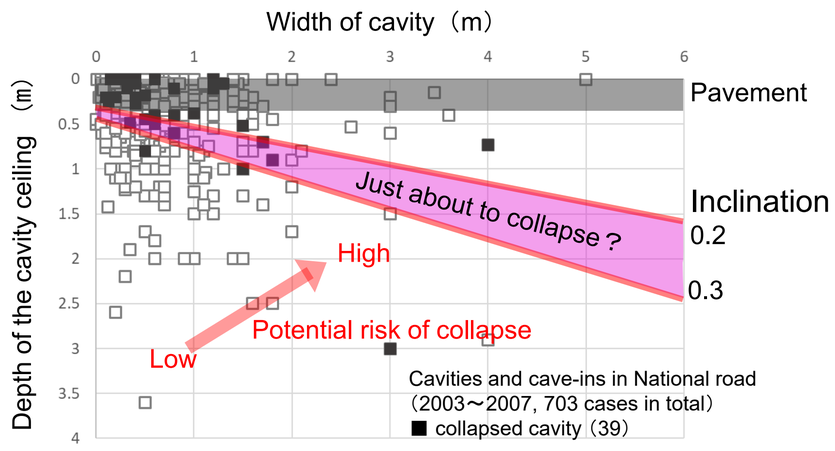
↓

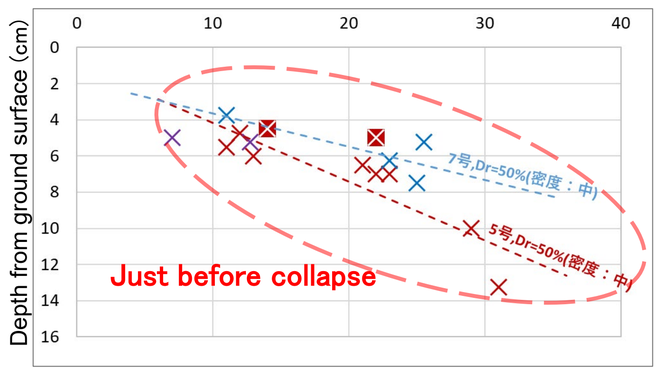
Soil above the cavity collapses

When the thickness of covering soil is large enough compared to the width of cavity, a cavity is stable as the ground arching and apparent cohesion seems to work.

Potential risk of road cave-in

Cases of real cavity and collapse in roads





Wet uniform sand above a cavity collapses due to its self weight, when the ratio of average depth and cavity width becomes below 0.2 to 0.3.

Potential risk of collapse can be evaluated by width and depth of the cavity

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Study on Mechanism of Naturally Generated Sinkhole

自然生成型地盤陥没の発生メカニズムの研究

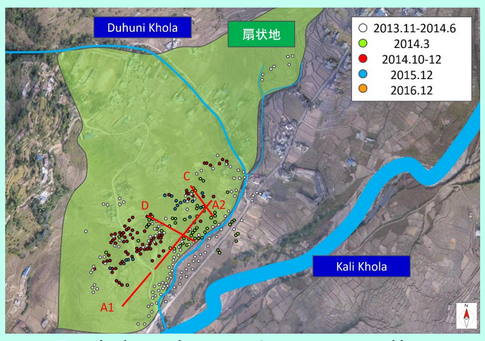
Sinkhole can be naturally generated due to underground soil erosion by waterflow. Here proposed is water path detection by measurement of the sound of underground waterflow. Its effectiveness was considered with field survey and model test, and sound pressure and frequency spectrum can show where water is flowing and in some cases it may have potential to show the grain size distribution of the soil at the place.
To avoid effects of friction between grains and walls in two-dimensional cavity formation tests, cavity formation test was conducted using three-dimensional soil tank. The result implied that the process of cavity formation can be divided into two part, the first part influenced by ground water level and the latter part affected by soil property.

自然環境の中で発生する地盤陥没は、地下の水みち沿いに土砂が流出し空洞が形成されることで主に発生します。空洞調査として、ボーリング調査は点でのデータしか得られず、表面波探査は地下の空洞を有効に検出できないため、新しい調査手法のひとつとして地下流水音測定による水みち探索を提案し、フィールド調査と模型試験によって有効性を検討しました。音圧と周波数スペクトルの解析によって、水みちの径路のほか土の粒径の推測ができる可能性が得られました。また、既存の二次元土槽による空洞生成模型試験には壁面との摩擦の影響がある可能性を考慮して、三次元土槽において空洞生成模型試験を行った結果、空洞の生成過程が、地下水位の影響を受ける前半の過程と砂の性質の影響を受ける後半の過程に分けられることが確認されました。

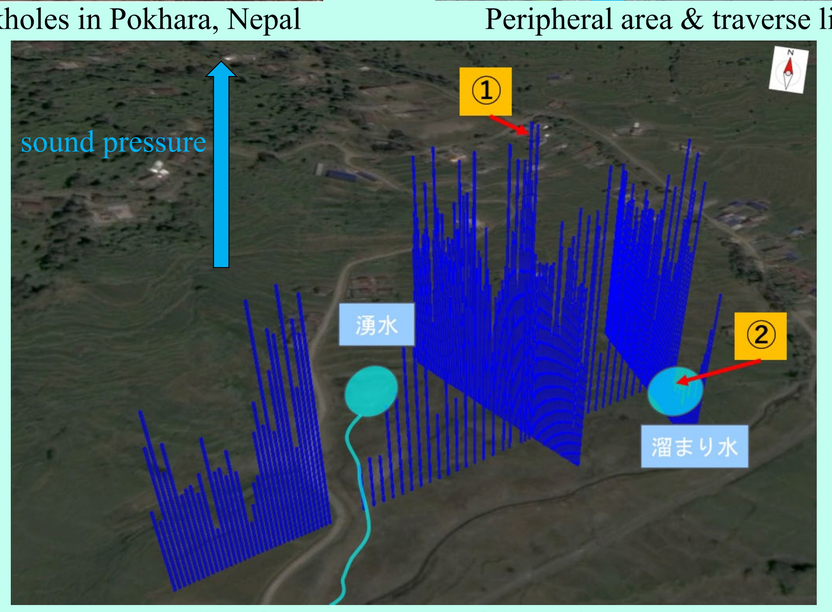
流水音測定による水みち調査
Water path detection by the sound of underground waterflow



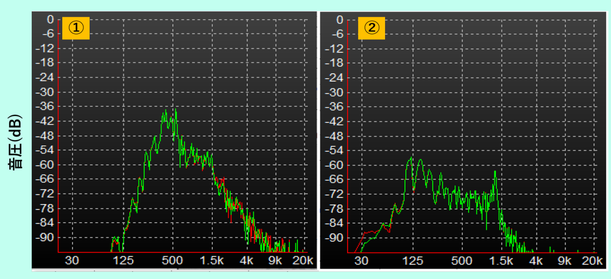
Sinkholes in Pokhara, Nepal



Peripheral area & traverse lines



The results of measurements of the underground sound



Frequency spectra at point ①, where the sound pressure was high and waterflow seems to be intense, and point ②, where the pressure was low and waterflow is supposed to be stagnant. There is a peak around 500Hz at point ①.

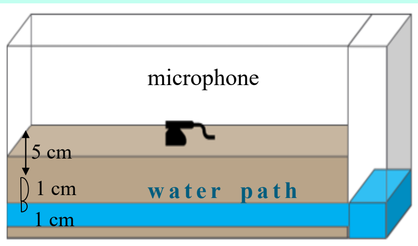
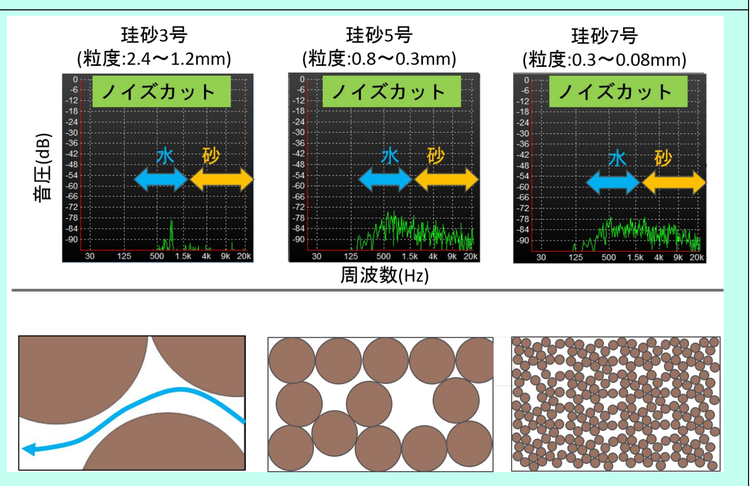


Illustration of the apparatus

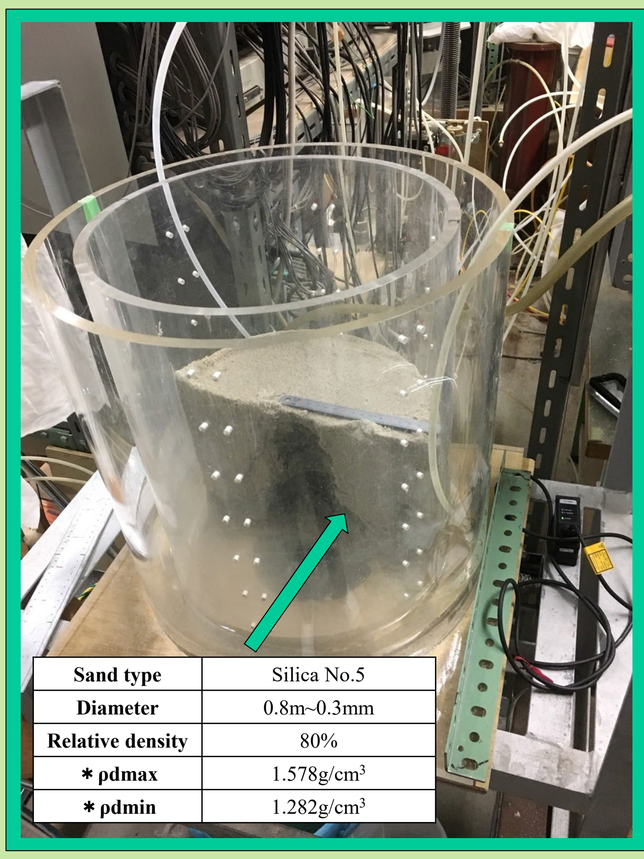


Model ground conditions

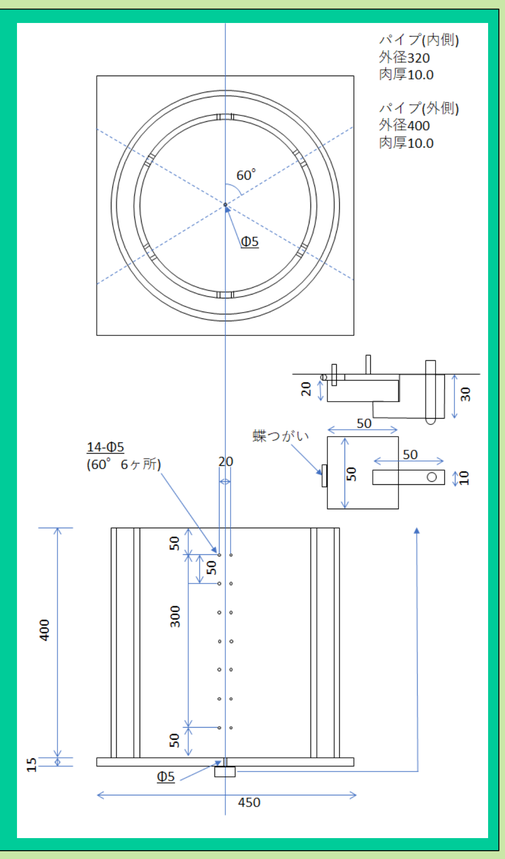
Dry density: 1.50g/cm3
Water content: ≈20%
Material: silica sand No.3 (1.2～2.4 mm)
silica sand No.5 (0.3～0.8 mm)
silica sand No.7 (0.08～0.3 mm)

In all the cases there are peaks at 500Hz, where it's supposed to represent sounds of waterflow. In the cases of silica No.5 and No.7, sounds are recorded at higher frequency, where it's supposed to represent sounds of sand. With smaller size of grains, waterflow can move sand particles and make those sounds.

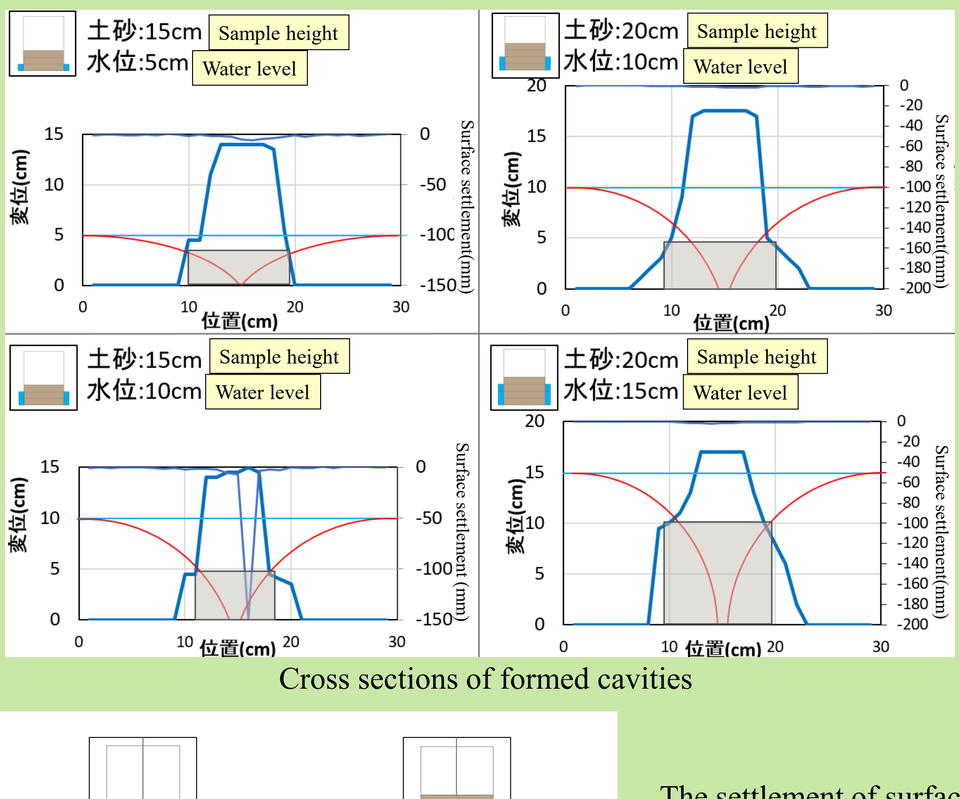
三次元的土槽を導入した空洞生成実験
Cavity formation test using columned soil tank



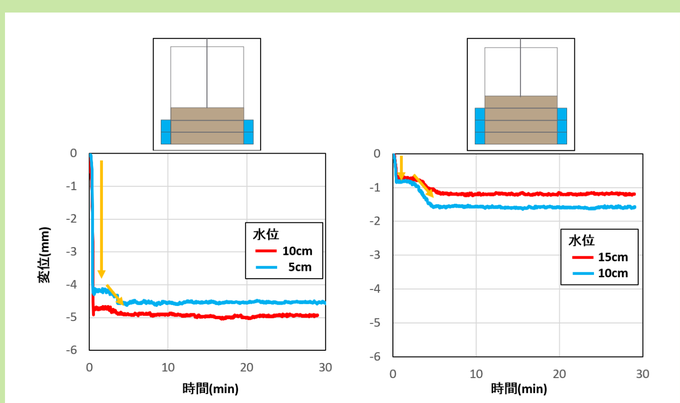
Sand type	Silica No.5
Diameter	0.8m~0.3mm
Relative density	80%
* ρdmax	1.578g/cm³
* ρdmin	1.282g/cm³



The soil tank



Cross sections of formed cavities



Surface settlement

The settlement of surface has two stages, which coincides with the shapes of formed cavities. It is supposed that at first the grey square part falls according to ground water level and later the upper part falls off according to the adhesiveness of the soil.

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小南直翔 (2018)

Study of Cavity Formation with DEM

土砂流出に伴う地盤の空洞・ゆるみに関する個別要素法解析

Road cave-ins and cavities are a serious problem in modern cities with developing infrastructure. Experimental study for investigation of the cave-in and cavity problems has not been fully able to understand the fundamental mechanism of cavity-growth and resultant cave-in events due to their limited extent of measurable physical quantities. In this study, discrete element method (DEM) is used to investigate the cavity formation process and to quantitatively evaluate the loosening of soil surrounding a cavity. It was confirmed that particle shape and initial density play important rolls in cavity expansion rate whereas the particle shape influences the shape of a cavity.

路面下空洞あるいは道路陥没は，現代都市の社会基盤施設に対して甚大な影響を与えます．桑野研究室では模型実験を実施することで，このような現象の解明に取り組んでいます．しかし，実験で計測可能な物理量が限られているため，空洞成長・路面陥没の根本的なメカニズムの解明には至っていません．そこで，砂粒の動きを計算する個別要素法（DEM）解析手法を用いることで，空洞の生成・成長過程を理解に取り組み，空洞周辺の地盤のゆるみに関する評価が可能となりました．本研究の結果，土粒子の形状と地盤の初期密度は空洞の形成過程・速度において大きな影響を及ぼし，特に，土粒子形状は発生する空洞の形状とも密接な関係があることが明らかとなりました．

Vertical displacement of particles associated with opening a bottom slit (5 mm or 15 mm)

スリット開口に伴う土粒子の流出と鉛直変位

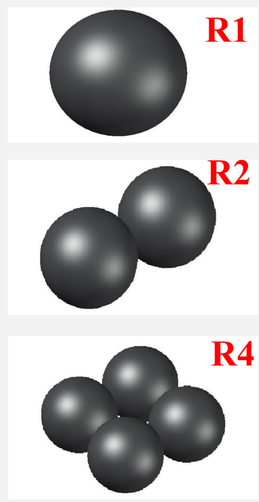
DEM software : LAMMPS

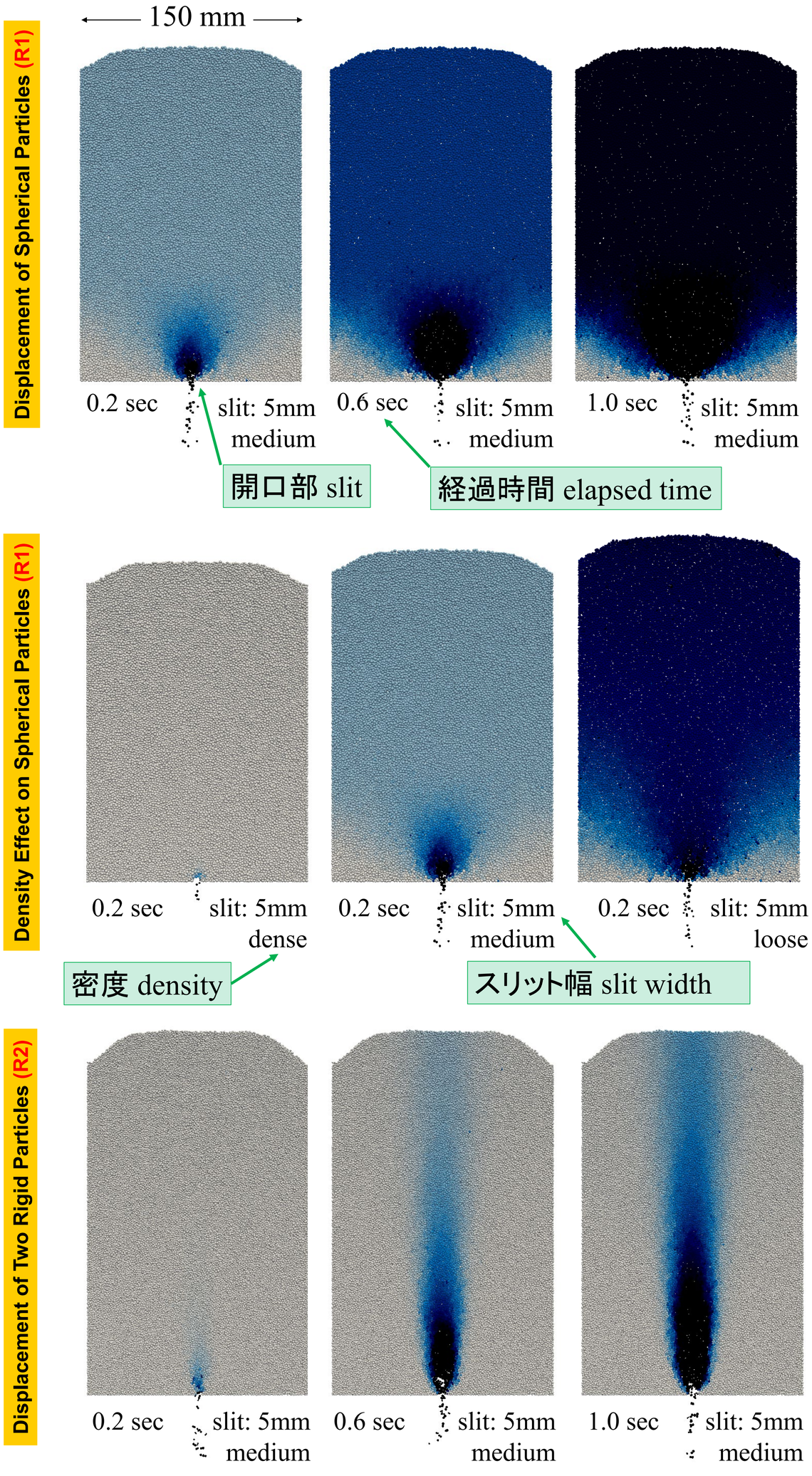
Sample size : 150mm (X) : 20mm (Y) : 220-400mm (Z)

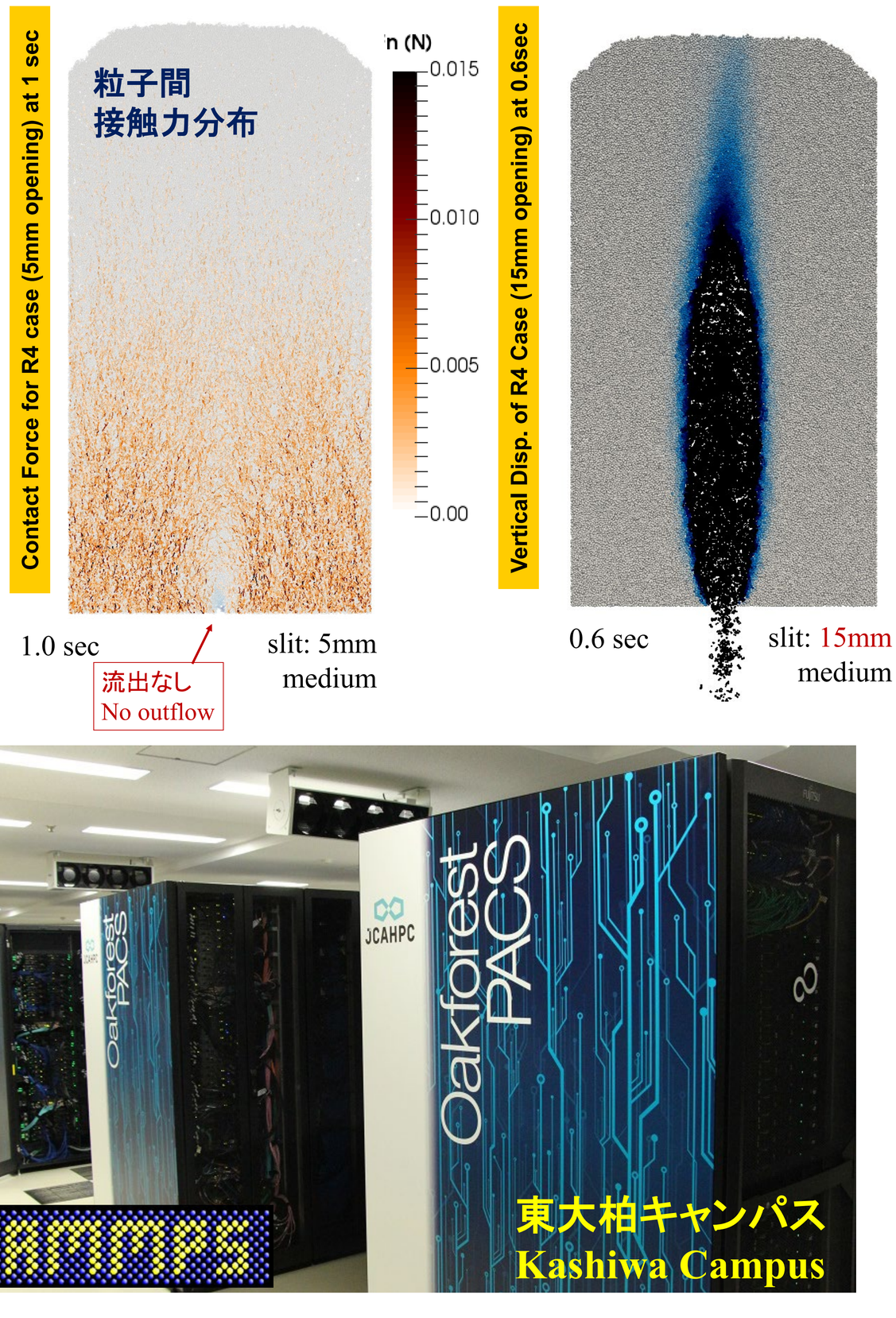
Particle properties :
Spherical (R1), Two rigid (R2), Four rigid particles (R4)
Diameter of spherical particle (R1)**:** 1.2 – 2.2mm
Rigid particles with equivalent volume with R1

Coefficient of inter particle friction:
•0.01, 0.1, 0.4 (during preparation)
•0.5 (when opening the bottom slit)

Young's modulus:71.6 GPa, **Poisson's ratio:** 0.23, **Gs :** 2.5







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大坪正英 (2018)

Survey of Multiple Sinkholes in Pokhara, NEPAL

ネパール・ポカラにおける多発陥没の調査

A number of sinkholes occurred in Pokhara, Nepal, in November 2013. The locations of sinkholes are mostly on fields of rice and other crops. About 50 families had to evacuate since sinkholes also appeared beside houses. Most of the sinkholes had been filled after the preliminary survey conducted by the local government.

Field investigations were conducted by the IIS members since June 2014. It was found that the sinkholes seemed to be caused by large scale internal erosion of white-greyish calcareous silt layer. Although exact location and depth of the erosion is unknown, judging from apparent depth of sinkholes, a soil pipe can be deeper than GL-6～7m. Development of internal erosion and soil pipe seemed to continue until June 2016 .

ネパール、ポカラの近郊の村で2013年11月に陥没が多発しました。発生箇所は主に田畑でしたが、住居近くにも発生し、一部の住民は退去を余儀なくされました。ネパール政府は地質や自然災害の専門家による調査委員会を立ち上げ、一次調査結果を発表すると共に、陥没孔の埋戻しを実施しました。

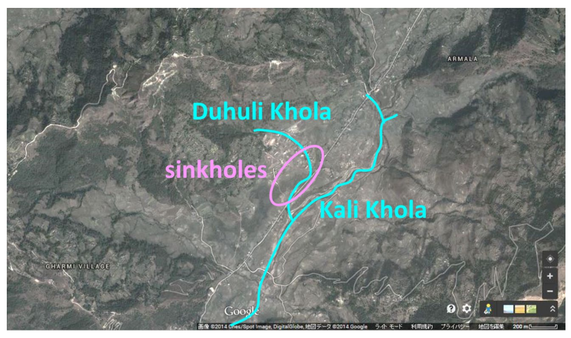
2014年6月以来7度にわたり現地調査を実施したところ、白色の石灰質土の大規模な内部侵食が陥没の主な原因であると推定されました。内部侵食によって形成された水みちの詳細な径路や範囲は不明ですが、陥没孔の深さから判断して地下の水みちは地下6～7mより以深であると考えられます。陥没孔に湧き出る白濁した水の流量や濁度が日々変化していたことから、水みちおよびその周辺の内部侵食は2016年夏頃まで継続していました。2014年6月に埋め戻された状態だった陥没孔が同年11月の調査時に再陥没している例が多数見られました。

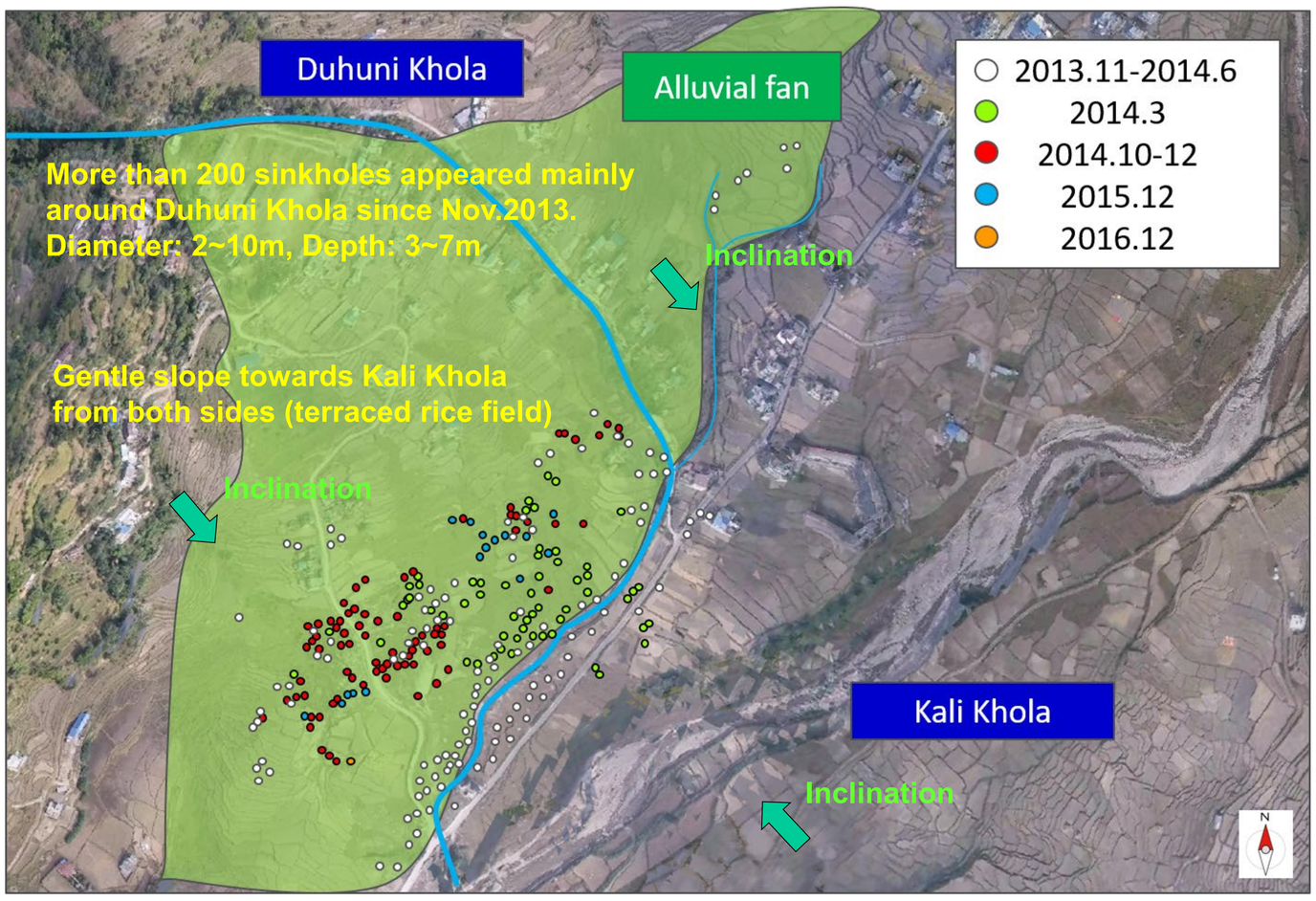
陥没地の場所と概況

Outline of area subjected to multiple sinkhole

Almara, Pokhara, Nepal

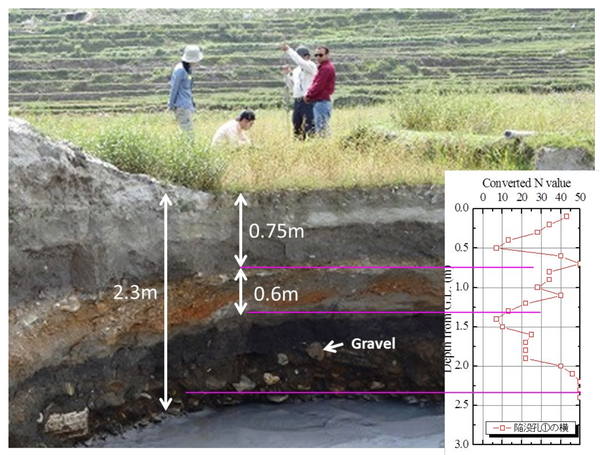






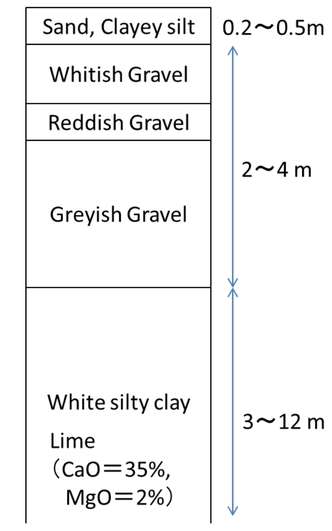
継続的内部侵食の痕跡

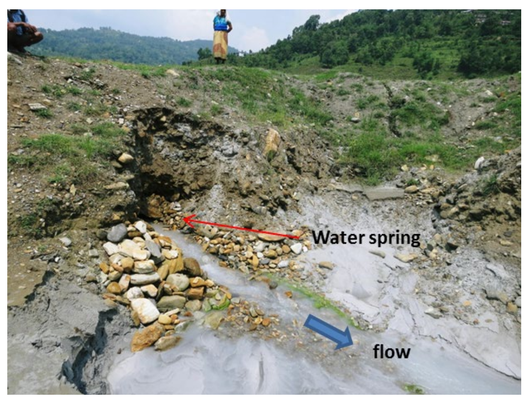
Sign of large scale internal erosion



陥没孔の断面

Soil profile observed at a sinkhole





白濁した湧水（隣接した陥没孔は連結か？）

White turbid water sprang at a depth of 2m from the ground surface, possibly connecting between sinkholes

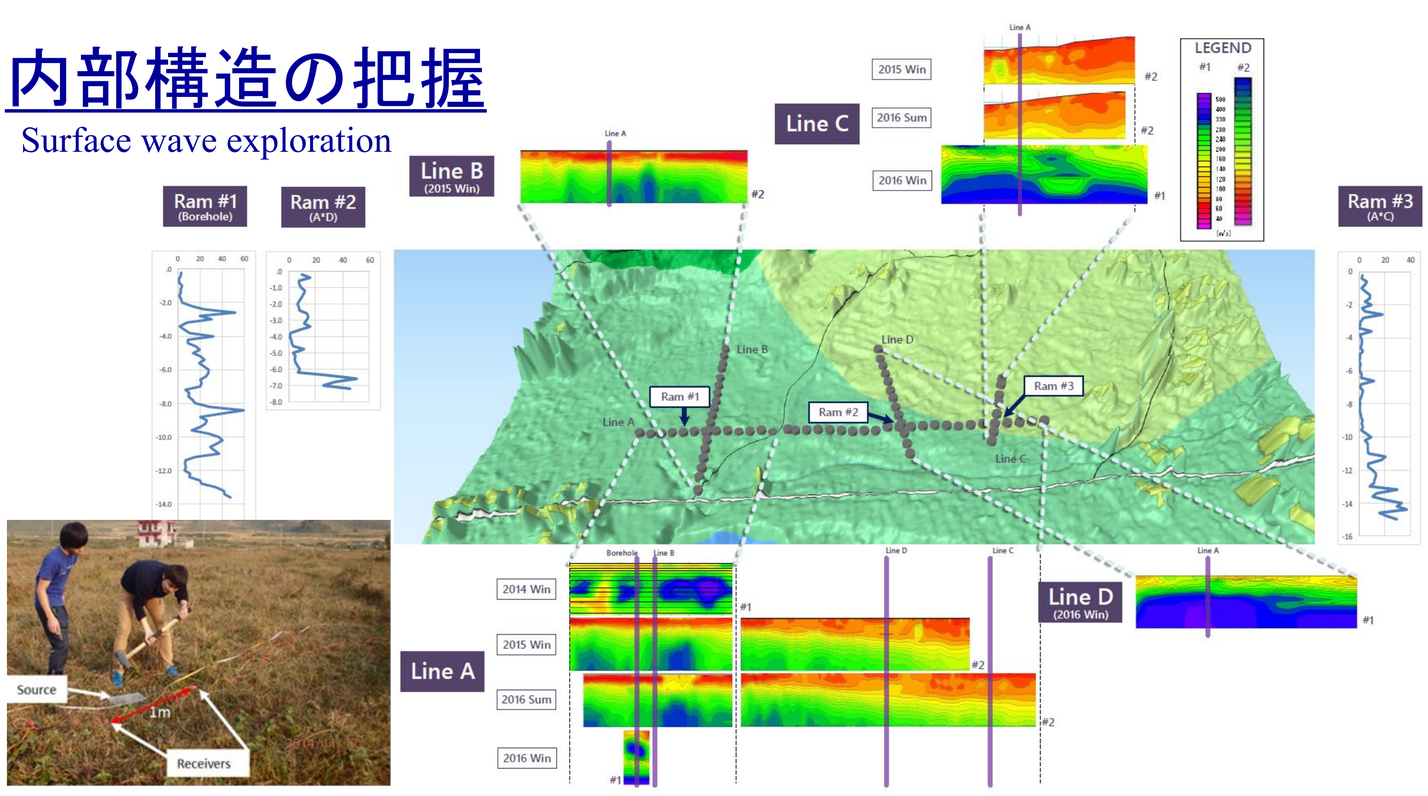


陥没孔底に堆積したシルト

Soft clayey silt sediment in the bottom of sinkhole

内部構造の把握

Surface wave exploration







Photos taken from the same location

(June 2014) (November 2014)

埋め戻された陥没孔の多くが雨季を経て再陥没

Refilled sinkholes had collapsed again after the rainy season

本研究に関する担当研究室は桑野研究室です.
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小南直翔 (2018)

SURVEY OF SINKHOLE AREA IN MIYAKONOJO, MIYAZAKI

宮崎県都城市の陥没発生地における地盤調査

小南直翔 (2017)

[概要] ~OVERVIEW

Due to the typhoon on Sept.19, 2016, a large sinkhole occurred in a potato field of Miyakonojo, Miyazaki, leading to a soil outflow of 1500㎥ to the road nearby. Fortunately, there were no human casualties, but sinkholes may lead to serious accidents depending on the time and place of occurrence. Therefore it is important to investigate the cause and take measures to prevent these accidents. Surveys including dynamic cone penetration tests and surface wave surveys were conducted to understand the cavities, waterpaths and loosening of underground.

平成28年9月19日の台風16号による影響で、宮崎県都城市で大規模陥没孔が出現した。陥没は五十町IC付近の畑に発生し、志布志道路に1500㎥の土砂流出が生じた。今回は人的被害はなかったものの、地盤陥没は発生箇所や発生時間帯によって人的被害を伴う事故に繋がる可能性があるため、その未然防止のためにも発生原因を解明し必要に応じて対策することは重要である。本報では、陥没孔周辺の地盤のゆるみ、地下空洞、及び水みちの把握を目的として実施した簡易動的コーン貫入試験、表面波探査の結果について報告する。

[調査地概況] ~AREA OUTLINE

発生地と土砂流出の様子 Sinkhole and its outflow





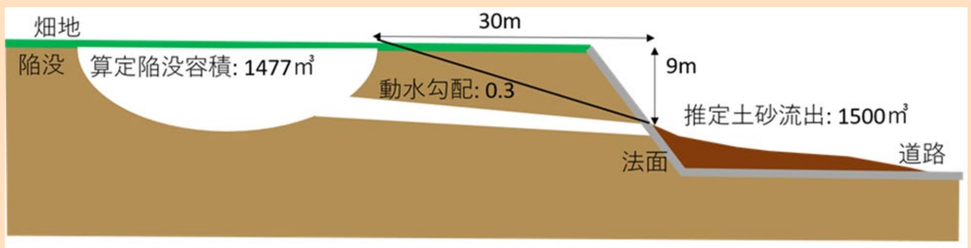
・延長31m,幅13m,深さ7mの半楕円体の形状　Length..31m Width..13m Depth..7m

・陥没発生地はシラスによって形成されている台地状の地形で、普通の畑に比べて雨水浸透が速いと言われている。陥没容積は報告された土砂流出量とおよそ一致する。

Sinkhole area is a Shirasu plateau, and it is said that the field's permeability is high. Soil outflow was reported as 1500㎥, which matches with the estimated volume of the sinkhole.

上空写真と断面図概形 Aerial photo and Cross section





[調査結果] ~RESULTS

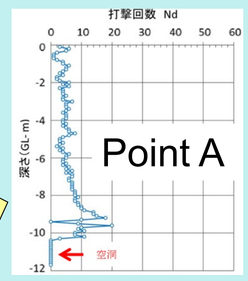
動的コーン貫入試験 Dynamic cone penetration test

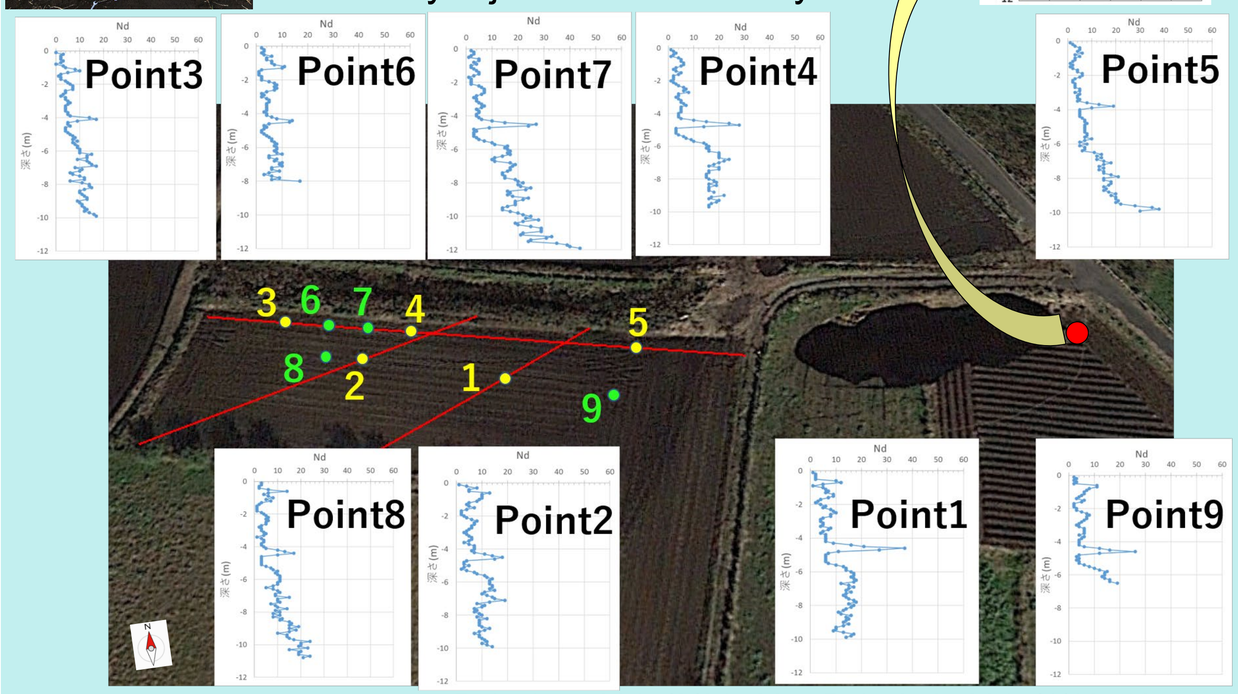


杭を打ち込み、地盤の強さを測定

・Point Aの10m以深に空洞
・4m付近に固い層、その下に軟弱地盤

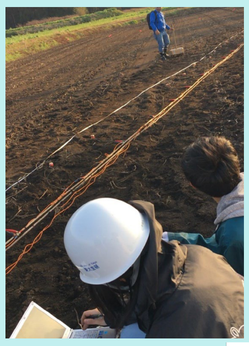
✓Cavity found in 10m at Point A
✓Hard layer at 4m
✓Soft layer just below hard layer





Point A 2016/12/12~15　Point1~5 2017/3/21~22　Point6~9 2017/4/18~19

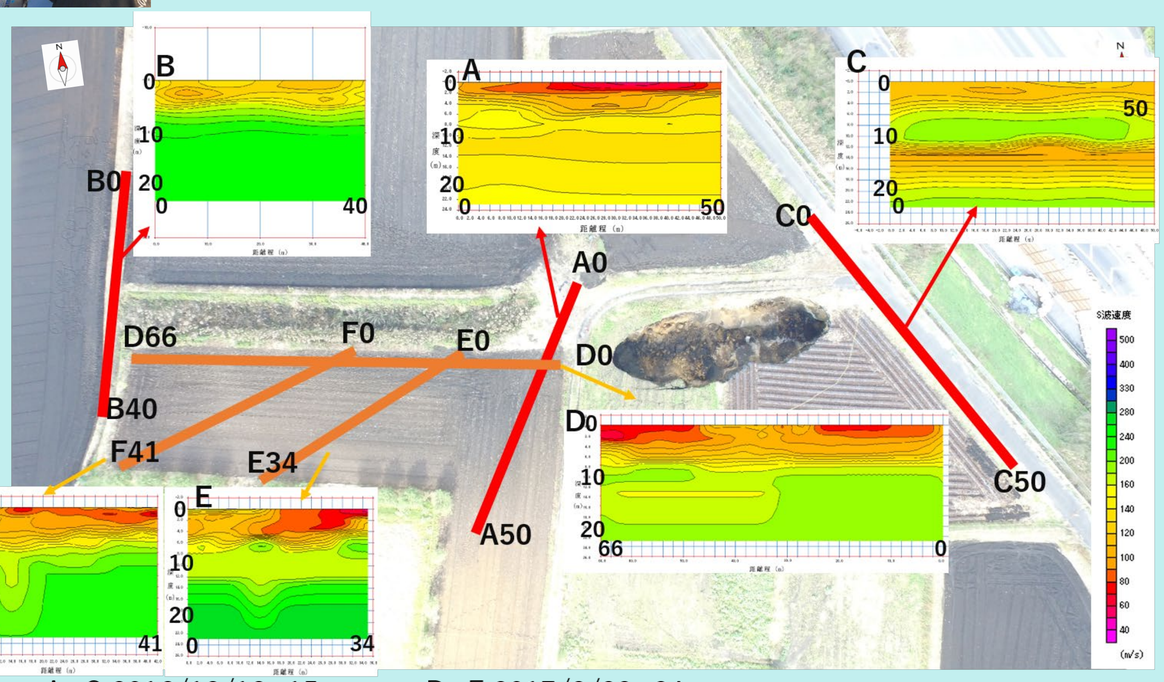
表面波探査試験 Surface wave survey



波を起こして伝播速度から地盤のゆるみを測定

・陥没西側のA測線の10m付近に弱部
・D測線の西側に目玉のようなゆるみ

✓Weak layer around 10m depth of line A
✓Loosening at the west side of line D



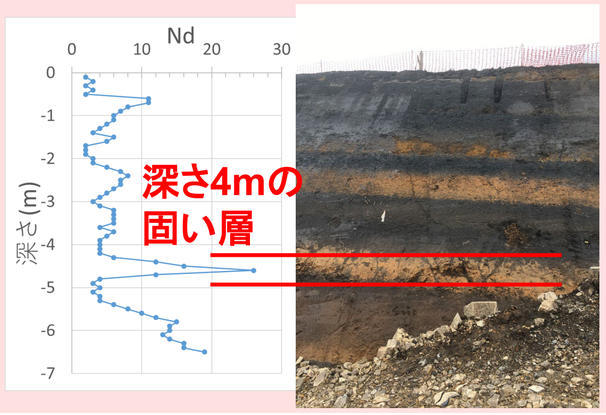
A~C 2016/12/12~15　D~F 2017/2/22~24

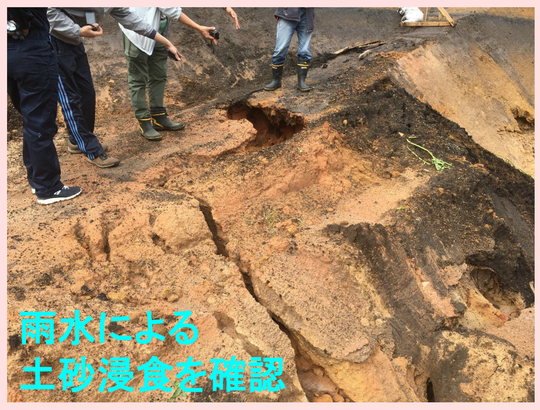
追加調査 復旧工事による掘削ため、より詳細な地盤の様子が把握された Excavation of sinkhole due to restoration work was conducted

掘削の様子
Excavation of sinkhole



2017/5/12~14





・深さ4mの固い層の特定
・工事中に固い層の下に空洞が発見された
・雨水による侵食が起きる層も見られた

✓Hard layer at 4m depth was confirmed
✓Cavities under the hard layer were found during the excavation
✓Layers apt to erode were also confirmed

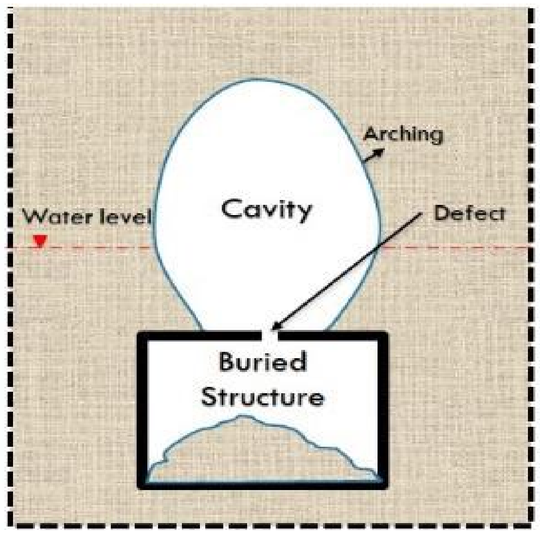
For further information, contact: Prof. Reiko Kuwano, Bw-304, Institute of Industrial Science , Tel：03-5452-6843　Mail: kuwano@iis.u-tokyo.ac.jp

DEM Simulations on Development of Subsurface Cavity using Suction-Tension Model

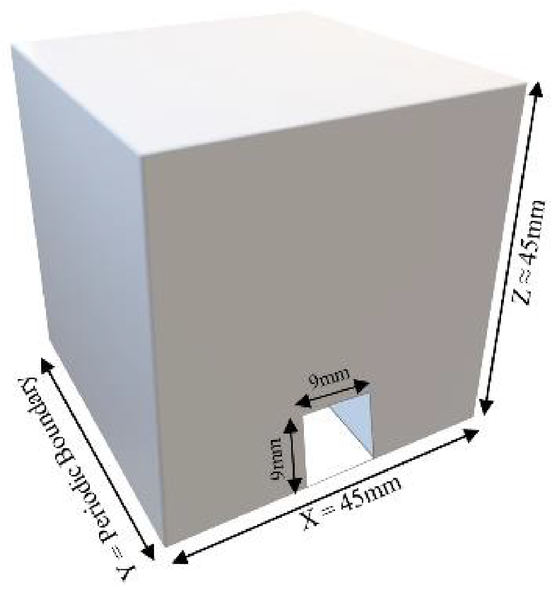
不飽和サクションモデルによる地中空洞DEMシミュレーション

Defects in buried structures along with ground water interaction, can cause formation of underground cavities. Typical DEM models do not account for capillary forces that are needed for realistic simulations of cavity growth. A new suction-tension model was introduced in the present DEM simulations to study the stability of cavity and the soil arching developed around the cavitated region. It was found that the inter-particle capillary force is a key to sustain a subsurface cavity, and both particle shape and particle size also play a vital role for the stability. A strong arching was visible in the ground with stable subsurface cavities.

地下埋設物の破損は地下水の影響を受けて地中空洞を形成する原因になると考えられています。地盤工学の分野で一般的なDEMモデルでは空洞の形成に不可欠な毛細管力を考慮していません。そこで、空洞の安定性と空洞周辺のアーチ効果を表現するため、DEMシミュレーションに新しいサクションテンションモデルを導入しました。結果として、空洞の安定には粒子間のサクションが最も重要であり、さらに粒子形状と粒径も重要な役割を担うことが明らかとなりました。また、安定した空洞を形成した地盤では強いアーチ効果も観察されました。



Cavity formation due to a defect in substructure

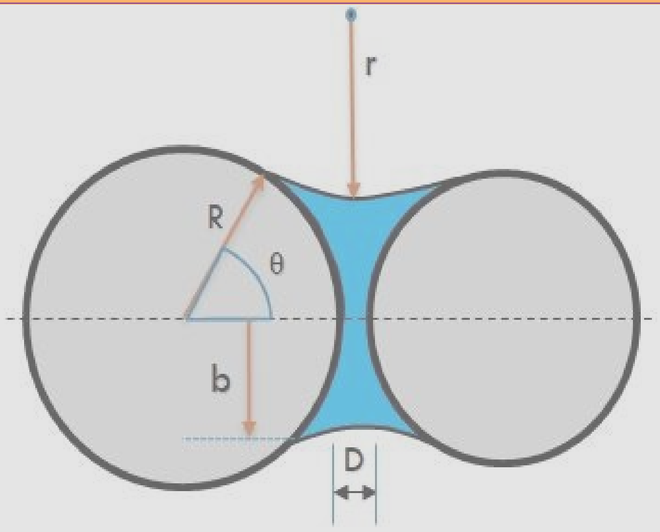


Model space for DEM simulations

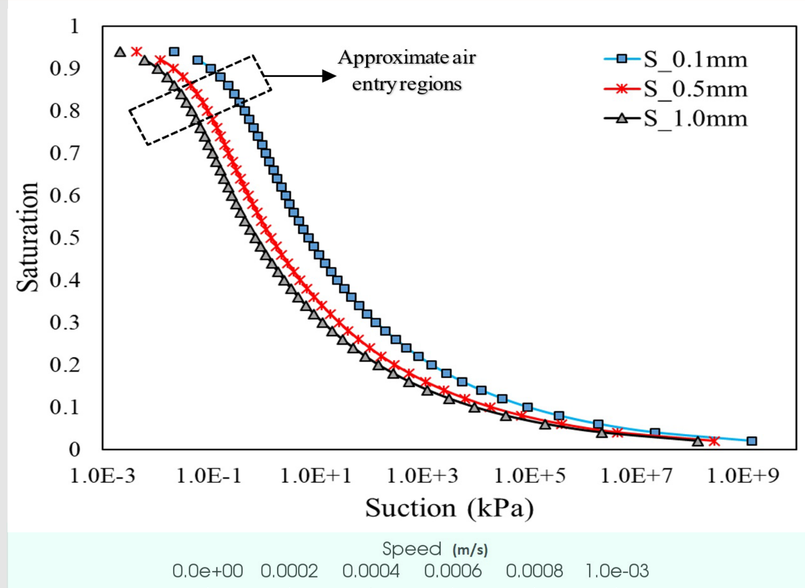


DEM Simulations: X: 45 mm Y: 10xD_{50} Z: 45 mm **Diameter of particle:** 0.6 – 1.7mm **Particle type:** Spherical & non-spherical

Friction coefficient (μ): 0.35 **Young's modulus:** 71.6 GPa **Poisson's ratio:** 0.23 **Specific gravity:** 2.5



Contacting particles through water bridge



$$b = R(S_r)^3$$

$$\theta = sin^{-1}\left(b/R\right)$$

$$b' = R(tan\theta + 1 - sec\theta)$$

$$r = R(sec\theta - 1)$$

$$S = T_c\left(1/r - 1/b\right)$$

$$f_c = S(\pi b')^2 + 2\pi T_c b'$$

$$f = f_c + f_N \quad \text{if } D < 0$$

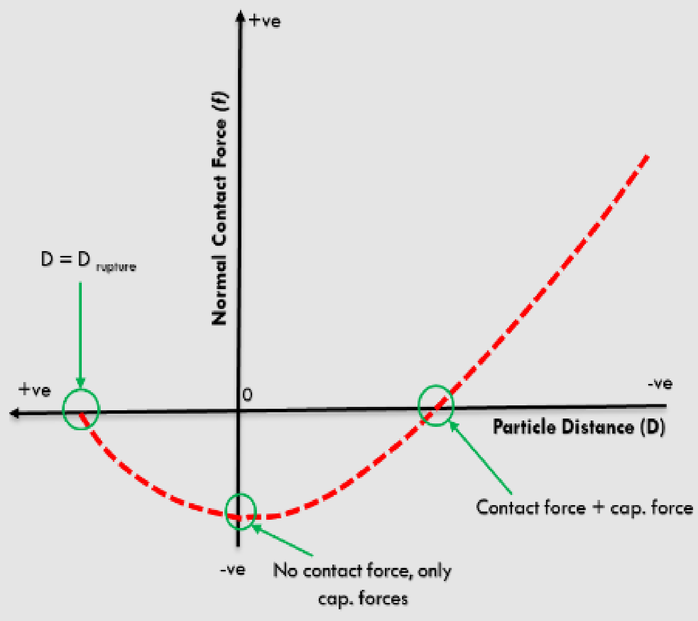
$$f = f_c \quad \text{if } 0 \le D \le D_{rupture}$$

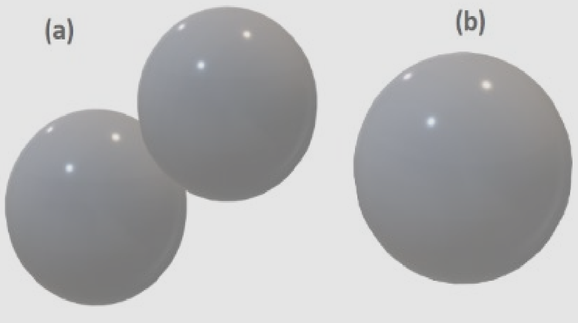
$$f = f_c = 0 \quad \text{if } D > D_{rupture}$$

f = Total force

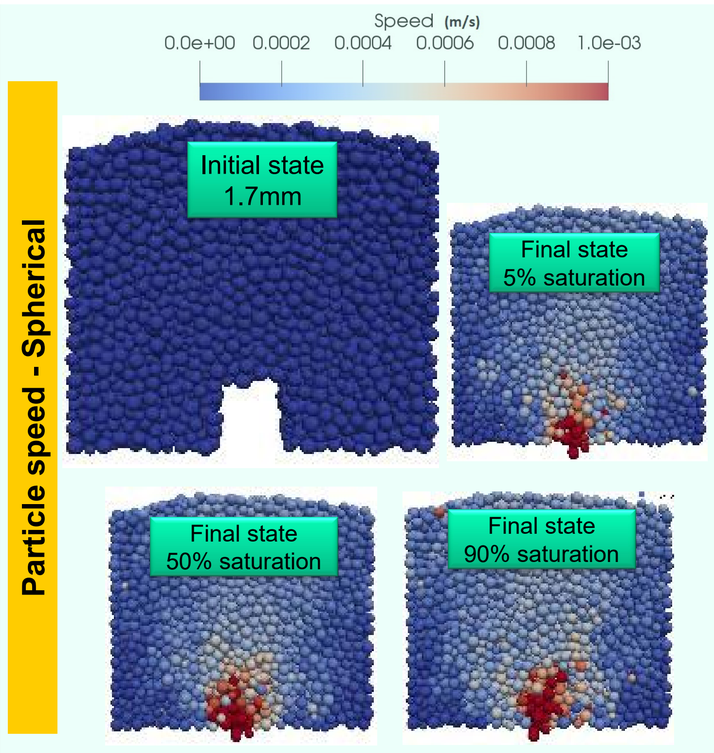
f_c = Capillary force

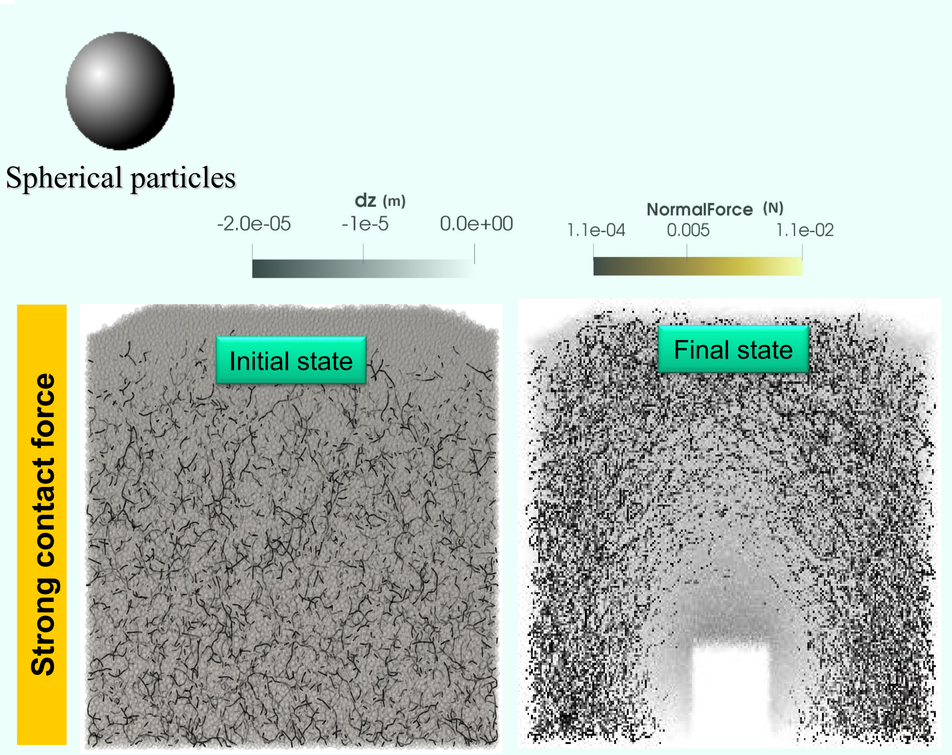
f_N = Hertzian force

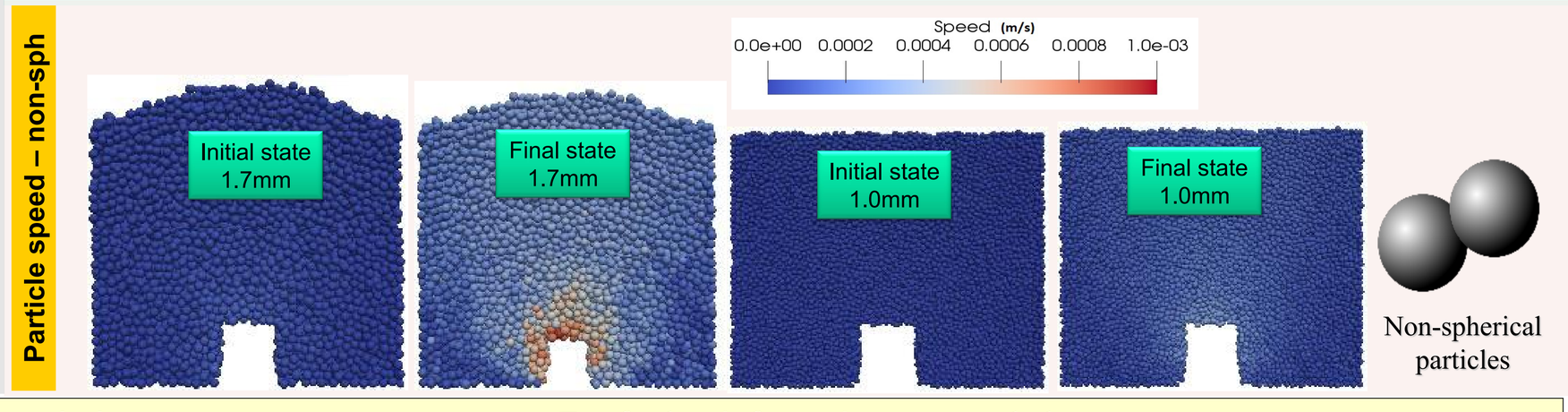




(a) non-spherical (b) Spherical particle







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Syed Umair
Ali Naqvi (2019)

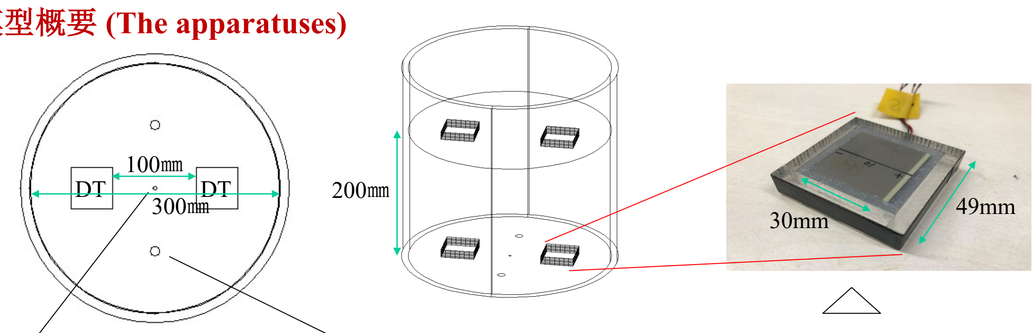
Dynamic wave propagation in soil around a cavity

地中空洞周りの波動伝播特性

Dynamic wave survey is usually conducted to investigate the structure of the ground. However it is not effective for detection of subsurface cavities. In this study, with the aim of improvement on cavity detection method, model tests were conducted to look into wave propagation through the model ground during the process of cavity formation. DEM (Discrete Element Model) simulations were also conducted with the presence of a subsurface cavity to compare it with the model test results. In the model tests, decrease in wave velocity and lowpass frequency ($f_{lowpass}$) was observed while in DEM simulations, only decrease in $f_{lowpass}$ was observed.

地盤中の地層構造を認識するために弾性波探査による方法が多く用いられているが、地中に空洞がある場合にその存在は一般に検知が困難である。本研究では、空洞検知手法の改善を目的として、地盤中に空洞が発生する過程の弾性波伝播特性の遷移を、模型試験および、個別要素法を用いて検討した。模型試験ではゆるみと回折による速度と$f_{lowpass}$の減少、DEMでは回折による$f_{lowpass}$の減少が確認された。

模型概要 (The apparatuses)



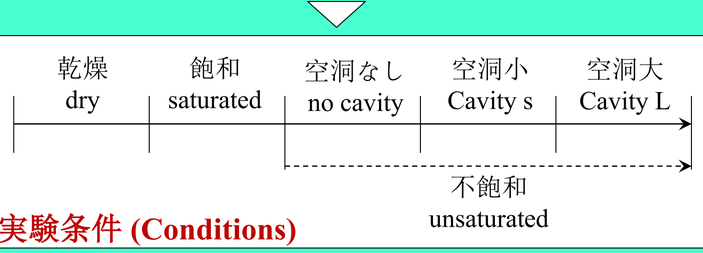
空洞生成時に開閉する
スリット(直径5mm)
An opening through which soil and water can be drained and form a cavity
(5mm in diameter)

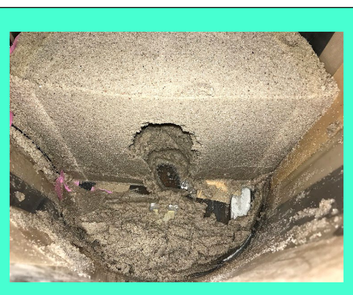
飽和状態調節用の給水・排水口(直径5mm)
An opening used to change saturation condition by supplying and draining water.
(5mm in diameter)

ディスクトランスデューサー
：電圧と変位を変換する
Disk Transducer
: It converts voltage into displacement and vice versa.

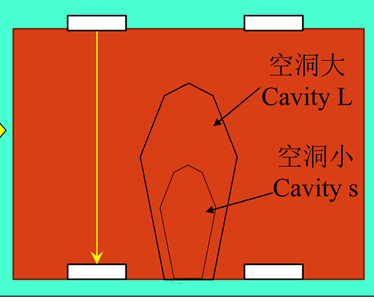
上部のDTから数nmの弾性波(2kHz-30kHz)を発生させ、下部のDTで受信する試験を以下の5通りの地盤状態で行う。
Elastic waves (2kHz-30kHz in frequency, a few nanometers in displacement) are transmitted from the upper DT and received by the lower DT. The ground conditions were as below.

実験条件 (Conditions)



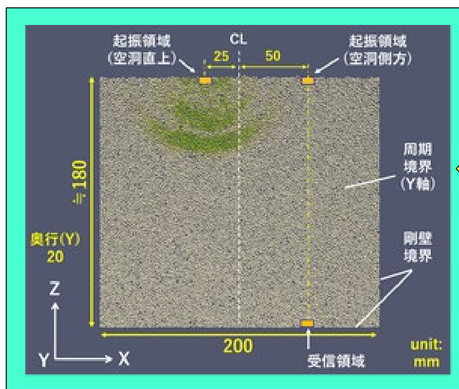


試験後の断面と推定される試験中の空洞断面
The cross section after the experiment and the assumed cross section during the expansion of the cavity.

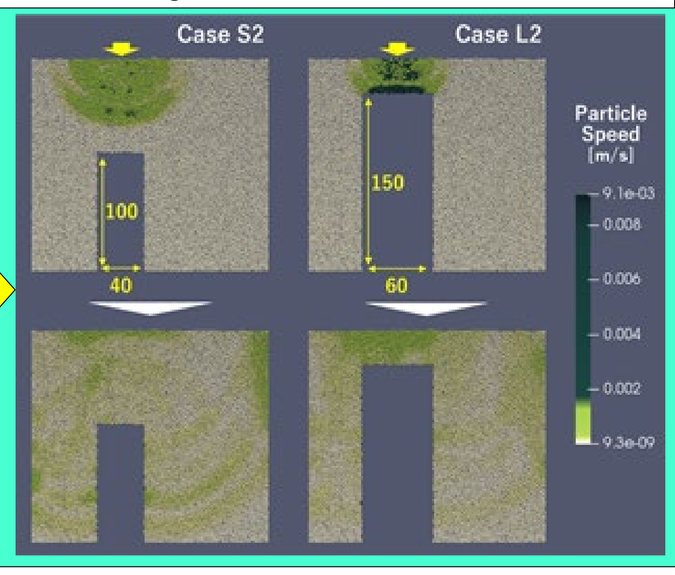


個別要素法で用いたモデル (DEM Model)

上部の2領域いずれかで発生させた弾性波を底面上の領域で受信する。以下では空洞直上の領域から発生させた弾性波について示す。
The model designed for DEM simulation. Elastic wave transmitted from either of two regions at the surface is received in a region at the bottom.

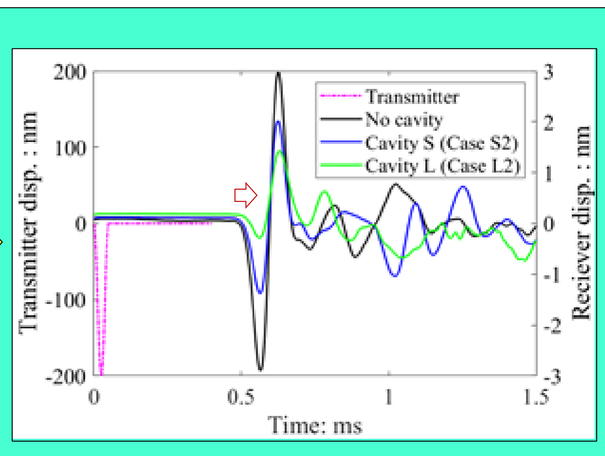


空洞は右のサイズで発生させた。空洞の安定のために粒子間に5kPaのサクションを考慮した。剛壁境界と同様、空洞境界でも波の反射を確認した。
Cavities were arranged as shown on the right. For the stability of cavities, suction of 5kPa was given. The reflection of elastic wave was observed both at the sample boundaries and the cavity boundaries.

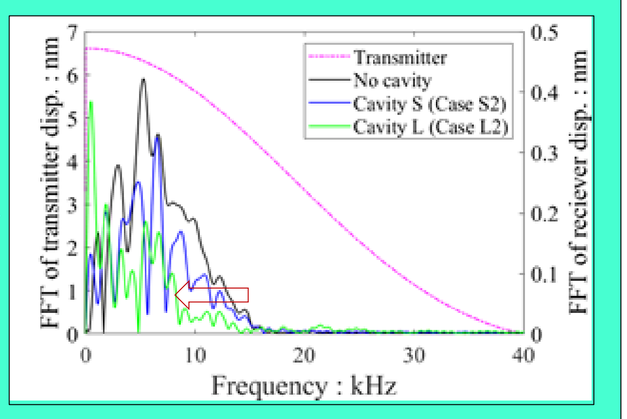


DEMの結果 (DEM results)

受振領域での時刻歴応答。空洞なしの場合に比べて空洞が大きいほど波の立ち上がりが若干遅いことが確認された。
The response at the receiver region. The dropping point was observed a little later when the size of the cavity was large.

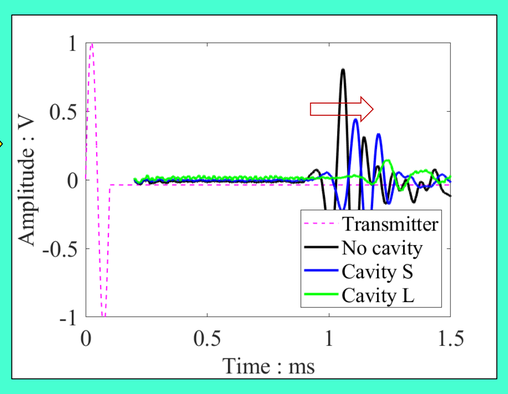


受信領域での時刻歴応答の周波数スペクトル。模型試験と同様、空洞の拡大に伴って高周波数帯成分の減衰がみられた。
The frequency spectra of the received waves. Same as the model test, the higher frequency component dropped for the cases with a large cavity.

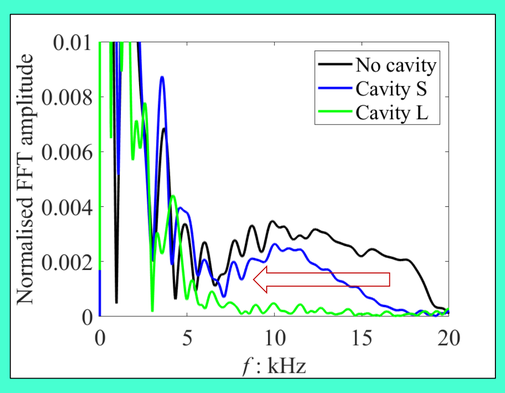


実験結果 (Results)

地盤状態ごとの弾性波伝播速度。空洞の拡大とともに伝播速度の減少が見られる。これは空洞とともに周りのゆるみが拡大したためと思われる。
Measured elastic wave velocity in the process of cavity formation. Decrease in velocity can be observed in accordance with cavity expansion. The cause is assumed to be the expansion of loosened area around the cavity that accompanied cavity expansion.



また受信波の周波数成分について比較した。ここで、地盤が伝播可能な最大周波数$f_{lowpass}$は地盤状態に応じて決定されることが分かっている。空洞の拡大に伴って$f_{lowpass}$の減少がみられた。
Comparison of frequency components of the received waves. $f_{lowpass}$ (the maximum frequency that can pass through the ground) is determined by the ground condition. $f_{lowpass}$ decreased in accordance with the expansion of the cavity.



結果の比較 (Comparison of the results)

模型実験での結果の変化には空洞周りのゆるみの発生により、密度の低下と伝播経路の回折という二通りの影響があったと考えられる。一方でDEMではサクションを大きくした結果回折のみの影響を反映した結果になった。粒子の条件を考慮することで空洞周りのゆるみをDEMで再現しその影響を可視化する研究が必要である。
In the model test, the results were affected by ground loosening around the cavity in two ways: the decrease in density and the diffraction of the propagating path. On the other hand, in the DEM simulation, the results were affected only by the diffraction because suction had to be increased in order to sustain the structure. By considering the particle conditions, the loosening around the cavity has to be reproduced in DEM modeling to visualize its impact on the results.

本研究に関する担当研究室は桑野研究室です.
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中田祐輔 (2019)

DEM analyses on P-wave propagation around a subsurface cavity

地中空洞周りの圧縮波伝播特性に関するDEM解析

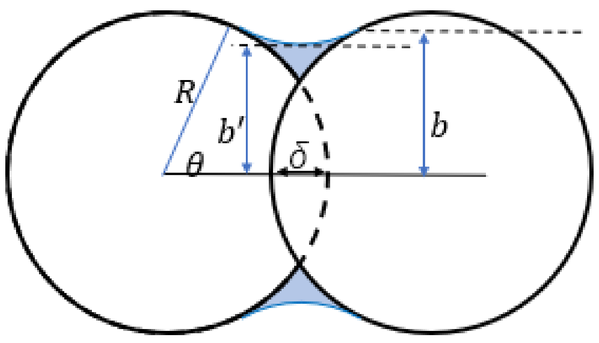
Research purpose　研究目的

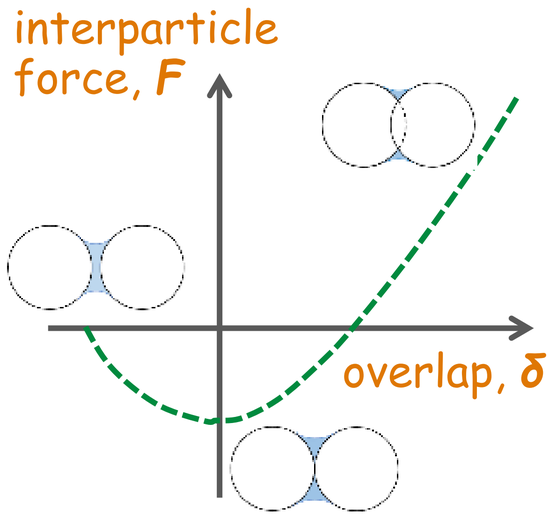
Road cave-in or sinkhole event is often triggered by growth of subsurface cavities. However, it is not easy to detect a subsurface cavity and estimate their locations accurately in ground. Our previous experiments revealed that elastic wave velocities are reduced when propagating in the vicinity of a cavity. In this study, discrete element method (DEM) simulations have been performed to understand how compression (P-) waves propagate around a subsurface cavity.

地盤陥没現象は地中空洞が成長することで発生すると知られていていますが，地中空洞の存在やその位置を検知することは容易ではありません．当研究室で過去に実施した模型試験では空洞近傍を伝播する弾性波の伝播速度が低減することを確認しましたが，実際の波動伝播の様子を可視化することは困難です．本研究では個別要素法（DEM）数値解析を実施することで，地中空洞周りの圧縮波（P波）の伝播特性の解明を目指しています．

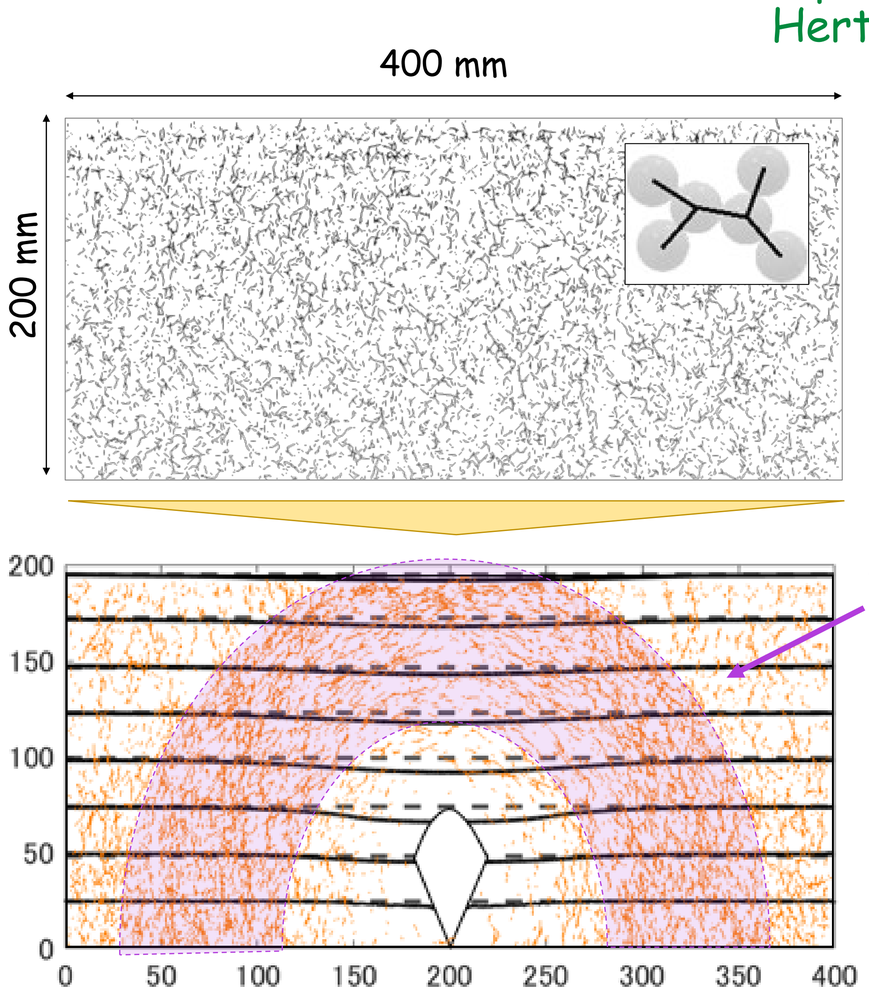
Capillary force model

毛管力モデルによる粒子間付着力を考慮





F = capillary force + Hertzian contact force



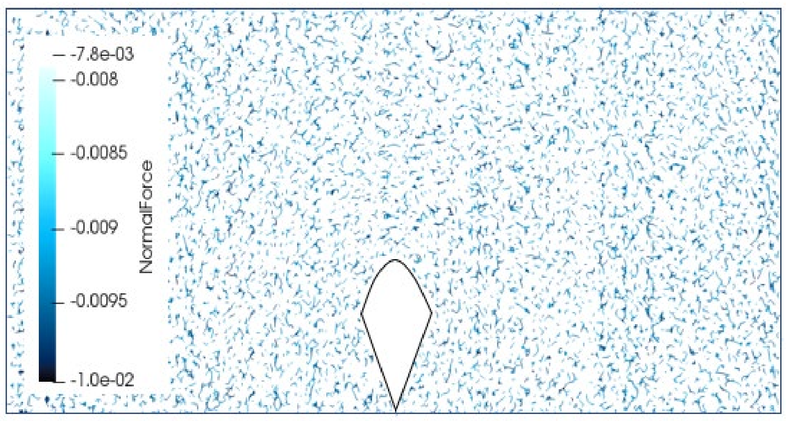
Force chains before creating a cavity

粒子間接触力網（空洞生成前）

Soil arching

Force chains after creating a cavity

粒子間接触力網（空洞生成後）



Distribution of capillary forces after creating a cavity

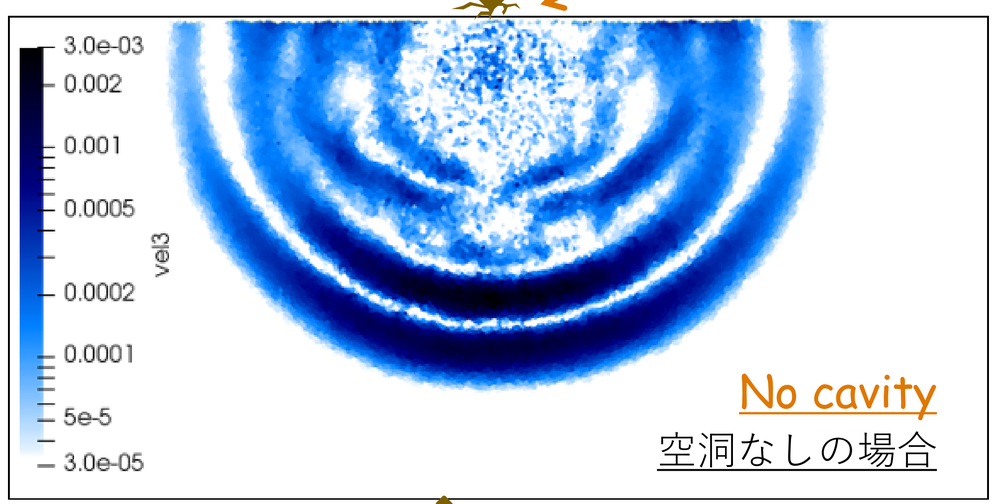
毛管力による粒子間付着力分布（空洞生成後）

P-wave propagation

P 波伝播性状

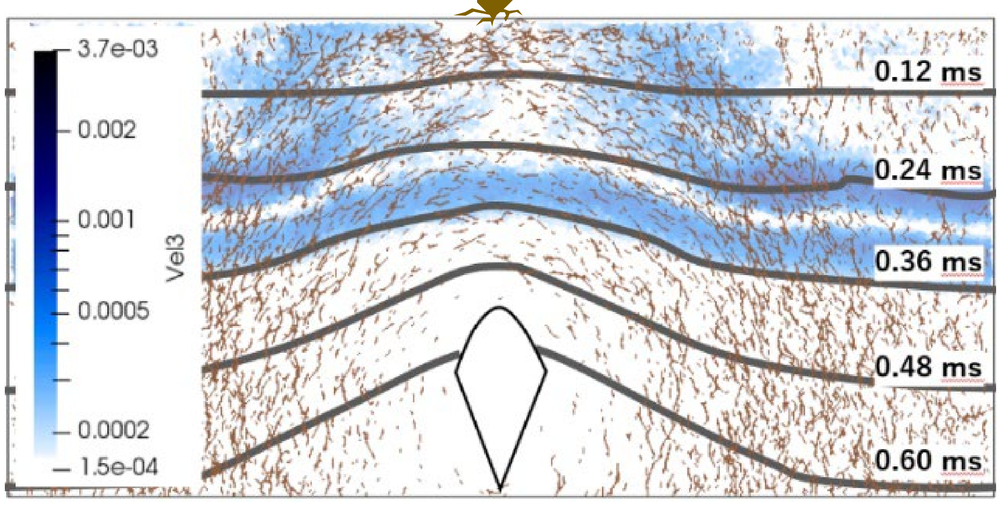
Downward excitation

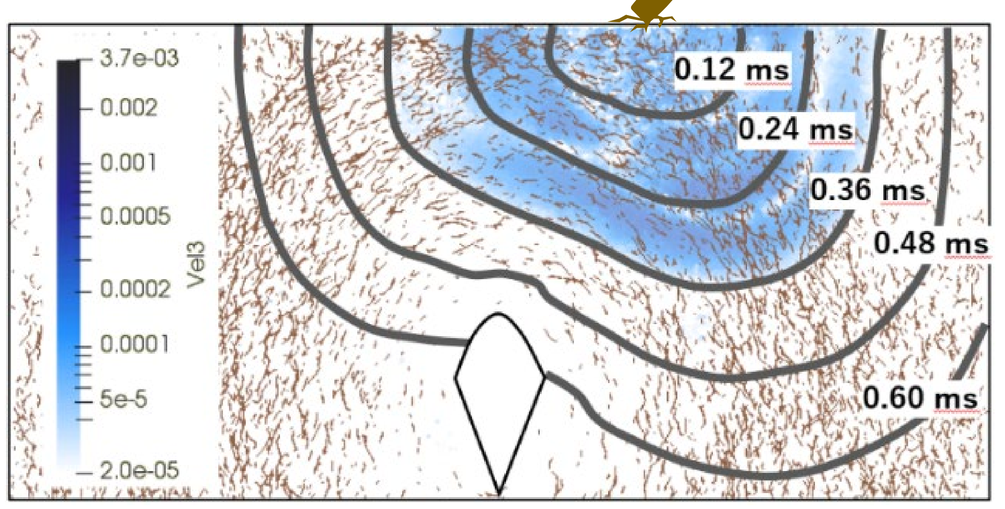
下向きに加振



No cavity

空洞なしの場合





- P-waves propagate along an arch around a cavity.
- 空洞周りのアーチに沿って伝播することを確認した．

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中田祐輔(2020)
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Exploration for Wave Propagation Around Ground Loosening Using Discrete Element Method

地盤内ゆるみ検知のためのDEM弾性波伝播解析

The ground cave-in accident caused by shield tunnel excavation in Chofu, Japan in 2020 revealed that ground loosening and subsurface cavities potentially cause ground cave-ins even deep in the ground. Although ground-penetrating radar method has been utilized to detect them, its applicability is limited to the shallow ground about 1.5 m below the ground surface. This contribution is a fundamental study aimed at detecting loosening depth in the ground, with the goal of measuring dynamic waves from inside a tunnel. To understand wave propagation and particle-scale response around loosened sandy soil, this study adopts the discrete element method (DEM).

2020年に調布市で発生したシールドトンネル掘削に伴う地盤陥没事故は，大深度であっても地盤のゆるみや地下空洞が地盤陥没を引き起こす可能性を明らかにした．空洞を検知するために地中レーダー法が実用化されているが，その適用範囲は地表から 1.5 m程度の浅い地盤に限られる．そこで本研究は，トンネル内部から地下深くの地盤内のゆるみを検知するために，弾性波の伝播特性を理解することを目的とする．一連の個別要素法（DEM）数値解析を行い，ゆるんだ砂地盤周りの粒子スケール応答を評価した．

1. Modelling approach

Using U-Tokyo Supercomputer (Wisteria/BDEC-01)



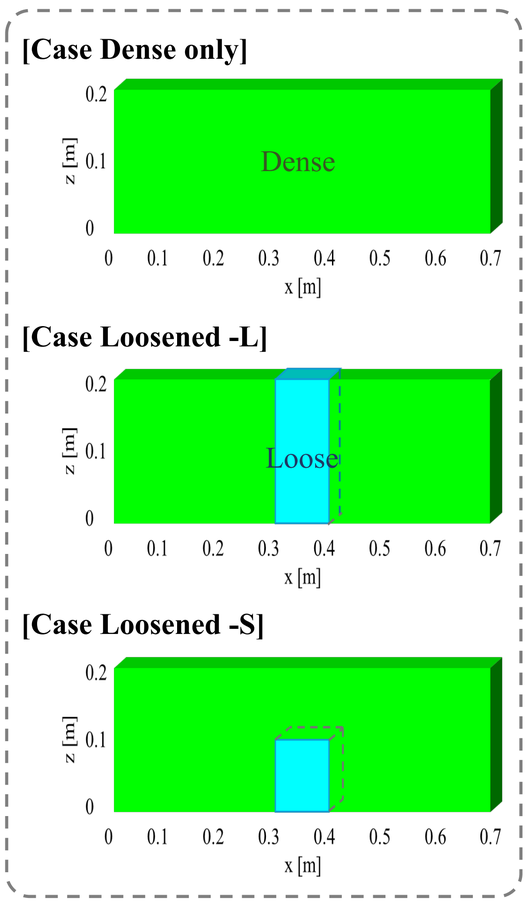
1) Particle generation
- Spherical particle

↓

2) Air-pluviation process
- Hertz-Mindlin contact model

↓

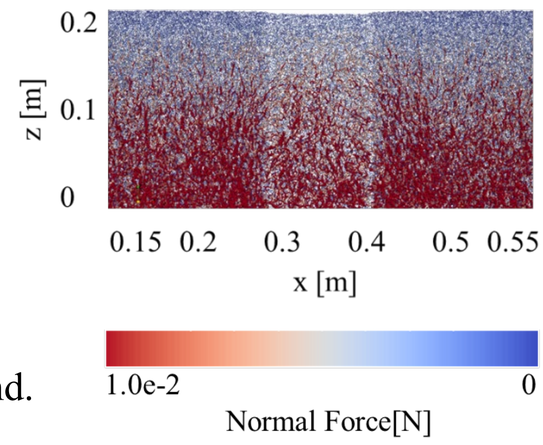
3) "Patchwork" process
- Dense + Loose ground model



2. Inter-particle contact forces

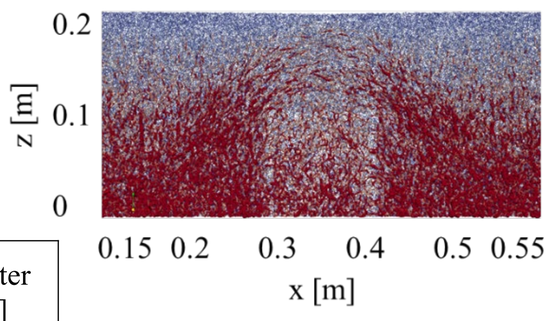
[Case Loosened –L]

- The vertical contact forces are predominant over the horizontal ones due to the effect of gravity.
- At the boundary between Dense and Loose, the horizontal forces are dominant in which soil pressure is exerted to support each other's ground.



[Case Loosened –S]

- Soil arching is generated over the loose area.



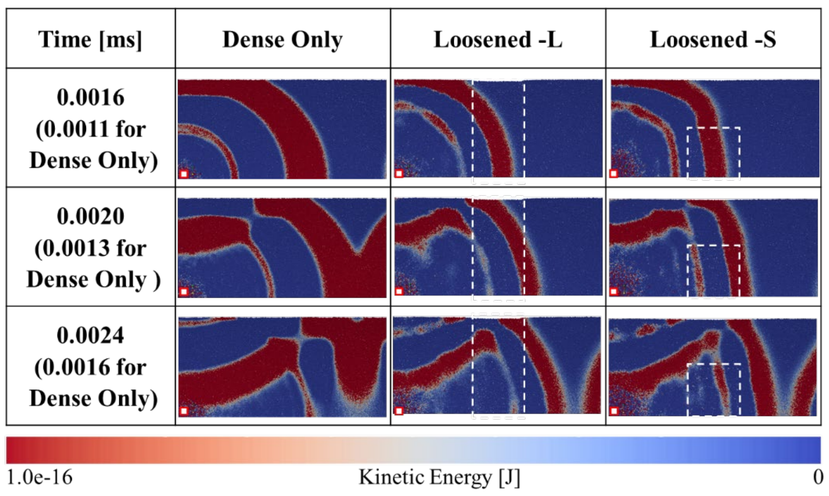
Young's modulus [GPa]	Poisson's ratio	Specific gravity	Diameter [mm]
71.6	0.23	2.65	1.4~2.2

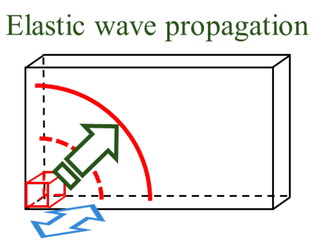
3. Wave propagation simulations

The particles inside the region of the transmitter were excited in the Y-direction to generate elastic S-waves, with a single period of cosine wave form (double amplitude displacement: 10 nm; frequency: 1 kHz)

Excitation inside Dense area

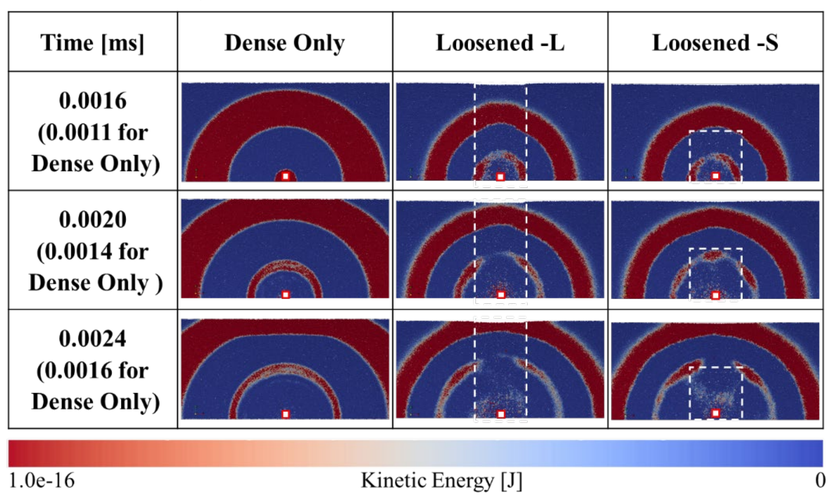
- In model grounds with loosening, the decrease in energy as the wave passes through the loose area is indicative of lowpass filtering effect.
- The property of the transmission energy is also explained by the concept of acoustic impedance (ZI)

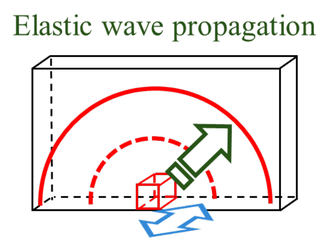




Excitation inside Loose area

- In model grounds with loosening, residual energy around the bottom loose area can be observed.
- Especially in Case Loosened -S, the first traveling S-wave is transmitted, but the second is reflected at the Loose-Dense boundary.





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Fundamental study for detecting deep underground cavity and loosening by shield tunneling

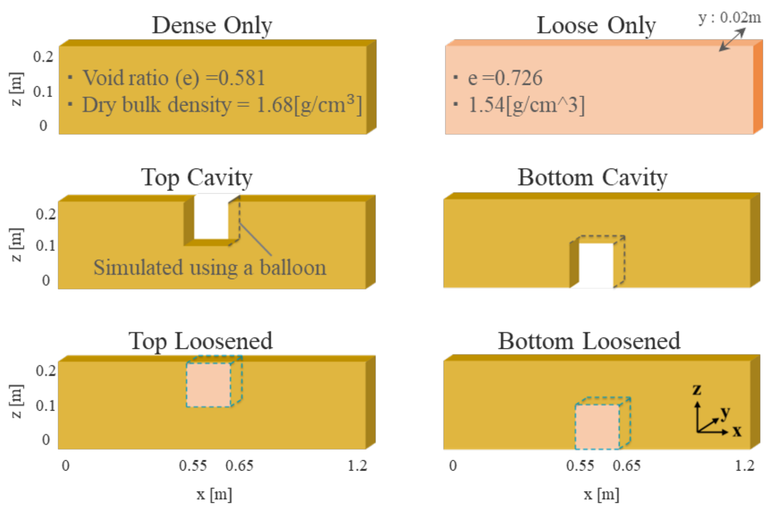
シールドトンネル掘削に伴う大深度空洞・ゆるみ検知のための基礎的検討

The ground cave-in accident associated with shield tunnel excavation in Chofu, Tokyo (2020) revealed the risk that cavity and loosened ground, even at great depths, can cause ground cave-ins. Current exploration methods have limitations in exploration depth, and the detailed mechanisms of elastic wave propagation around deep-seated cavity and loosened ground have not yet been clarified. Therefore, this study aims to enable early detection by elastic wave exploration from inside tunnels and conducts a fundamental study through numerical analyses (Discrete Element Method) and laboratory soil tests.

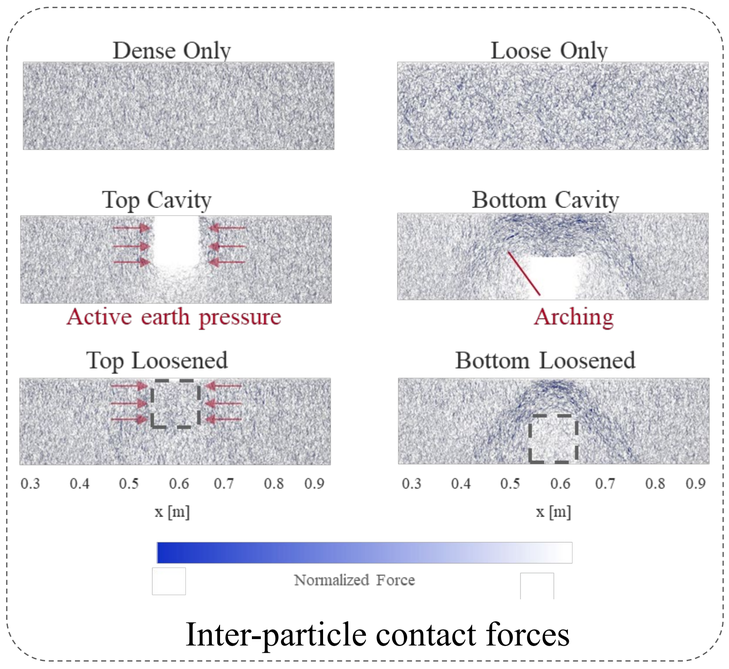
東京都調布市でのシールドトンネル掘削に伴う地盤陥没事故（2020）により，大深度における空洞やゆるみであっても地盤陥没を引き起こす危険性が新たに示された．現行の探査手法では探査深度に限界があり，また大深度空洞やゆるみ周辺における弾性波伝播の詳細なメカニズムは明らかになっていない．そこで本研究はトンネル内部からの弾性波探査により早期検知することを目的とし，数値解析と室内土質試験により基礎的な検討を行った．

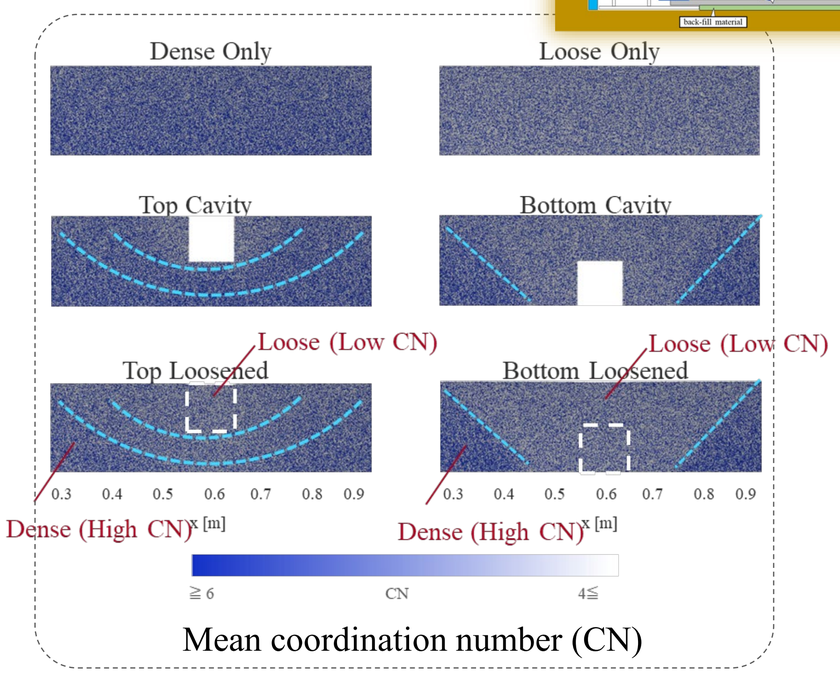


1. The Discrete Element Method (DEM) simulation method and physical characteristics of models



Young's modulus [GPa]	Poisson's ratio	Specific gravity	Diameter [mm]
71.6	0.23	2.65	1.4~2.2

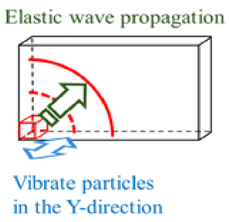


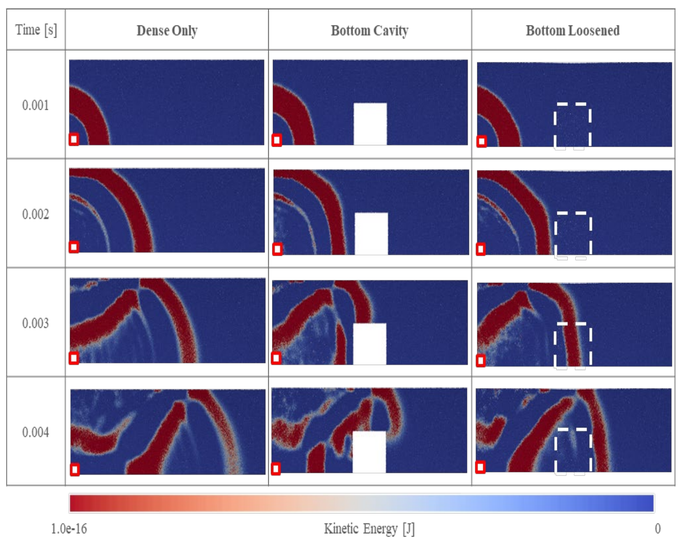


2. Investigation of exploration mechanisms for deep-seated cavity and loosened ground

Cavity
generate reflected waves

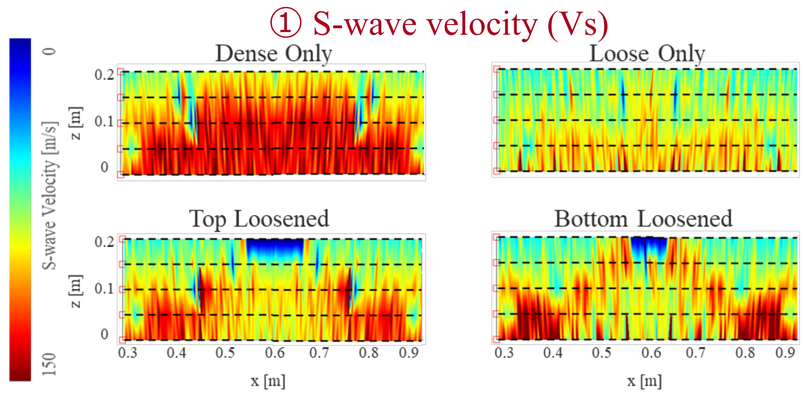
Loosened ground
no significant reflections



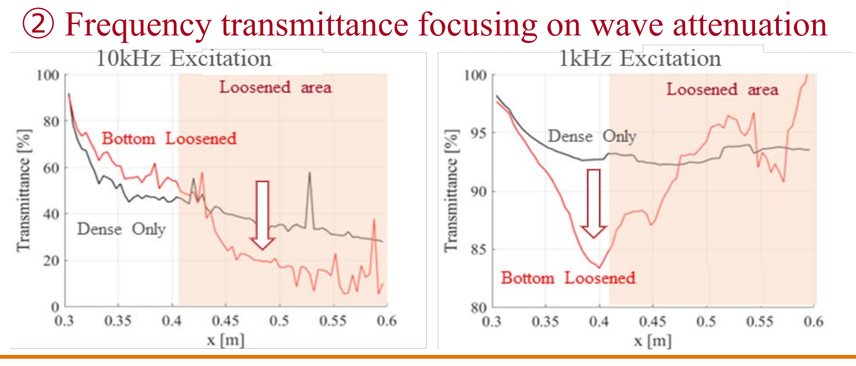


How can loosened grouond be detected?

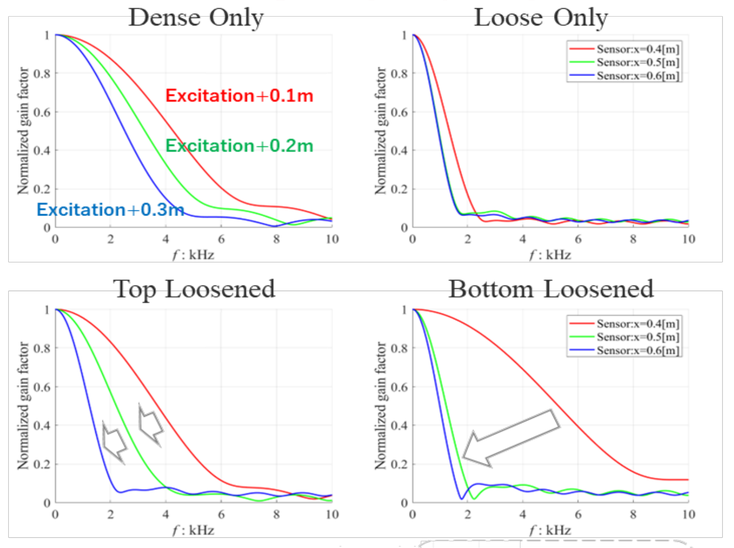
① S-wave velocity (Vs)



② Frequency transmittance focusing on wave attenuation



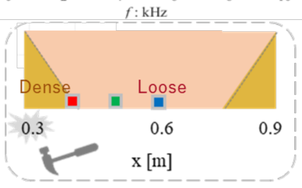
③ Cutoff of high-frequency components



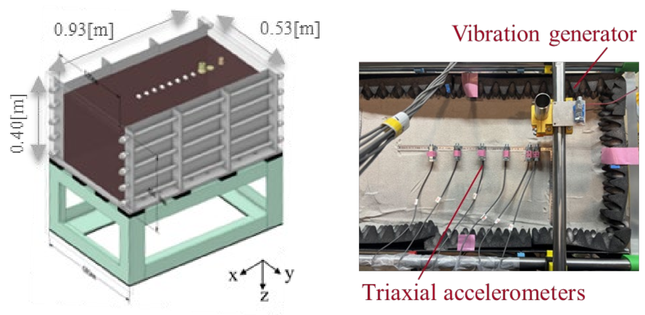
Gain Factor = $|FFT_{out}|/|FFT_{in}|$

FFT_{in} : The frequency components of the input wave

FFT_{out} : The frequency components of the output wave

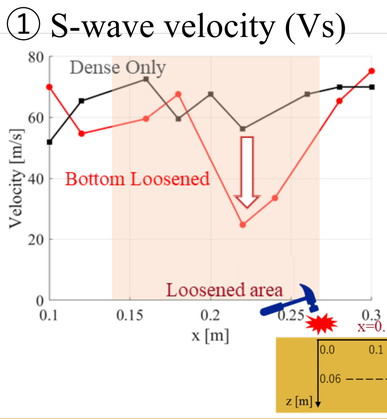


3. Evaluation of exploration mechanisms through laboratory soil tests

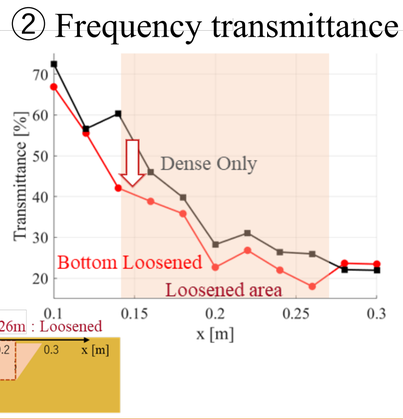


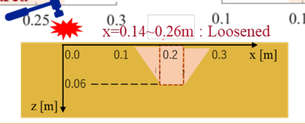
- Surface loosened area & vibration generation + sensing (upside-down setup)

① S-wave velocity (Vs)



② Frequency transmittance





4. Conclusion

- Reflected waves from cavity may enable detection of deep-seated cavity.
- In loosened area, contact forces and CN affect wave behavior (Vs reduction).
- Vs reduction, transmittance attenuation, and high-frequency cutoff are effective indicators of loosened ground.

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Surface-wave survey at a ground cave-in site in Abira town, Hokkaido

北海道安平町の地盤陥没跡地における表面波探査

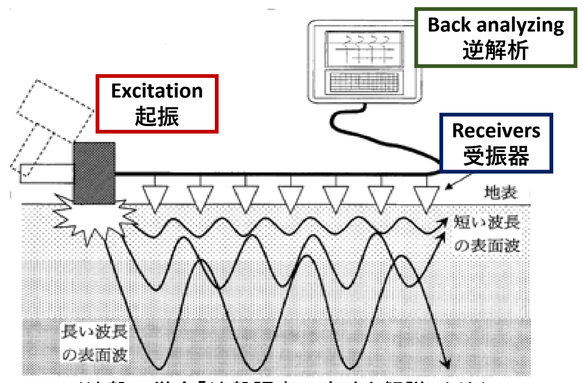
Cave-ins occur in various places both in Japan and overseas. If a cavity is located deep underground, there is a risk that the cavity grows to a large size and results in a large-scale cave-in. Radar surveys can detect cavities near the ground surface with high accuracy, but it is difficult to detect cavities deeper than 2m below the ground surface. Currently, there is no effective non-destructive exploration for deep cavities. In this report, the results of the surface wave survey conducted at a ground cave-in site in Abira Town, Hokkaido were summarized, and the possibility of using surface wave surveys to explore deep cavities is discussed.

地表に突如として穴があく地盤陥没現象は国内外問わず様々な場所で発生しています。地盤陥没の芽となる空洞が地中深いところにある場合、条件によっては空洞が大きく成長し、大規模な陥没に至る危険性があります。地表近くの空洞は、レーダー探査によって高い精度で空洞の検出が可能ですが、地表から2mを超える深さの空洞探査には対応が困難とされています。したがって現在は深部の空洞に対して非破壊での探査は困難な状況です。本研究では、2009年4月に北海道安平町内のゴルフ場で発生した地盤陥没の跡地において実施した表面波探査の結果を整理し、表面波探査による深部空洞の探査可能性について検討を行っています。

Surface wave survey　表面波探査の概要

In surface wave surveys, **Rayleigh wave**, which is one of the surface waves, is used. The amplitude of Rayleigh waves decays rapidly in the direction of depth. The larger the wavelength, the deeper the wave propagates. In general, the stiffness of the ground is different in the vertical direction, and the velocity of elastic waves changes with depth. By back-analyzing the difference in propagation velocities with wavelengths (**dispersion**), the **S-wave velocity structure** of heterogeneous ground can be roughly determined.

表面波探査では、地盤内を伝播する表面波の一つである**レイリー波**が用いられます。レイリー波の振幅は深度方向に急激に減衰し、波長が大きいほどより深くまで伝播します。不均質な地盤は深度方向に剛性が異なり、地盤内を伝播する弾性波速度は深度に応じて変化します。この波長による伝播速度の違い（**分散**）を逆解析することで、地下約20mまでの地盤の**S波速度構造**が大まかに求まります。



（地盤工学会「地盤調査の方法と解説」より）

Cave-in accident in Abira town, Hokkaido　北海道安平町の地盤陥没について

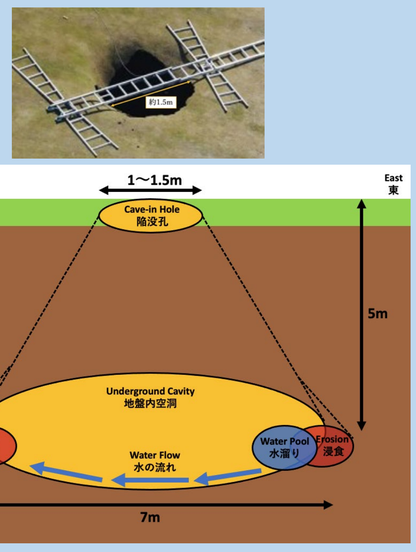
✔The cave-in accident occurred in April 2009.
陥没事故は2009年4月に発生。

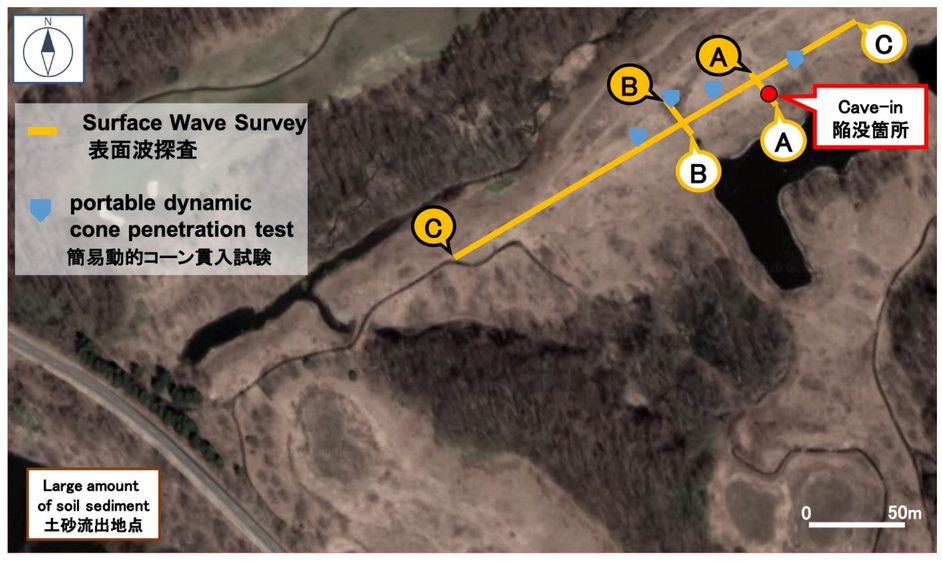
✔The sinkhole was 5m deep with a maximum diameter of 7m.
陥没孔は深さ約5m、最大直径約7m(陥没孔底部付近)。

✔The site is where **a large-scale embankment was built on the former stream topography**.
陥没箇所はかつて**沢地形上に大規模な盛土造成**がされたところだった。

✔**Water channels were detected at depths of 5m and 8m** near the sinkhole.
陥没孔付近の**深さ5mと8mの位置で水みち**が確認された。

✔After the excavation, the sinkhole was backfilled.
掘削調査の後、陥没孔は埋め戻されている。





Results of Surface wave survey 表面波探査の結果

Line A　測線A

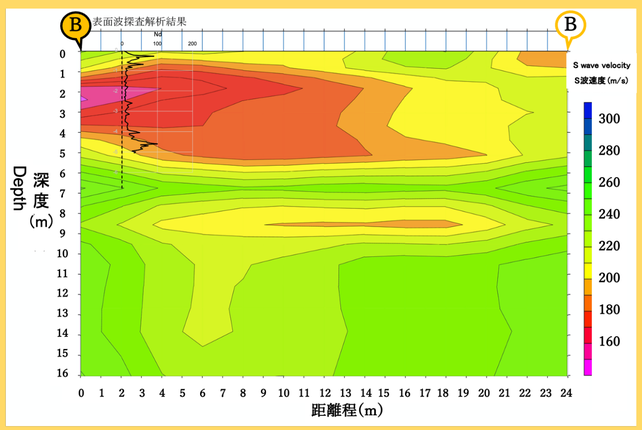
・S-wave velocities were especially low near the point of the sinkhole.
→ **Possibility of a loosening area**
陥没箇所の地表付近において、特にS波速度が小さい。
→ **緩み領域の可能性**

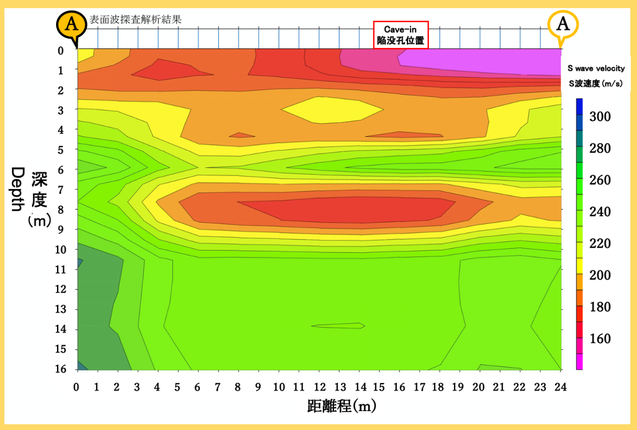
Line B　測線B

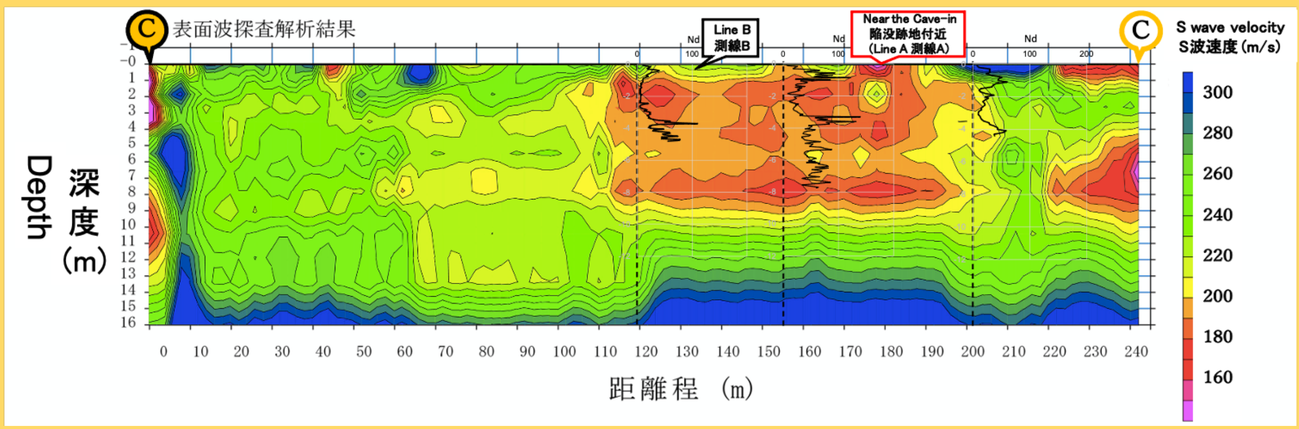
・A portable dynamic cone penetration test was conducted where particularly low S-wave velocities were observed.
→ **Consistent with the S-wave velocity distribution**
特に小さいS波速度の地点で簡易動的コーン貫入試験を実施
→ **表面波探査で得られたS波速度分布との整合性を確認**

Line C　測線C

・From about 110 to 200m, there are bands of low S-wave velocities at the depths of 2m, 5m, and 8m.
→ **Possibility of erosion by water channels**
距離程110～200mにかけて、深さ約2m、5m、8mでS波速度が小さい帯状の領域を確認
→ **水みちによる浸食の可能性**





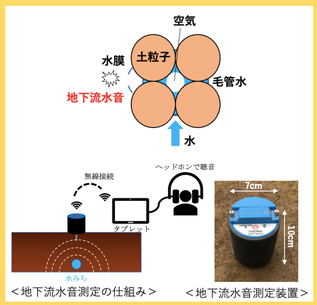


The results suggest that ...

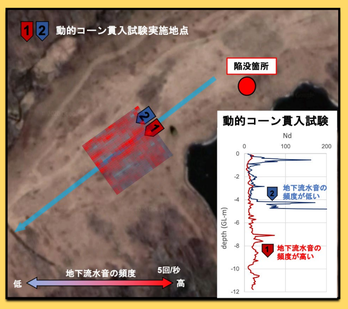
✔ **The ground is susceptible to erosion because of the large-scale embankment.**
盛土造成により、侵食されやすい地盤である可能性

✔ **The ground has water channels that promote sediment flow.**
土砂流出を促進する水みちが地中に存在する可能性

(A groundwater flow sounding survey was conducted with this study and its effectiveness was confirmed.)
（桑野研究室では、本調査と合わせて地下流水音調査を実施しており、その有効性を確認しています。）



＜地下流水音測定の仕組み＞　＜地下流水音測定装置＞



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Challenge of Detecting Deep-Ground Cavities Using Wave Propagation in Soil

地盤内波動伝播特性に着目した深部空洞探査の可能性

Cave-ins, which occur in various places both in Japan and overseas, are serious problems that may cause economic damages and human casualties. Radar surveys can detect relatively shallow cavities with high accuracy, but it is difficult to detect cavities deeper than 2m below the ground surface. Currently, there is no effective non-destructive exploration for deep cavities. In this study, the characteristics of elastic wave propagation around cavities were investigated by DEM (Discrete Element Method) analysis and field tests, and the possibility of detecting such deep cavities is considered.

地表に突如として穴があく地盤陥没現象は経済的被害や人的被害が生じ得る重大な問題となっています。地中レーダーを利用した空洞探査技術により、地下約2m以浅の空洞は探査可能で陥没の予防策が講じられています。一方、地下約2m以深の深部空洞は、場合によっては拡大し大規模な陥没に至る危険があるものの、現行の地中レーダーは適用が困難とされ、探査手法はボーリングやコーン貫入等の直接の確認に限られています。本研究では、そうした地下約2m以深の深部空洞の探査可能性を見出すことを目的として、個別要素法解析(DEM)とフィールド試験によって空洞を有する地盤を作製し、弾性波伝播特性および空洞探査可能性について検討を行っています。

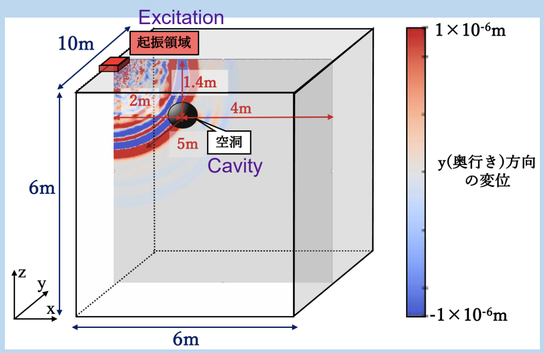
個別要素法解析 DEM Analysis

モデル地盤 Model ground

- 高さ6m×幅12m×奥行10m
  6m high x 12m wide x 10m deep
- 1.1億個の粒子により構成
  consisting of 110 million particles

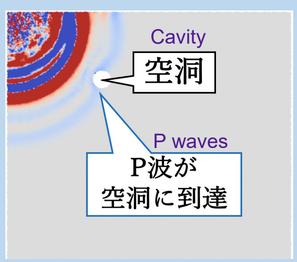
起振 Excitation

- Y方向に1kHz、振幅1μmの正弦波パルス
  1 kHz, 1 μm amplitude, 1 sine wave pulse

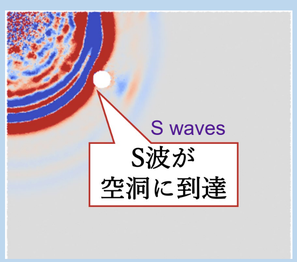


DEMモデル地盤
DEM Model Ground

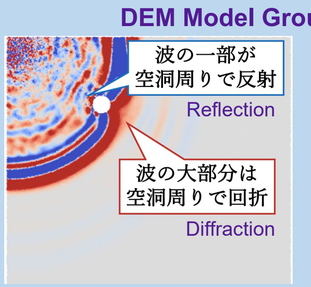




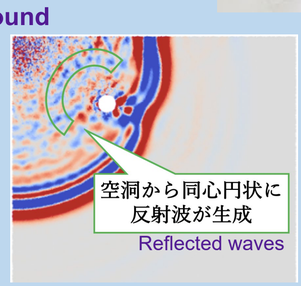
起振から6ms後
6ms after Excitation



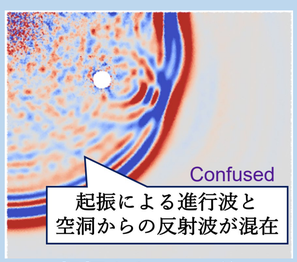
起振から8ms後
8ms after Excitation



起振から10ms後
10ms after Excitation



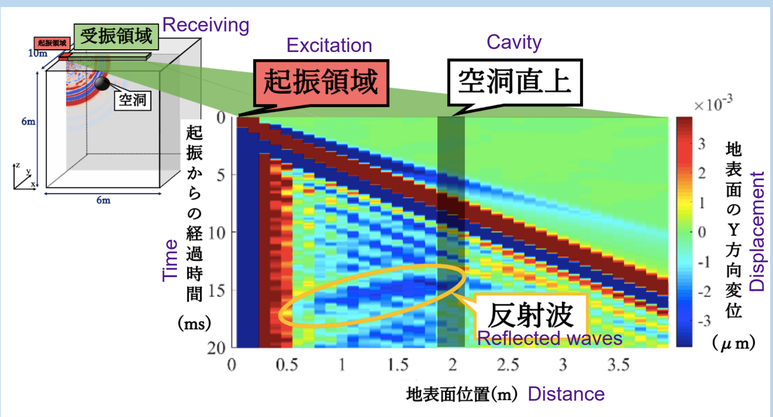
起振から12ms後
12ms after Excitation



起振から14ms後
14ms after Excitation

- 起振領域と空洞直上の間の地表において、起振による進行波(図の右下向き)と空洞からの反射波(図の左下向き)が混在。
  The initial waves from the excitation area and reflected waves from the cavity are mixed together on the ground surface between the excitation area and the cavity.

L 進行波と反射波を明瞭に区別する必要性。
It is necessary to distinguish clearly between initial waves and reflected waves.



時間-位置-地表面変位の関係
The Relationship of Time-Location-Displacement of ground surface

フィールド試験 Field Test

試験地盤 Test ground

- 深さ2.4mの位置に直径約0.5mのバルーンを設置。
  A balloon with a diameter of 0.5m was placed at a depth of 2.4m.
- バルーンをブルーシートで被覆し、埋戻し・締固めを行い空洞を模擬。
  The balloon is covered with a blue poly tarp, backfilled and compacted to reproduce a cavity.

起振・測定 Excitation・Measurement

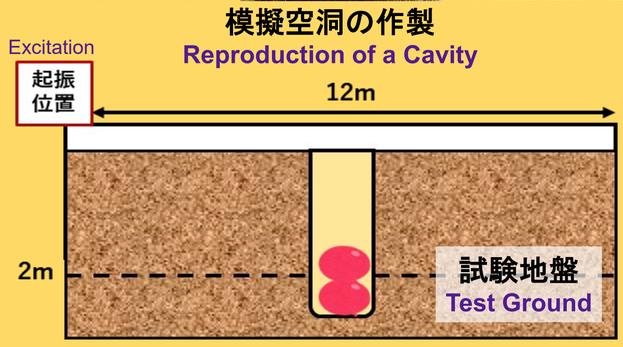
- 掛矢により、Y方向(空洞に対して地表面垂直方向)に起振。
  Excitation was created with a hammer in Y direction.
- 表面波探査で一般に使用されるジオフォンと測定器を使用。
  Geophones and measuring device commonly adopted in Surface Wave Survey were used.



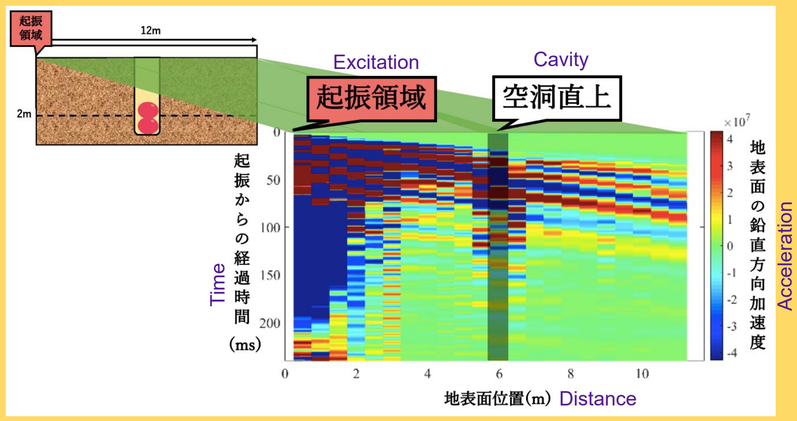




模擬空洞の作製
Reproduction of a Cavity



- 空洞直上付近の地表において比較的大きな加速度が長く持続している様子を確認
  Relatively large acceleration was observed for a long period on the ground surface just above the cavity.



時間-位置-地表面加速度の関係
The Relationship of Time-Location-Acceleration of ground surface

空洞からの反射波の抽出
Extraction of Reflected Waves from Cavities

二次元フーリエ変換 2-Dimensional Fourier transform

- 時空間の2変数関数である受振波データを用い、縦軸に周波数、横軸に波数(空間周波数)を取得。
  2-variable function of space-time is used to obtain frequency & wave number (spatial frequency).

解析結果 Analysis Results

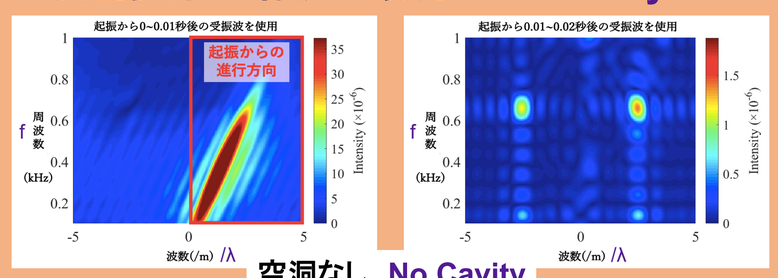
- 個別要素法解析・フィールド試験ともに、
  Both in DEM Analysis and in Field Test,

起振直後：起振による進行波を表す領域(図右側)で強いスペクトル
Just after excitation：
Strong spectrum of the initial waves from the excitation

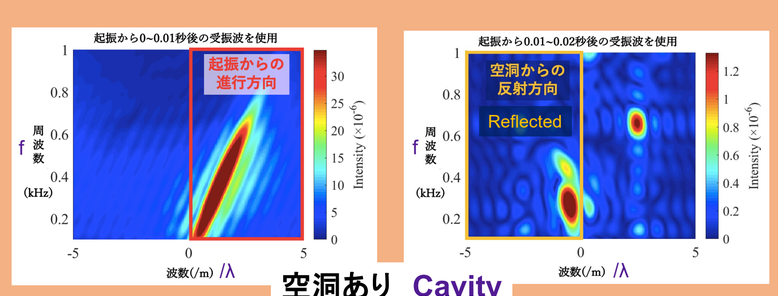
空洞有りの反射波到達時：
空洞からの反射波を表す領域(図左側)で強いスペクトル
At the reflected waves arrival from the cavity：
Strong spectrum of reflected waves from the cavity

L 空洞の存在に伴う反射波の影響を抽出できる可能性
Possibility to extract reflected waves from cavities

個別要素法解析の場合 DEM Analysis



空洞なし No Cavity

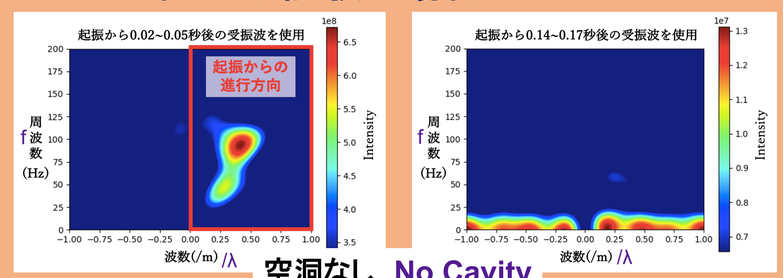


空洞あり Cavity

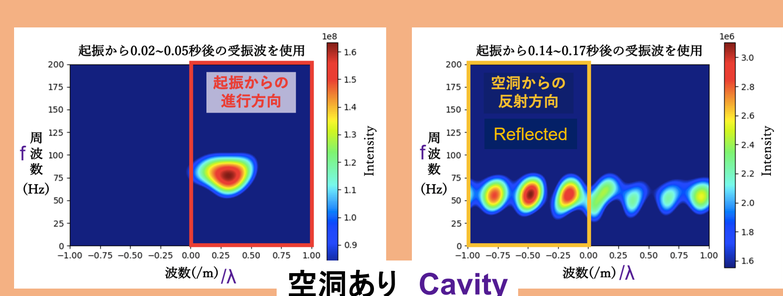
起振直後
Just after Excitation

反射波到達時
At Reflected Waves Arrival

フィールド試験の場合 Field Test



空洞なし No Cavity



空洞あり Cavity

起振直後
Just after Excitation

反射波到達時(推定)
At Reflected Waves Arrival

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Fundamental Study on the Applicability of Seismic Surveys for Detecting Deep Cavities

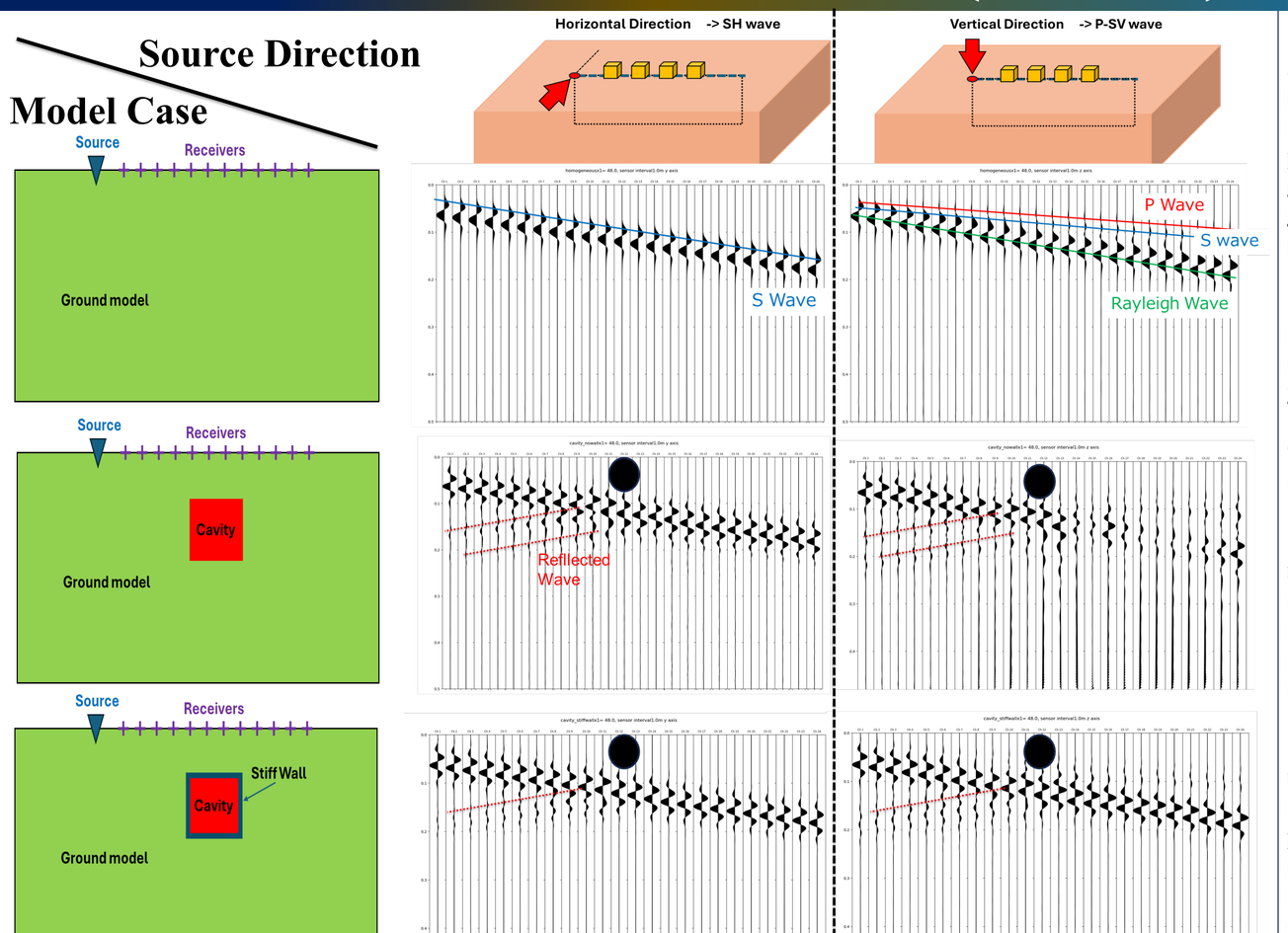
深部空洞検出のための地震探査の適用性に関する基礎的研究

Introduction

Nondestructive exploration technology in the ground is needed in many fields, such as infrastructure development, anti-disaster measures, archaeological investigations. However, high-resolution exploration deeper than 2m is difficult in a nondestructive exploration today. This study investigated the applicability of seismic surveys in the exploration of underground cavities by numerical model based on the finite difference method and field tests. The results indicated that detecting reflected waves from the cavity would be effective.

地盤内空洞の非破壊探査はインフラ整備や災害対策、考古学の調査など多くの分野で必要とされる。しかし、現在の非破壊探査では2m以深の高分解能探査は困難である。本研究では、有限差分法による数値モデルと実地試験により、地下空洞探査における弾性波探査の適用性を検討した。その結果、空洞からの反射波を検出することが有効であることが示された。

Numerical Simulation (FDM)



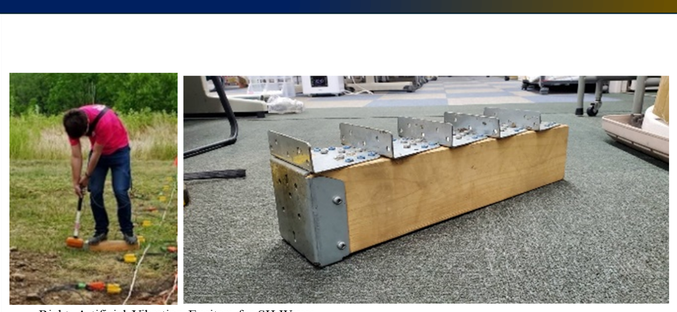
A subsurface survey generally inversely analyzes the distribution of geophysical quantities in the ground under investigation based on the results of wave propagation measurements. In seismic surveys, data is acquired by several receivers installed on the ground surface that receive wave propagation from a point source artificially generated on the ground surface. **The presence of regions such as cavities in the ground, where the geophysical quantities are significantly different** from those of the surrounding layers, modifies the propagation of elastic waves in the ground, which is reflected in the response at the ground surface.

In this study, **the ground is modeled as an elastic body by the finite difference method**, and elastic wave propagation at the ground surface is simulated in the presence of cavities in the ground. Here, from the viewpoint of stability of the analysis, **the cavities were assumed to be very low density, low wave velocity layers, and the shear stress was set to zero** in the cavities. In the homogeneous model propagation, only S waves were observed during horizontal excitation, while coupling of P and S waves and propagating surface waves were observed during vertical excitation.

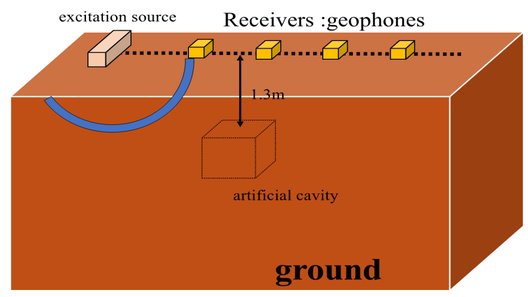
In the case of a cavity in the ground, the cavity surface was assumed to be a free surface. As a result, **reflected waves from the cavity were observed** in both the horizontal and vertical directions. On the other hand, in the case of vertical excitation, most of the surface waves were observed to decay just above the cavity. This was due to the fact that the cavity was regarded as an ultra-low velocity region, which confines part of the energy of the waves propagating in the cavity.

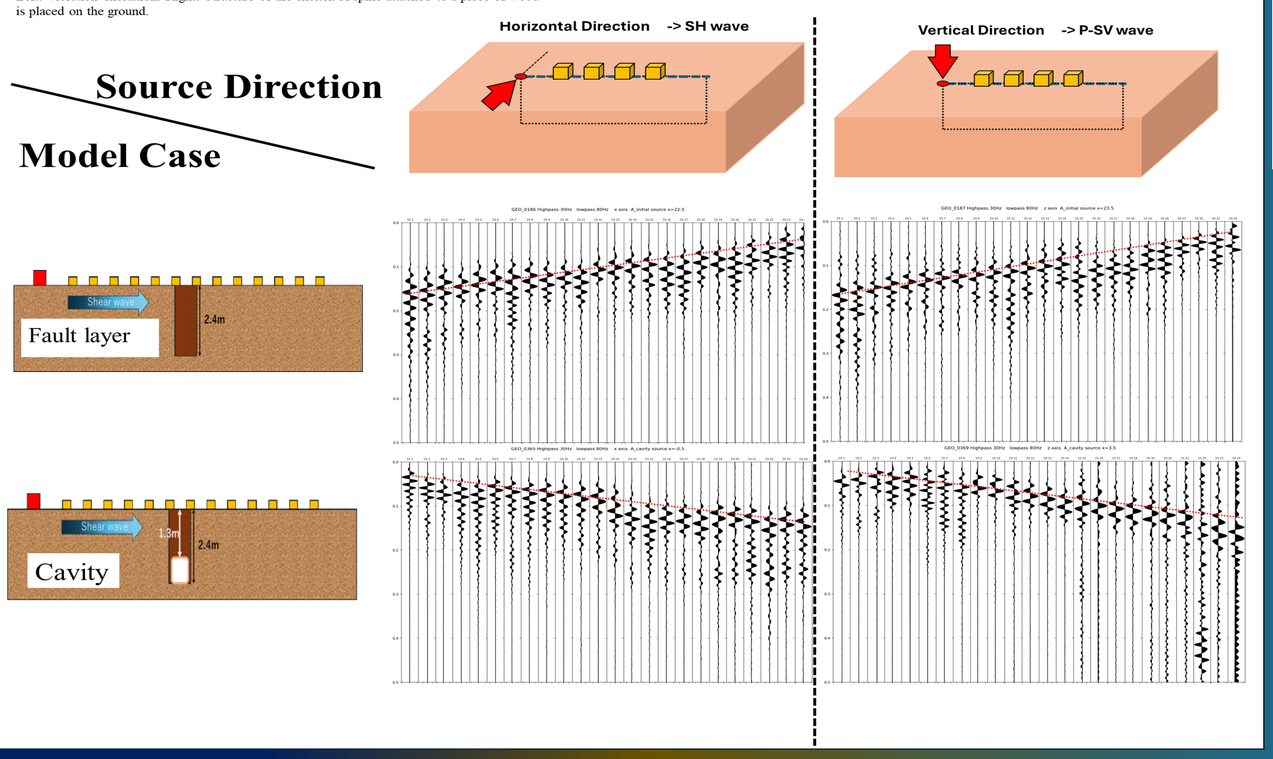
In the actual ground, wave attenuation due to dissipation was significant, as will be explained in the field test part. Waves that appeared to be P waves were also generated in the horizontal excitation model, whereas only s waves were generated in the elastic body model. This phenomenon indicates that the ground is microscopically granular and does not guarantee isotropic wave propagation, suggesting that the conventional elastic body model may not be sufficient. The author is currently interested in a propagation model that takes into account the dissipation inherent to granular ground.

Field Test



Right: Artificial Vibration Exciters for SH Waves
Left: Vibration excitation. Right: Structure of the exciter. A spike attached to a piece of wood is placed on the ground.





The detection of subsurface cavities using seismic wave propagation was investigated in field tests using a real ground surface in the Le Petau golf course in the town of Hokkaido, Japan. A horizontal excitation method was introduced along with a conventional vertical excitation method and its effectiveness in identifying wave reflections.

An artificial cavity was created to simulate subsurface anomalies. 24 geophones connected to an automatic data logger were used for the measurements, and the acquired data were subjected to extensive analysis, including bandpass filtering, amplitude normalization, and deconvolution, to elucidate the interaction between the elastic waves and the subsurface structure. Both vertical and horizontal excitation methods were employed to measure the reflection characteristics of artificially created cavities in a test field.

The results suggest that the cavities may be more clearly visible due to reflected waves when the excitation is done horizontally. Since the method of inversely analyzes seismic waves uses reflected and refracted waves from the cavity, it is important to compensate for distinct excitation and decaying waves.

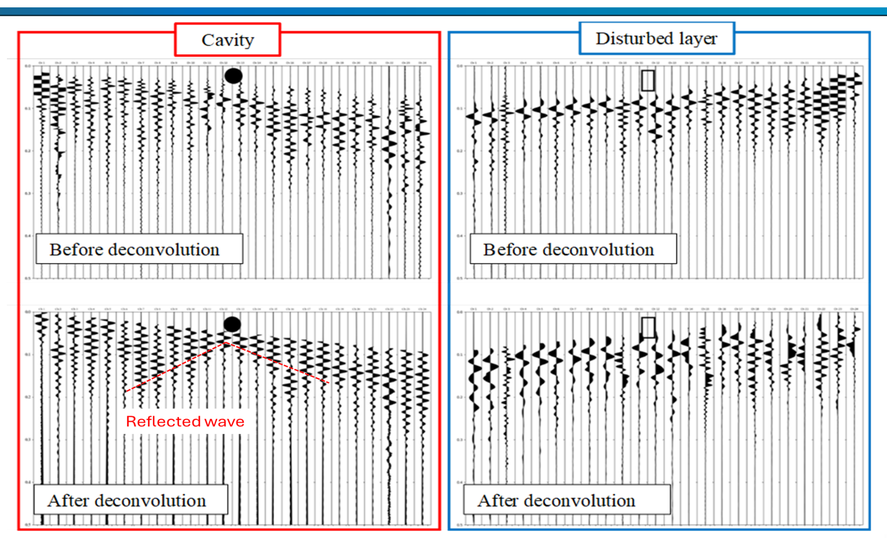


Figure. 8 Raw trace data from horizontal excitation and deconvolution processed data. The black circles in the left panel indicate the location of population cavities, and the rectangular area in the right panel indicates the location of the disturbed layer.

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Ground Water Sound Measurement to Search for Water Paths

地下流水音測定による水みち探査の可能性

概要　Overview

都市部では埋設管の老朽化や破損に起因する道路陥没が毎年多く発生しているが、必ずしもそういう原因によらない地盤陥没も都市部に限らず時折発生する。その多くは地下に生成した水みちが地盤の内部を侵食して空洞を作り、その空洞が成長して地表面近くに達して発生する。通常、路面下空洞を見つける方法として用いられる地中レーダー探査は深さ1.5m程度以下の浅層部が適用範囲で、深層部の空洞を探知する方法はいまだ確立されていない。本研究では空洞生成の原因となりうる地下の水みちに着目して、地下流水音測定装置を用いて北海道安平町ゴルフ場にて地下流水音を測定し、陥没を引き起こす水みち探査の可能性を探った。地下流水音調査の結果、周波数や音の鳴り方の特徴を考慮することで、従来のD値（音の大きさ）を用いて地下流水音を抽出する方法に比べて、精度よく曝気音のみを抽出でき、地下の水みち把握の可能性が示唆された。

In urban area, many road cave-ins happen due to aging and defects of buried pipes. Ground cave-ins can also occur due to underground cavities formed with internal erosion caused by ground water flow. The ground penetrating radar technique is usually used to detect subsurface cavities, but it is only effective for cavities up to 1.5m deep. The way for detection of deep cavities has not yet been established. In this study, the ground water sound survey was conducted in Abira town to search for ground water paths. It was found that the certain range of frequencies in the collected sound seemed to indicate the ground water flow.

調査地概況と調査方法　Area outline and survey method

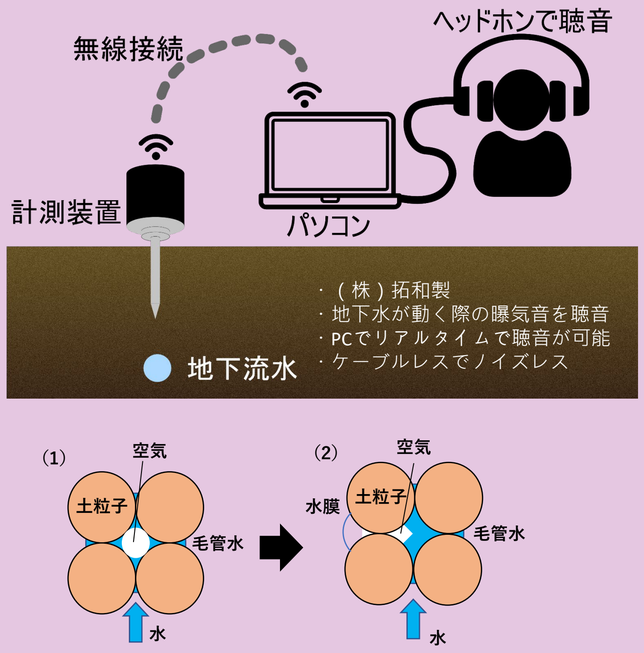
陥没の上空写真（当時）　Aerial photo

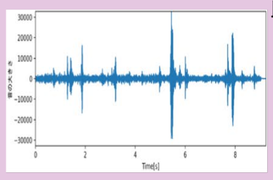


・ ゴルフ場内で2009年に陥没が発i生
A cave-in occurred on the golf course in 2009.
・ 陥没発生場所から離れた場所で大量の土砂が流出
Large amount of sediment was found at a distance from where the collapse occurred.
・事故発生時の調査で地下に水みちが確認された
Water paths were identified under the ground during the investigation at the time of the accident.

地下に水みち？　Water paths in the ground?

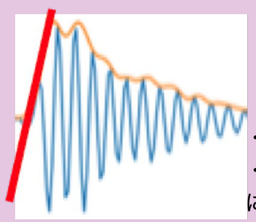
地下流水音測定装置と周波数解析の方法　Ground water sound measurement and frequency analysis





既往の研究で分かった曝気音の特徴
・突発的に発生すること
・大きな音がすること

包絡線処理



・「波形」から「音量」へ変換
・データの簡素化

エッジ判定

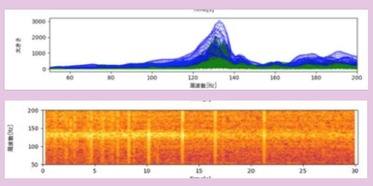
・突発的という特徴から傾きの大きさ
・大きな音という特徴から音量の大きさ
に着目

機械的に曝気音を判定

曝気音発生箇所と発生していない場所(ノイズ)が自動で検出された

フーリエ変換

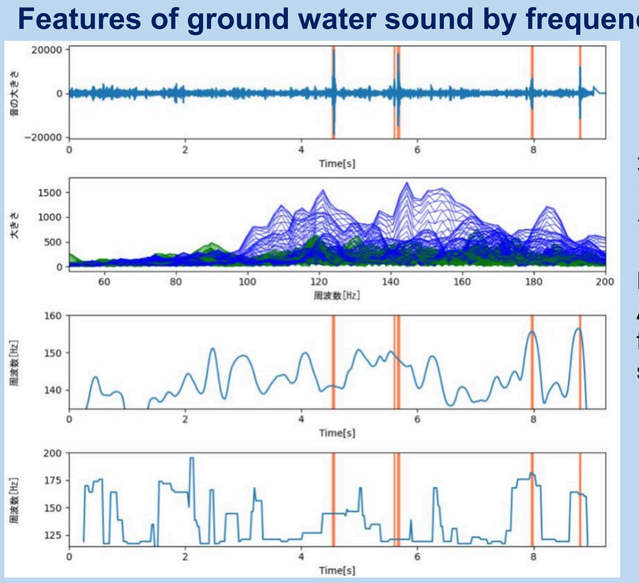
曝気音とノイズの周波数を関数の形状を比較する



地下流水音発生のメカニズム
Mechanism of ground water sound　（株）拓和　技術資料より

調査結果　Field survey result

周波数解析による地下流水音の特徴
Features of ground water sound by frequency analysis



地下流水音の特徴：
100～200Hz付近、曝気音毎に周波数関数の形状が異なる

Features of ground water sound:
Around 100-200 Hz, the shape of the frequency function differs for each aeration sound

流水音の頻度を色ごとに区別したマップ
Map of the ground water sound frequency

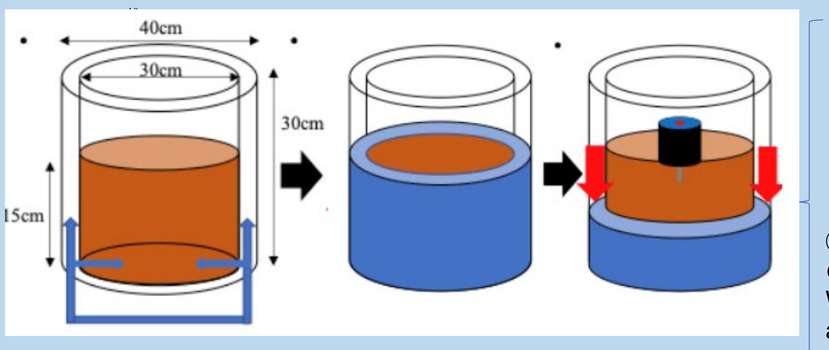


地下流水音は切り盛り境界において高い頻度で確認でき、一連の流れのように分布していた。これは標高の高い方から低い方へと切り盛り境界を通じて水が流れたためだと考えられる。
Ground water sound was frequent at the border of cut and filled ground.

室内模型実験による地下流水音測定　Laboratory model test

試験方法　Test method and procedure

土質や水位による地下流水音の変化
ground water sound in the different types of sand, ground water levels



①2重槽の外槽に水を注入
Fill the outer tank of the double tank with water
②内槽の穴から材料に注水
Water is poured into the material through holes in the inner tank
③外槽の水位低下に伴い内槽の水位上昇
Water level in inner tank rises as water level in outer tank drops

材料の変化と流水音の関係　Occurrence frequency of ground water sound

地盤材料	硅砂7号	硅砂3号 (80%)	硅砂3号 (20%)	硅砂1号
地下流水音	無	無	有	有
周波数スペクトルの形状	-	-	特徴的な周波数が１箇所	特徴的な周波数が１箇所
周波数帯(Hz)	-	-	135,125,120	130,123,113

✓ 粒径が大きな（透水係数の大きな）砂の方が地下流水音の頻度が高い。
, The larger the grain size, the larger occurrence frequency of ground water sound

✓ ゆる詰め砂においてが流水音の頻度が高い。
The looser the density state is, the greater the frequency of ground water sound.,

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The Applicability of Electrical Prospecting for Underground Cavity Detection

電気探査の空洞探知への応用可能性のための基礎的検討

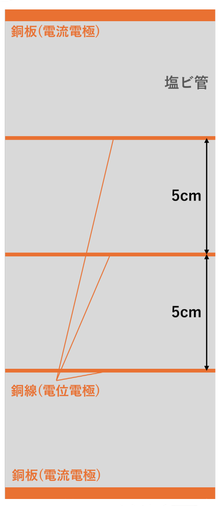
Overview

新たな空洞探査手法確立を目指して比抵抗法電気探査の適用を検討している。地盤内空洞の周辺域には空洞生成に伴う緩み領域が存在することがわかっているため、比抵抗と密度の関係を把握するため、豊浦砂を同一含水比（10%）のもと密度を変えながら比抵抗値を測定した（モールド試験）た。また、密度の異なる2層を持つ模型地盤を作成し垂直電気探査の模型実験を行った。

The application of electrical prospecting was studied to establish a new method of cavity detection. Resistivity was measured using Toyoura-sand of 10% water content while changing the density (referred to as the mold test) in order to understand the relationship between resistivity and density. The model test was then conducted.

Methods

①モールド試験 Mold test



モールド断面



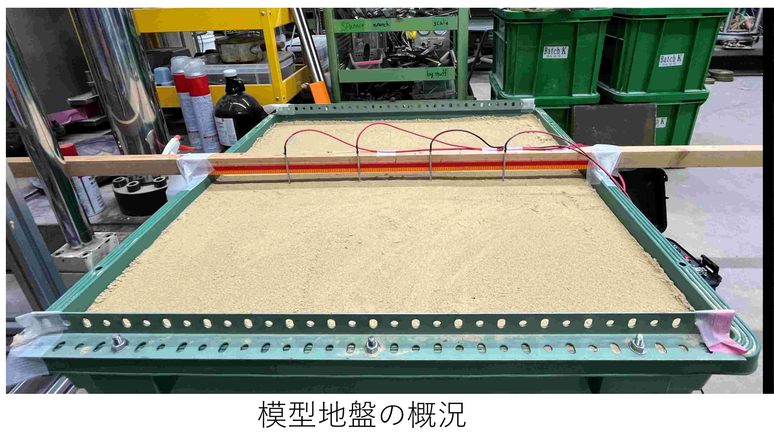
モールド試験器(左)と電気探査機器(右)

長さ20cm、内径9cmの塩化ビニル管内周に設置した銅線を電位電極とし、両端の銅板から流した電流により生じる電位差を測定

$$R_s = \frac{S}{L}\frac{V}{I}$$

R_s: 比抵抗値 [Ωm]　　V: 電位差 [V]
S: モールド断面積 [m²]　　I: 電流 [A]
L: 電位差測定区間長さ [m]

②模型実験 Model test



模型地盤の概況



針貫入試験装置

85cm四方・高さ30cmの模型地盤を、上部10cmが高密度、下部20cmが低密度となるよう作成
・Wenner法垂直探査 (4 ≤ a[cm] ≤ 22, 2cmごと増加)
・針貫入試験 (Φ4mm, 貫入速度3.4mm/s)
を模型地盤中央にて実施

Results

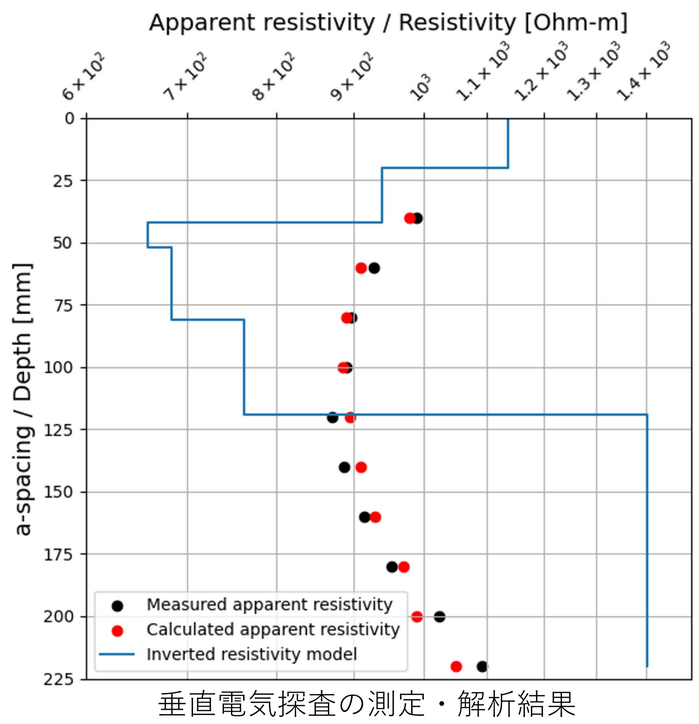
①モールド試験 Mold test

密度の上昇に従い比抵抗値は低下

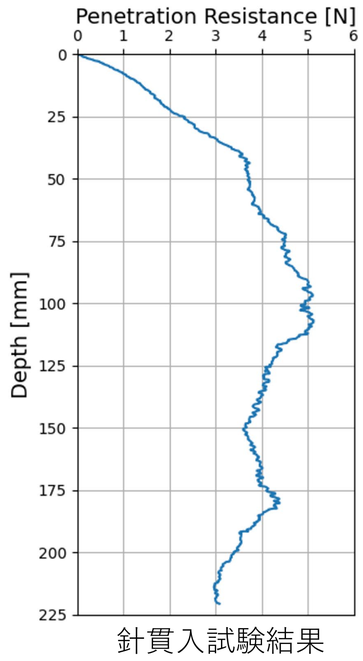
湿潤密度 [g/cm³]	比抵抗値 [Ωm]
1.05	1398
1.60	464.5

モールド試験結果

②模型実験 Model test



垂直電気探査の測定・解析結果



針貫入試験結果

<u>針貫入試験</u>

100mm地点で抵抗値がピークに達し、以降は概ね減少傾向
⇒低密度の層を下部に作成できていることを確認

<u>垂直電気探査</u>

GL -40mmからGL -120mmに低比抵抗値の層、GL -120mm以深に高比抵抗値の層が存在
⇒針貫入試験の解析結果およびモールド試験により得られた比抵抗値と整合
⇒電気探査により地盤内密度変化を検知可能な可能性が示された

地盤高 [GL -mm]	湿潤密度 [g/cm³]
20	1.80
40	1.82
60	1.95
80	2.00
100	2.19
300	1.04

模型地盤作成時の密度分布

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Test Field Pavement for the Evaluation of Collapse Risk of Subsurface Cavities

路面下空洞の陥没危険度評価のための実物大試験道路の構築

Many subsurface cavities are being generated under roads in the urban area. Some of them would collapse and may cause road cave-in accidents. In order to prevent this, the ground penetrating radar technique is effective to find cavities before their collapse. Appropriate repair treatment should be then carried out for the cavities according to their properties and collapsing risk. In this research, the test filed pavement was constructed to evaluate the collapse risk of subsurface cavities and loading tests on the artificial subsurface cavities were conducted.

道路下の空洞は、都市の成熟と共に様々な要因で生成し、場合によっては道路陥没を引き起こします。陥没防止のためには、地中レーダ探査によって路面下空洞を探知し、補修などの対策を施すことが、対症療法として効果的です。本研究では、室内模型実験や既存データの分析による陥没危険度評価方法の検証とともに、舗装構造を考慮した評価方法を開発するために、人工空洞を設置した実物大試験道路を埼玉大学構内に構築し、空洞載荷試験を実施して路面陥没の限界耐力を計測しました。

Development of the solution to prevent road cave-ins
道路陥没予防ソリューションの開発

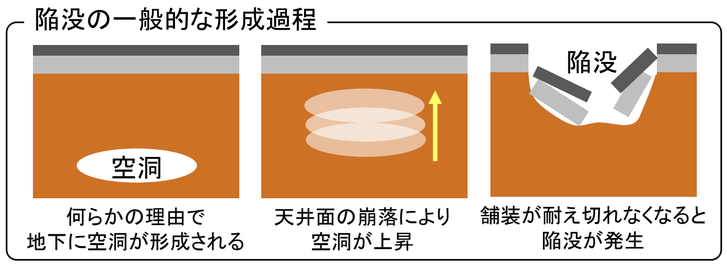
現状の技術的課題:

① 地中の状態の把握が困難 → 空洞を見つける **発見**
② 空洞の成長速度や陥没危険が不明 → 特性を把握する **診断**
③ 合理的な補修方法の選択肢がない → 補修する **治療**

陥没させない **予防**

空洞を作らない・拡大させない

陥没の一般的な形成過程

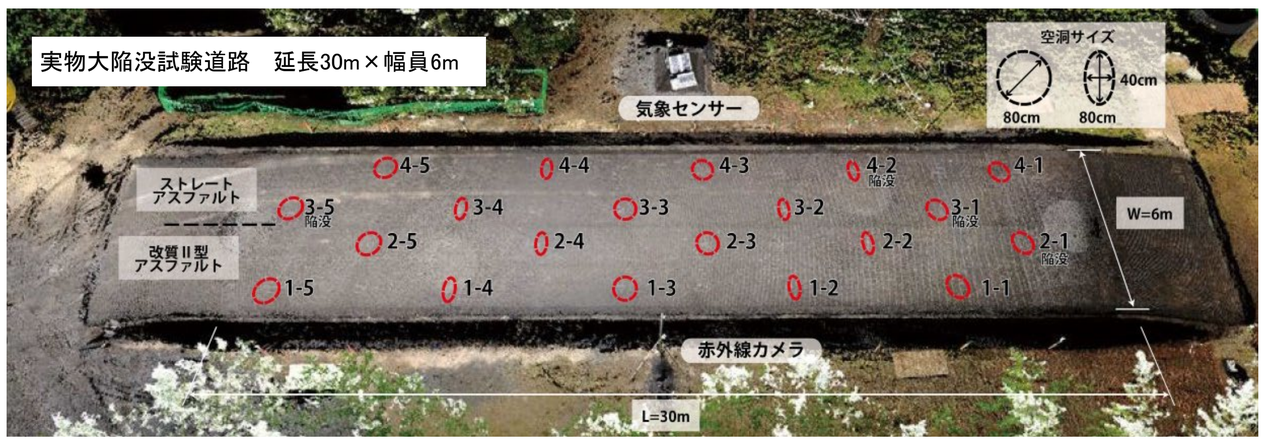


課題解決のために目指すアウトプット

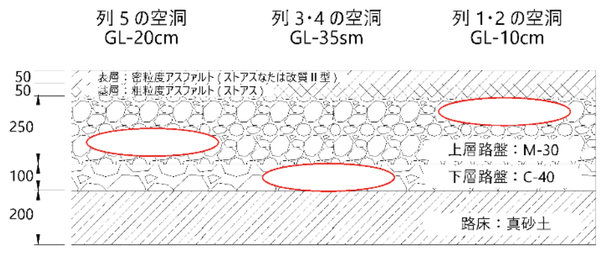
- 発見: 空洞探査方法の体系化・高度化
- （調査） 空洞ポテンシャルマップの開発
- 診断: 空洞成長速度の評価
- （評価） 陥没危険度チャート
- 治療: 空洞対策メニューの提案
- （補修） 空洞補修用充填材の開発
- 予防: 空洞/陥没に強い舗装の開発

技術開発およびその検証のため、
室内模型実験、数値解析、
現道におけるモニタリング、および
実物大試験道路におけるフィールド試験

Construction of test field pavement test
実物大試験道路の構築



・長さ30m×幅6m
・表層はストレートアスファルトと改質Ⅱ型の2種
・Φ80cmまたは80×40cmの空洞を計20個設置
・気象、路面温度、路面変位をモニタリング

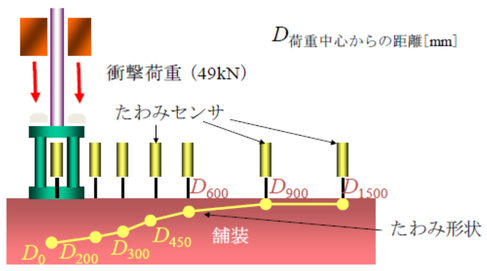


細礫を詰めた土嚢を路盤内に設置した上に表基層を転圧し、路面から削孔して礫を吸引することで人工的に空洞を作製



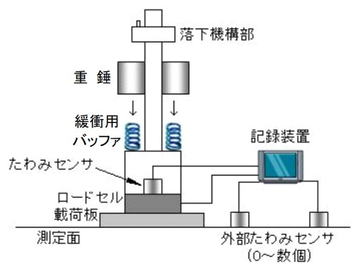
Loading test on cavities
空洞載荷試験

FWD試験





小型FWD試験





平板載荷試験

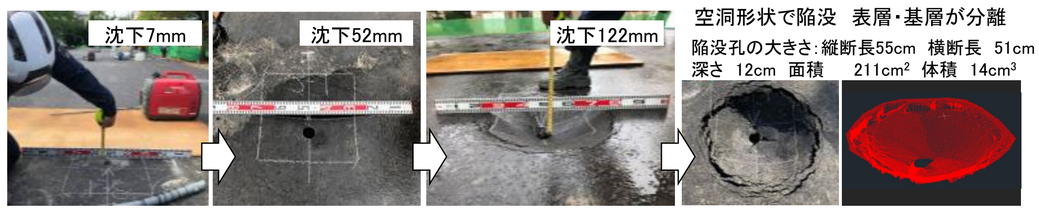




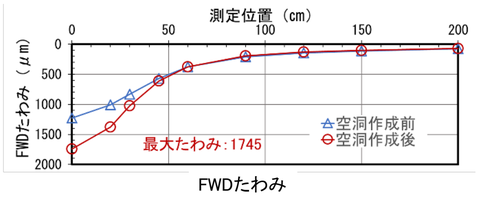
Behaviour of cavities in loading tests
空洞の陥没挙動

自然陥没
［ストAs ・As直下(Dp10cm)・ φ80cm・舗装温度約40℃］

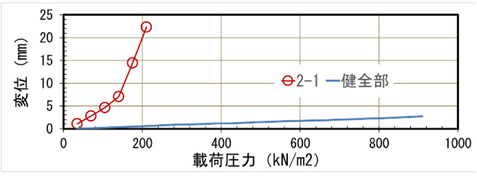
空洞作製から1時間後 → 23時間後 → 27時間後 → 46時間後



空洞形状で陥没　表層・基層が分離
陥没孔の大きさ：縦断長55cm　横断長　51cm
深さ　12cm　面積　211cm²　体積　14cm³



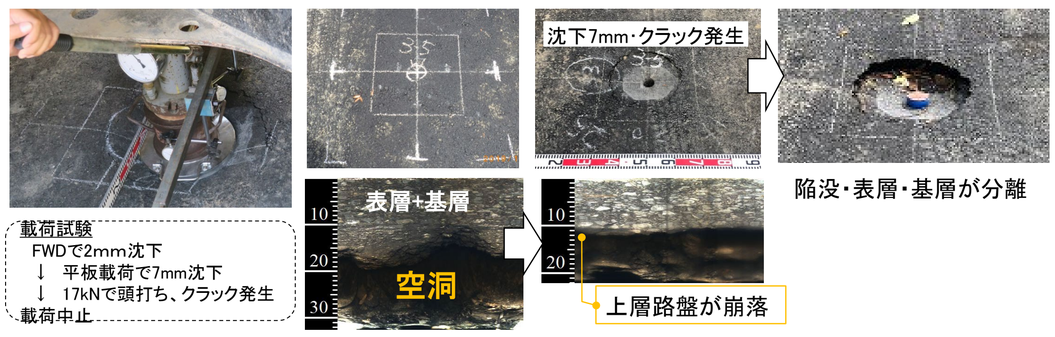
FWDたわみ



平板載荷試験の荷重－変位関係

FWD+平板載荷で路盤崩落、その後陥没
［ストAs・上層路盤内(Dp20cm)・φ80cm・舗装温度約40℃］

平板載荷試験 → 試験前 → 試験後 → 5日後

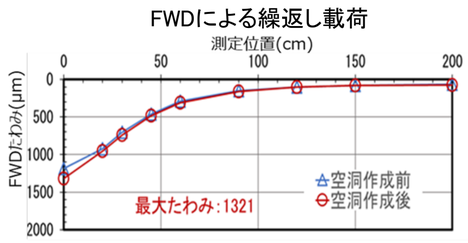


陥没・表層・基層が分離

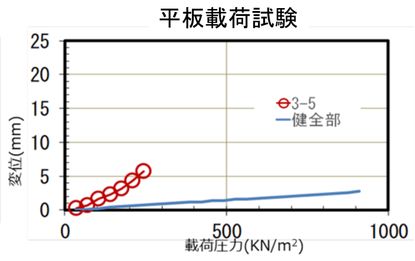
載荷試験
FWDで2mm沈下
↓ 平板載荷で7mm沈下
↓ 17kNで頭打ち、クラック発生
載荷中止

上層路盤が崩落

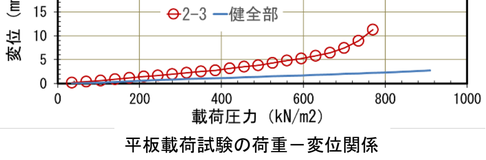
FWDによる繰返し載荷



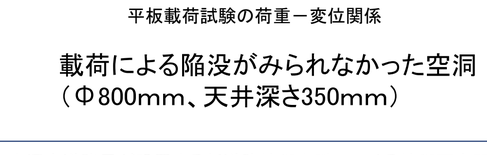
平板載荷試験



平板載荷により陥没した浅い空洞
（Φ800mm、天井深さ100mm）



FWDたわみ



平板載荷試験の荷重－変位関係

載荷による陥没がみられなかった空洞
（Φ800mm、天井深さ350mm）

本研究は，国土交通省道路局が設置する新道路技術会議における技術研究開発制度により，国土交通省国土技術政策総合研究所の委託研究「道路構造及び空洞特性に適応した陥没危険度評価と合理的路面下空洞対策についての研究開発」において、東京大学、埼玉大学、ジオ・サーチ(株)、NIPPO(株)、住友大阪セメント(株)の共同研究で実施されています

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CART project (2018-2020)
桑野研究室
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INFLUENCE OF UNDERGROUND STRUCTURES ON EXPANSION OF CAVITIES AND LOOSENING

地中構造物躯体の地盤内空洞・ゆるみ形成に対する影響の検討

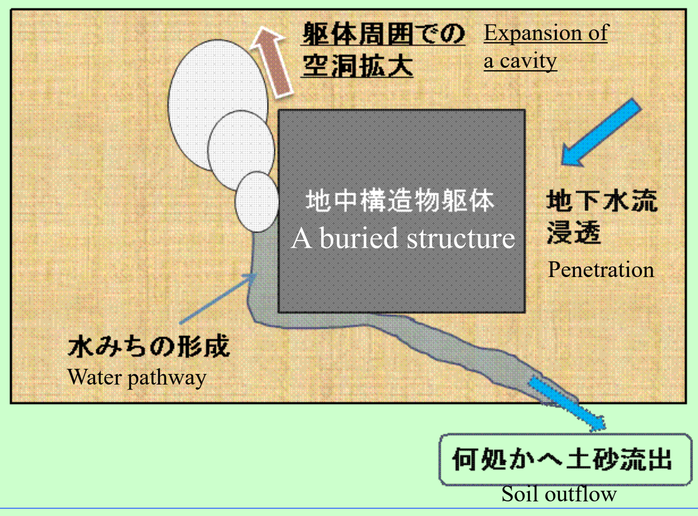
Many cave-in accidents occur and sometimes injure people in urban area. Expansion of a subsurface cavity and loosening cause ground cave-in. It was found that some types of cavities developed close to underground structures.

It is not clear why cavities are generated surrounding buried structures. It is empirically suggested that there is “water pathway” around underground structures and soil flows out through this water pathway to faraway spot of soil drainage. In order to study the effects of buried structures when cavities are generated due to water penetration, a series of model tests was conducted with a small soil chamber in various soil conditions.

近年都市部において地盤陥没事故が多発しており人命が損なわれるなど看過できない問題となっています。地盤陥没は地中で土砂流出による地中空洞・ゆるみが形成される事が原因であると考えられています。そうした中、近年地中構造物近辺で空洞が発見される事例が数多く報告されています。地中構造物周辺で空洞が多発する原因は明らかではありませんが、構造物周辺に水みち(水が局所的に流れやすい箇所)が存在し、その水みちを通って遠方の土砂流出口に土砂が排出されているという可能性が指摘されています。本研究では地中構造物が水の浸透による空洞形成に与える影響を小型土槽を用いた模型実験により調べました。

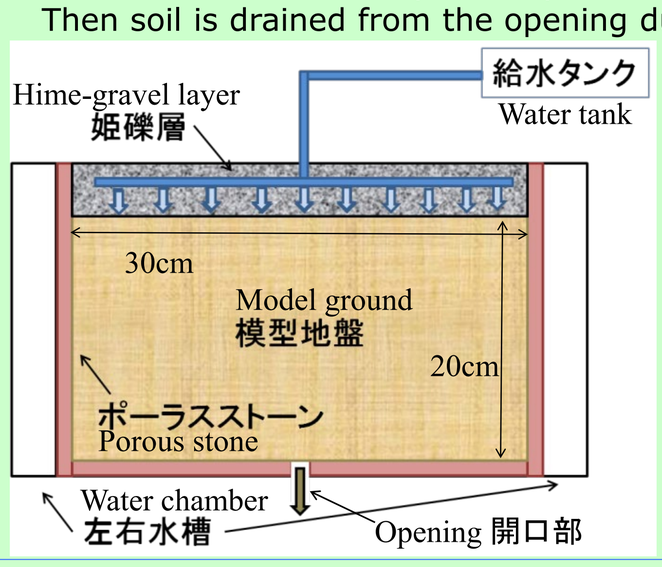
地下構造物まわりのゆるみ発生プロセス
Loosening process surrounding basement structures

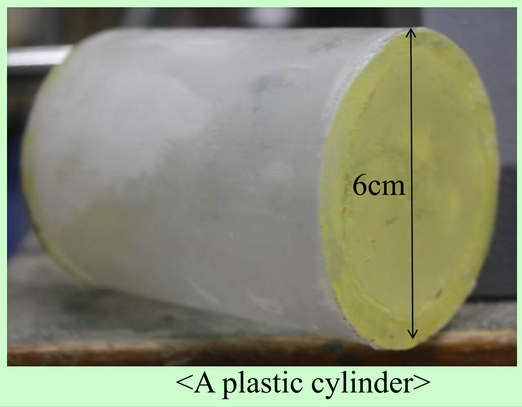
地下浸透流により構造物まわりで水みちを通って
土砂が流出し空洞やゆるみが形成される.
Soil is drained through water pathway surrounding buried structures due to water penetration.



躯体周囲での土砂流出を模擬した小型土槽実験
Model test simulating soil drainage surrounding an underground structure

模型地盤内に地中構造物を模擬した円筒を設置.
地盤表層部から一様な水の浸透を行って底面開口部から土砂流出を発生させる.
Put a plastic cylinder into the model ground.
Then soil is drained from the opening due to water penetration from the surface





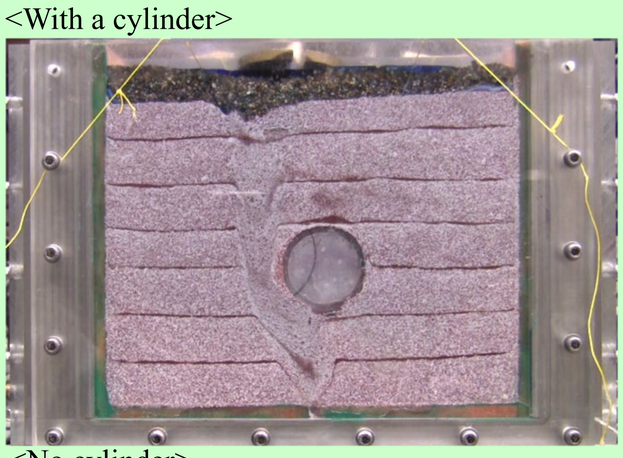
<A plastic cylinder>

円筒の有無・地盤材料による空洞・ゆるみ形成の変化
Influence of a cylinder and material on cavity and loosening formation

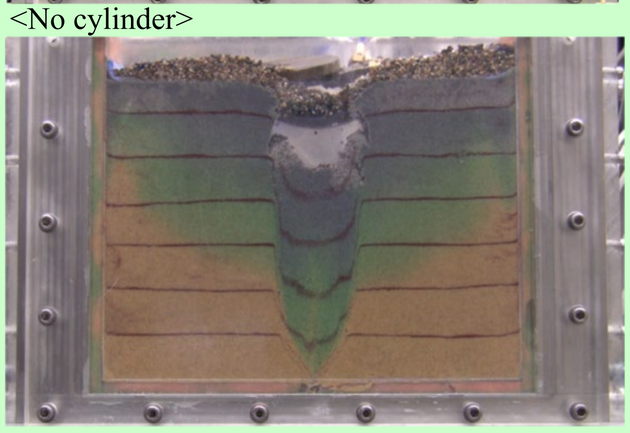
豊浦砂と混合ケイ砂を用いて空洞形成の様子を観察、実験終了後貫入試験を実施
Toyoura sand and mixed silica sand were applied. Cone penetration test was conducted after soil drainage.

空洞・ゆるみ形成の様子
Cavity & loosening Formation

<With a cylinder>



<No cylinder>



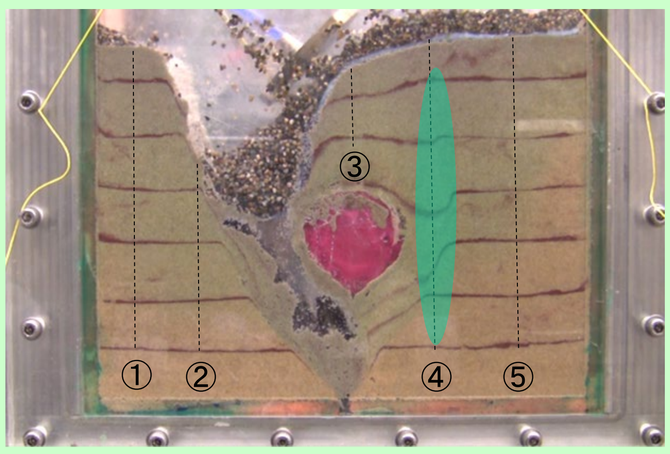
円筒の設置によって空洞・ゆるみ形成の
様子が大きく変化
Cavity & loosening formation was affected
by putting the cylinder

貫入試験
Cone penetration test

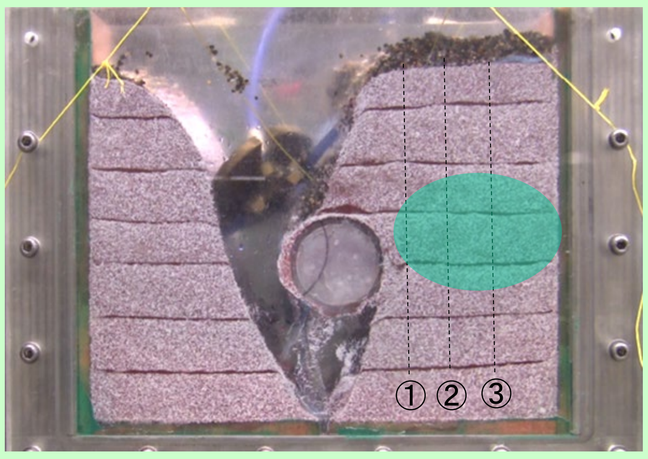

<Cone・・・3mm diameter>

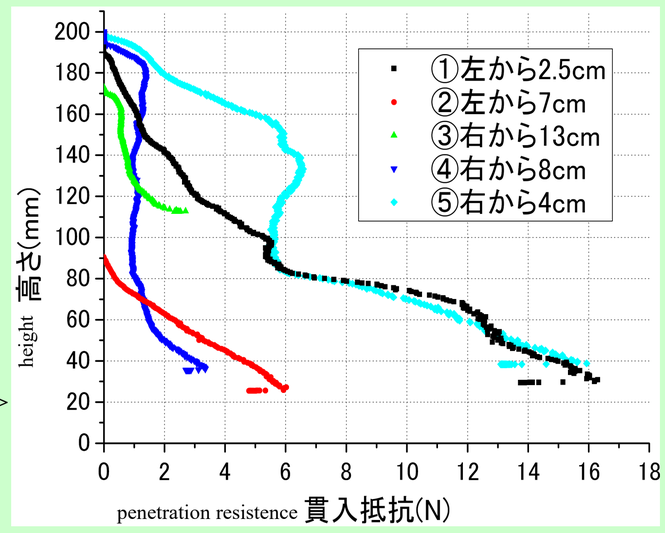
地盤材料によってゆるみ領域が大きく変化
Type of geomaterial affects formation of loosening in the model ground

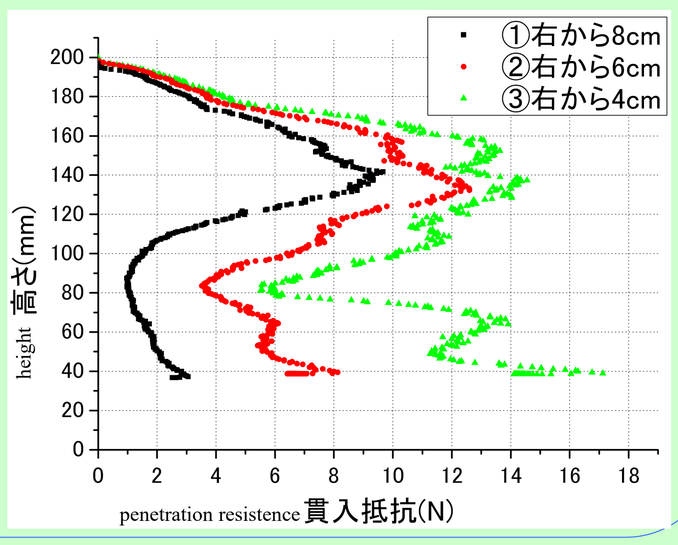
<Toyoura sand>



<Mixed silica sand>







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部屋は東京大学生産技術研究所B棟3階のBw-304

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佐藤真理 (2012)

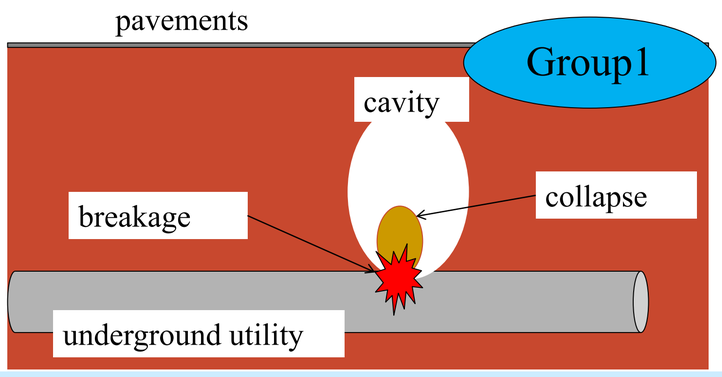
Development of Subsurface Cavity Potential Map in FUKUOKA City

福岡市における路面下空洞の生成傾向分析とポテンシャルマップ作成

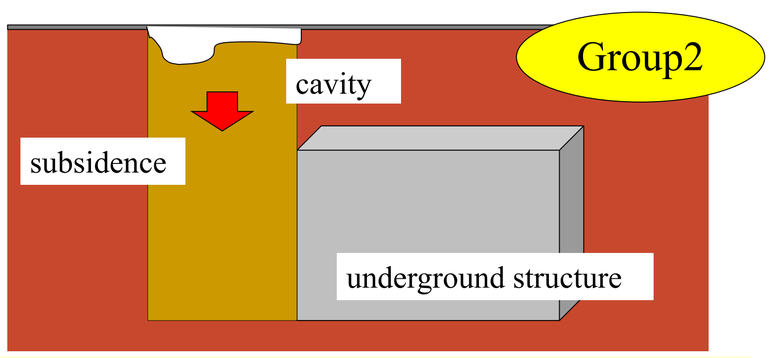
Road cave-in accidents occur frequently in many parts of the world in recent years. Some advanced initiative including improved sub-surface cavity survey technology and newly developed repair material reduced the number of cave-ins. Research of cavity mechanism has been conducted continually for prevention of road cave-ins in Japan. The purpose of development of the subsurface cavity potential map is to understand the regional characteristics and especially vulnerable zone about cavity occurrence ratio. The further value of the maps firstly is to get important information for preparation against disaster such as earthquake, heavy rain which cause cavities. And it makes available to compare the characteristics of cavity with another region. In this study, data of subsurface cavities obtained in Fukuoka city were examined with some geographic factors using GIS. Target cavities were divided into two groups based on the cause of cavity generation. A prototype of cavity potential map was proposed.

道路陥没は毎年日本でも数多く発生していますが、最近は特に道路下空間に対する危機意識が高まっています。道路陥没予防には、その前段階の路面下に発生する空洞に適切な対策を施す必要があります。路面下空洞調査は様々な自治体で行われていますが、どのような箇所に空洞が出来やすくどのような空洞がより危険なのか等を分析し調査に活かしている例は少ないのが現状です。
本研究では、福岡市の空洞の生成傾向と空洞発生箇所の地理的特徴との相関を分析しました。空洞発生メカニズムに基づいて空洞を2種類に分類し、場所の特徴から空洞の発生しやすさを評価した結果をGIS上で整理し、福岡市の空洞ポテンシャルマップの作成を試みました。

主な空洞生成メカニズム
Mechanism of Cavity Occurrence



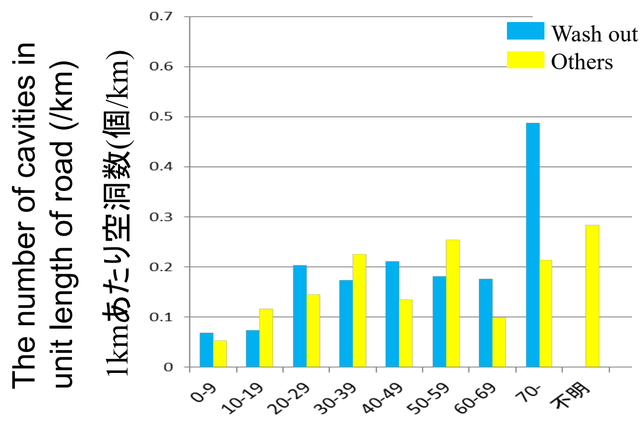
埋設物の破損等による土砂が流出や吸出しする現象
Washing out of soils from the breakage of underground utilities.



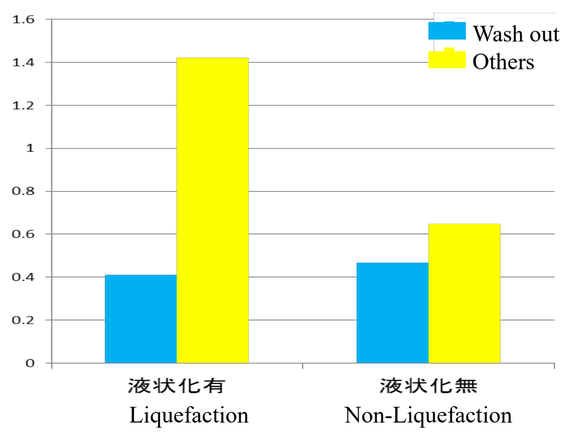
吸出し以外の現象、地下構造物の周辺地盤が沈下など
Subsidence around underground structure by the fluctuations of groundwater level.

空洞箇所の地域特性分析
Analysis of Characteristics of Location Relevant Factors of

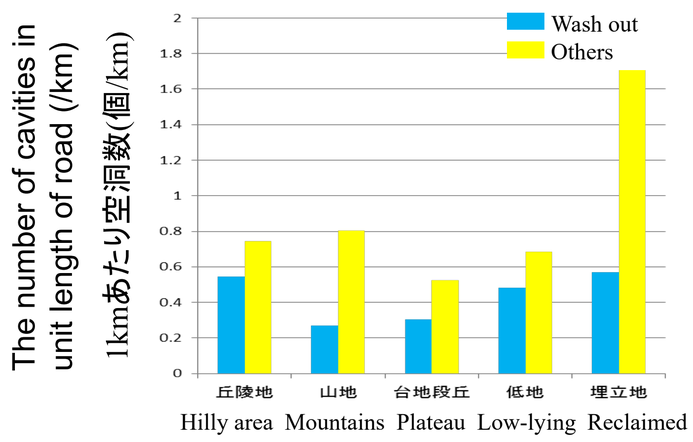
下水供用年と空洞頻度
The age of sewage and occurrence ratio of cavity



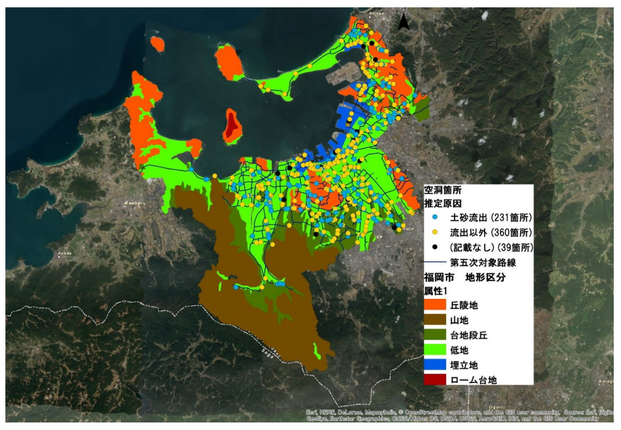
液状化被災履歴と空洞頻度
The experience of liquefaction and occurrence ratio of cavity



地形区分と空洞頻度
The ground form and occurrence ratio of cavity

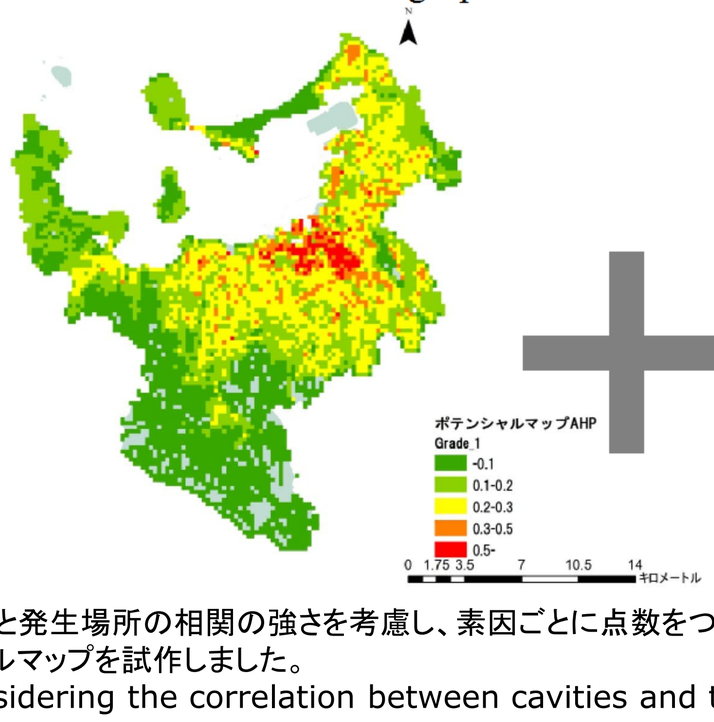


地形区分と空洞発生分布
The ground form and location of cavities

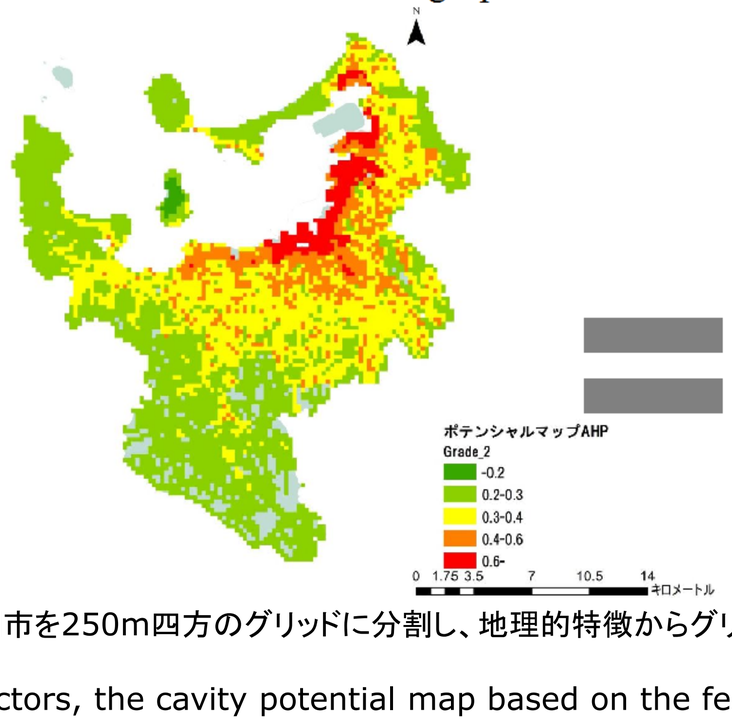


空洞ポテンシャルマップの試作　Prototype of cavity potential map

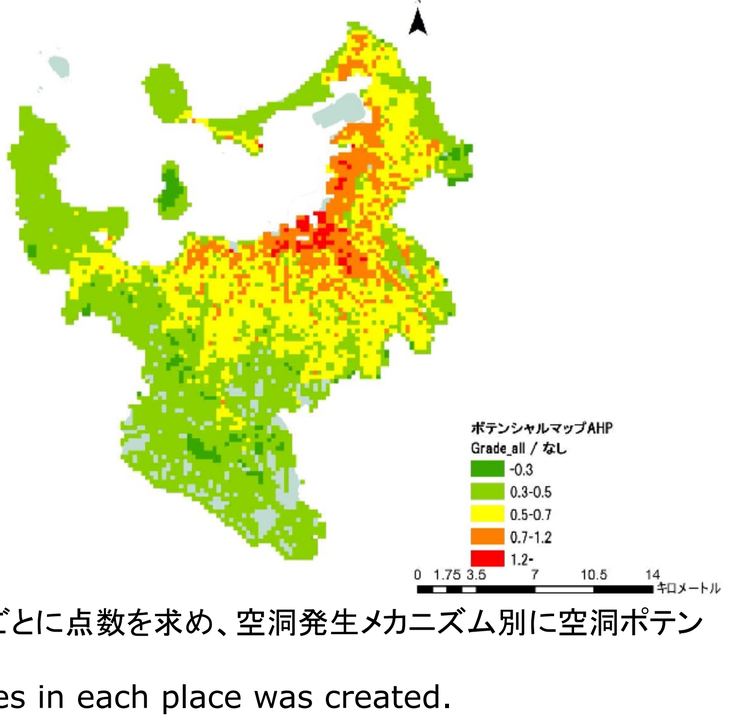
Cavity potential Map due to washout
The Central zone has high-potential.



Cavity potential Map due to not washout
Northern reclaimed area has high-potential.



Cavity potential Map of FUKUOKA city



空洞と発生場所の相関の強さを考慮し、素因ごとに点数をつけ、福岡市を250m四方のグリッドに分割し、地理的特徴からグリッドごとに点数を求め、空洞発生メカニズム別に空洞ポテンシャルマップを試作しました。
Considering the correlation between cavities and their factors, the cavity potential map based on the features in each place was created.

本研究に関する担当研究室は桑野研究室です.
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堀田真由子 (2018)

Development of Effective Solution for Prevention of Road Cave-in in FUJISAWA City

藤沢市における効率的な道路陥没防止手法の研究【官学産共同研究】

Preventing road cave-in ensures road traffic functions and a disaster-resistant system. A collaboration among Fujisawa city and IIS Univ. of Tokyo and GEO SEARCH address to develop effective solutions for prevention of road cave-in accidents in Fujisawa city. The purpose of the study is to analyze the trends of cave-in occurrence using valuable information managed by Fujisawa city, the results of surveys at ten monitoring roads in this study and investigation of causes of cavity occurrence and accumulations of details of restoration works etc. Based on knowledge obtained from these collaborative activities, the effects and the evaluation techniques of cavity/cave-in potential with the factors, the number of utilities, the oldness of sewage, the level of groundwater and the permeability of soils, which demand local conditions were discussed. And a cave-in potential map of Fujisawa City was created experimentally. The study will enable prevention of road cave-in events using advanced countermeasures so that sustainable maintenance as a disaster-resistant city can be achieved.

道路陥没を防止することは、円滑な交通の確保や災害に強いまちづくりを実現する有効な方策です。
本研究は、藤沢市の「安全で安心な暮らしを築く」ことを目的に、藤沢市が管理する道路での最適な道路陥没防止手法および体制について、官学産共同で取組んでいるものです。研究では、藤沢市域における空洞の潜在性と拡大性を評価するために、10のモニタリング路線で半年に一度のフィールド調査を行い、空洞の発生頻度と拡大傾向を把握しながら、空洞補修時の原因調査・空洞周辺地盤の土質分析と土槽実験・補修記録の蓄積を行っています。現場で得られた空洞に関わる情報のうち、地盤・地下水・下水道施設など地域が擁する空洞の素因と、これまでの藤沢市で実施してきた路面下空洞調査結果と陥没記録からの空洞/陥没発生傾向、さらにはモニタリング調査で明らかになってきた空洞拡大傾向との関係性を分析し、藤沢市が今後、減災および予防保全として道路陥没対策を進めていくための効率的な点検手法や補修情報の活用など、有用な仕組みを講じています。

共同研究体制
Organization of the Collaborative Project

安全で安心な暮らしを築く 藤沢市に最適な道路陥没防止手法と体制
Developing Effective Solution for Prevention of Road Cave-in Accidents in Fujisawa City

藤沢市 Fujisawa City
・これまでの空洞調査結果および所管データの提供
・モニタリング路線の提供
・予防保全として道路陥没対策を進めていくための有用な仕組みを検討

Provision Of Survey Field and City-management Data

東京大学生産技術研究所 IIS Univ. of TOKYO
・学術的な検討；評価手法の検討、および土槽実験等による検証
・空洞発生の地域性/潜在性
・空洞拡大性の数値化

Academic Research on Quantifying Of Cavity Mechanism

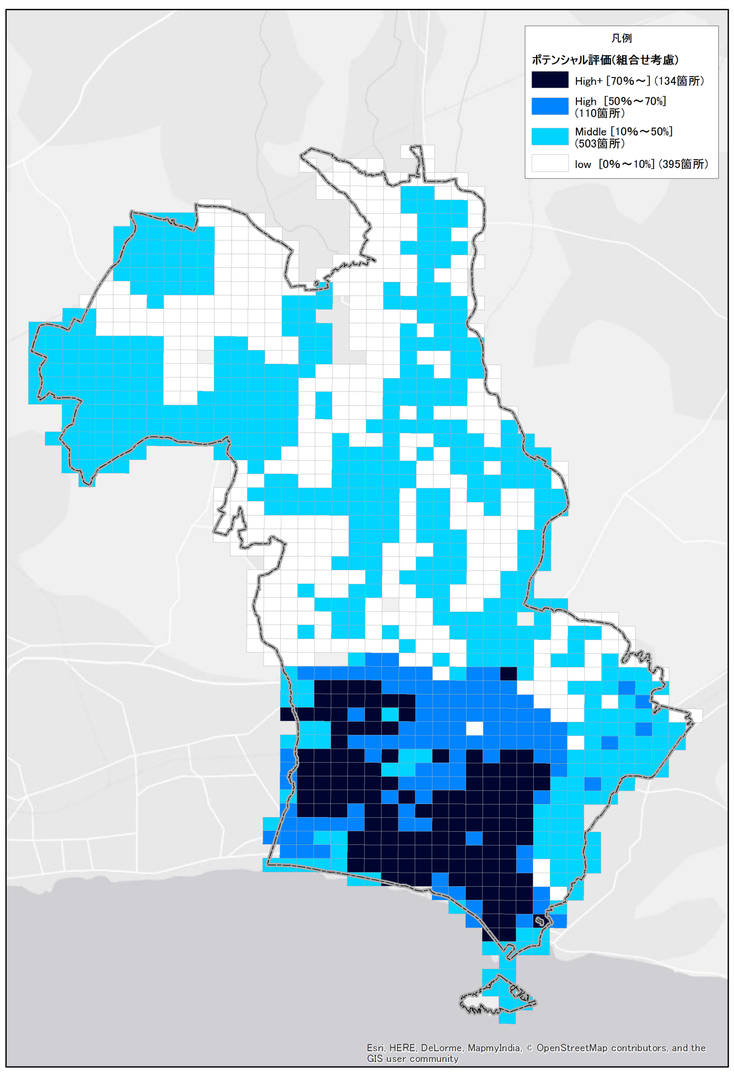
ジオ・サーチ株式会社 GEO SEARCH Co.,LTD
・モニタリング調査の試行 （現地調査及び検討・分析）
・空洞発生原因調査



藤沢市の地域評価；陥没ポテンシャルマップの試作
Prototype of Cave-in Potential MAP

本研究の活動をとおして得られた知見から、藤沢市の地域性を踏まえた因子（地下埋設物の多さ・地下埋設物の老朽化・地下水位の高さ・地盤の透水性）で、空洞潜在性や陥没顕在性を評価する手法を検討し、マップ化を試みました

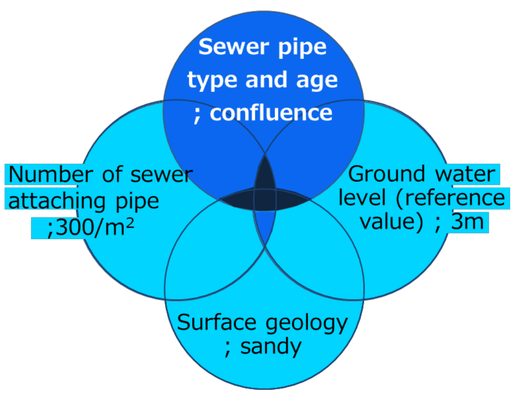
Based on knowledge obtained from this collaborative activities, the evaluation techniques of cavity/cave-in potential with themselves factors, the number of utilities, the oldness of sewage, the level of groundwater and the permeability of soils, which demand local condition. And the cave-in potential map of Fujisawa City was created experimentally.



Grade of potential (probability of occurrence)		occurrence tendency /average number in unit length of road	
		cave-in (number/km)	cavity (number/km)
	High+ (70% -)	1.4	4.6
	High (50-70%)	0.7	2.4
	Middle (10-50%)	0.2	0.4
	Low (0-10%)	0.1	0.3

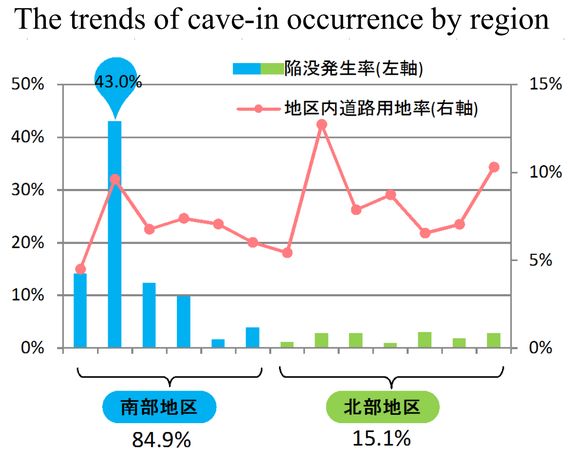
Approximate expression; Potential value: Y and occurrence tendency of cave-in/cavity : X

Cave-in	$Y = 0.46x - 0.085$, $R^2 = 0.918$
Cavity	$Y = 1.508x - 0.352$, $R^2 = 0.8977$

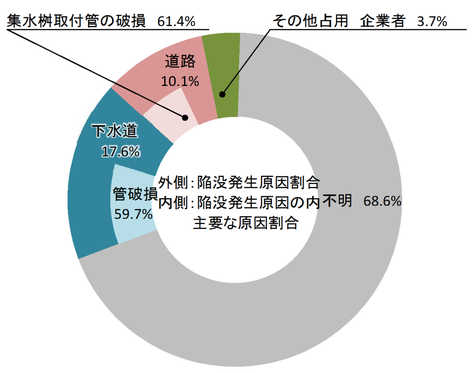


空洞/陥没に関連する情報の収集と分析
The Collection and Analysis about Cavity and Cave-in in Fujisawa City

地区別の陥没発生傾向
The trends of cave-in occurrence by region

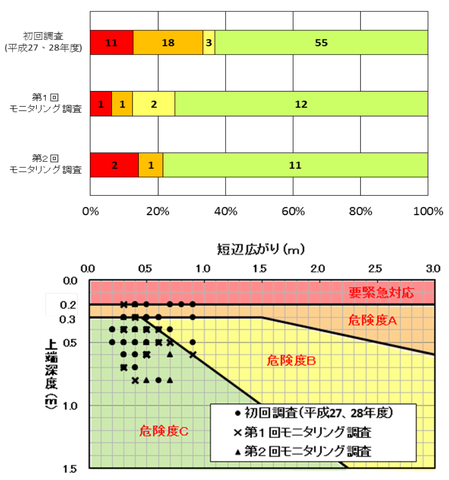


陥没原因割合
The ratio of Factors of cave-in



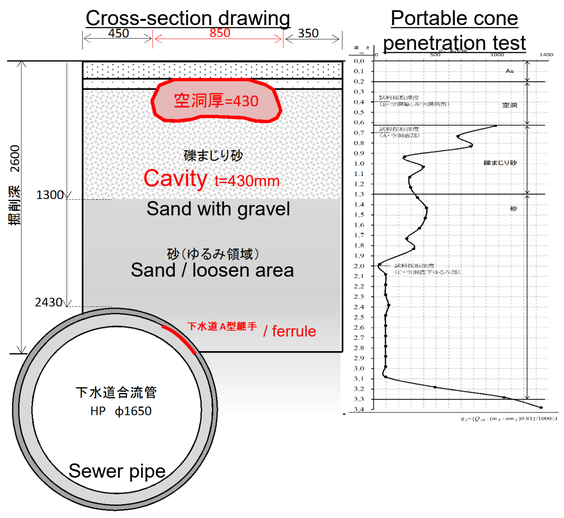
空洞の発生と拡大メカニズムの究明 Investigation of Mechanism of Cavity Occurrence and Expansion in Fujisawa City

空洞モニタリング調査結果
Results of Monitoring Survey of Cavities



空洞補修時の原因・発生状況調査 Investigation of Causes of Cavity Occurrence

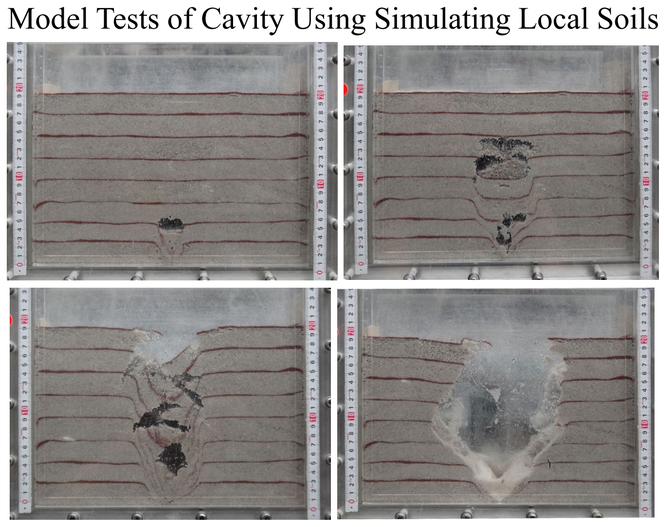




空洞原因の特定には至りませんでしたが、空洞下の砂層に厚いゆるみと下水管路継手部に隙間が確認されました

Although not fully revealed about the identification of causes of cavity, loosened soils were observed beneath the cavity and a small gap was found at the ferrule of pipe.

空洞再現実験
Model Tests of Cavity Using Simulating Local Soils



本研究に関する担当研究室は桑野研究室です.
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瀬良良子(2019)

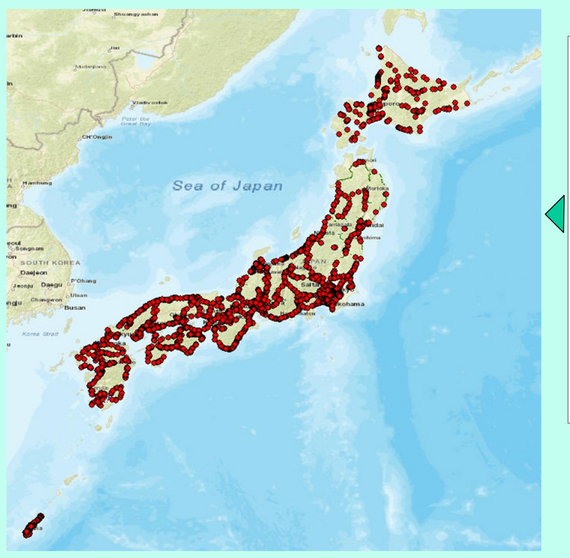
Subsurface Cavities under National Road

国道の路面下空洞

Thousands of sinkholes occur in Japan in a year. A sinkhole occurs with expansion of a subsurface cavity. Once the ceiling of a cavity reaches the pavement, it would collapse. Data of cavities under national roads in Japan were analyzed to investigate the distribution and growth of the subsurface cavities.

日本で年間数千件発生する道路陥没は、路面下に発生した空洞が成長しその天井が路面に達することで発生します。まず日本全国の国道下における空洞の発生状況を整理し、いくつかの地理的条件によって分類ました。さらに、一部の空洞発生個所の経年変化を観察したデータの内容を確認し、成長空洞の割合とその規模についてまとめ、その分布特徴を調べました。

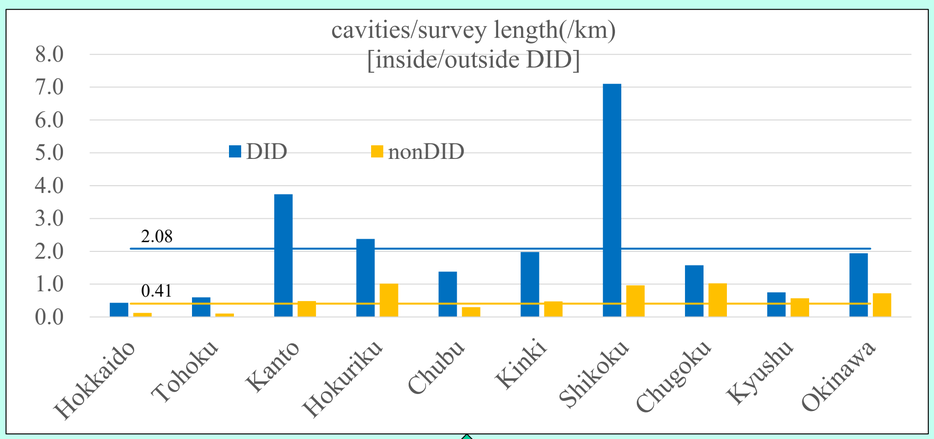
空洞生成の分布
Distribution of subsurface cavities



平成24年度から平成28年度の間に路面下空洞は全国の国道で左図のような分布で見つかった。地方ごとの内訳は右表のようになり、平均して1kmあたり0.8個の空洞が発生しているものの頻度に大幅な差が出ている。

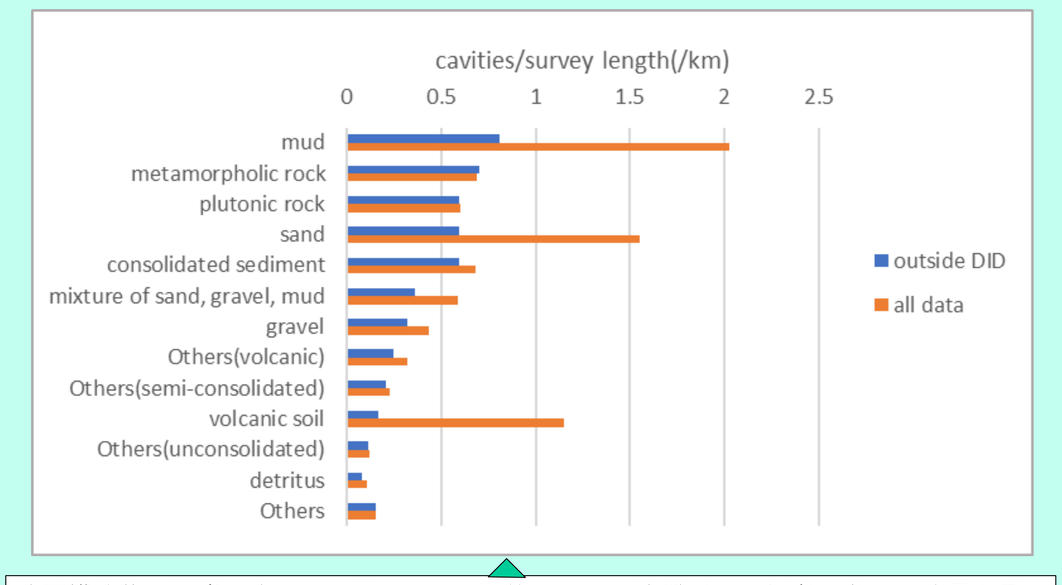
Subsurface cavities that were found from 2012 to 2016 are distributed as shown in the left map. The details are shown in the right table. In average 0.8 cavities per 1km of survey length were found. There are distinct difference in cavity occurrence frequency among regions.

	cavity/length(/km)	survey length(km)	number of cavities
Hokkaido	0.17	3547.8	587
Tohoku	0.19	2381.5	456
Kanto	2.08	2351.7	4893
Hokuriku	1.32	607.2	801
Chubu	0.51	1851.1	947
Kinki	0.90	1510.0	1366
Shikoku	1.72	435.7	748
Chugoku	1.16	1468.1	1698
Kyushu	0.61	1236.8	749
Okinawa	0.99	428.0	425
Total	0.80	15817.9	12670



空洞の発生頻度をDID(densely inhabited district) 内外で比べると、DID内の方が平均して5倍程度多い。これは地下構造物の多さに起因するとみられる。

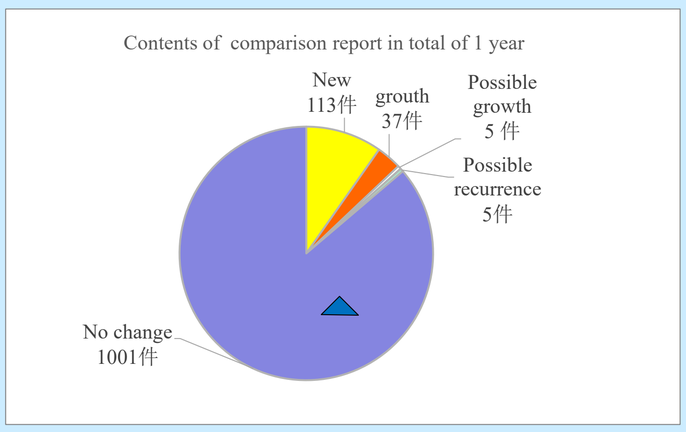
The frequency value in DID is 5 times larger than the value outside DID, which can be attributed to the crowded underground structure.



地下構造物の影響の少ないと思われるDID外において地質ごとの頻度を求めた結果を示す。全データの記録と比較すると、いくつかの地質において特に地下構造物の影響を受けやすい可能性が示されている。

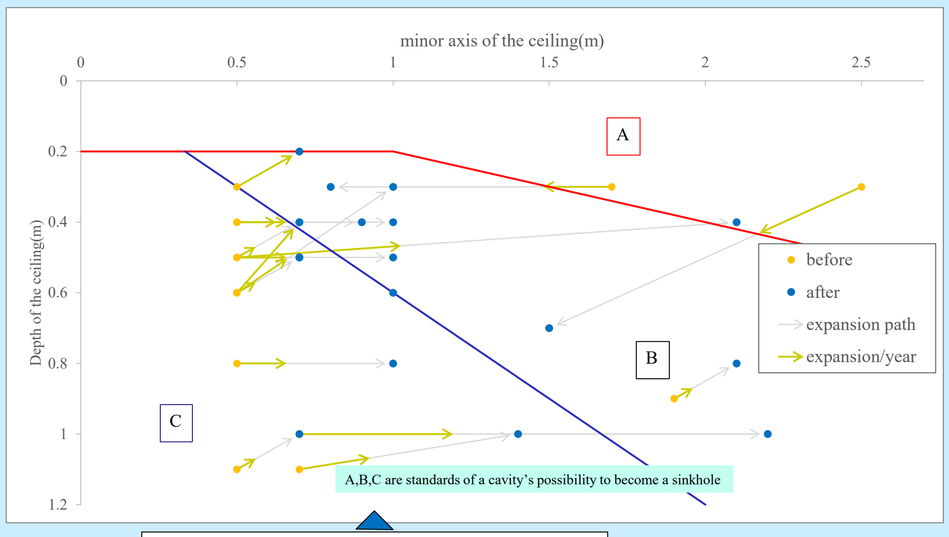
In some geologies, the frequency value was much lower when the area was limited to outside DID. Some geologies may have tendency to cause more cavities affected by underground structure.

空洞の成長
Growth of cavity



危険度の低い空洞について5年以内の成長を確認した結果、ほとんどは変化せず、成長の可能性があるものは4%以下であった。

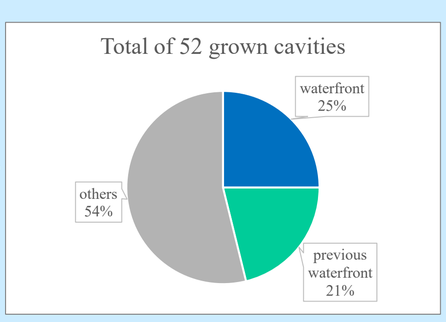
Cavities which were assumed less dangerous were left and their growth were observed. Over 80% showed no growth and the proportion of grown cavities was less than 4%.

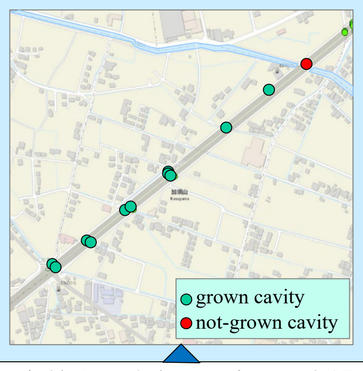


成長空洞の天井部の変位
Expansion paths of grown cavities.

空洞の成長にDID、地質の影響は確認できなかった。現在と過去の水環境への近接性の影響を検討したところ、全空洞を対象にしては影響を確認できなかったが、個別の事例には影響を認める特異点が存在した。

Population density and geology didn't affect growth of cavities. Effect of proximity to water - both at present and in the past - was investigated and it didn't show linkage over all. However, in some successive cavities, irregular cavity growth were observed at the waterfront.





水路に交差する地点に発生した空洞
A cavity growth which occurred at the intersection of a road and a channel.



過去に池淵であった地点で発生した空洞
A cavity growth which occurred at the previous waterfront(1909).
Modified from 「今昔マップ on the web」
(http://ktgis.net/kjmapw/)

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中田祐輔 (2018)

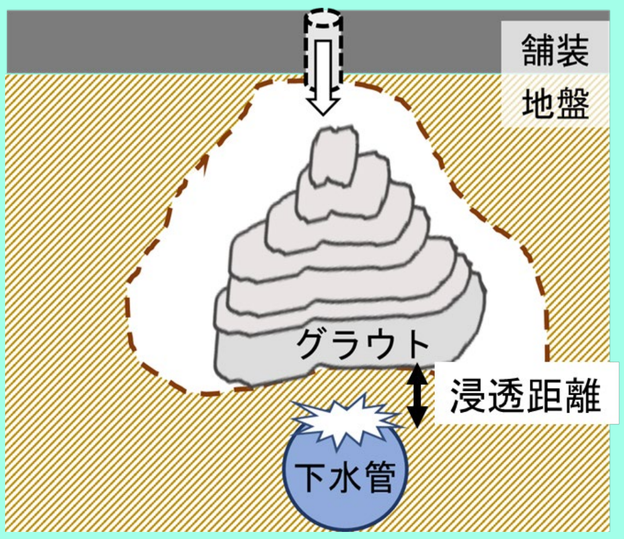
Permeation Behavior of Subsurface Cavity Filling Material

路面下空洞補修用の充填材の浸透挙動

Ground penetrating radar survey has been used to detect subsurface cavities and excavation methods have been carried out to repair. However, backfilling using an excavation method usually takes huge amount of time and cost. Hence, maintenance using a cavity filling material is considered to be effective. The performance of cavity filling material is highly affected by the material fluidity, and its ability not to flow into the sewer pipes. Model tests are conducted to investigate the permeation behavior of filling material into surrounding ground. The main motive of this research is to develop new cavity filling material which meets the required performance.

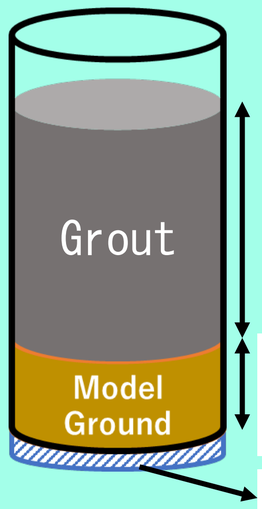
道路陥没の一般的な対策として，地中レーダ探査によって探知された路面下空洞の開削埋め戻しが行われている。しかしながら時間とコストがかかるため、充填材を用いた空洞充填を併用することが今後の補修対策として効果的だと考えられる。空洞充填材には隅々まで充填できる流動性，そして下水管に漏出しない性能が求められる。このような性能を満たす充填材の開発を目的として，本研究では充填材の周辺地盤への浸透挙動について検討した。

模型実験(Model Test)



実験装置(Apparatus)

一次元カラム浸透試験



グラウト投入高さ
Amount of grout
(20cm)

模型地盤の初期位置
Height of ground model

透水フィルター
Water-permeable filter

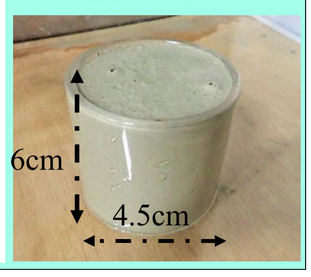
材料(Material)

- 5号珪砂 Silica sand No.5　　D50=0.50mm
- 3号珪砂 Silica sand No.3　　D50=1.80mm
- 充填材(All in Oneフィルコンライト)　Filling Material

実験手順(Test method)

1. 円柱土槽に模型地盤を作成
   Build a ground model with cylinder shape
2. グラウトのフロー値（流動性）を測定
   Measure the flow value (fluidity) of the grout
3. 模型地盤上にグラウトを投入して所定の高さに設定
   Pour the grout into the cylinder model to a certain height
4. 8時間硬化後，模型地盤へ浸透した距離を測定
   Measure the permeation height of filling material after 8 hours

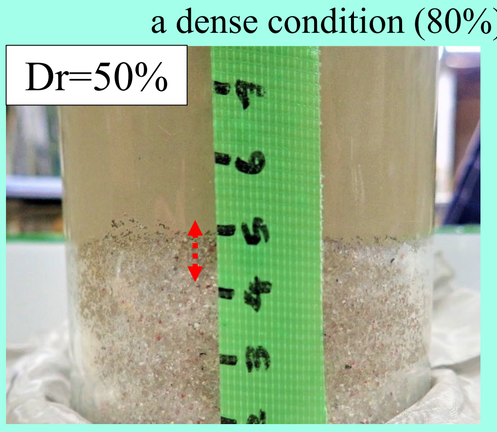
フロー値の測定
Measurement of flow value



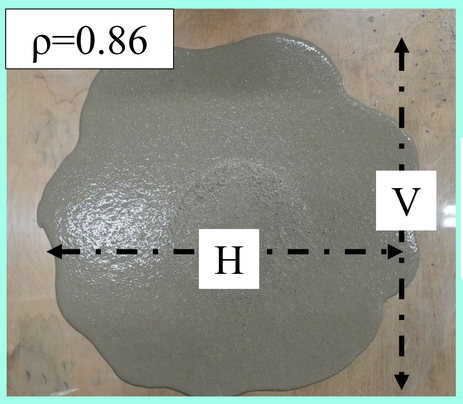
浸透試験 － 5号珪砂(Permeation Test - Silica sand No.5)

対象：相対密度が50％(緩)と80％(密)の5号珪砂
Subject : Relative density of Silica sand No.5 with a loose condition (50%) and a dense condition (80%)

Dr=50%

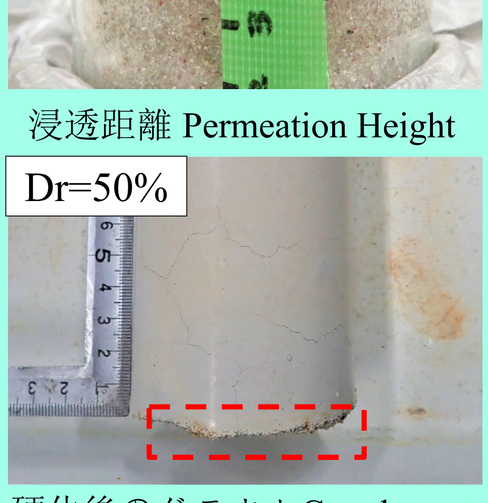


浸透距離 Permeation Height



フロー値
Flow Value
(420×450mm)

Dr=50%



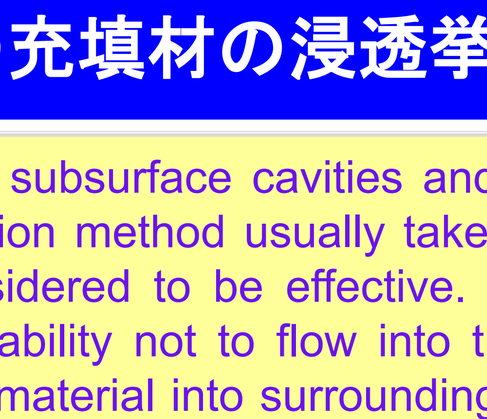
硬化後のグラウトCured grout

Silica No.5		
相対密度 Relative Density, Dr(%)	50	80
含水比 Water Content, w(%)	0	0
初期位置 Initial Height(cm)	5.0	5.0
浸透距離 Permeation Height(cm)	0.3	0.2

浸透試験-3号珪砂(Permeation Test-Silica sand No.3)

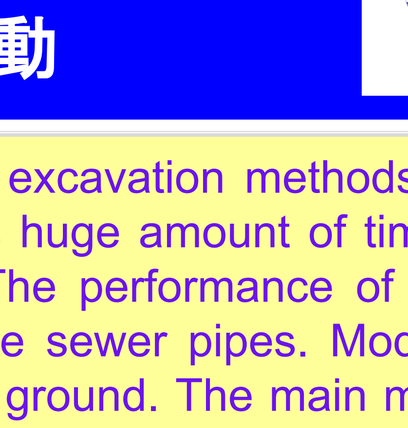
対象：相対密度が50％(緩)と80％(密)の3号珪砂
Subject : Relative density of Silica sand No.3 with a loose condition (50%) and a dense condition (80%)

Dr=50%



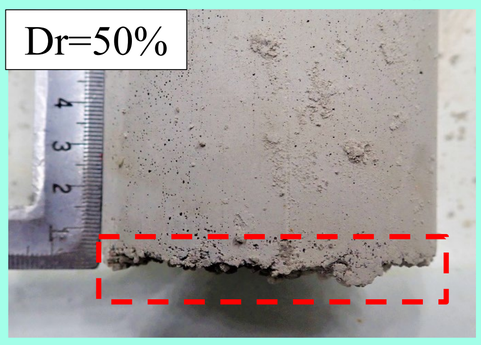
浸透距離 Permeation Height

ρ=0.756



フロー値
Flow Value
(340×360 mm)

Dr=50%

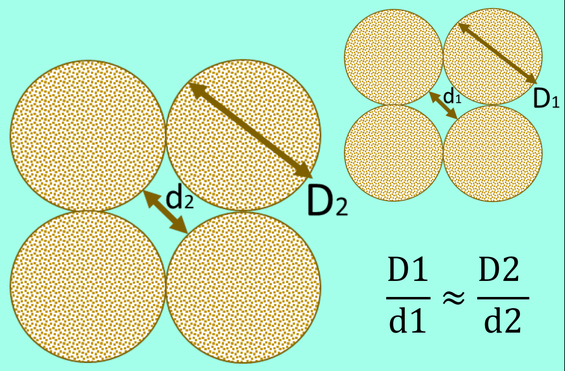


硬化後のグラウトCured grout

Silica No.3		
相対密度 Relative Density, Dr(%)	50	80
含水比 Water Content, w(%)	0	0
初期位置 Initial Height(cm)	5.0	5.0
浸透距離 Permeation Height(cm)	1.0	0.8

浸透試験結果の検討 (Analysis on Permeation Test)

相対密度 Relative Density, Dr (%)	浸透距離 Permeation Height(cm)	
	5号珪砂 Silica sand 5	3号珪砂 Silica sand 3
50	0.3	1.0
80	0.2	0.8



$$\frac{D1}{d1} \approx \frac{D2}{d2}$$

- 密な砂ほど，グラウトが砂への浸透が軽減される
  The denser the sand, the less the effect of permeation of grout.
- 粒径が大きい砂では，グラウトの浸透距離が大きくなる
  The larger the size particle of sand, the larger the permeation height.
- グラウトの地盤浸透現象において，間隙比よりも粒径が支配的
  Compared to void ratio, size of particle is a dominant factor in permeation behavior of grout into sand.

Kozeny-Carman Formula(1927)

$$k = \left(\frac{\gamma}{\mu}\right)\left(\frac{1}{C_{K-C}}\right)\left(\frac{1}{{S_0}^2}\right)\left[\frac{e^3}{(1+e)}\right]$$

k = 粘性流域の透水係数
Permeability (cm/sec)
μ = 粘性係数
Viscosity coefficient (Pa/s)
C_{K-C} =Kozeny定数
Kozeny coefficient ≈ 5.0
S_0 =粒子の比表面積
Specific surface area (1/cm)

球状粒子において，
$S_0 \approx 6/D$
粒径Dの大きい砂
➢ S_0が小さくなり，kが大きくなる
➢ 浸透距離も長くなる

In ball-shaped particle,
$S_0 \approx 6/D$
The bigger the particle size,
➢ The smaller S_0, the larger the k value
➢ The longer the permeation height

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Tingshen Tan (2019)

Development of Grout for Filling Subsurface Cavities

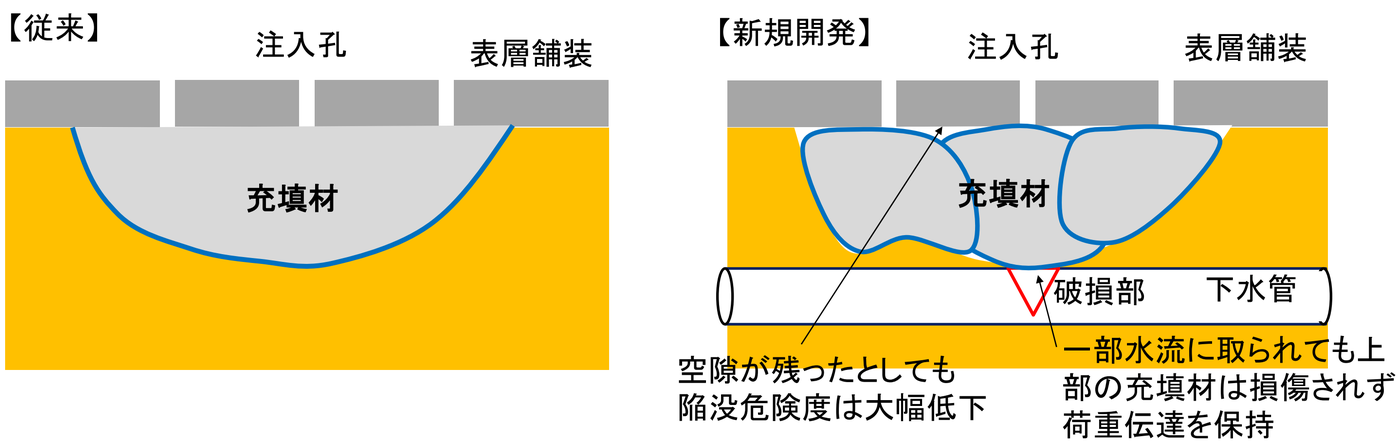
空洞補修用充填材の開発

The grout for filling subsurface cavities was newly developed in collaboration with Sumitomo Osaka Cement Co., Ltd. It has thixotropic nature as well as re-excavation potential. Field and laboratory tests were conducted to check the bearing capacity and the efficiency of re-excavation.

道路陥没は、老朽化した下水管の破損部からの土砂の流出を主な要因として空洞が発生し、それが拡大して、最終的に路面が崩落することにより起こります。一般的な空洞対策として開削埋め戻しが行われていますが，より効率的な方法として充填材の埋め戻しが挙げられます。空洞充填材には隅々まで充填できる高い充填性（流動性）が求められますが、一方で，下水管の破損部から漏出すると下水施設へ影響を及ぼします。また、埋設インフラの維持管理のために再掘削する場合も多いので、高すぎず低すぎずの適切な強度設定が求められます。本研究では流動性を抑えた空洞補修用充填材を住友大阪セメント(株)との共同研究にて開発しました。人工空洞を設置した実物大試験道路で開発したの充填材の充填試験および再掘削性評価試験を実施しました。

Development of thixotropic grout mixture for subsurface cavity with re-excavation potential
再掘削性を考慮した可塑性充填材の開発

付近に破損した下水管があっても漏出しないような可塑性充填材



従来の高流動性充填材は空洞をすみずみまで充填するのに適しているが、近傍に破損した下水管があり地盤内に水みちが通じている場合は、下水管内へ漏出する危険がある。また道路下、埋設管路周辺に用いることから再掘削性を考慮する必要がある。

新規開発充填材の目標物性:

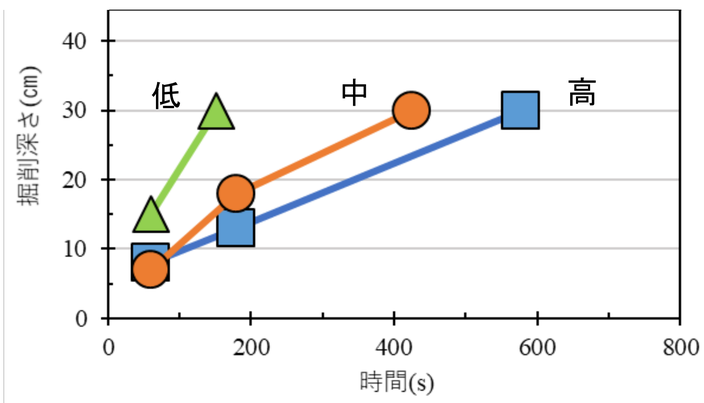
可塑性、水中不分離性、分離抵抗性、単位容積質量（軽量、1.0以下）、一軸圧縮強さ （再掘削性を考慮）、速硬性.

Field test for re-excavation potential
再掘削性のフィールド試験

小型重機を用いて試験体の掘削を実施し掘削時間と深さを測定

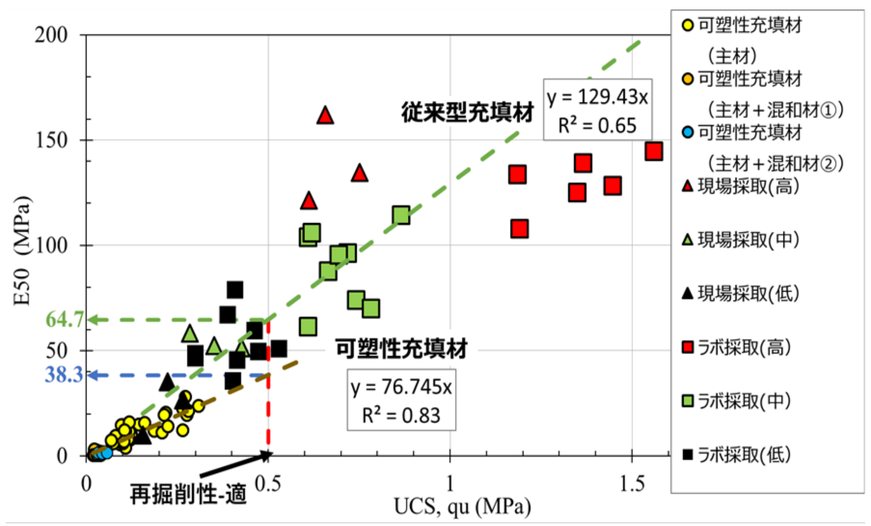


低強度 500kPa以下　　高強度 500~1000kPa　　中強度 1000kPa以上



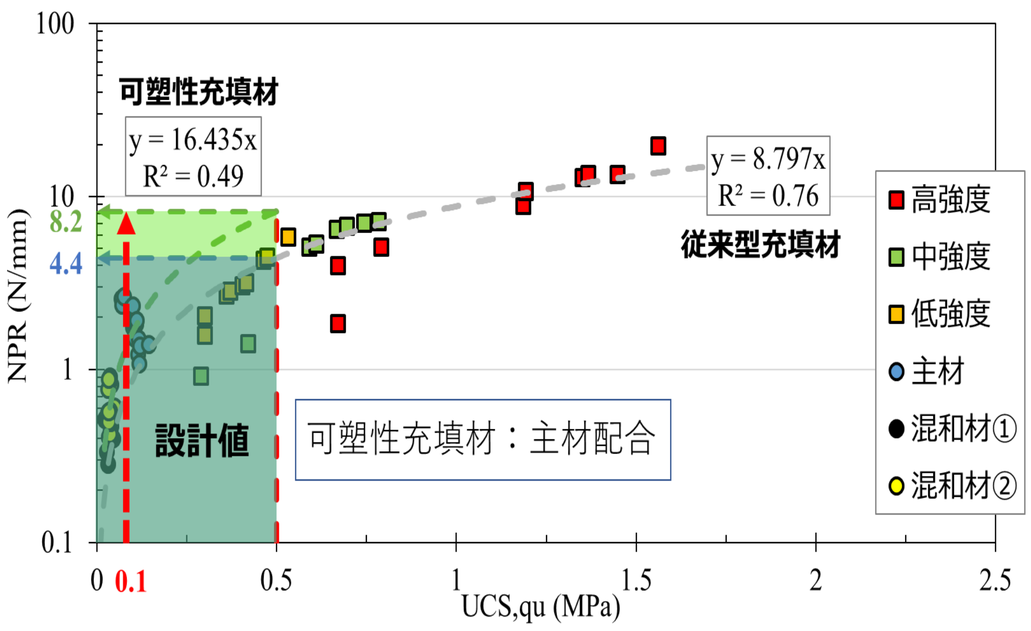
掘削深さと時間の関係

Strength and stiffness of the grout
空洞補修用充填材の強度と剛性



一軸圧縮強度とE50の関係

- 一軸圧縮強度とE50、および針貫入抵抗には相関あり。
- 路面の十分な支持力、および再掘削時の効率の両方を考慮した充填材の強度設定は一軸圧縮強度を指標とできる。



一軸圧縮強度と針貫入抵抗の関係

FWD test on the filled cavity
空洞充填箇所のFWD試験

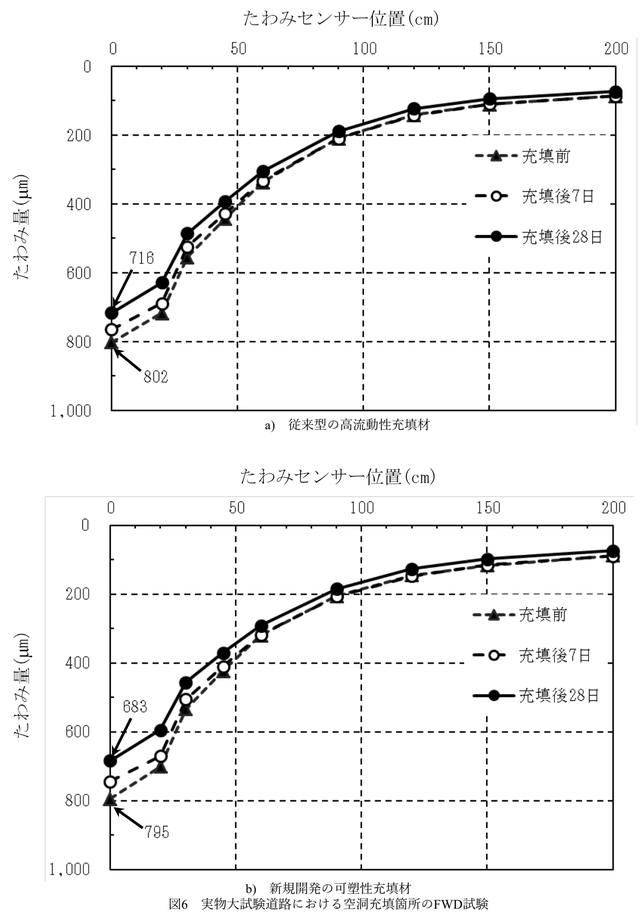


図6 実物大試験道路における空洞充填箇所のFWD試験

従来型の充填材と同様のたわみ軽減効果を確認

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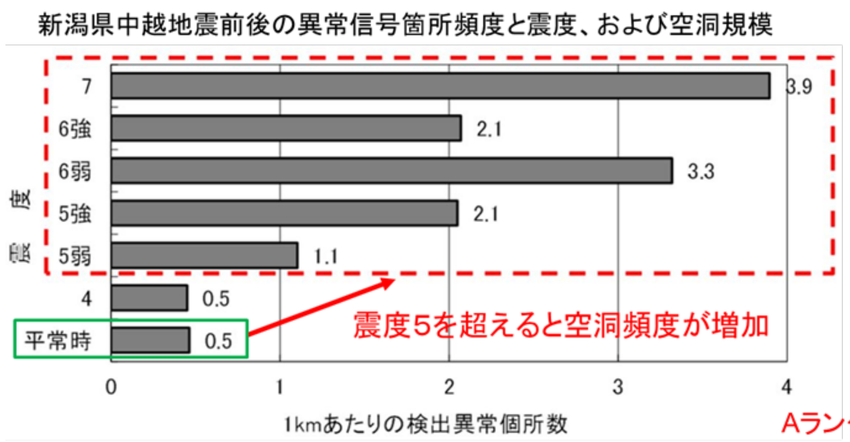
Subsurface Cavity Behaviour in Earthquake

路面下空洞の地震時挙動

路面に突如として穴が生じる「道路陥没」は、人命やインフラへ被害を及ぼしうる災害で、その数は日本全国で年間10,000件を超える。この陥没は、地中に存在する空洞が徐々に成長することで発生するため、空洞の危険度を予測することで陥没に至る前に対策を講じることが可能になる。既往研究によると、震度5以上の地震動の後に空洞が増えることが確認されており、この事実から地震は空洞成長の一因だと考えられる。そこで本研究では、空洞の陥没危険度予測のために、地震によって空洞が成長するメカニズムの解明を目的とした。振動により空洞下部が液状化したり空洞側壁部が空洞内部に向かって滑り破壊するなど、水の浸透に伴う空洞拡大と異なるパターンが観察された。

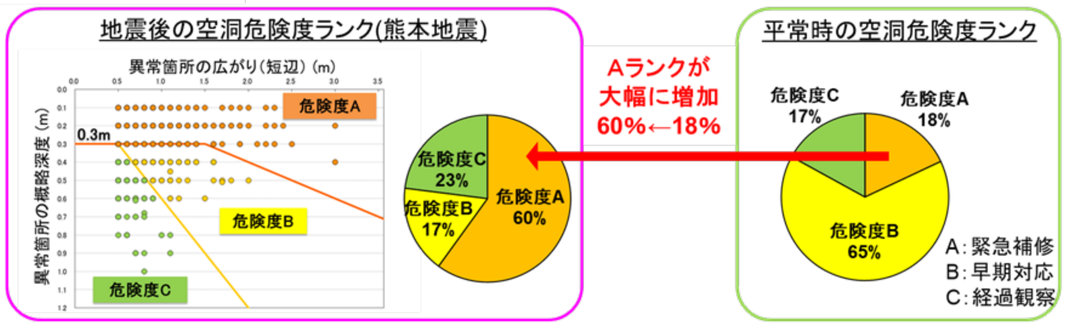
Road cave-in is one of the disasters that can cause loss of life and damage to infrastructure and occurs more than 10,000 cases per year throughout Japan. Since road cave-ins are caused by the growth of cavities in the ground, predicting the danger level of cavities makes it possible to take countermeasures before a road cave-in occurs. Previous studies have confirmed that cavities increase after seismic tremors of intensity 5 or higher, and this fact suggests that earthquakes are a factor in cavity growth. The purpose of this study was to investigate the mechanism of cavity growth caused by earthquakes. Different patterns from cavity growth caused by water seepage were observed, such as liquefaction of the lower part of the cavity due to vibration and sliding failure of the cavity sidewalls toward the cavity interior.

地震動による空洞増加・拡大　Increase in the size and the number of subsurface cavities



揺れの大きな（震度5以上の）地域は
空洞の数が増える

地震により危険度の高い
空洞の割合が増える

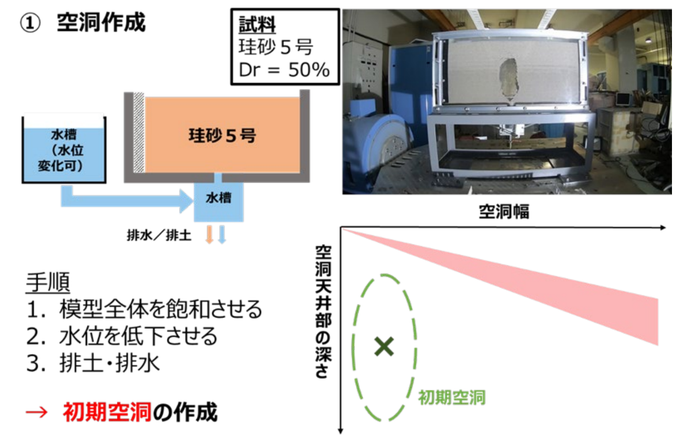


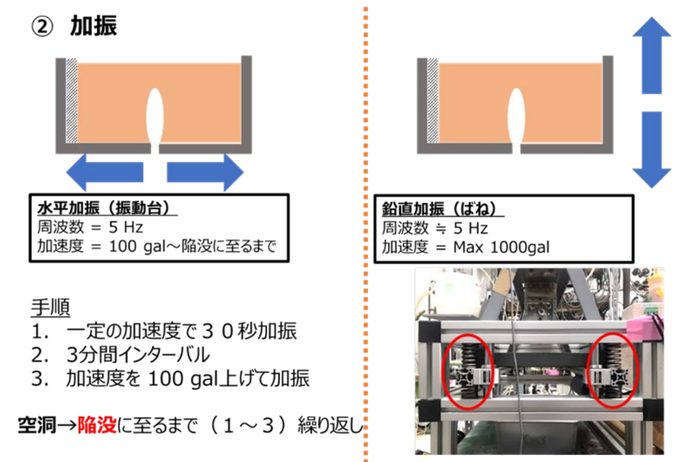
(岡本ら，地震災害後の早期道路復旧に向後の早期道路復旧に向けた路面下空洞調査の活用，土木学会第72回年次学術講演会(平成29年9月)．
これまで最も早く被災後に現地計測がされた調査結果から分析されたもの(熊本地震から10日後))

(小池ら，路面下に発生する空洞の発生状況の分析と考察，土木学会第72回年次学術講演会(平成29年9月))

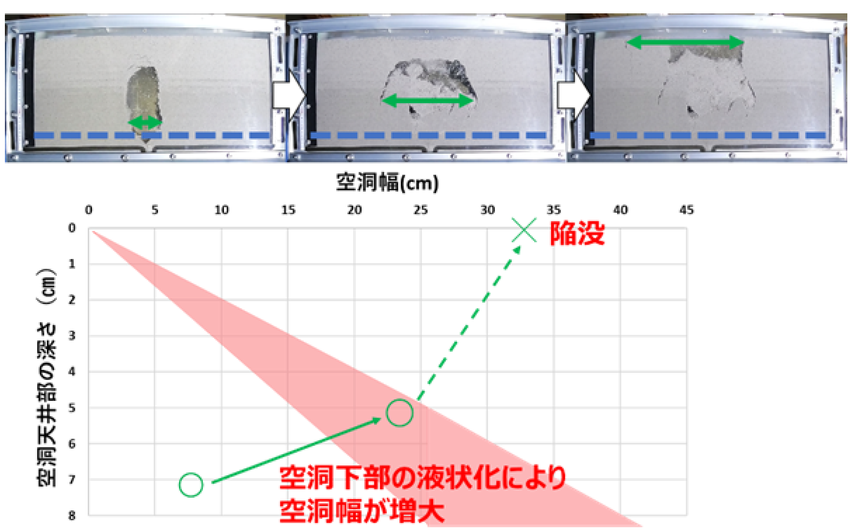
Aランク：いつ陥没してもおかしくない危険度の高い空洞

試験方法　Test method

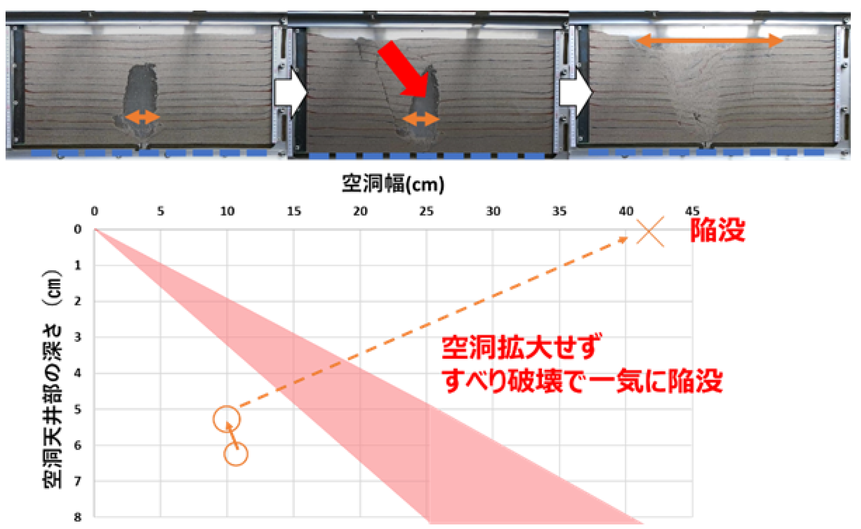




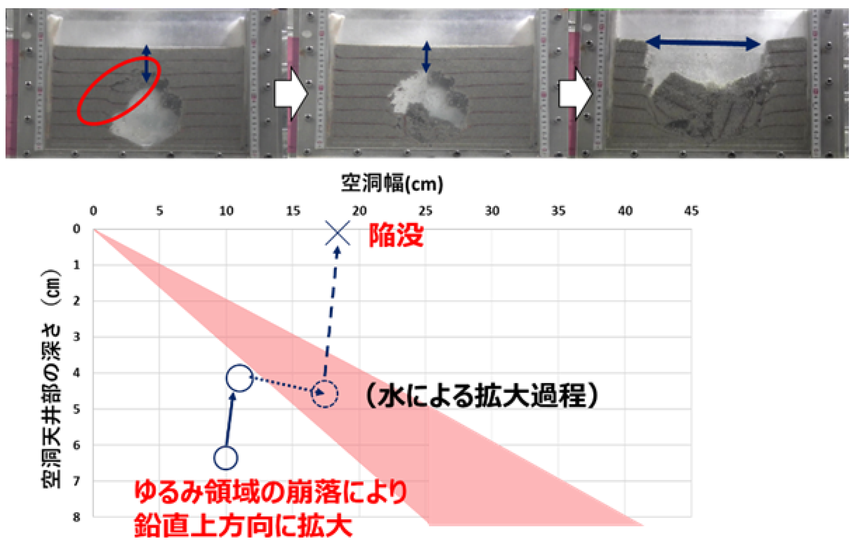
空洞の拡大パターン　Pattern of cavity expansion



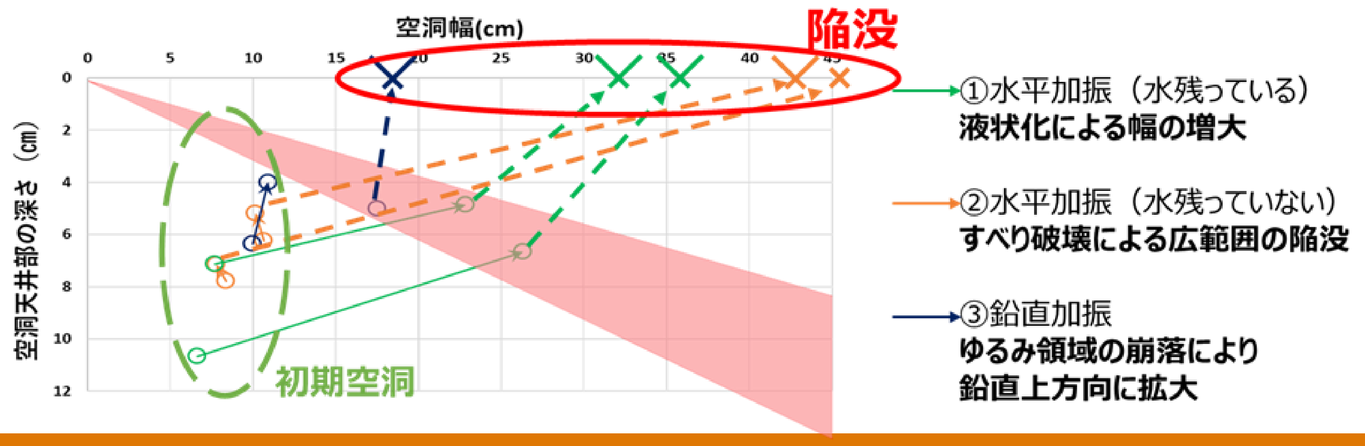
水平加振（水あり）



水平加振（水なし）



鉛直加振（水なし）



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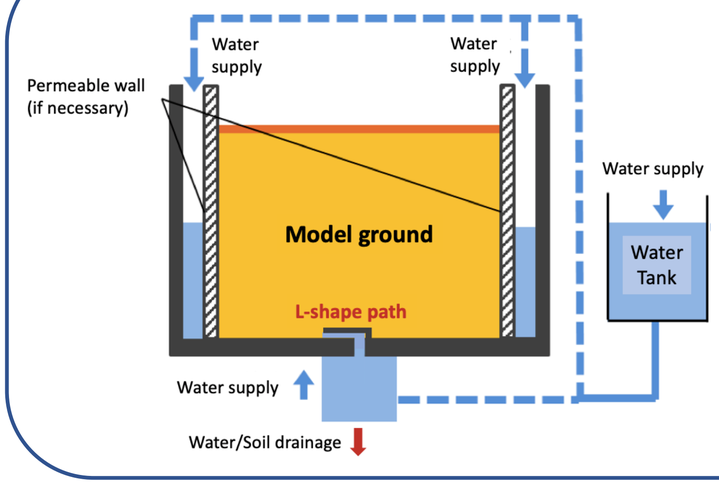
Generation and Expansion of Subsurface Cavity around a Joint of Buried Pipe

埋設管の止水不良箇所における地盤内空洞の生成・成長過程

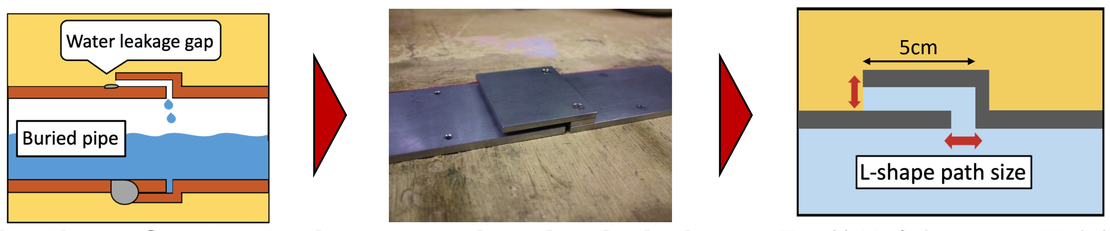
A road cave-in is becoming a serious problem in accordance with the aging of infrastructure. Recently, a field excavation survey on subsurface cavities revealed that small damage in pipe joints can be a cause of cavities. Those damages are regarded as water leakage, not regarded as a structural breakage of pipe. In this study, the process of generation and expansion of subsurface cavities around the location of water leakage in buried pipes are investigated through a series of model tests.

インフラ老朽化に伴い道路陥没現象が深刻な問題となっています。近年実施された地盤内空洞の開削調査から、一見して破損が確認できないような下水管上に空洞が発生する場合があることがわかりました。構造上の破損とは言い難い継手部の軽微な隙間、いわゆる止水不良箇所における地盤内空洞の生成・成長過程に対して、模型実験による考察を行ないました。

Model test apparatus and test procedure　実験装置と手順



① Model ground is made in a soil chamber and and a L-shape path is set on the bottom.　模型地盤を作成しL字型土砂流出口を底部に配置。
② Water is supplied into the model ground.（=the rise of the ground water level)　模型地盤内に水を供給。(=地盤内水位の上昇を再現)
③ The L-shape path is opened and soil and water drain through the path.　L字型土砂流出口を開けることで土砂と水が流出する。
④ The cycle of water supply and drainage is repeated and a cavity grows up.　②と③のサイクルを繰り返すことで空洞が生成・成長。



Reproduction of water leakage gap in a buried pipe　埋設管接合部の止水不良箇所の再現

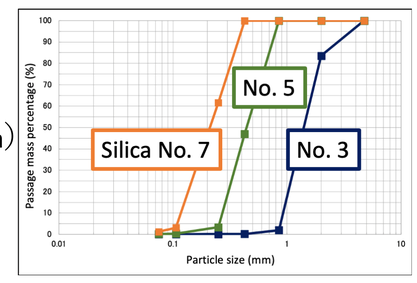
Model test with single-particle-size ground
均一粒径地盤を用いた模型実験

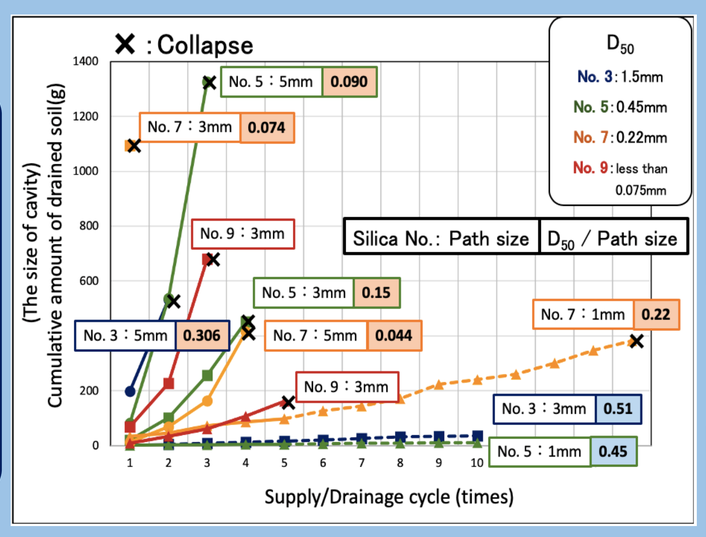
Material　地盤材料

Silica 硅砂
No. 3（D_{50}：1.5mm)
No. 5（D_{50}：0.45mm）
No. 7（D_{50}：0.22mm）
No. 9（D_{50}：Less than 0.075mm）

※ D_{50}：50% pass particle size
通過重量百分率50%の粒径

Relative density：50%
相対密度：50%





✔**The ratio of particle size to path size is related to the degree of soil drainage.**
・土粒子の粒径と土砂流出口の幅との比が土砂流出の程度に関与。

D_{50} / Path size　D_{50} / L字型土砂流出口の幅
Less than 0.31 → Cavity growth (→Collapse)
0.31以下　空洞成長あり（→陥没）
More than 0.45 → No cavity growth
0.45以上　空洞成長なし

✔**The degree of soil drainage is not necessarily in proportion to the path size.**
・土砂流出の程度は土砂流出口の幅に必ずしも対応しない。

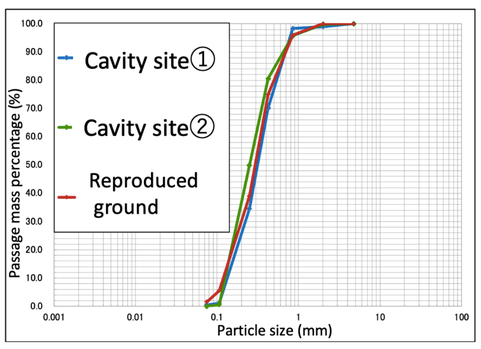
The degree of soil drainage　土砂流出の程度
Path size 土砂流出口の幅　**3mm > 5mm > 1mm**
※ In the case with Silica No. 7　硅砂7号を用いた実験

Model test with real cavity site ground
空洞発生現場の再現地盤を用いた模型実験

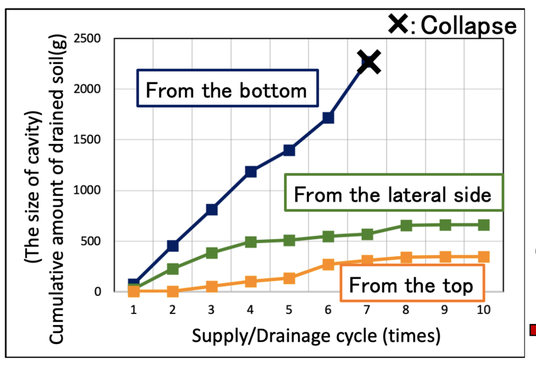
Material　地盤材料

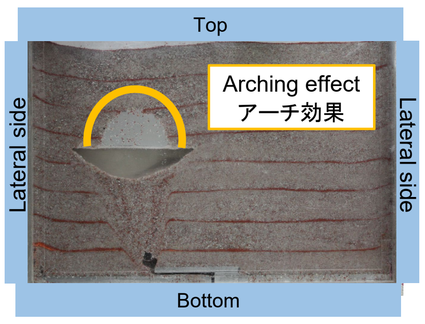
Same particle-size-distribution ground of real cavity site which is based on the data of a field survey in Fujisawa city
藤沢市にて実施された現地調査のデータをもとに、実際に空洞が生じている地盤と同一の粒度分布を持つ再現地盤を作成。

Relative density：50%
相対密度：50%



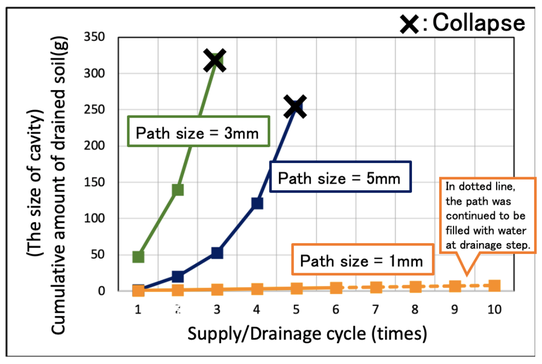
The effects of water supply method
給水方式が土砂流出に及ぼす影響





①Rise of water level 地下水位の上昇 ➡ ②Collapse of arching アーチの崩壊
➡ ③Reformation of arching アーチの再形成 ➡ ④Growth of cavity 空洞の成長

The effects of path size
土砂流出口の幅が土砂流出に及ぼす影響

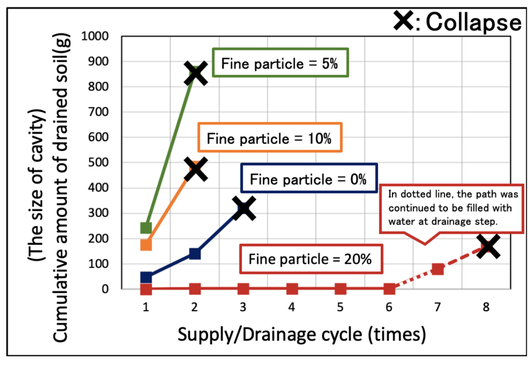


The degree of Soil drainage　土砂流出の程度
Path size 土砂流出口の幅　**3mm > 5mm > 1mm**

✔**In the 3mm-path-size case, Soil and water filled the horizontal part of the path and sustainably drained together as fluid.**
・流出口幅が3mmのケースでは、土砂と水が流出口の水平部を満たし、流動体として一体となって持続的に流出。

＝The Mechanism which can promote soil drainage
土砂流出を促進し得るメカニズム

The effects of fine particle
細粒分が土砂流出に及ぼす影響



In the case in which fine particle rate is 20%, the tendency of soil drainage was smaller.

The increase of fine particle rate　細粒分含有率の増加
↓
The decrease of Permeability　透水係数の低下
↓
The suppression of water stream　水流の抑制
↓
The decrease of soil drainage　土砂流出の低減

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Evaluation of collapse risk of subsurface cavities and development of its countermeasures

道路構造及び空洞特性に適応した陥没危険度評価と合理的路面下空洞対策についての研究開発

Many subsurface cavities are being generated under roads in the urban area. Some of them would collapse and may cause road cave-in accidents. In order to prevent this, aiming at the rational countermeasures for road cave-ins, techniques of survey, diagnosis, repair and prevention for subsurface cavities are developed. Those techniques are integrated as the solution.

道路下の空洞は、都市の成熟と共に様々な要因で生成し、場合によっては道路陥没を引き起こします。本研究では、道路陥没対策の合理化を実現するため、空洞の調査・診断・補修・予防に資する道路陥没ソリューションの提案を研究目的として、空洞調査方法の高度化、危険度評価指標の開発、空洞の補修・予防方法の開発を産官学の共同研究プロジェクトとして実施しました。

Development of the solution to prevent road cave-ins
道路陥没予防ソリューションの開発

調査計画：
空洞ポテンシャルマップに基づく計画
・素因と誘因の評価

空洞探査：
・1次調査（車載型地中レーダによる空洞信号の抽出）
・2次調査（地中レーダ，削孔による空洞確認
→　状況によっては同時補修

補修：（空洞特性や危険度に応じて）
・開削埋戻し　・充填　・経過観察

陥没抑止：
空洞補修までの応急対策：路面補強
空洞拡大抑止による路盤保全：路盤補強

診断：
空洞特性および陥没危険度評価
・生成要因
・広がり・深さ
・成長速度

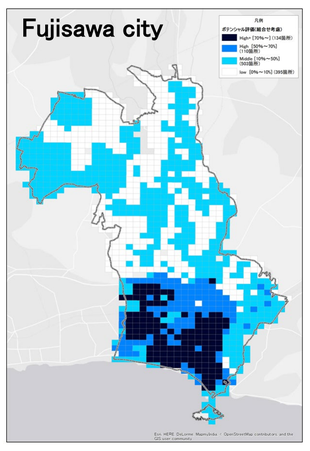
空洞補修用可塑性充填材
下水管が近傍にある場合：流動性低
その他の場合：流動性高

空洞・陥没データの蓄積：
空洞・補修履歴の記録・分析

Subsurface cavity potential map
空洞ポテンシャルマップの試作と検証

調査

既存の空洞・陥没データと周辺状況・環境条件を分析し，
空洞ポテンシャル：空洞の出来やすさの指標（生成可能性）を設定

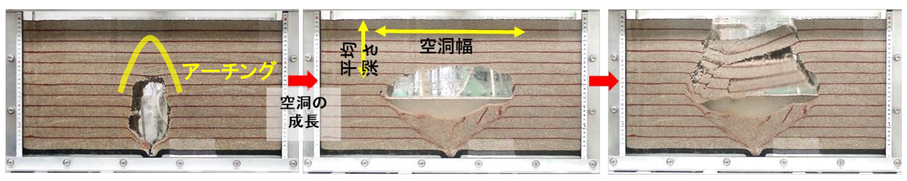


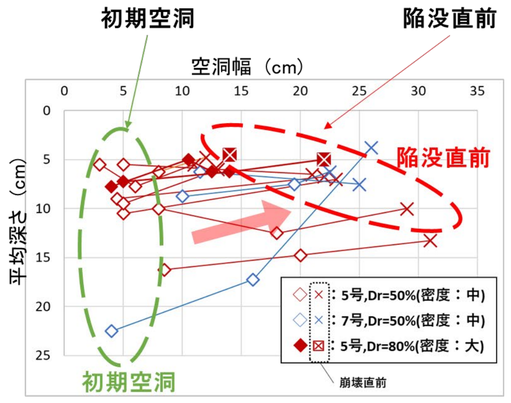
空洞形成に影響する４つの支配要因
・下水合流式・1960-1980年代
・下水管取付管多い
・砂質土
・地下水位（参考）GL-3m以浅

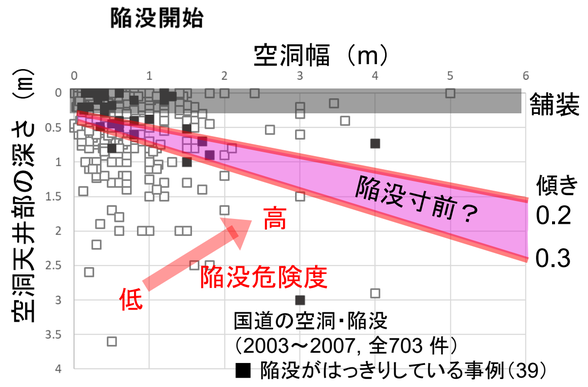
ポテンシャル	要因	頻度 (/km) 陥没	空洞
High+	3因子以上	1.2	4.6
High	下水･砂質	0.7	2.4
Middle	上記以外	0.4	0.4
Low	なし	0.1	0.3

Mechanism of cavity expansion and surface collapse
空洞拡大メカニズムと陥没危険度

診断

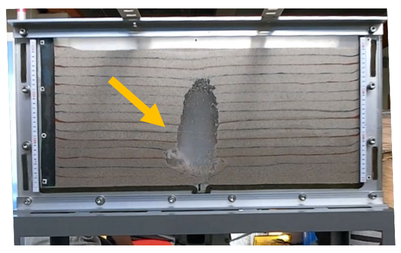




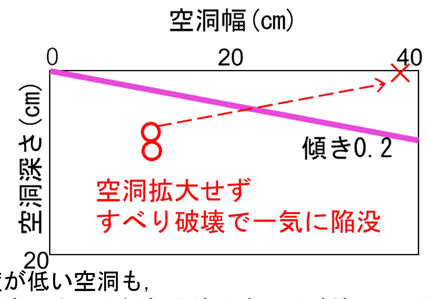


空洞は，土砂流出が継続する場合，地下水位以下で水平方向に広がり成長する
地盤の支持力喪失に関する限界状態は，空洞幅と空洞天端深さで概ね表現でき，空洞深さと空洞幅の比が0.2を切ると空洞上の土は自重による崩落の危険がある

地震時の空洞拡大



初期空洞を作製して加振



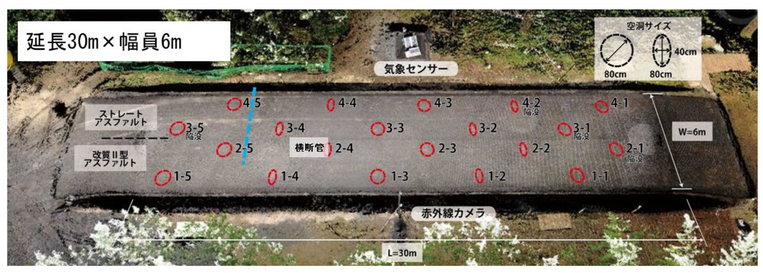
陥没危険度が低い空洞も，
地震時には空洞内への側部土塊のすべり破壊により拡大
↓
地震時に危険度ランクが高い空洞が増加する調査結果に整合

Behaviour of cavities in test field pavement
実物大試験道路の構築と空洞載荷試験

診断

試験体の構築

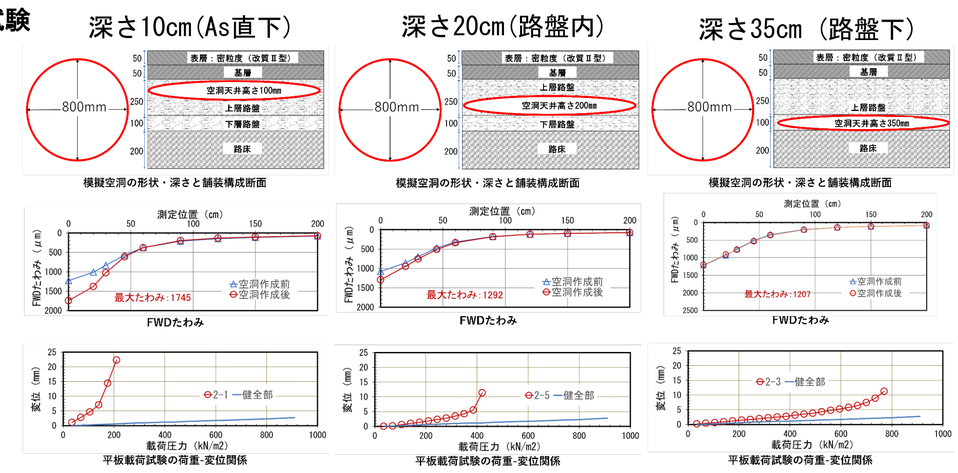
表層：
ストレートアスファルト
改質Ⅱ型
上層路盤：
粒調砕石
瀝青安定処理
モニタリング：
気象
路面温度
路面変位





細礫詰め土嚢を路盤内に設置し舗装を敷設し，その後細礫を吸引し空洞生成
φ80×h10cmおよび80×40×h10cmの空洞を天井深さ10～35cmに1～3期で計51個設置

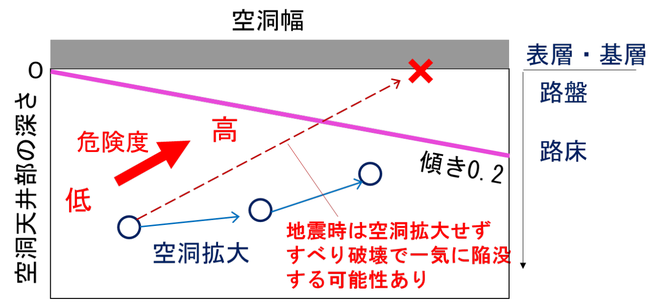
空洞載荷試験



FWDたわみ量と平板載荷試験沈下量は空洞が深いほど変状が小さい

夏季（日射・路面温度）の影響
最大たわみ量＝2000μm超～陥没までの余寿命(時間)
夏場は日単位・他は月単位

舗装構造を考慮した陥没危険度評価
舗装構造によらず，路面下空洞により路盤が侵食されると，路面陥没は時間の問題
陥没危険度は路盤以下からの空洞深さで評価

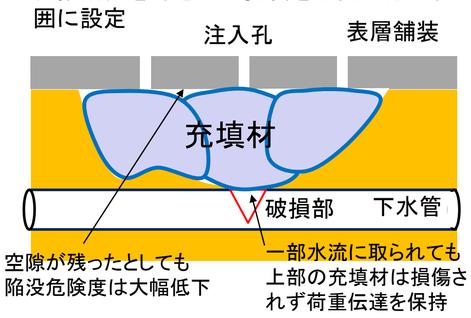


Repair and prevention of subsurface cavity
空洞の補修と予防

補修・予防

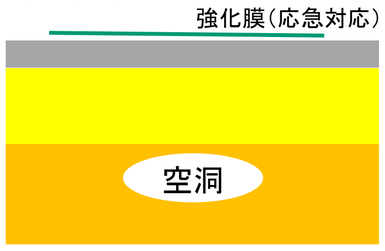
空洞補修用可塑性充填材

周囲に破損した下水管がある場合は低流動性，無い場合は高流動性に調整可能。再掘削性を考慮して強度を必要十分な範囲に設定



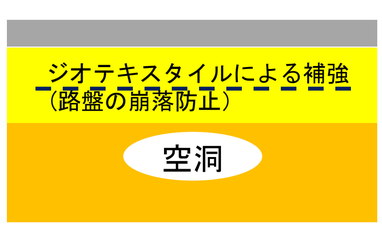
路面補強

空洞を認知してもすぐに補修できない場合のために，路面に応急対策として補強材を貼り付け，強化膜を作ることにより陥没を抑制。



路盤補強

空洞上に地盤（路盤）が残りアーチ効果が期待できると陥没は起こりにくい。路盤内に補強材を敷設し路盤の崩落を防止。



本研究は，国土交通省道路局が設置する新道路技術会議における技術研究開発制度により，国土交通省国土技術政策総合研究所の委託研究「道路構造及び空洞特性に適応した陥没危険度評価と合理的路面下空洞対策についての研究開発」において、東京大学、埼玉大学、ジオ・サーチ(株)、NIPPO(株)、住友大阪セメント(株)の共同研究で実施されました

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CART project (2018-2020)
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STUDY ON MECHANICAL AND EROSION PROPERTIES OF AGGREGATED SOIL

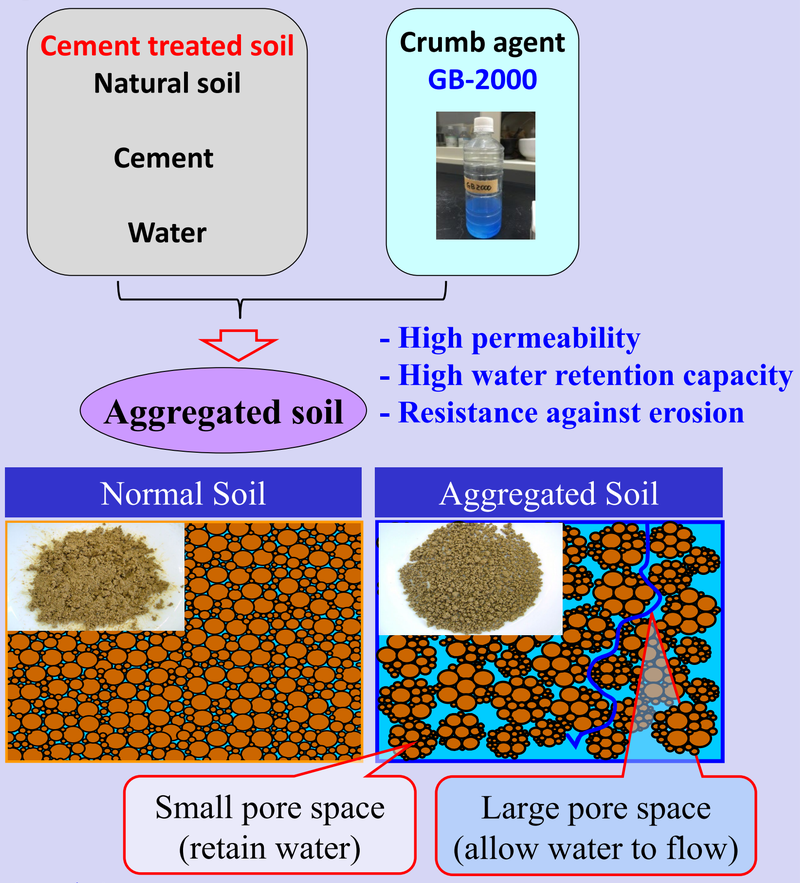
団粒化土の力学特性と侵食性に関する研究

Aggregated soil is a chemically stabilized soil, to increase the permeability and water retention capacity of natural soil. The geotechnical properties of aggregated soil is not yet properly understood to be used as a major construction material. In this study mechanical and erosion properties of aggregated sand with natural sand and cement treated sand were compared. Masado was used as natural sand. Basic soil tests, unconfined compressive strength test(7 & 28 curing days), and permeability test were conducted for each type of soils. A new permeability apparatus was used to evaluate internal erosion of the soil. Turbidity of the outflow was measured to evaluate the degree of internal erosion. The microstructure of the treated soil was observed using scanning electron microscope (SEM) images.

団粒化土とは自然土の透水性や保水性を向上させるために化学的に安定化させた土として知られていますが、その地盤工学的な特性は未だ理解されておらず、主要な建設材料として用いられる段階にはいたっていません。本研究では団粒化土と自然土である真砂土やセメント処理を施した土の工学的性質や侵食性を比較しました。物理試験、一軸圧縮試験(養生期間7日間・28日間)、及び透水試験を各試料について行いました。新しい透水試験装置を使用し、流出水の濁度を測定することで土の内部侵食を評価しました。また、団粒化土の微小構造をSEM(走査型電子顕微鏡)を用いて観察しました。

(1)Introduction on aggregated soil

Aggregated soil is a chemically stabilized natural soil, made by mixing cement (Hexavalent Chromium Soluble cement), polymeric liquid called crumb agent, and water to create three dimensional meshes like structure by attaching fine particles to larger particles.

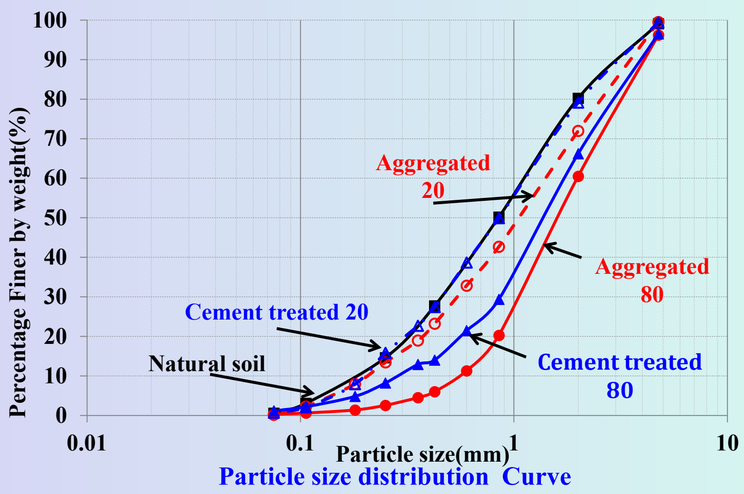


http://www.cimaconsul.co.jp

(2) Tests, Apparatus and testing method

Materials and mix proportions

Test set	Cement (by volume)	Crumb agent (by volume)	Water (by weight)	Dense condition
SET 1	80kg/m^3	1.5l/m^3	16.5%	Dense DC>95%
SET 2	20kg/m^3	1.5l/m^3	14.5%	Dense DC>95%
SET 3	20kg/m^3	1.5l/m^3	14.5%	Loose DC<85%

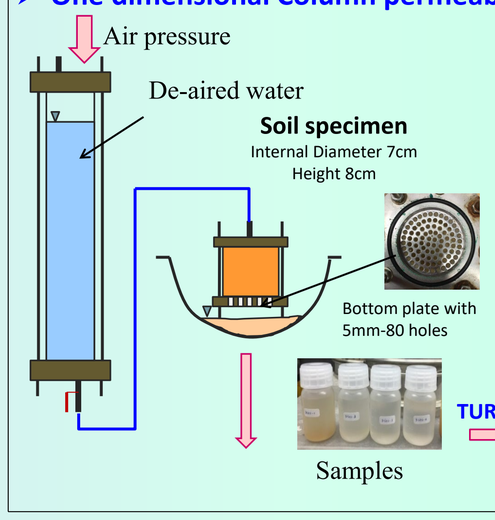


Particle size distribution Curve

- Addition of crumb agent of aggregated soil has caused to formation of larger sized clusters than in natural soil and cement treated soil
- When increase cement content flocculation ability is increased in both cement treated and aggregated soils

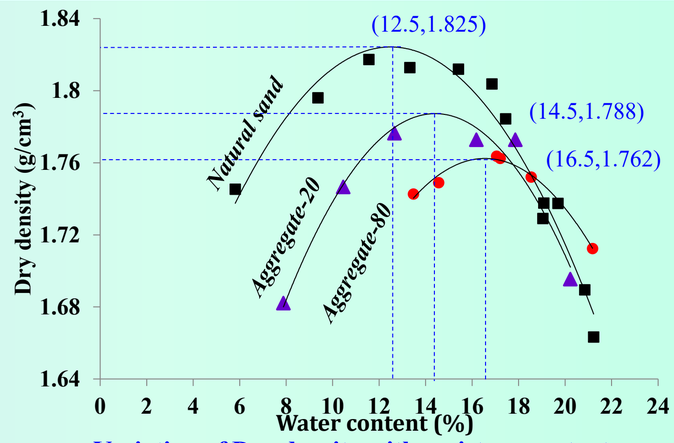
・セメントや土壌団粒促進剤を加えた団粒化土は自然土に比べ、大きい塊を形成し、透水性が向上した。
・セメント量を増加させると、どちらの試料についても凝集力が増加した。

One dimensional Column permeability test and Turbidity test



-Out flow of water collected for checking turbidity

- Time duration to complete each water cycle was also measured



Variation of Dry density with moisture content

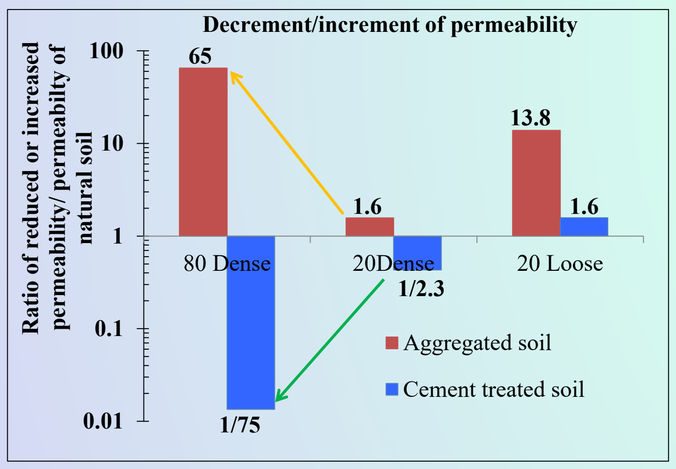
- When increase the cement content of aggregated soil, the increase of voids reflects the decrease in maximum dry density

・団粒化土のセメント量を増加させると、最大乾燥密度の減少が空隙量の増加に反映された。

(3)Test results

Permeability test results

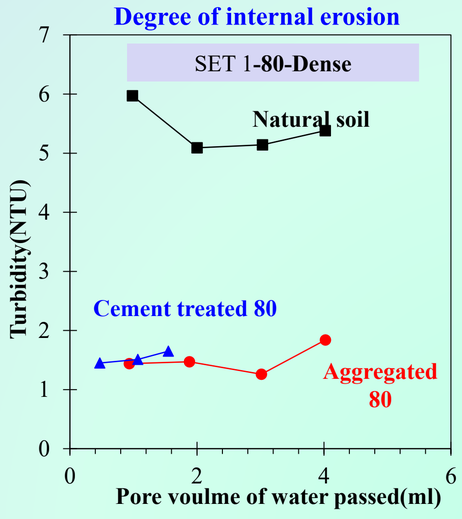
	Soil type	Coefficient of permeability (cm/s)
SET 1 80kg/m^3 Dense	Natural soil	3.12E-5
	Cement treated soil	4.20E-7
	Aggregated soil	2.03E-3
SET 2 20kg/m^3 Dense	Natural soil	2.51E-4
	Cement treated soil	1.08E-4
	Aggregated soil	3.94E-4
SET 3 20kg/m^3 Loose	Natural soil	7.48E-4
	Cement treated soil	1.17E-3
	Aggregated soil	1.03E-2



- Aggregated soil shows higher permeability in all three conditions due to larger amount of interconnected pores

団粒化土は全ての条件において空隙の相互連結によって透水性が向上した。

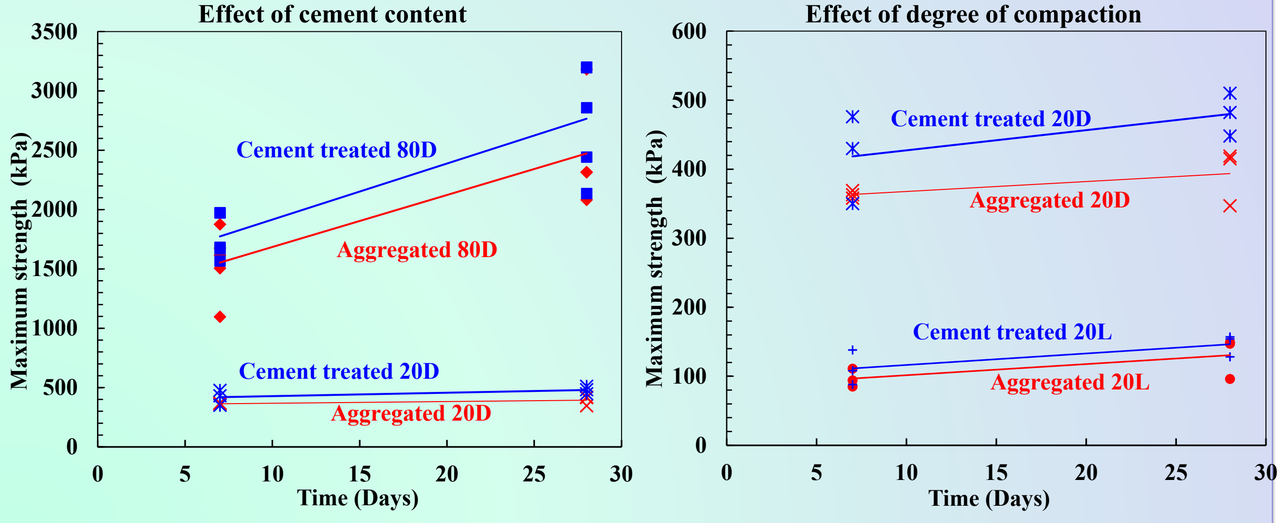
Degree of internal erosion

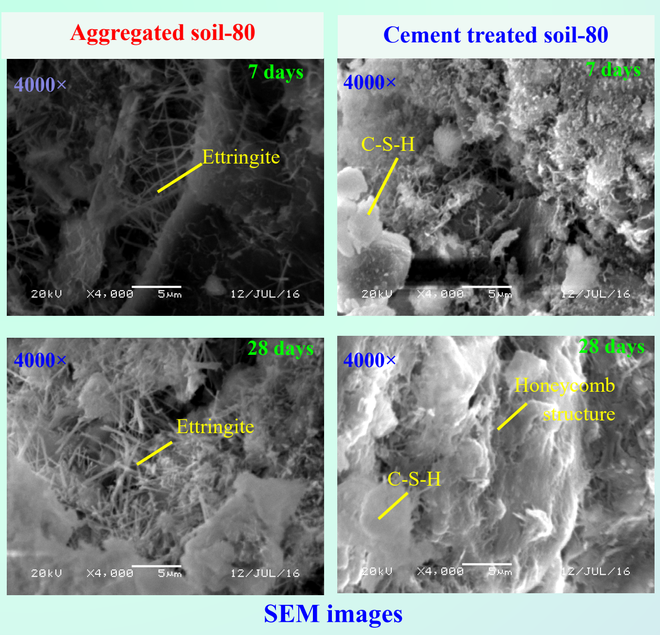


- When increasing the cement content permeability of aggregated soil is increased and the permeability of cement treated soil is decreased
- Aggregated soil has severe condition to erode with higher water flow velocity due to higher coefficient of permeability
- But it shows lower turbidity values which reflect higher erosion resistance even with higher flow velocity

・セメント量を増加させると、団粒化土の場合は透水性が向上し、セメント処理をした土の場合は低下した。
・団粒化土は透水係数が高いめ、間隙の水の流速がくなるが、濁度の数値は低く、高い侵食抵抗が見られた。

Behavior of Strength with curing time of aggregated soil and cement treated soil





SEM images

- Maximum strength of the aggregated soil depended on the cement content and the degree of compaction and enhance when increasing the curing time
- But the strength increment rate of aggregated soil with curing time was a little bit lower than cement treated soil
- As shown in SEM images, a stabilized honeycomb structure has formed in the cement treated soil with 28 curing days, than in aggregated soil
- As a result, it shows a higher strength gain rate and lower permeability in cement treated soil

・団粒化土の最大強度はセメント量と締固め度に依存し、養生期間を長くすると増加した。
・しかし、強度発現率はセメント処理をした土に比べて低かった。
・SEM画像から、養生期間28日において、セメント処理をした土の方が団粒化土に比べてより安定したハニカム構造を形成することが確認された。
・その結果、セメント処理をした土は高い強度増加率と低い透水性を見せた。

本研究に関する担当研究室は桑野研究室です.
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Digala Mudiyanselage Dayani Nadeesha Sanjeewani (2017)

Properties of Aggregated Soil
- Effect of confining pressure -

団粒化土の力学特性　ー拘束圧の影響ー

Aggregated soil is a chemically-improved soil that consists of double pores where the macro-pores allow water to flow through easily which improves water infiltration, and the micro-pores can retain water to slowly release back to the atmosphere through evaporation. Since aggregated soil is a relatively new material, its properties need to be well understood before its application in large-scale projects. In this study, its mechanical properties under various confining pressure is being studied using triaxial apparatus. The microstructure of aggregated soil is also studied using scanning electron microscope.

細粒土を凝集した粒で構成されマクロ間隙とミクロ間隙を有する団粒化土は、高い透水性を有する一方で団粒内のミクロ間隙に水を保持することができる。団粒化土は現状では歩道やグラウンドなどに使われているが今後大規模土にな適用を検討するにあたって、その特性の把握が求められている。ここでは、一連の三軸試験によりその力学特性と拘束圧の関係を検討した。また走査型電子顕微鏡を用いて、団粒化土の微細構造を調べた。

1) Introduction

Urban areas, with their increased paving, buildings, and other infrastructure, can lead to the reduced permeability of the surface, which can cause more rainwater to run off on the ground surface, leading to flash flooding and other issues. Aggregated soil is a type of chemically-improved soil that exhibits a dual-pore structure. This structure consists of macro-pores, which facilitate the easy flow of water, enhancing water infiltration into the soil. Additionally, the soil contains micro-pores that have the ability to retain water, gradually releasing it back into the atmosphere through the process of evaporation. Aggregated soil is made using 4 ingredients: base soil, cement, polymer and water. The term “aggregated soil” is derived from the aggregation process after combining with cement and a crumbing agent.

(2) Methodology and Apparatus

Triaxial apparatus arrangement

The triaxial apparatus employed a strain-controlled, small-sized setup. It incorporated essential components such as an AC servo motor, a reduction gear system, as well as electromagnetic clutches and brakes.

Saturation by double vacuuming method

To enhance saturation of the specimen, specimen is first vacuumed. De-aired water is then allowed to flow through the specimen from the bottom to the top.
Back pressure is then applied to further saturate the specimen.



Consolidation and shearing

The specimen undergo triaxial compression under various confining pressure of 50kPa, 100kPa, 200kPa and 400kPa. Following the consolidation phase, the specimen is subjected to drained triaxial compression with an axial strain rate of 0.2 mm per minute.

(3) Sample Preparation

Mixing proportion

Specimen	Cement	Polymer	Water	Compaction degree
AS80	80 kg/m3	1.5 liter/m3	16.5%	95 %

Using the mixing proportion in the table above, aggregated soil is made by mixing all components together. After that, initial cure is required for initial setting of cement and allow the crumbs to be firmer before compacting into molds.
After initial curing phase, the sample is being compacted into mold with compaction degree of 95%. To ensure consistency and uniformity throughout the whole specimen, the under compaction method is utilized. Following that, the specimen is cured in a moisture box for 28 days before testing.


Base soil (Masado)


Freshly mixed AS


Compacted into mold

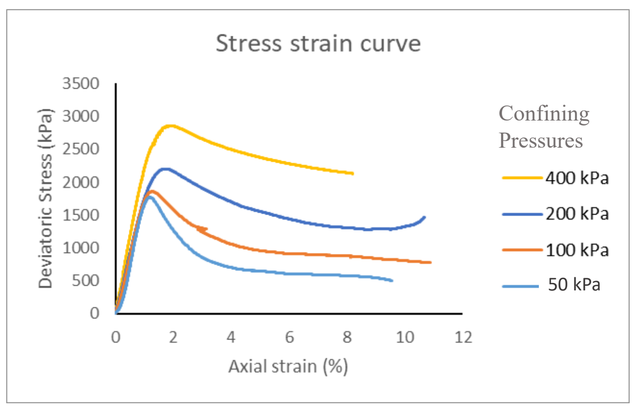



Specimen

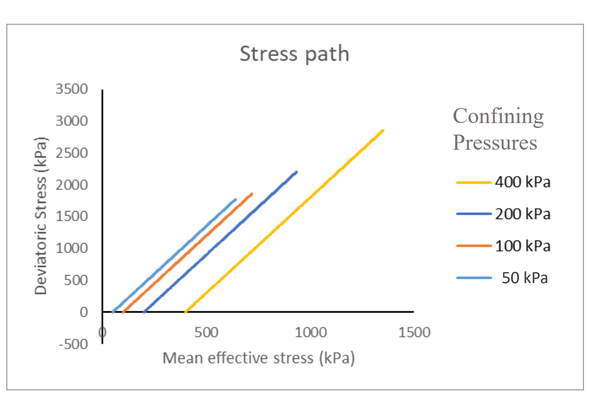
(4) Experimental Results

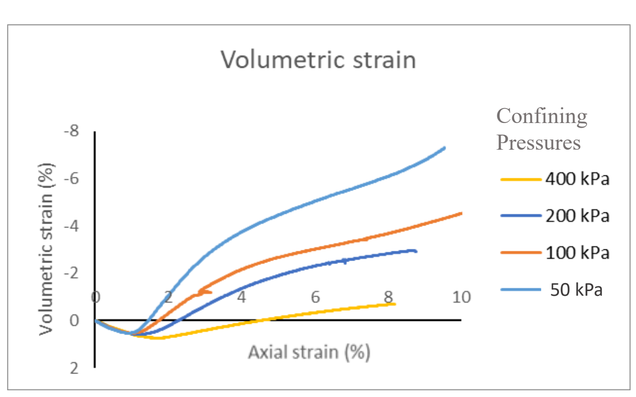
Aggregated soil strengthens as confining pressure increases. It shows a clear peak strength at lower confining pressures as expected for dense soil. As confining pressure rises, the peak strength diminishes while the residual strength remains close.

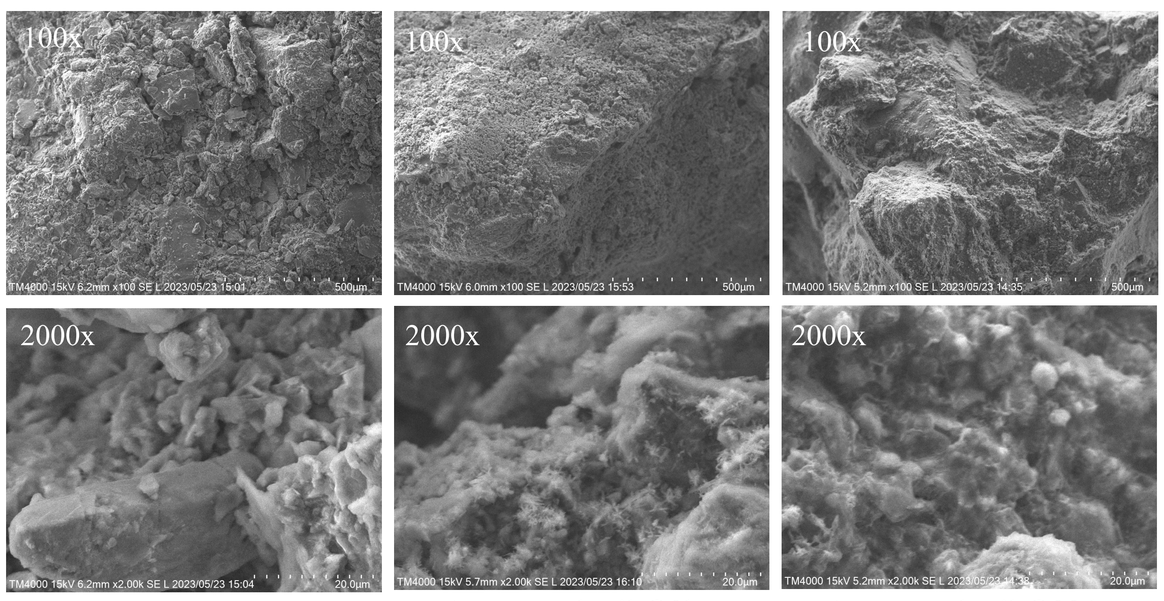
At low confining pressure, the material demonstrates a high peak strength, indicating strong cementation and specimen integrity.



The specimen expands considerably at low confining pressure, shown by a high volumetric strain.
In contrast, the volumetric strain decreases with high confining pressure.







Untreated soil　Aggregated soil @2h　Aggregated soil @28d

The microstructure of aggregated soil was analyzed using scanning electron microscope (SEM) to gain insights into its composition. In the case of untreated soil (Masado), the observation revealed that smaller particles were loosely attached to larger particles, appearing separate from one another. However, when polymer and cement were introduced during mixing, the particles exhibited a cohesive behavior and formed a unified structure. Remarkably, at a magnification of 2000x, the SEM images unveiled the presence of etringite, a product of cement hydration, even in the freshly mixed aggregated soil.

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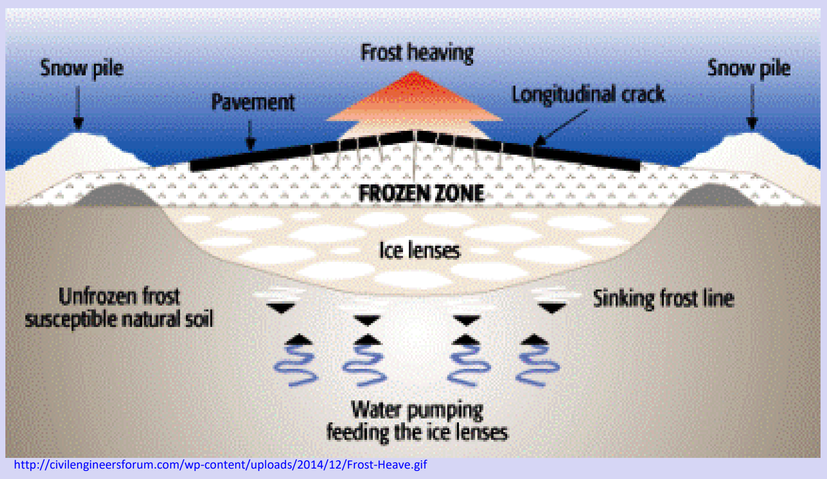
Effect of Freezing and Thawing on the Durability of Aggregated Soil and Cement Treated Soil

団粒化土とセメント改良土における凍結融解の影響

The durability of the aggregated soil which is subjected to freezing and thawing is not yet properly understood to be used as a major construction material in cold regions. In this study, the behavior of unconfined compressive strength (UCS) of aggregated soil and cement treated soil which are subjected to 12 freezing thawing cycles were studied and compared with the UCS of controlled specimens. The intension was to distinguish the behavior of aggregated soil compared to cement treated soil since higher amount of water is retained in aggregated soil.

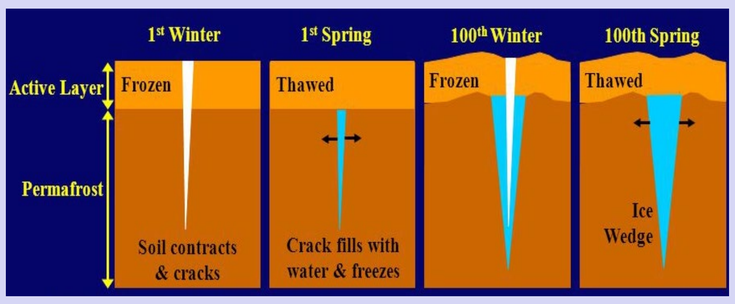
寒冷地で団粒土やセメント改良土を適用する場合、凍結融解による間隙水の体積膨張・収縮の影響が問題になります。団粒土とセメント改良土に、12回の凍結融解履歴を与え、その力学特性に与える影響を、一軸圧縮試験で調べました。

(1) Effect of freezing and thawing on soil



http://civilengineersforum.com/wp-content/uploads/2014/12/Frost-Heave.gif

- During phase transition freezing process associates with volume expansion of the water by about 9 + %.
- **Vertical shrinkage cracks** appear due to desiccation process.



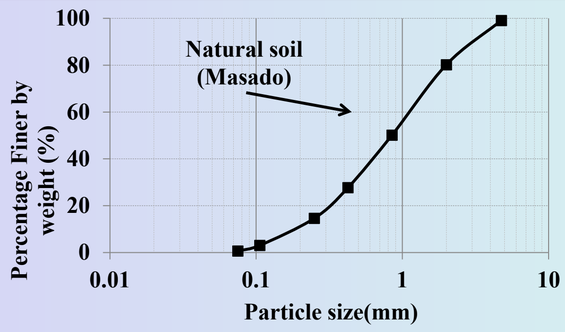
http://slideplayer.com/slide/6096408/

Repetition of freezing and thawing cycles increase crack widths while increasing number of cycles and lead to reduction in strength of improved soils.

(2) Materials and testing method

Materials and mix proportions

Mix designation	Cement (by volume)	Crumb agent (by volume)	Water (by weight)	Degree of saturation	Ice forming system
Aggregated soil (A)	80kg/m^3	1.5l/m^3	16.5%	100 % (Saturated)	Open
				80 % (Unsaturated)	Closed
	20kg/m^3	1.5l/m^3	14.5%	100 % (Saturated)	Open
Cement treated soil (C)	80kg/m^3	-	16.5%	100 % (Saturated)	Open
				80 % (Unsaturated)	Closed
	20kg/m^3	-	14.5%	100 % (Saturated)	Open



Particle size distribution Curve

- Under each mix designation two controlled and two exposed specimens were prepared with the size of 50mm in diameter and 100mm in height by applying static compaction larger than 90 % of their maximum dry density.
- 12 cycles of freezing at -23^{o}C for 24 hours and subsequent thawing at 21^{o}C for 23 hours were applied.(ASTM-D559(1996).
- After that Unconfined compression test (JIS A 1216) were conducted on all specimens.

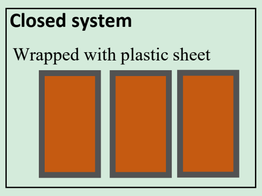
Testing procedure

Unsaturated- Closed system

Specimen preparation *Day 1* → Curing in the moisture room *Starts on Day 1* → Exposed → 12 freeze/thaw cycles **Sealed** *Starts on Day 8, Duration: 24days* → UCS test *Day 33*

Controlled → UCS test *Day 21*

Closed system: Wrapped with plastic sheet

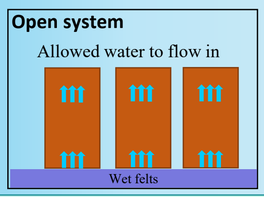


Saturated – Open system

Specimen preparation *Day 1* → Curing in the moisture room *Starts on Day 1* → Exposed → 12 freeze/thaw cycles **Allowed water to infiltrate** *Starts on Day 8, Duration: 24days* → UCS test *Day 33*

Controlled → **Saturation** *Day 20* → UCS test *Day 21*

Open system: Allowed water to flow in

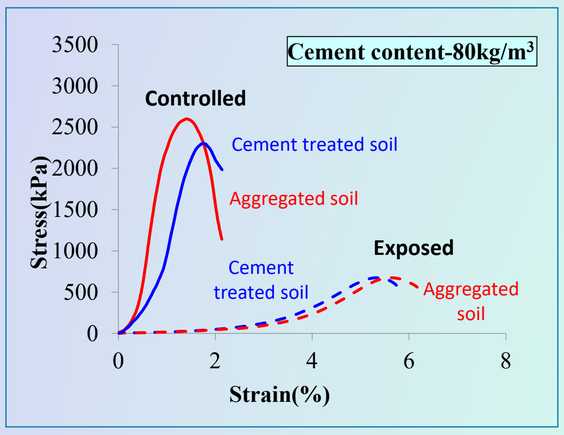


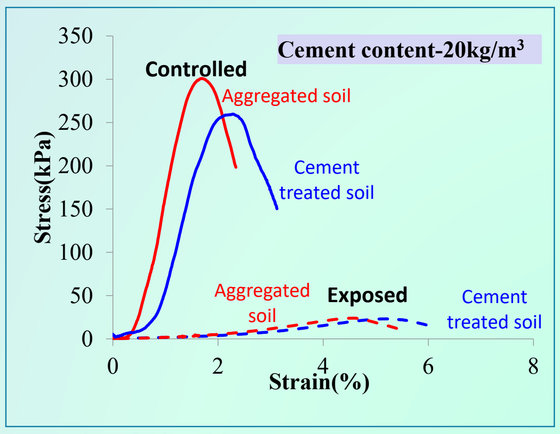


供試体作製・養生後、12回の凍結融解履歴を与える
凍結融解プロセスの際に水の出入りを許す場合（Open system）
は飽和供試体、許さない場合（Closed system)は不飽和供試体

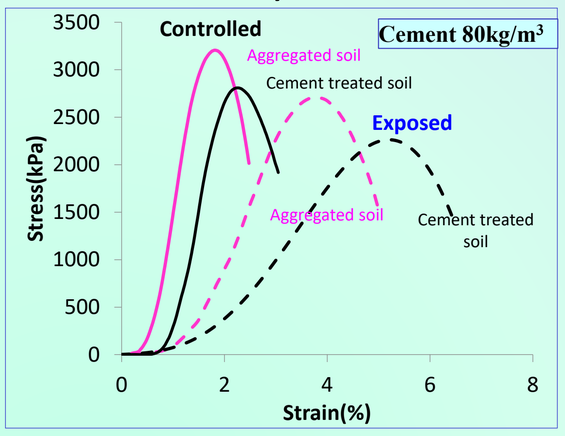
(3) UCS Test results

Saturated- Open system

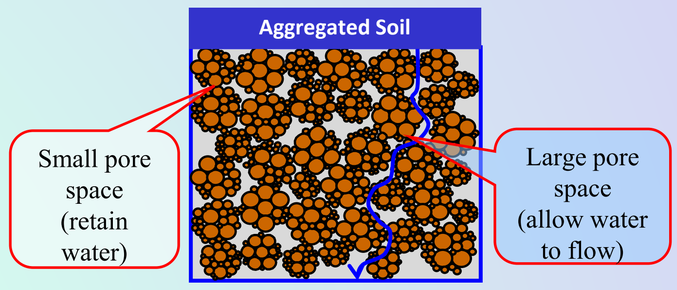




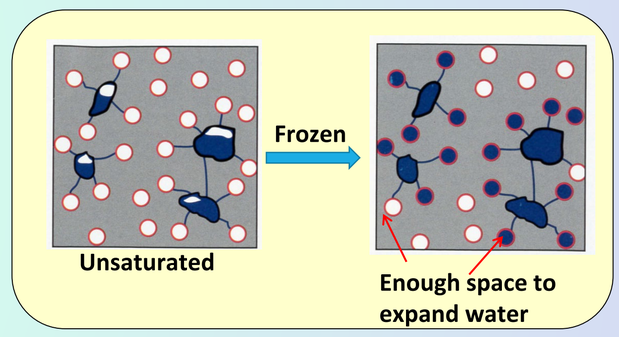
Unsaturated- Closed system



stress –strain relationships



- Under unsaturated condition reduction of E_{50} is lower and reduction of strength is higher in aggregated soil than in cement treated soil.



http://precast.org/2012/12/air-entrainment-versus-air-entrapment/

- The behavior of aggregated soil under freezing is complicated. Availability of **macro pores** resist expansion of soil on the other hand the **ability of water retentivity and permeability** provide more water to expand .
- More studies are required to understand the relationship between soil freezing and soil water retention characteristics of aggregated soil since those factors depends on the amount of cement and crumb agent .

(4) Discussion

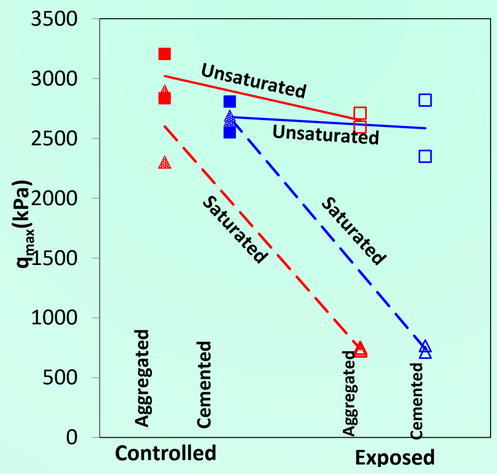
Effect of cement content

Cement content (kg/m^3)	Soil type	Reduction relative to controlled data (%)	
		q_{max}(kPa)	E_{50}(MPa)
80	A	72	92
	C	72	87
20	A	92	98
	C	91	97

- The maximum strength, (q_{max}), and deformation modulus, E_{50} , of both aggregated soil and cement treated soils were reduced due to the freeze and thaw exposure.
- When increasing cement content reduction of q_{max} became lower.
- Both used cement contents were not suitable to resist against freezing thawing effect in open system.

団粒土とセメント改良土は、凍結融解履歴により強度と剛性が著しく低下する。低下の程度は団粒土とセメント改良土でほぼ同等で、セメント量が多い方が低下の程度はやや小さい。

Effect of degree of saturation



Reduction of q_{max} and E_{50} is lower in unsaturated condition (closed system) than in saturated condition (open system).

Sr (%)	Soil type	Reduction (%)	
		q_{max} (kPa)	E_{50} (MPa)
100	A	72	92
	C	72	87
80	A	12	36
	C	4	48

凍結融解履歴による強度と剛性の低下は、供試体が飽和している場合に著しい

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Digala Mudiyanselage Dayani Nadeesha Sanjeewani (2018)

Effect of Curing Conditions on Long Term Strength of Lime and Cement Treated Soils

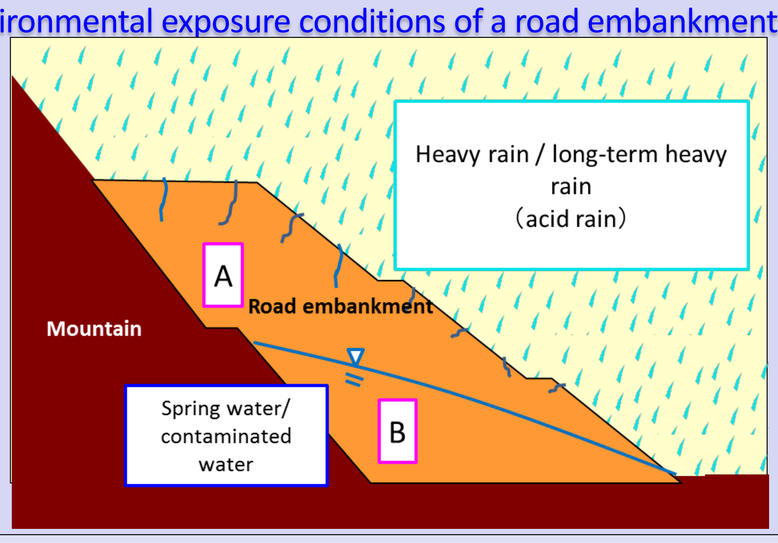
セメント/石灰改良土の長期挙動

Stabilization using lime or cement has been a widespread technique for soils with poor geotechnical performances. Various studies have been conducted on their physical and mechanical properties including strength and durability. However, the effect of curing conditions on the long term strength of lime and cement treated soils with lower binder contents are not well understood. In this study, therefore, unconfined compression tests were conducted on lime and cement treated surplus soil under two curing conditions called “sealed” and “soaked”. It was inferred that the differences in strength were caused by the differences of physical and chemical properties of stabilized soils which changed due to curing conditions.

本研究は（国研）土木研究所と共同研究で実施しています。低改良率のセメント改良土と石灰改良土を種々の条件で168日間養生し、一軸圧縮試験により強度特性を調べました。水浸養生の供試体では高い飽和度と共にカルシウムの溶出等により強度低下がみられました。

(1) Introduction

Environmental exposure conditions of a road embankment

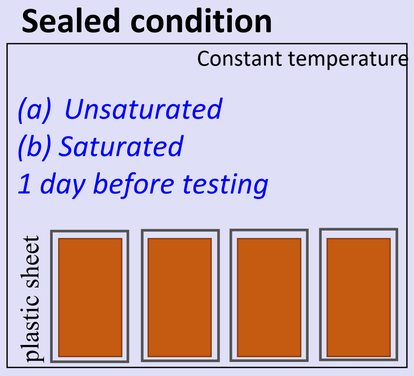


Simulation of curing conditions in laboratory

Case A
Sealed condition

Constant temperature

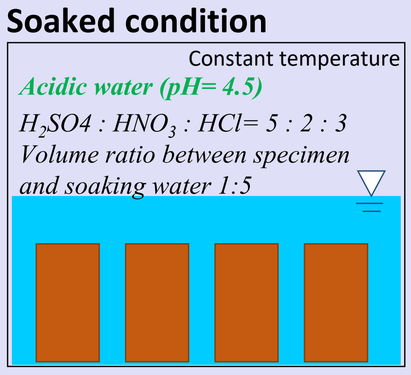
(a) Unsaturated
(b) Saturated
1 day before testing



Case B
Soaked condition

Constant temperature

Acidic water (pH= 4.5)
$H_2SO4 : HNO_3 : HCl$= 5 : 2 : 3
Volume ratio between specimen and soaking water 1:5



（2）Materials and testing method

Physical and mechanical properties of Miho sand

Soil classification (JGS 0051)	SF (sandy soil)
Soil particle density, ρ_s (g/cm^3)	2.693
Optimum water content, w_{opt} (%)	21.6
Maximum dry density, ρ_{dmax} (g/cm^3)	1.624
Sand (%)	52.9
Silt (%)	21.6
Clay (%)	24.7

Mix proportions

Binder type	Binder content	Curing type	Water type
Lime	2.5%	Sealed	_
		Soaked	Acid water
	3.8%	Sealed	_
		Soaked	Acid water
Cement	3.5%	Sealed	_
		Soaked	Acid water
	5.3%	Sealed	_
		Soaked	Acid water

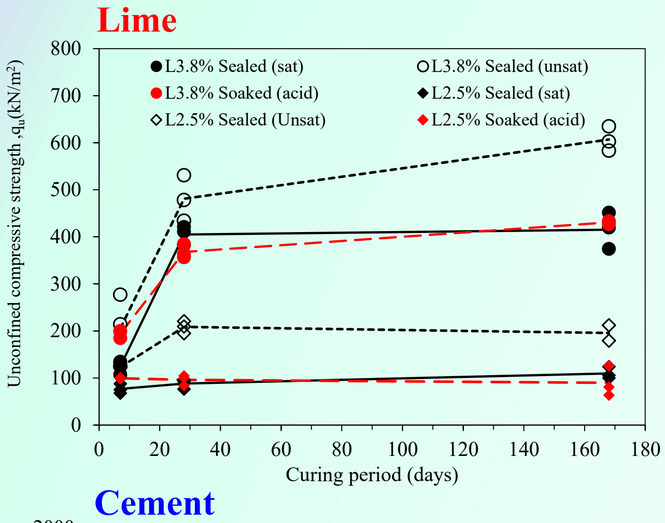
Chemical properties of Miho sand and binders

	SiO_2 (wt %)	TiO_2 (wt %)	Al_2O_3 (wt %)	Fe_2O_3 (wt %)	MnO (wt %)	MgO (wt %)	CaO (wt %)	Na_2O (wt %)	K_2O (wt %)	P_2O_5 (wt %)	S_{total} (wt %)
Miho sand	61.69	0.73	19.92	6.86	0.11	1.29	1.48	1.18	1.54	0.10	0.03
Cement	24.36	0.28	8.65	1.85	0.13	1.98	61.87	0.31	0.46	0.16	3.13
Lime	2.21	0.10	0.75	0.74	<0.01	1.02	102.2	0.16	<0.03	0.03	<0.02

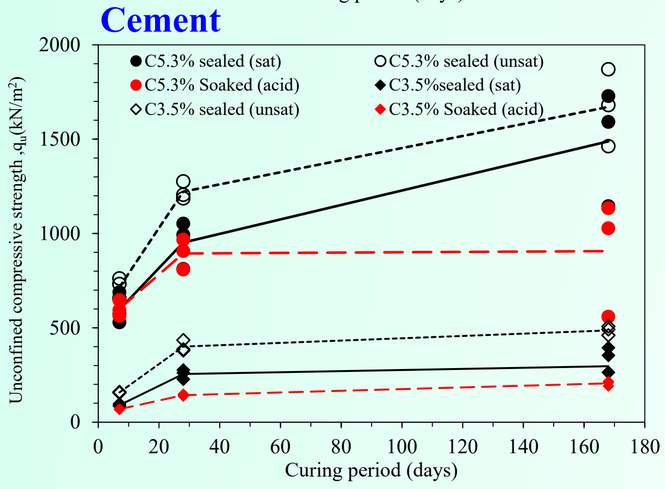
- Specimen size: Diameter 50 mm, Height 100 mm
- Degree of compaction, Dc= 90 %
- Unconfined compression test (JIS A 1216) conducted after 7, 28 and 168 days.
- The amount of calcium and sulfate ions and pH in the soaked water measured at each time water exchanged.

(3) Results and discussion

Lime



Cement

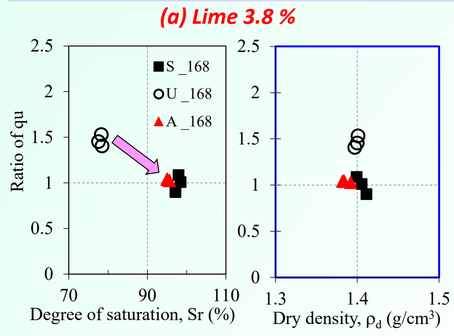


- Under sealed curing strength increased with curing period.
- For all cases Higher strength in particular curing age is in **sealed-unsaturated** condition.
- It was observed **almost the same strengths** in saturated and soaked specimens of lime treated soils.
- In cement treated soils, **soaked specimens** showed the smaller strengths after 168 days.

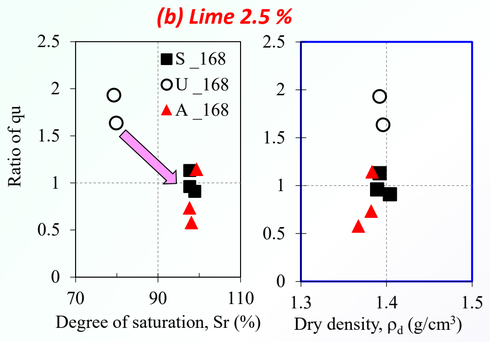
Effect of physical properties

Strength ratio at 168 days = $\frac{q_{u(soaked,unsat)}}{q_{u(average\ saturated)}}$

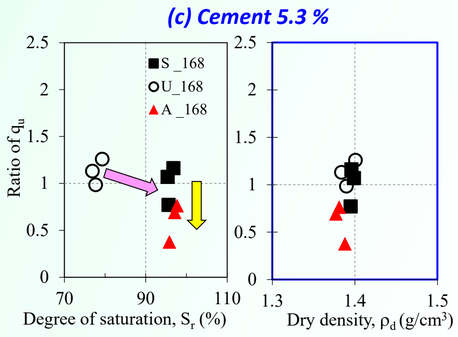
(a) Lime 3.8 %



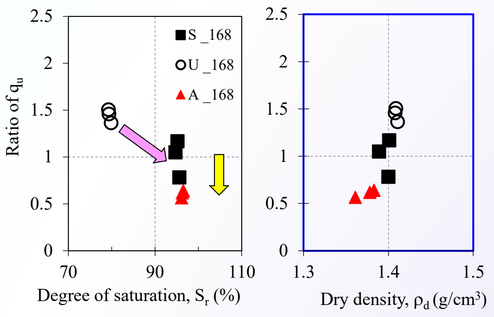
(b) Lime 2.5 %



(c) Cement 5.3 %

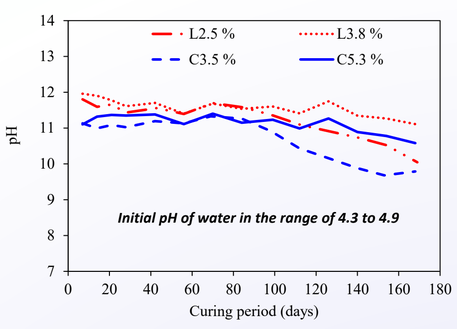


(d) Cement 3.5 %

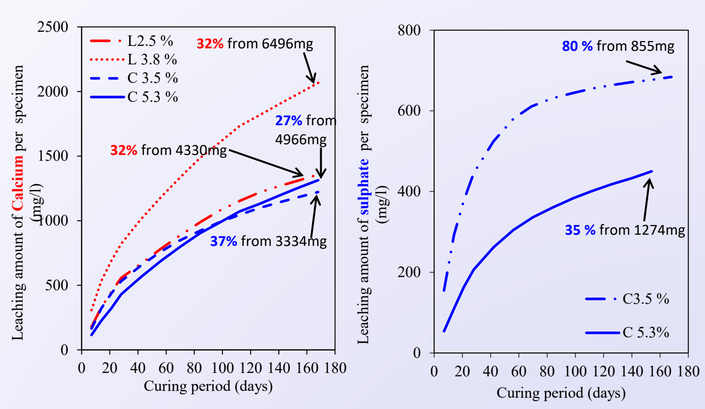


- ✓ In almost all the cases, the dry densities of specimens were maintained around 1.4 g/cm^3
- ✓ The degree of saturation of sealed (unsaturated) condition is the lowest.
- ✓ Degree of saturation of soaked curing and sealed (saturated) curing is same.
- ✓ Strength ratio of sealed (unsaturated) curing of **lime treated** soil is 1.5 or more. The strength ratios under soaked curing and sealed (saturated) curing was similar and always lower than sealed (unsaturated) curing due to the affection by the degree of saturation.
- ✓ In **cement treated soil**, strength ratio of soaked curing is less than 1. Difference in strength between sealed (saturated) curing and soaked curing is not only due to difference in physical properties but due to difference in **chemical properties**.

Effect of chemical properties



pH values of soaking acid water had increased up to **12** in lime treated soils and **11** in cement treated soils initially, while those values started to decrease gradually with the curing period.



- ❑ Leaching of hydration products containing Ca and sulfate ions may affect the uniaxial compressive strength under soaked curing in cement treated soil.
- ❑ In lime treated soil, leaching of Ca ions did not affect the uniaxial compressive strength under soaked curing until the age of 168 days .

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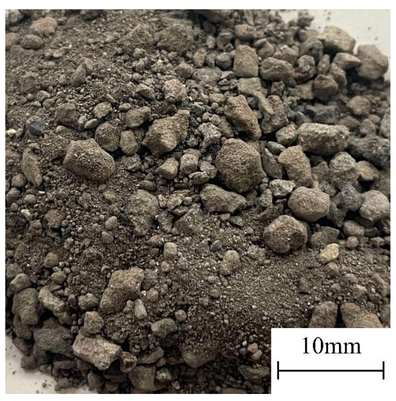
TEL：+81-3-5452-6843，FAX：+81-3-5452-6844
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Triaxial compressive properties of steel slag with hydraulic hardness

水硬性を持つ製鋼スラグの三軸圧縮特性

Steel slag is a by-product generated during the iron and steelmaking process—specifically, during the reduction and refining stages in which iron ore is converted into steel. It can be broadly classified into **blast furnace slag**, produced during the melting and reduction of iron ore, and **steelmaking slag**, generated in the steel refining process. Due to its excellent mechanical properties, steel slag has attracted attention as a sustainable material that can replace natural resources and cement, contributing to energy and resource conservation as well as CO_2 reduction. Among them, steelmaking slag contains high amounts of **free lime** (CaO) and **free magnesium oxide** (MgO), which react with water and cause expansion. This hydration-induced expansion poses **a long-term stability challenge** when using steel slag as a ground improvement material. This study aims to promote the effective use of steelmaking slag in ground improvement by investigating changes in its mechanical properties due to hydraulic hardness. Through triaxial compression tests and elastic wave velocity measurements, the research seeks to elucidate the mechanisms of mechanical and volumetric changes associated with the hydraulic hardness behavior of steelmaking slag.

鉄鋼スラグとは、鉄鋼製品の製造工程（鉄鉱石から鋼を作り出す還元・精錬段階）で生じる副産物であり、高炉で鉄鉱石を溶融・還元する際に生成する高炉スラグと、製鋼および精錬プロセスで生成する製鋼スラグに大別できる。その優れた力学特性から注目されており，天然資源やセメントの代替材として、省エネルギー・省資源、CO_2削減に貢献するサステナブル資材として認識・利用されている。そのうち、製鋼スラグは、高含有の**遊離酸化マグネシウム**（MgO）および**消石灰**（CaO）が含まれており，これらの成分は水と反応することで膨張し、**長期的な体積安定性**が地盤改良材としての利用上の課題になる。本研究では、製鋼スラグの地盤改良材としての有効利用を目指し、三軸圧縮試験と弾性波速度測定で、水硬性による製鋼スラグの力学特性の変化について検討し、水硬性に伴う製鋼スラグの力学・体積変化のメカニズムを解明することを目的とする。ここでは三軸試験結果について報告する。



Steelmaking Slag

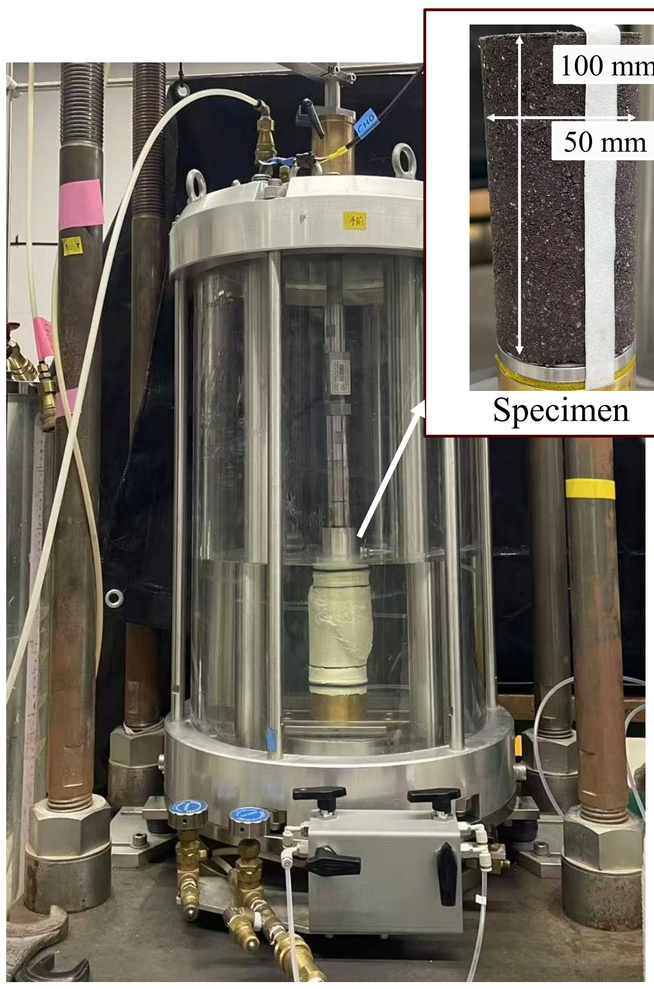


BFSFP

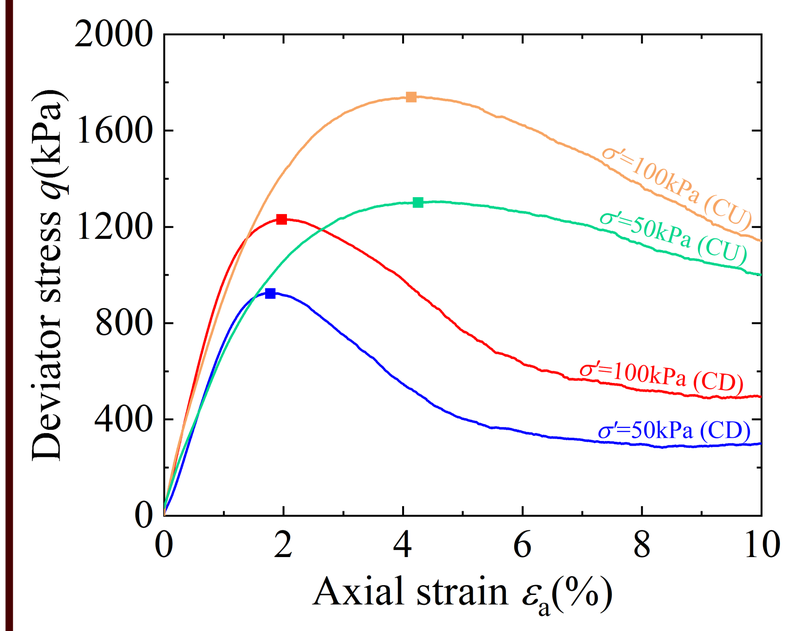
This study investigates the shear behavior of steelmaking slag-treated soils under consolidated drained (CD) and undrained (CU) conditions. The material used is the mixture of steelmaking slag and BFSFP (Blast furnace slag fine powder), in mass ratio 96:4. The results from triaxial compression tests on 3-day cured steel slag shows that:

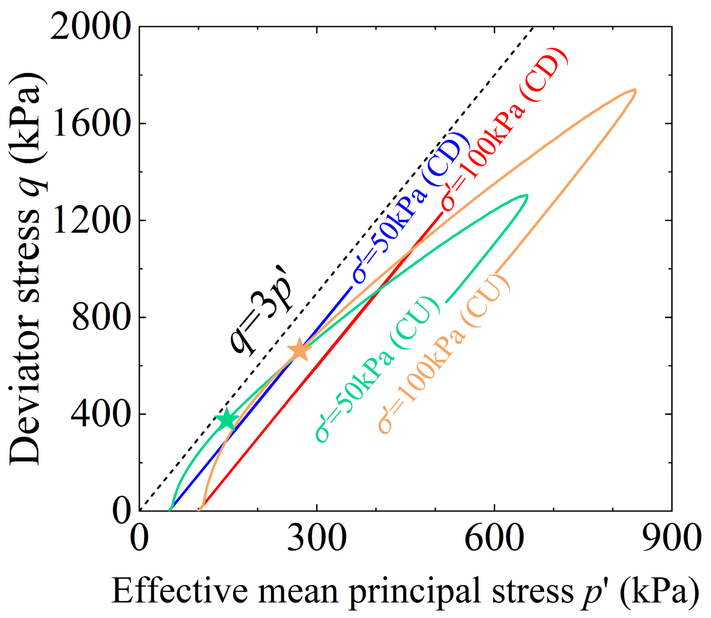
In CD conditions, the internal friction angle is approximately 45°. Under CU conditions, specimens initially follow the tensile cut-off line ($q=3p'$), where $\sigma'_3=0$, indicating shear-induced stress development at nearly constant mean effective stress. The maximum stress ratio (R_{max}) was identified by the peak points marked on the stress paths. Notably, the 3-day cured specimens did not reach the tensile cut-off line, suggesting incomplete hydration and insufficient solidification of free CaO/MgO. This highlights the importance of curing time in achieving stable mechanical performance. Further investigation using longer curing durations is required to evaluate long-term stability.

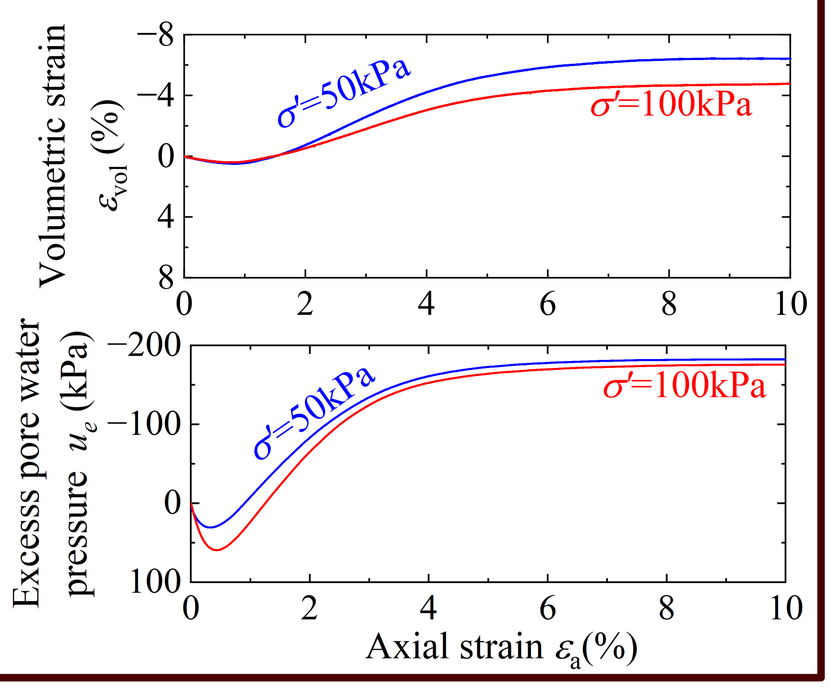
Furthermore, steel slag shows negative then positive dilatancy in CD tests, with volume change stabilizing at 6–8% axial strain. In CU tests, negative excess pore pressure develops early, increasing effective stress and undrained strength. Also, the pore pressure stabilizes around -180 kPa without signs of cavitation, indicating stable undrained behavior even at high suction levels.



Triaxial compression test machine







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Progression of Deterioration in Cement Treated Soil

セメント改良土の水浸による強度低下

The progression of deterioration in cement treated surplus soils under ground water was investigated by conducting mechanical and chemical testing periodically. Deterioration was identified in two stages; primary deterioration (0-25 days) and secondary deterioration. Primary deterioration appeared due to moving of soluble ions from pore solution before creating hydration products. Secondary deterioration was found as a result of leaching of ettringite. In addition to that it was found that secondary deterioration depth show a linear relationship with squared root of soaking time.

低改良率セメント改良土の水浸による強度低下について検討した。強度低下は水浸後1か月程度までに起こる一次劣化、その後徐々に起こる二次劣化の2段階で確認された。 一次劣化は、水和生成物が生成される前に間隙水から可溶性イオンが移動するため、二次劣化はエトリンガイトの浸出が原因であると考えられる。また、二次劣化深さの二乗と浸漬時間は線形関係を示した 。

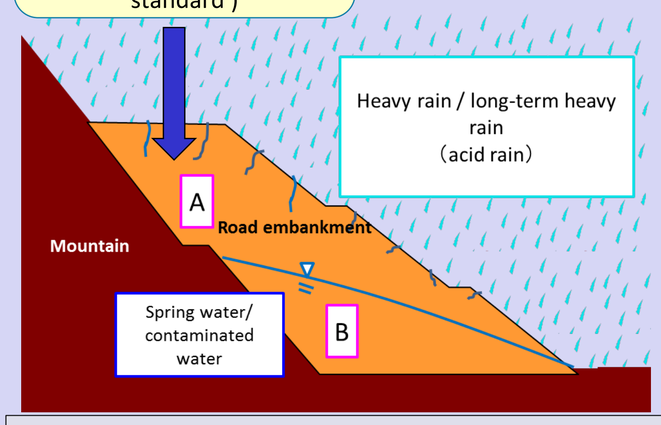
(1) Introduction

Low-quality construction generated soils

+

Cement 3.5 %
(equal to 50kg/m³ minimum amount recommended in standard)





Simulation of curing conditions in laboratory

Case A
Sealed condition

Constant temperature

Saturated 1 day before testing

plastic sheet

Case B
Soaked condition

Constant temperature

(a)Acidic water (pH= 4.5)

$H_2SO4 : HNO_3 : HCl$= 5 : 2 : 3
Volume ratio between specimen and soaking water 1:5

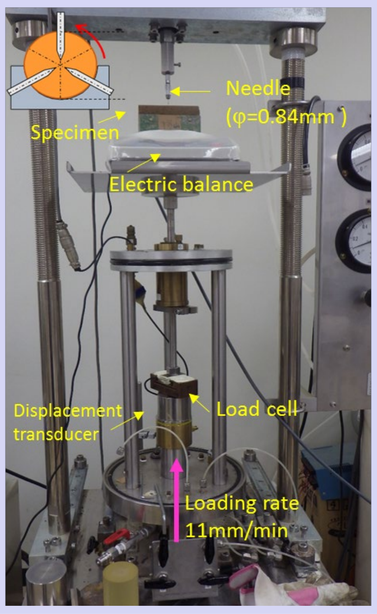
Materials and testing method

Soil classification (JGS 0051)	SF sandy soil
Soil particle density, ρ_s (g/cm³)	2.693
Optimum water content, w_{opt} (%)	21.6
Maximum dry density, ρ_{dmax} (g/cm³)	1.62
Cone index , qc (kN/m²)	68
Sand (%)	52.9
Silt (%)	21.6
Clay (%)	24.7

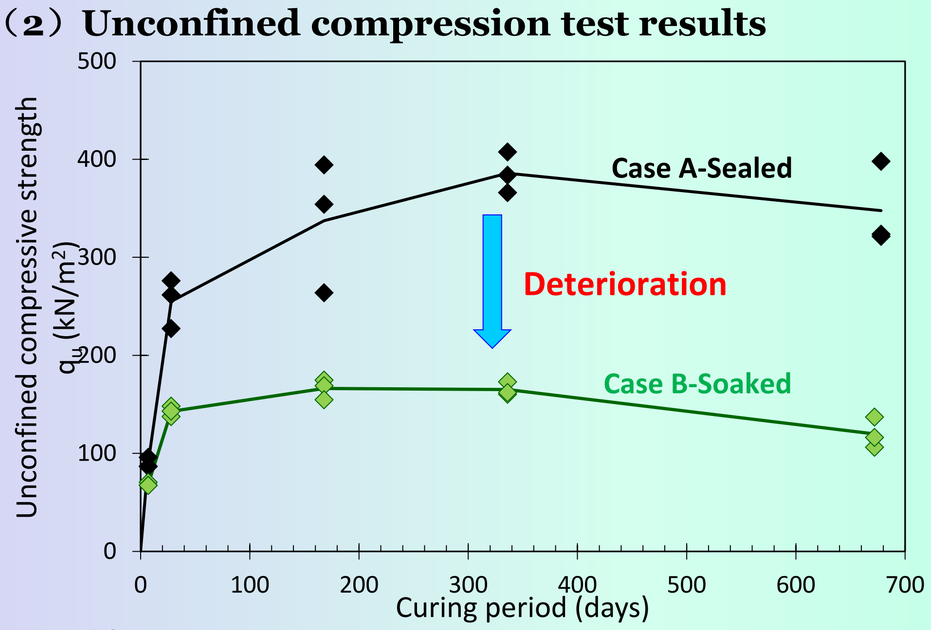
✓Unconfined compression test
✓Needle penetration test

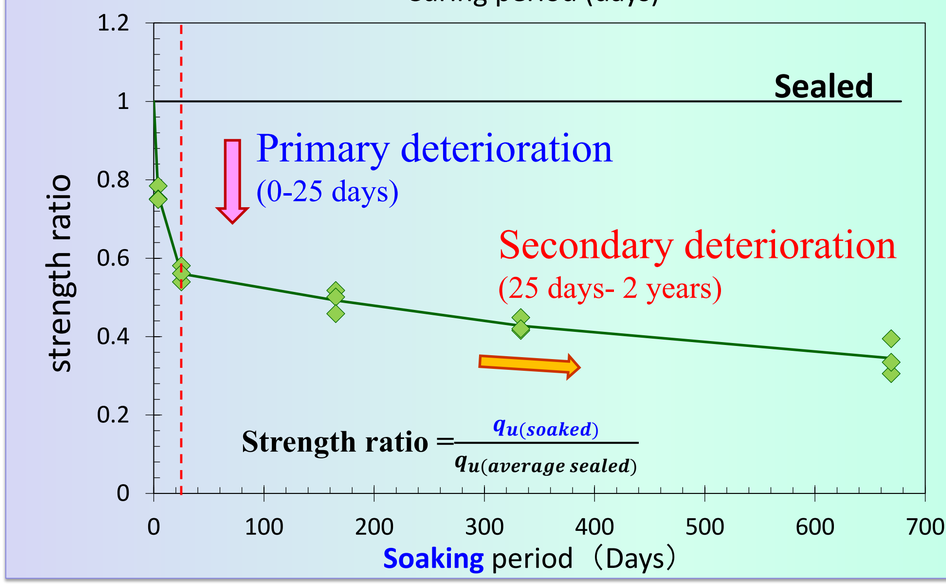
Specimen condition

- Diameter 50 mm, Height 100 mm
- Degree of compaction, Dc= 90 %
- Soaking start after 3 days of preparation
- Soaking water exchanged periodically

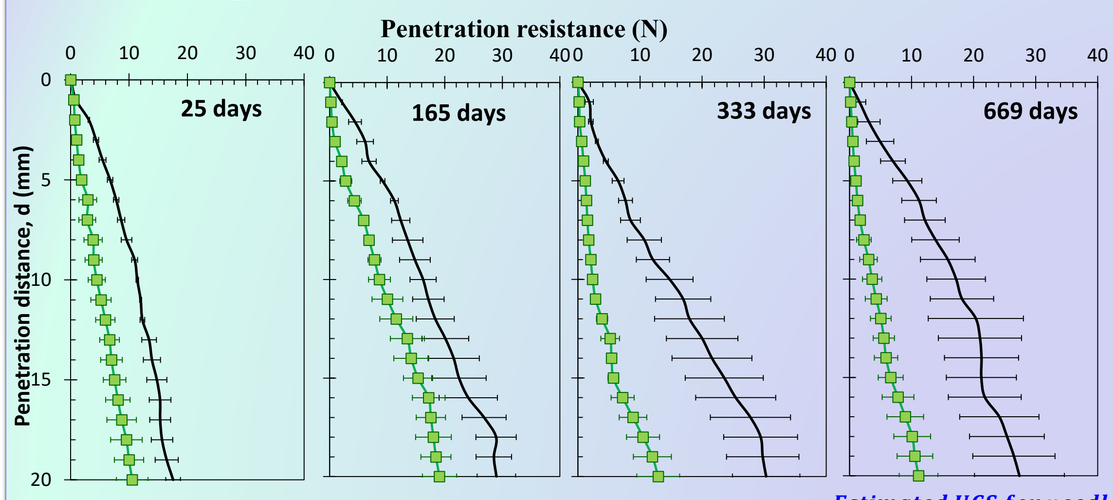


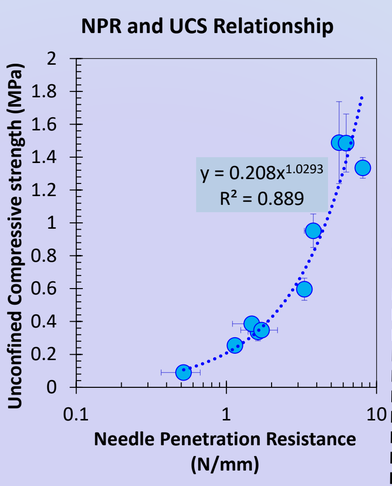
(2) Unconfined compression test results





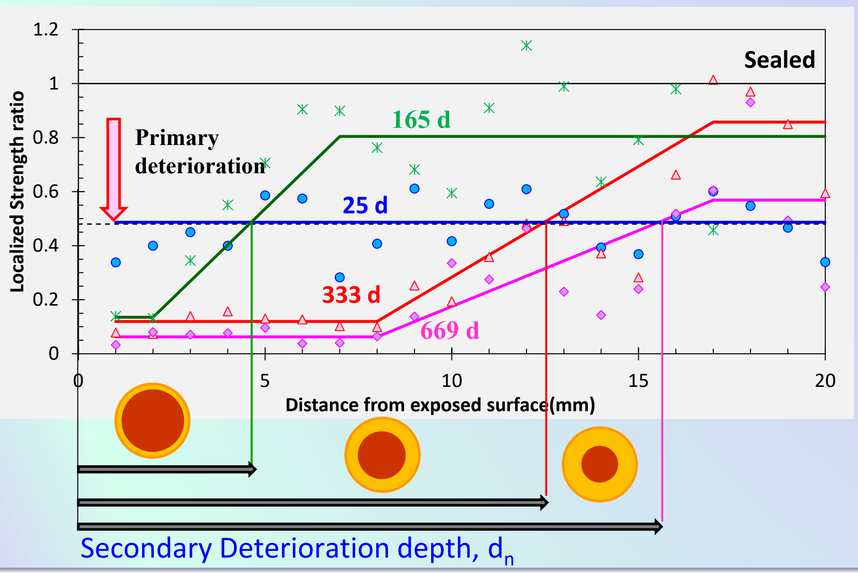
(3) Needle penetration Test results



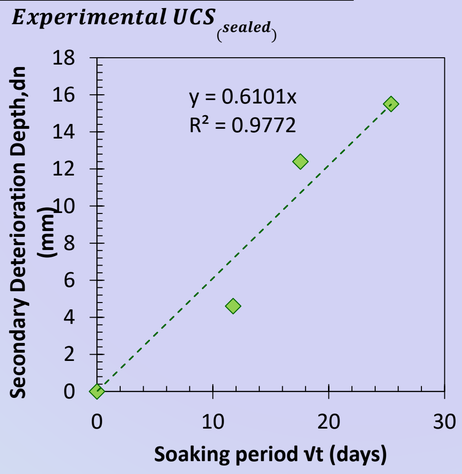


Estimated UCS for needle test

$$\text{Localized Strength ratio} = \frac{\textit{Estimated UCS for needle test}_{(soaked)}}{\textit{Experimental UCS}_{(sealed)}}$$



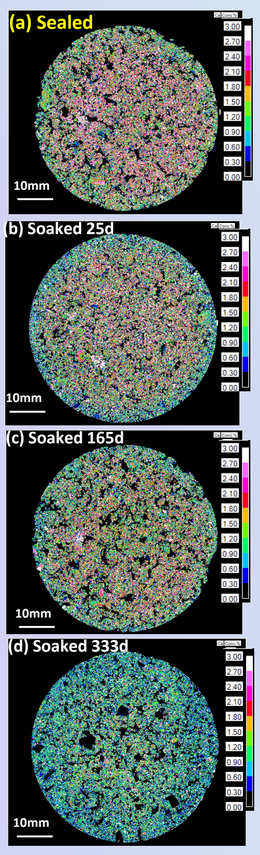
Secondary Deterioration depth, d_n

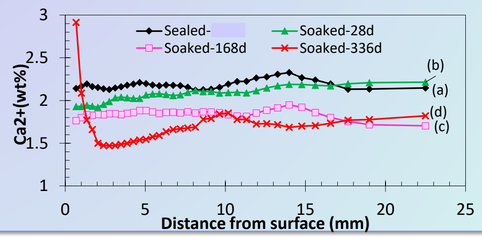


$$d_n = A\sqrt{t}$$

Secondary Deterioration coefficient

Electron probe micro analyser (EPMA)



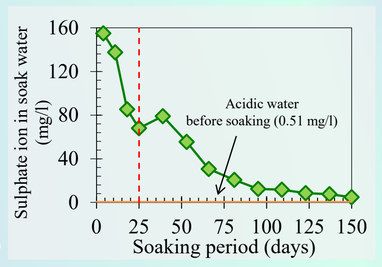


(4) Mechanism of deterioration

1. Primary deterioration (0-25 days)

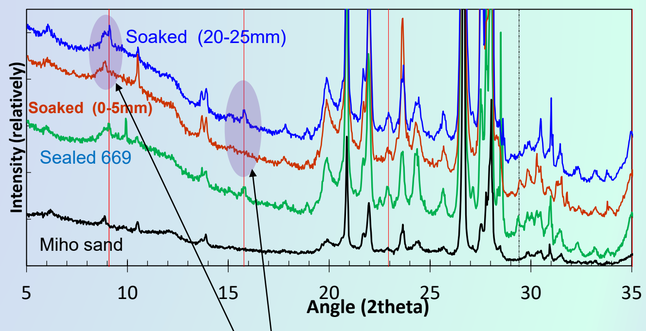
Moving of ions which required for proper hydration reaction, to water from pore solution (before creating solid hydration products)

Barbara et al 2006



2. Secondary deterioration

X-ray diffractometer analysis (XRD)



Ettringite leached out from the surface of the soaked specimen

本研究に関する担当研究室は桑野研究室です.
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Digala Mudiyanselage Dayani Nadeesha Sanjeewani (2019)

Deep Underground Cavity Formation Due to Extra-Excavation in Shield Tunneling

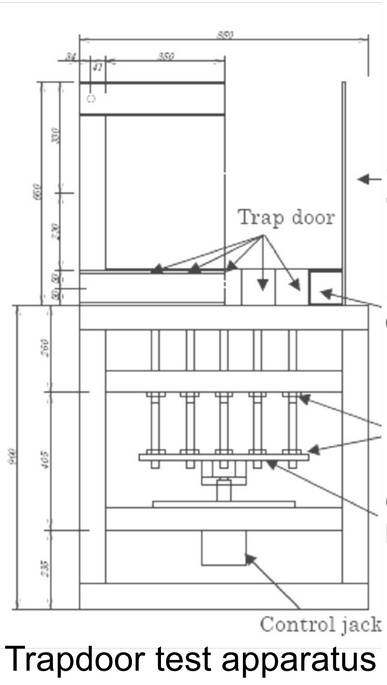
砂地盤内の空洞の発達過程と陥没メカニズム

シールドトンネル掘削時の過剰掘削に伴って地表に変状が表れる事象について、模型実験によりそのメカニズムを検討した。飽和した砂質地盤中の掘削を想定し、細粒分含有率および密度と地盤変状の範囲の関係について考察した。
従来から模型実験で確認されているような、土砂が継続的に流出して流出孔を中心として両側に扇形状に広がる空洞形状と異なり、土砂の亡失量が限定される場合は、土砂の変位が即時に上方に伝播して煙突状のゆるみが生成することが、水の動きが関与しない乾燥砂の実験で確認された。

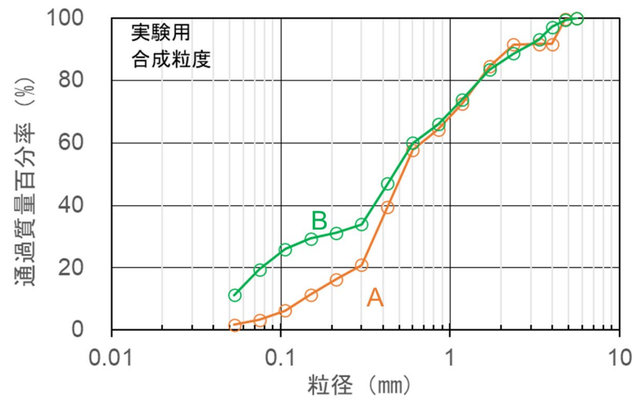
The mechanism of ground deformation that occurs during shield tunneling due to over-excavation was investigated by model experiments. The relationship between fine content and density and the extent of ground deformation were discussed, assuming excavation in saturated sandy ground. In contrast to the cavity shape that spreads out in a fan shape on both sides centering on the outlet hole due to continuous soil discharge, which has been conventionally confirmed in model experiments, the experiment with dry sand in which no water movement is involved confirmed that when the amount of soil loss is limited, ground displacement propagates upward immediately and chimney-like loosening is generated.

落とし戸試験による過剰掘削の模擬
Simulation of extra excavation with a trap door test





落とし戸試験装置　Trapdoor test apparatus

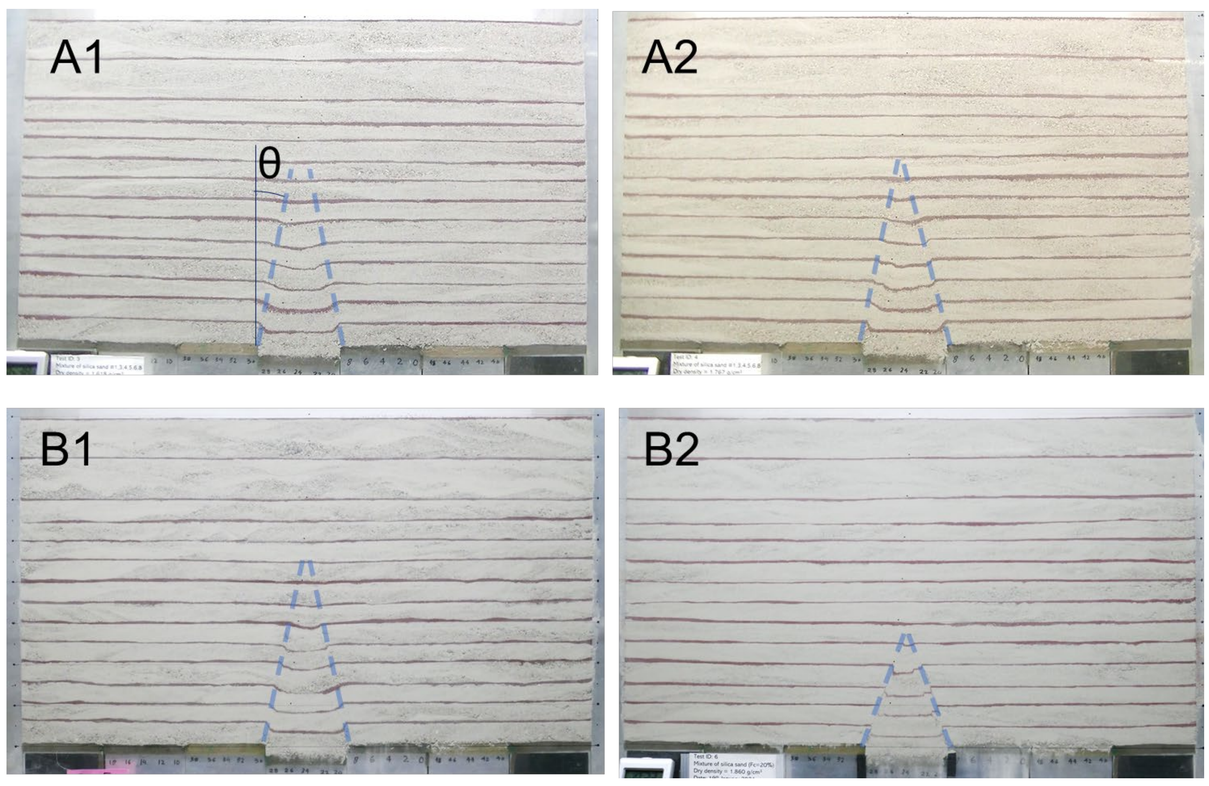


試験材料　Tested materials

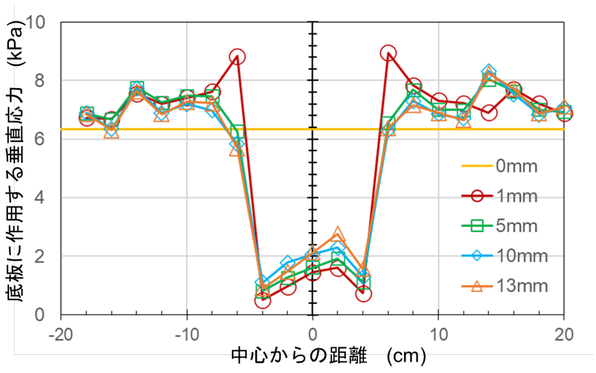
試験ケース　Tested cases

Test case	Material	Dry density (g/cm^3)	Maximum displacement (mm)
A1	A	1.62	13
A2	A	1.77	15
B1	B	1.68	15
B2	B	1.86	42

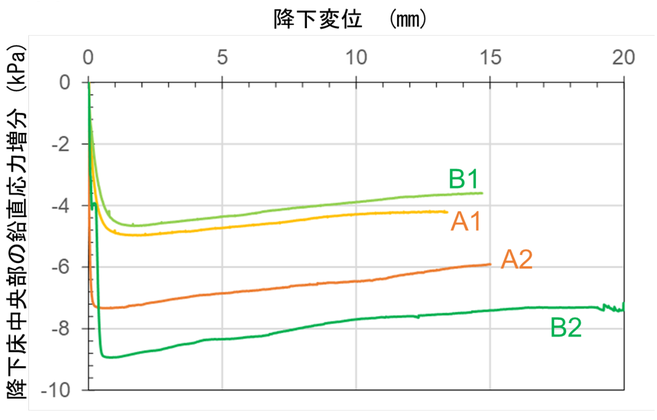
細粒分含有率を変えた2種の砂質土を用いて、密詰めとゆる詰め地盤を作製



降下床変位15mmにおける地盤の変位
Displacement within the ground at the trapdoor descent of 15mm

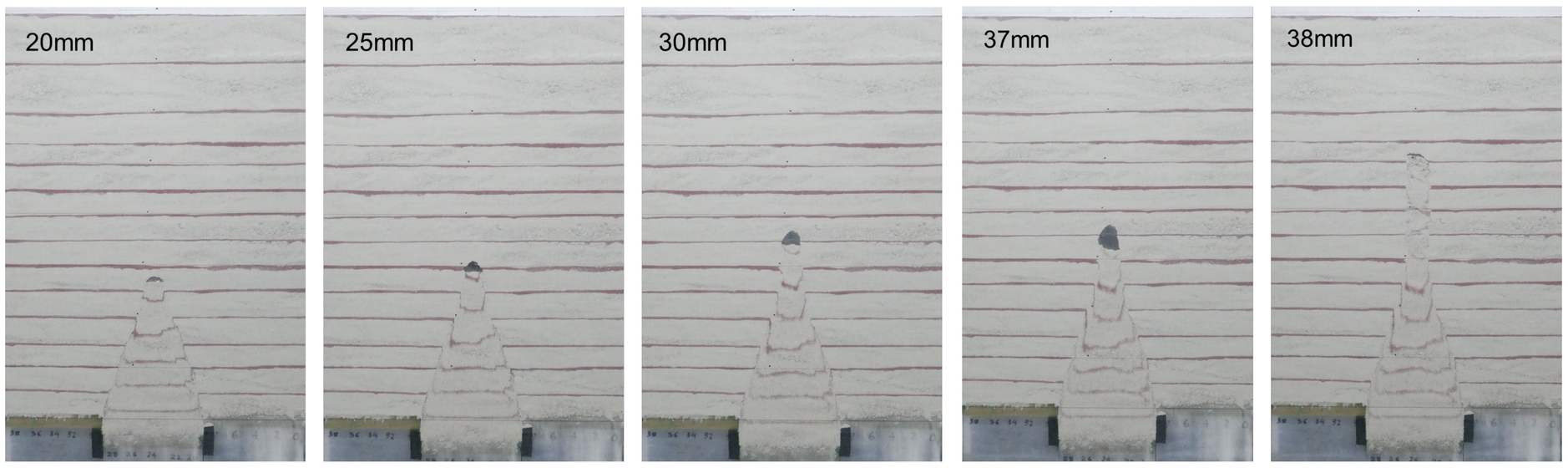


底板の作用応力分布（A1）
Normal stress distribution of bottom plates



降下床中央部の鉛直応力増分
Normal stress increment of trapdoor

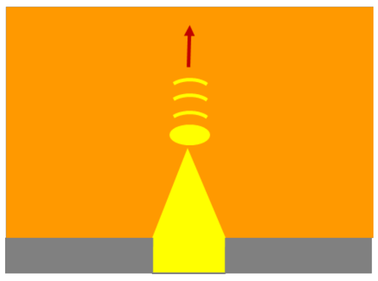
降下床の変位と空洞の生成・地表面陥没
Displacement of trapdoor and cavity formation / ground cave-in





地表面の陥没孔

煙突状のゆるみと地表面陥没
Chimney-like loosening



下方の支えを失った土砂が空洞内に次々と崩落し、煙突状のゆるみが生成する。側方の壁が空洞内に滑り落ちるより早く空洞天井部の土砂が崩落するので、水平方向にゆるみは大きく広がらない。

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Fundamental Study for Controlling Ground Vibration Associated with Deep Excavation Work

大深度掘削に伴う振動抑制のための基礎検討ー室内試験ー

Vibration caused by deep underground excavation is a serious problem that can cause not only human suffering but also economic damage such as ground subsidence. However, the actual conditions of vibration caused by underground excavation have not been clarified. In this background, this study began with the most basic issue, evaluating the damping characteristics of ground vibrations, to determine whether there are methods to suppress vibrations generated at great depths underground. A basic study was conducted on the idea of intentionally placing alternating hard and soft layers around the vibration source to dampen the vibration as much as possible before it reaches the ground surface.

地下大深度掘削により生じた振動が地表に与える問題は、人的被害が生じ得るだけでなく、地盤陥没といった経済的被害にもなりうる重大な問題である。しかし、地中での掘削工事により生じる振動の実態はほとんど明らかになっていない。本研究はこのような背景の中、地下大深度で発生した振動を抑制する方法は存在するのかという問題に対し、地盤振動の減衰特性を評価するという最も基礎的な検討から始めた。振動を抑制するために意図的に硬軟の互層を振動源周りに配置し、地表に振動が到達する前に出来る限り減衰させるというアイデアに関して、基礎的な検討を実施した。

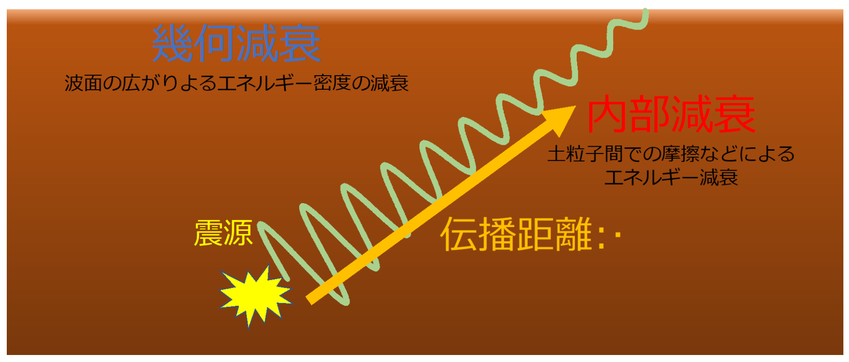
円柱状供試体による地盤内弾性波伝播の室内要素試験

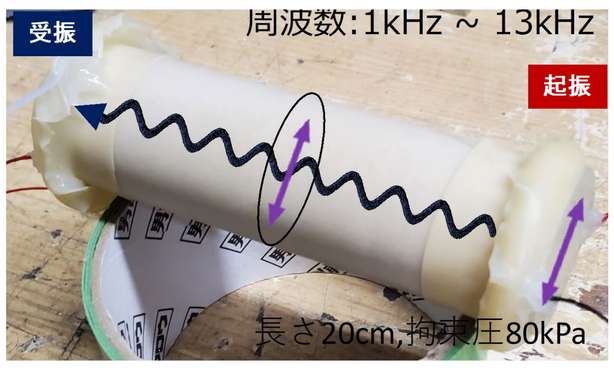
振動の振幅と距離の関係

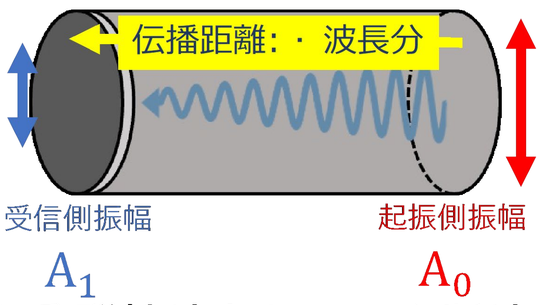
$$\text{振幅} = \text{幾何減衰}^{-n} \times \exp\left[\text{内部減衰}\right] \quad \text{(Bornitzの式.1931)}$$

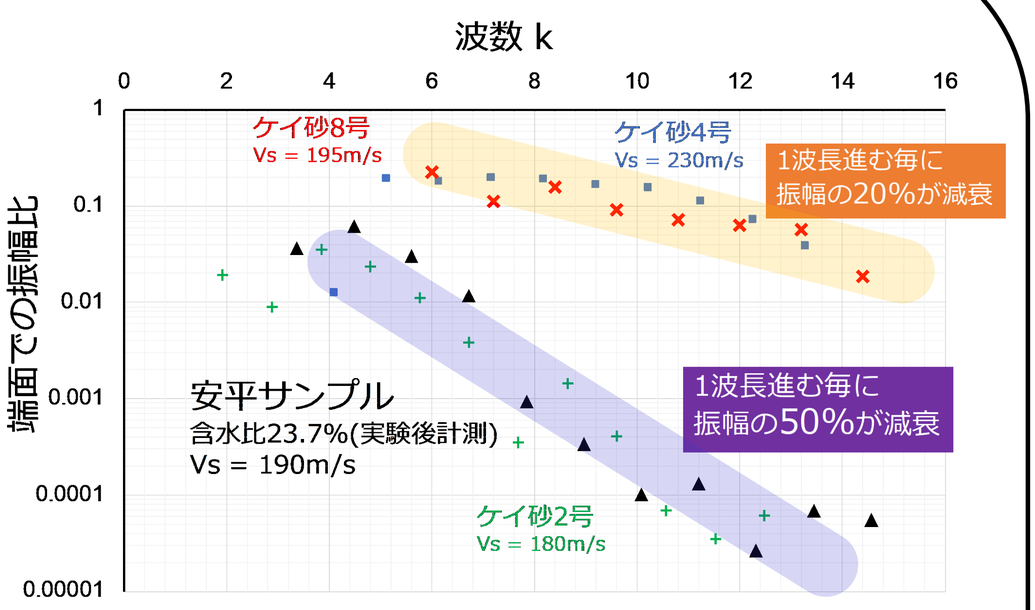
既知　未知

波長ごとに決まった減衰量→ 距離を波数kで換算（$R = k \times \cdot = \frac{f}{V} \cdot$）





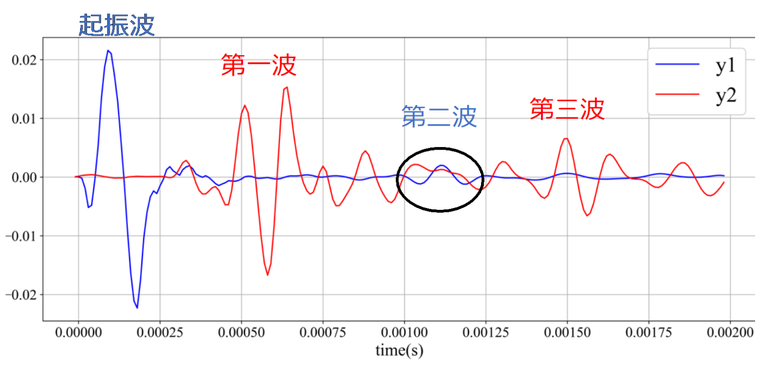




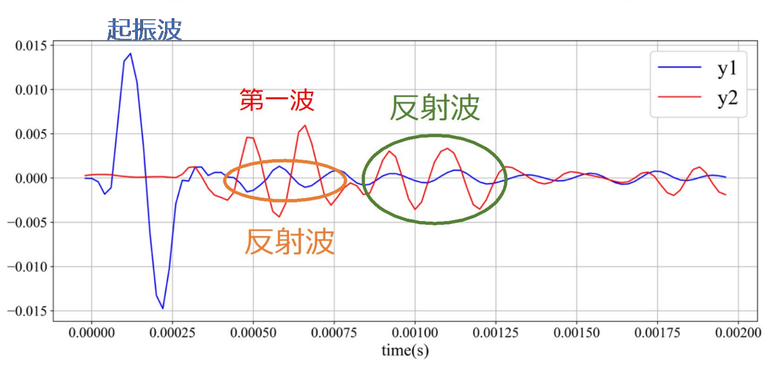
地盤振動の減衰の評価では、地中から伝わる弾性波としてせん断波の内部減衰に着目した。室内試験では円柱状供試体による一次元での室内振動伝播試験を行い、複数の起振方法や計測方法、解析手法から、電気的な起振による複数パルスの振動を周波数解析する方法を選択した。フィールド試験では定常波起振装置による振動伝播の計測を起振点近傍にて行い、幾何減衰を考慮した上で実体波としてのせん断波の内部減衰特性を評価した。室内試験で計測された内部減衰定数と北海道安平町でのフィールド調査で計測された内部減衰定数とを比較し、その結果、室内試験でも地盤の減衰が計測可能であることを示した。

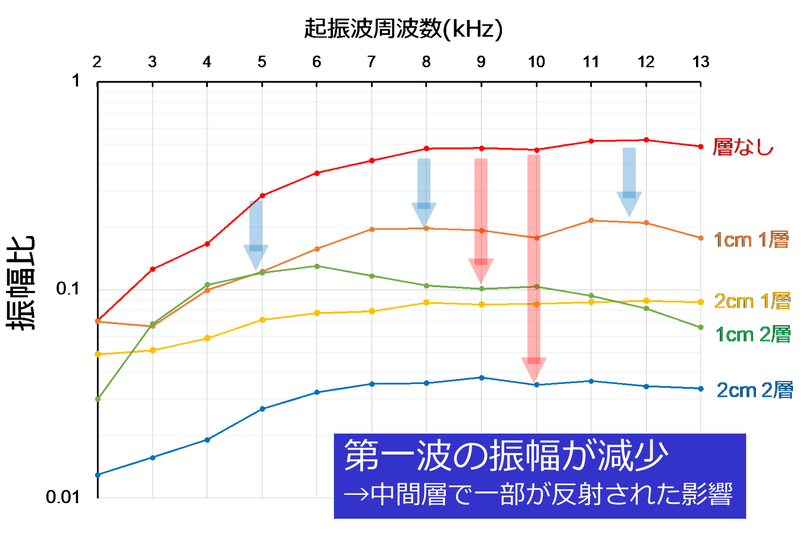
中間層の配置による弾性波振動の減衰効果











地中を伝わる地盤振動の抑制方法として地盤内に配置された硬軟の異質な中間層が弾性波の伝播に与える影響を検討し、室内試験ではプラスチックの中間層を配置した場合のせん断波の伝播特性の変化を検証した。単一パルスによる起振では、中間層が一部を反射し受信側に到達する第一波のエネルギーを分散させることで、振幅比が減少することを明らかにした。定常波振動では、中間層での透過波、反射波とが干渉して複雑な応答となるものの、層境界の不連続面でのエネルギー損失によって、振幅比が減少する傾向が確認された。密度や弾性波速度の異なる材質による中間層を配置すること、多層構造にして不連続面を増加させることで、地盤中を伝わる弾性波の振動伝播抑制が実現できる可能性が示唆された。

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A DEM study on the degree of mixture of soil particles stirred by rotation of rods

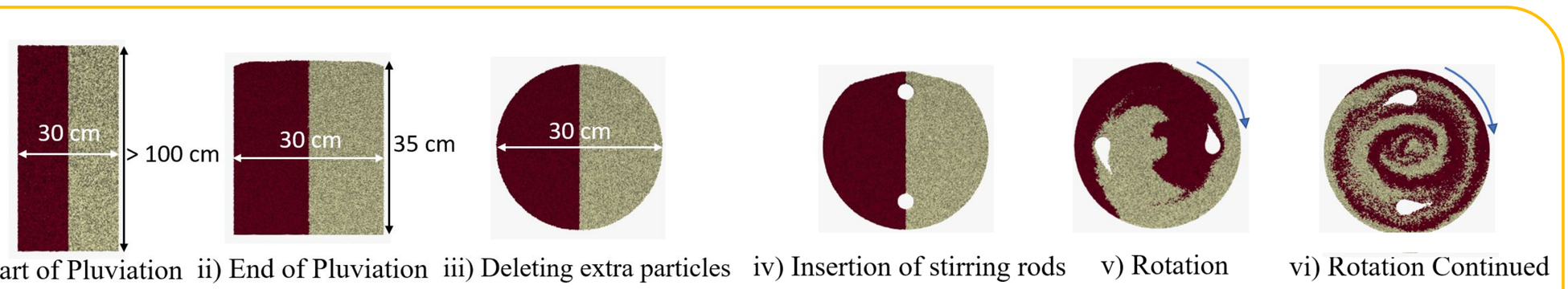
個別要素法による土の撹拌と混合に関する基礎的検討

Discrete element method (DEM) is used to simulate the stirring process and evaluate the degree of mixture at each rotation of stirring bars based on the initial positions of particles. This study focuses on monodispersed spherical particles where inter-particle cohesion is not considered.

シールドトンネルのチャンバー内の土の撹拌と混合度を評価するために、個別要素法を用いて、同一サイズの球形粒子を撹拌棒を回転させて撹拌する場合の混合特性について評価した。

Simulation steps

Particle Properties
Inter-particle friction coefficient = 0.05
Young's modulus = 71.6 GPa
Poisson's ratio = 0.23
Diameter = 2 to 2.2 mm
Density = 2650 kg/m^3

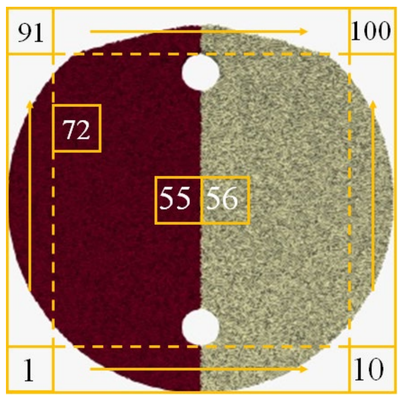


i) Start of Pluviation ii) End of Pluviation iii) Deleting extra particles iv) Insertion of stirring rods v) Rotation vi) Rotation Continued

Definition of degree of mixture

For **local degree of mixture (d_m)**, the particles were divided into the two regions (color 1 and color 2). The specimen was divided into one hundred equal-sized grids (10×10). For each grid, the d_m value was defined based on the difference in the numbers of type 1 and type 2 particles as follows.

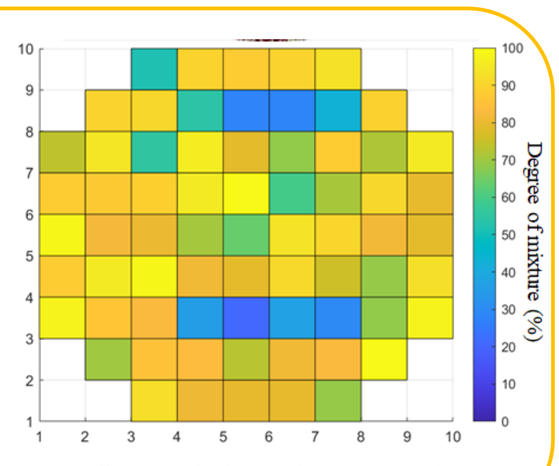
$$d_m = \left(1 - \frac{|n_1 - n_2|}{n_1 + n_2}\right) \times 100$$



Grid system



Mixed specimen



Spatial distribution of m

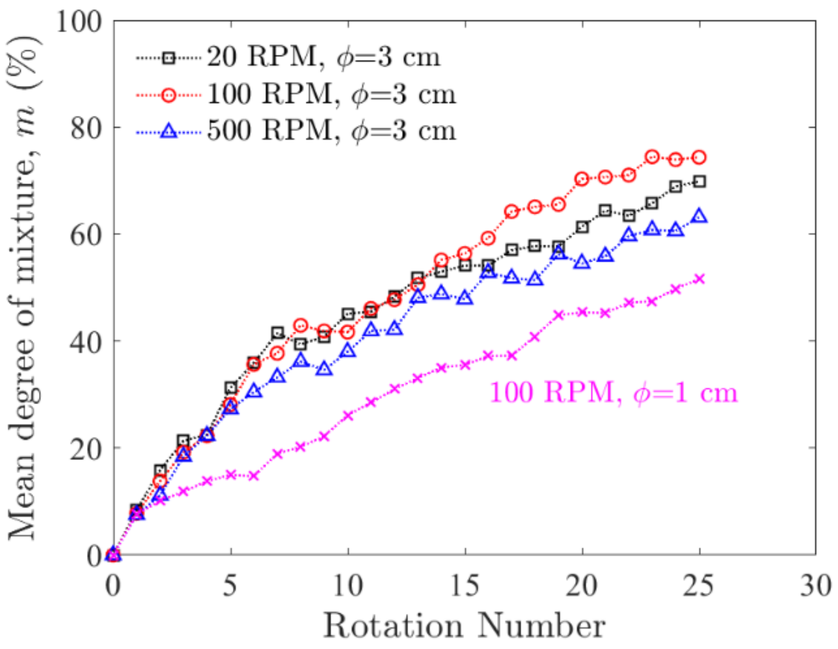
Evaluation of degree of mixture



Effects of mixing rate and size of stirring rods on the mixing condition after 25 rotations.

The **mean degree of mixture *(m)*** is defined by calculating the mean of d_m of all the grids at the given rotation number using the following equation.

$$m = \frac{\sum(d_m \; for \; all \; grids)}{Total \; number \; of \; grids}$$



Mean degree of mixture for different cases

Effect of the mixing rate of stirring rods

It is not easy to differentiate the degree of mixture by eyes. The left figure compares the evolution of m with the rotation number. The mixing rate appears less sensitive to m where there is no clear dependency of the mixing rate in the given results. It is noteworthy that the current simulation study focuses on non-viscous coarse particles only.

Effect of the size of stirring rods

The larger rods (i.e., diameter (φ) = 3 cm) are more effective to achieve higher m for a given rotation number at the same rate of rotation. Some locally concentrated zones for the two different colors are observed in Case 4 (φ = 1 cm), probably due to the less influenced zone generated by the motion of smaller rods during rotation.

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Effect of diameter of stirring rods on mixing of different-sized particles

異なる粒度の粒状体の混合における撹乱ロッドの直径が及ぼす影響

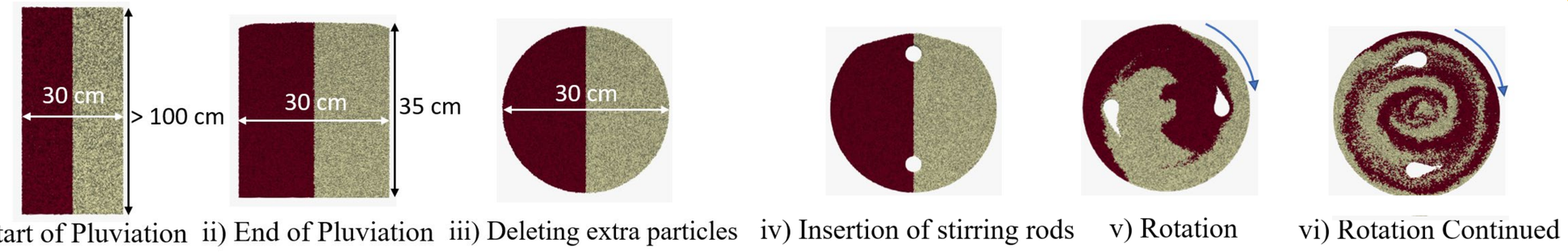
Introduction

This study intends to evaluate the effect of diameter of stirring rod on degree of mixture of two different size (i.e., gap-graded) particles mixed by the rotary action of these rods in a cylindrical soil specimen using discrete element method (DEM).

本研究は、円柱状粒状供試体の内部で攪拌ロッドの回転によって混合された粒度の異なる2種の粒状材料において、攪拌ロッドの直径が混合度に及ぼす影響を、個別要素法(DEM)によって評価した。

Simulation steps

Particle Properties
Inter-particle friction coefficient = 0.05
Young's modulus = 71.6 GPa
Poisson's ratio = 0.23
Diameter = 2 and 2.2 mm
Density = 2650 kg/m^3

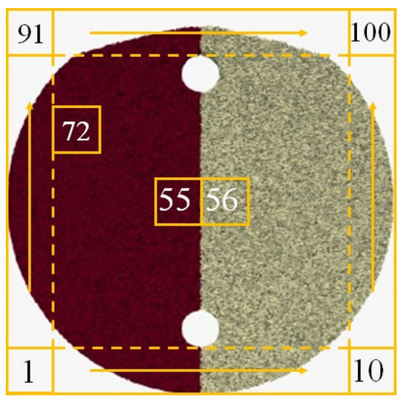


i) Start of Pluviation ii) End of Pluviation iii) Deleting extra particles iv) Insertion of stirring rods v) Rotation vi) Rotation Continued

Definition of degree of mixture

For **local degree of mixture (d_m)**, the particles were divided into the two regions (color 1 and color 2). The specimen was divided into one hundred equal-sized grids (10×10). For each grid, the d_m value was defined based on the difference in the volume occupied by type 1 and type 2 particles as follows.

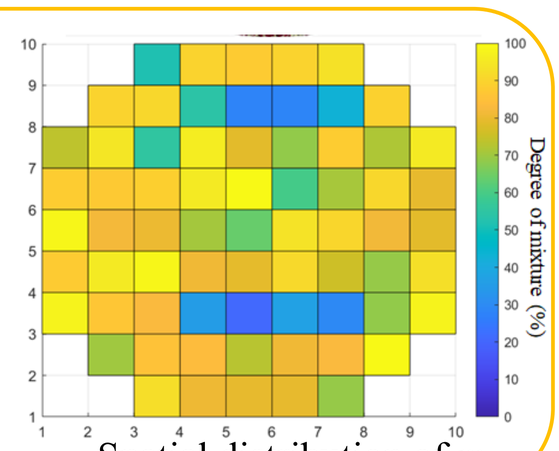
$$d_m = \left(1 - \frac{|V_1 - V_2|}{V_1 + V_2}\right) \times 100$$



Grid system

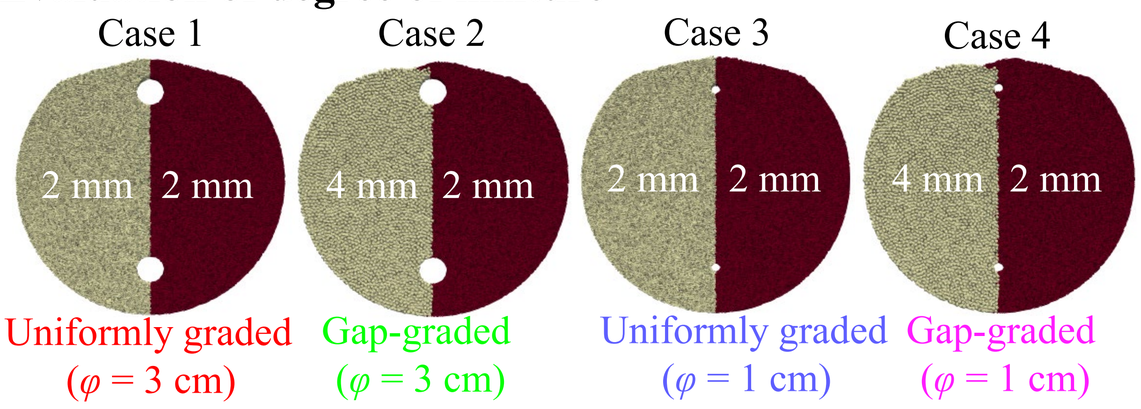


Mixed specimen



Spatial distribution of m

Evaluation of degree of mixture



Fig, 1: Initial configuration of all cases.

Table: Test cases and specifications.

Case	Dia. of particles	Dia. of stirring rod, (φ)	No. of particles
	mm	cm	
1	2	3	165,919
2	2&4	3	107,484
3	2	1	169,398
4	2&4	1	109,809

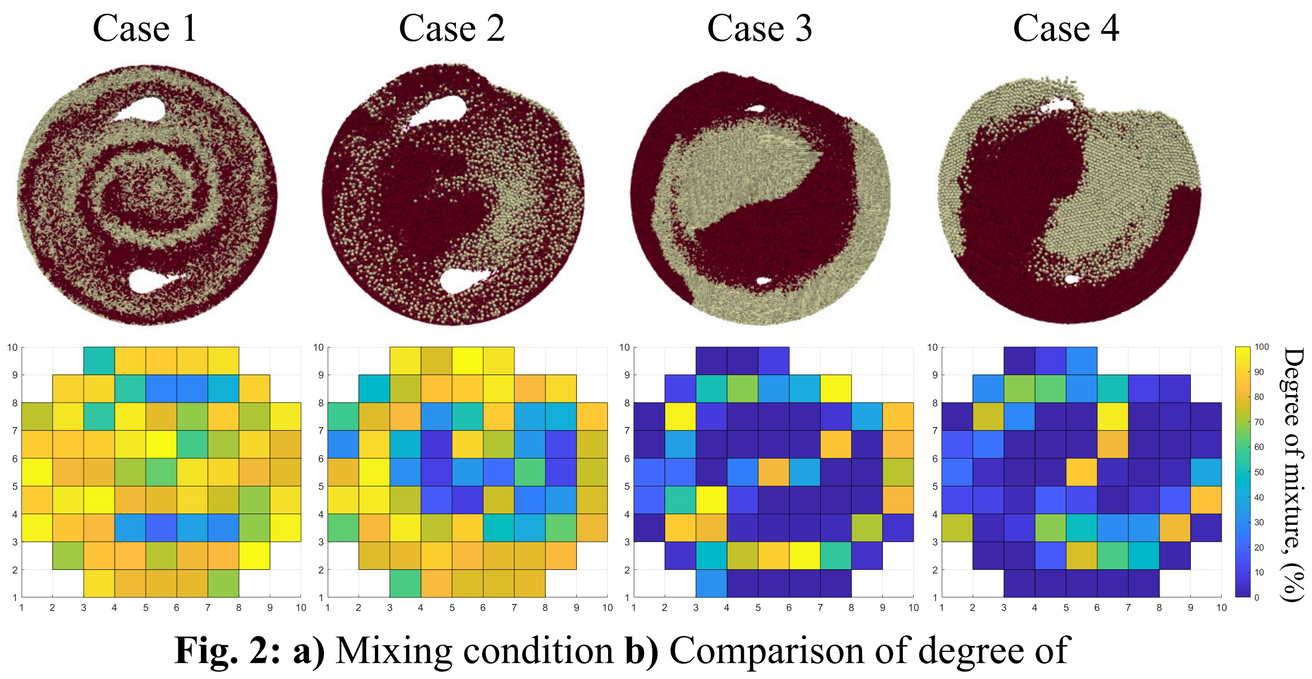


Fig. 2: a) Mixing condition **b)** Comparison of degree of mixture for all cases after 25 rotations.

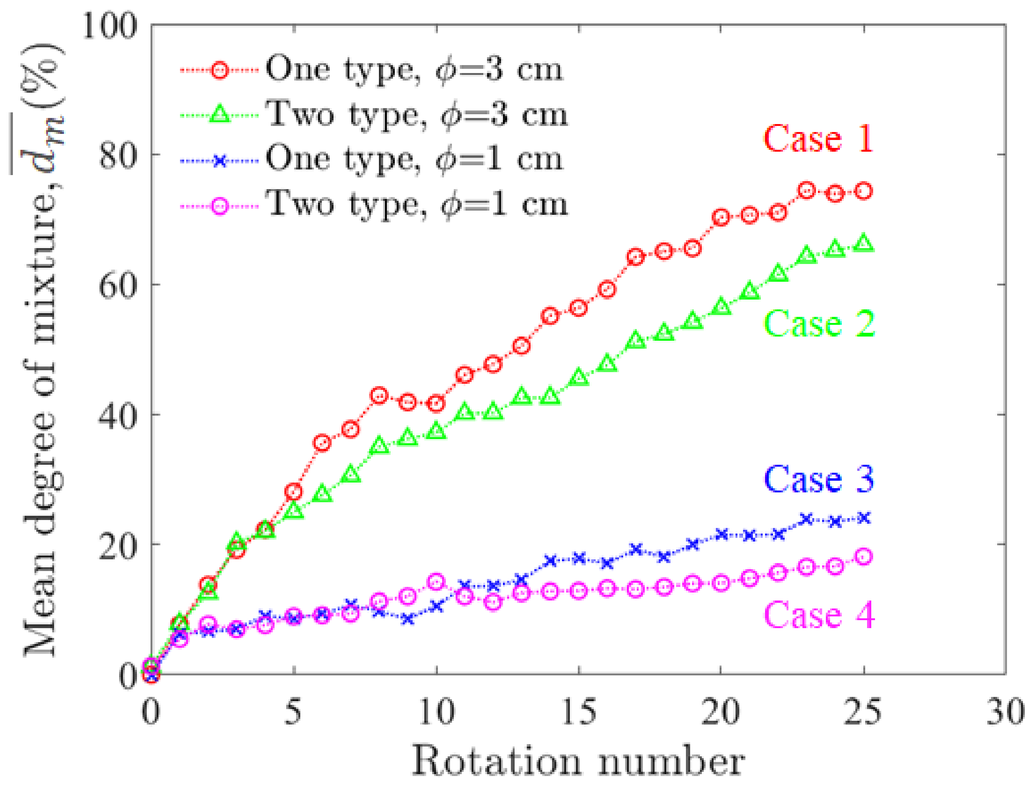


Fig: Mean degree of mixing of different diameter stirring rods for uniformly and gap-graded particles.

Conclusion

Mean degree of mixture is more sensitive to the size of stirring rods rather than the size of the particles being mixed, probably due to the less influenced zone generated by the motion of smaller rods during rotation. The $\overline{d_m}$ of gap-graded particles cases is slightly on the lower side as compared to that of uniformly graded particles.

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Effect of position of stirring rods on mixing of granular particles

攪拌棒の位置が粒状粒子の混合に与える影響

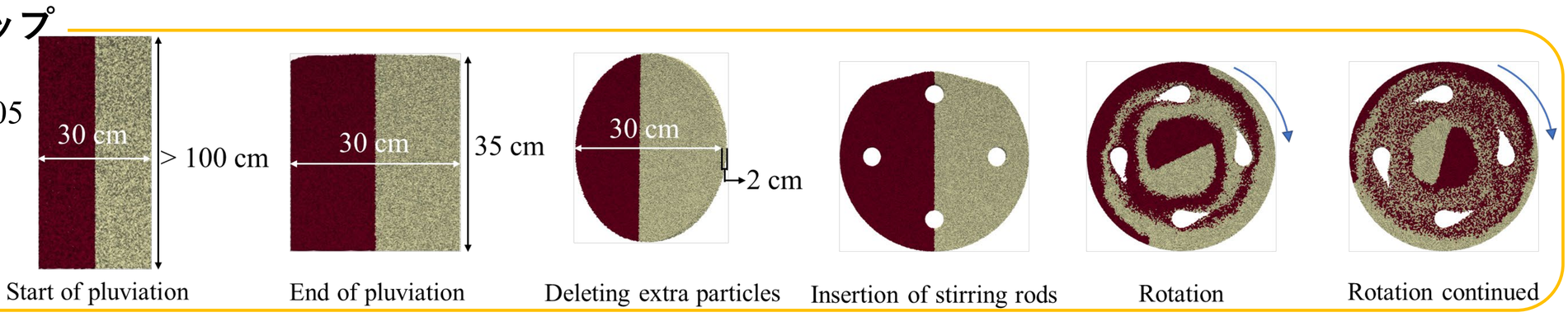
Introduction　概要

This study evaluates how the position of stirring rods in an earth pressure balance shield tunnel machine affects mixing efficiency of geomaterials. Using discrete element method (DEM), the rotary action of stirring rods is simulated. The results of DEM simulations are validated through physical model tests.

本研究は、泥土圧シールドトンネルマシンにおける攪拌棒の位置が掘削土の混合効率にどのように影響するか、個別要素法（DEM）により粒状体内の攪拌棒の回転動作をシミュレーションして評価しました。DEMシミュレーションの結果は模型実験を実施して検証しました。

Simulation steps　解析ステップ

Particle Properties
Inter-particle friction coefficient = 0.05
Young's modulus = 71.6 GPa
Poisson's ratio = 0.23
Diameter = 2 mm
Density = 2650 kg/m^3



Validation of DEM simulation results　模型実験による検証

For validation of DEM simulations, physical model tests are performed. 6mm and 4mm particles with different colors are mixed from two regions in both validation DEM simulation and physical model test. Images are captured at each rotation of stirring rods in both cases. These images are divided into one hundred equal-sized grids (10×10). The **local degree of mixture, d_m** is defined based on the balance between the number of red pixels, r_x and green pixels, g_x in each given grid x as follows:

$$d_m = \left(1 - \frac{|r_x - g_x|}{r_x + g_x}\right) \times 100$$

Mean degree of mixture, $\overline{d_m}$ is calculated by taking the mean of d_m of all the grids at each rotation of stirring rods.

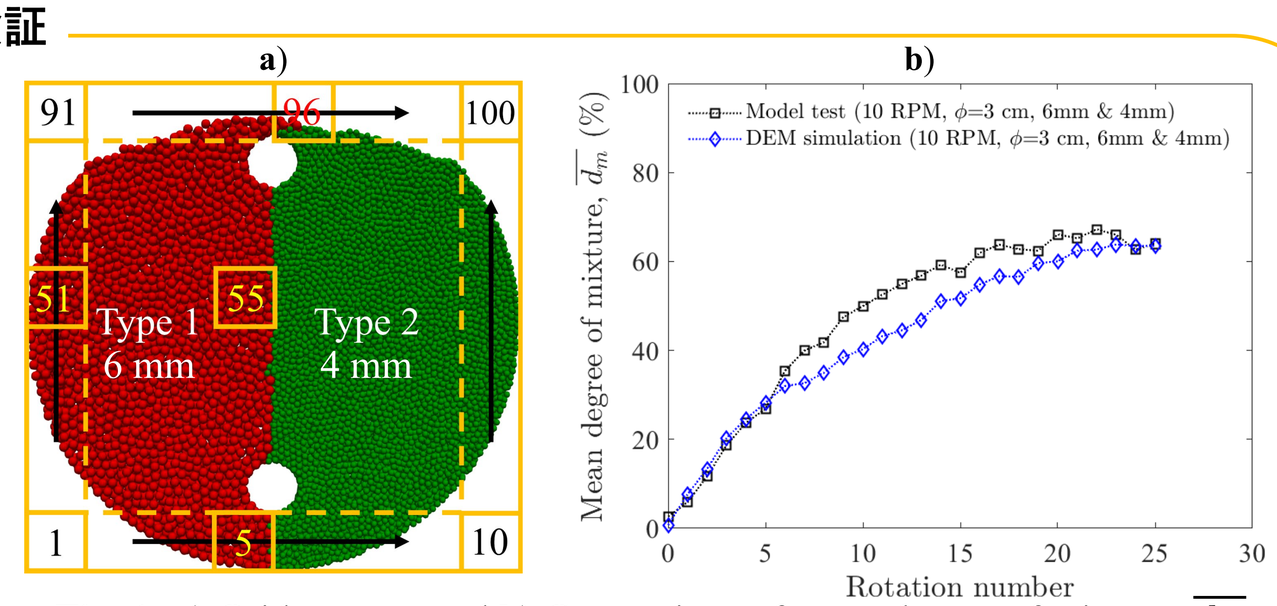


Fig. 1: a) Grid system, and **b)** Comparison of mean degree of mixture, $\overline{d_m}$ between validation DEM simulation and physical model test.

Effect of position of stirring rods on $\overline{d_m}$ 混合度に対する攪拌棒の位置の影響

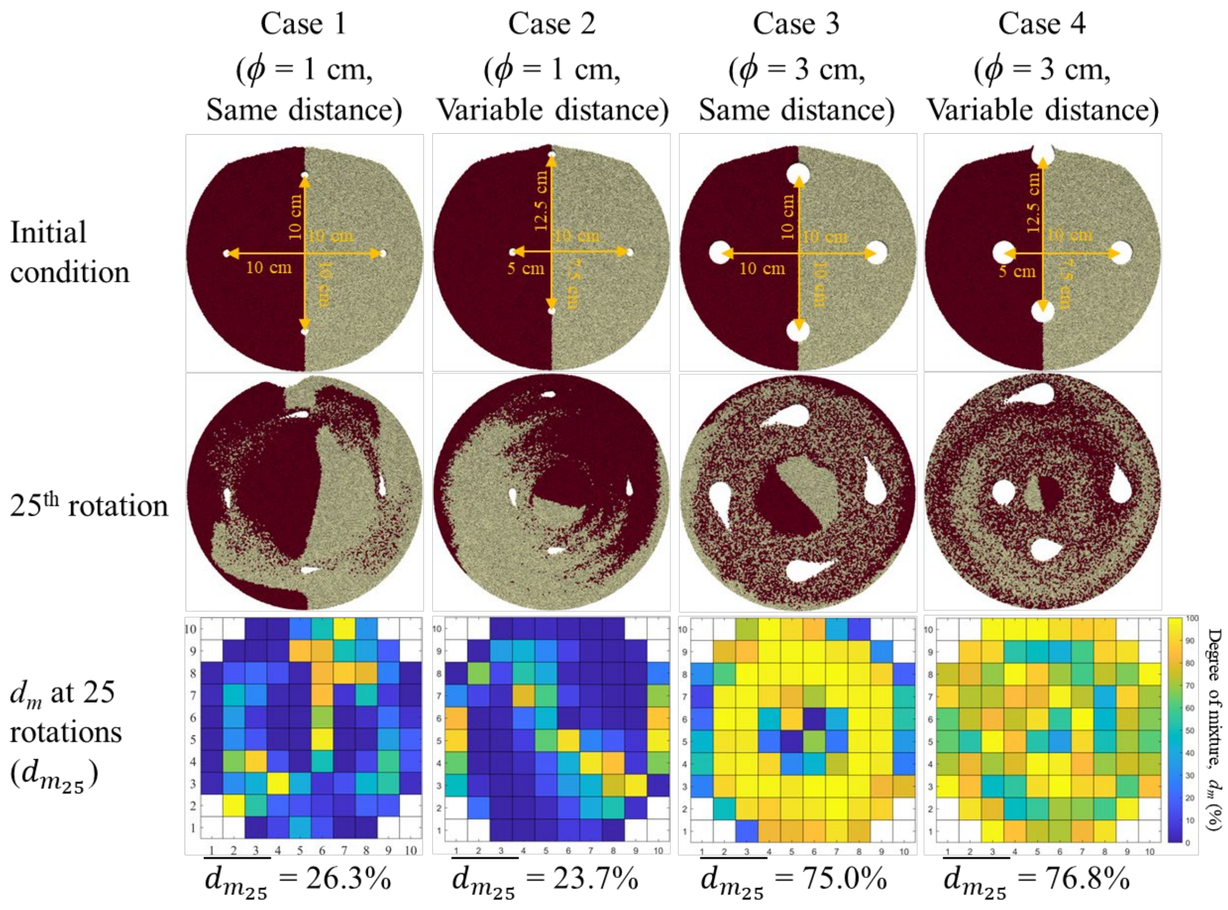


Fig. 2: Initial condition and comparison of spatial distribution of particles with d_m at 25 rotations for same and variable positions of stirring rods of varying diameters.

Table: Test cases and specifications.

Case	Diameter of stirring rods, (ϕ)	Position of stirring rod	No. of particles
	cm	-	
1	1	Same	168,817
2	1	Variable	168,815
3	3	Same	161,870
4	3	Variable	161,873

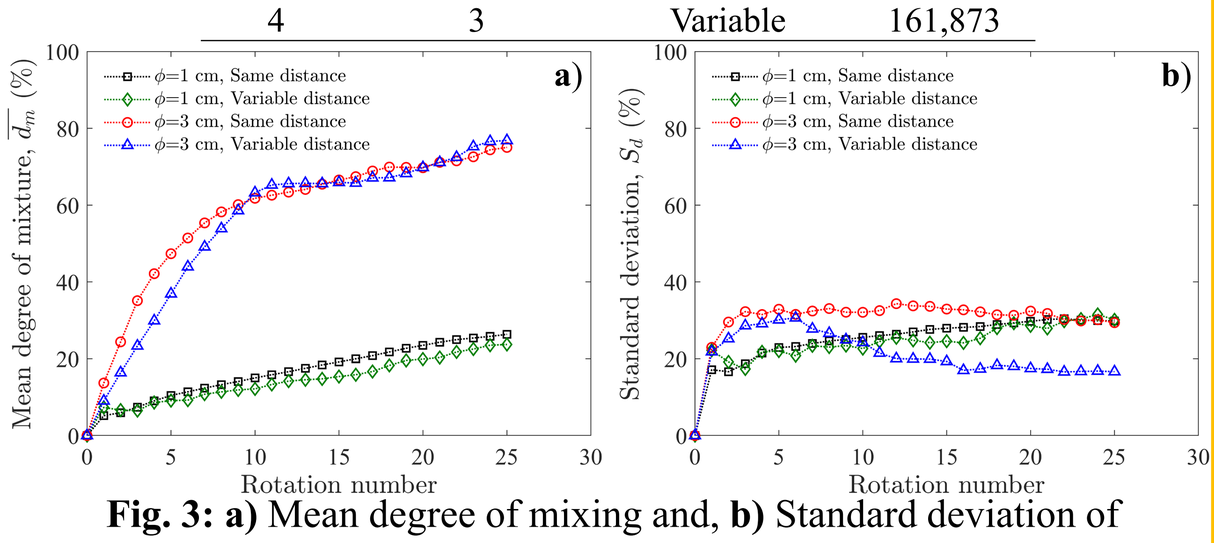


Fig. 3: a) Mean degree of mixing and, **b)** Standard deviation of different positions of stirring rods.

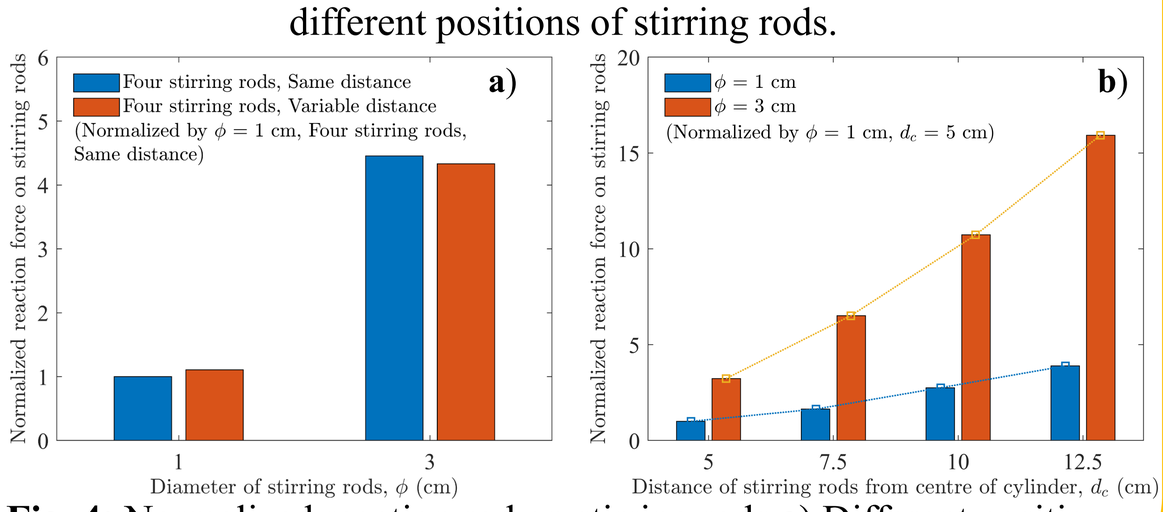


Fig. 4: Normalized reaction rod on stirring rods **a)** Different positions, and **b)** Variable distance from the center of cylinder.

Conclusion

Reasonable agreement is achieved between validation DEM simulation and physical model test. Although the $\overline{d_m}$ is not improved by changing the location of stirring rods, the homogeneity of mixture is enhanced significantly. The normalized reaction force on stirring rods remains unchanged when the size and number of stirring rods are constant, but it is directly proportional to the distance from the center of the mixing cylinder.

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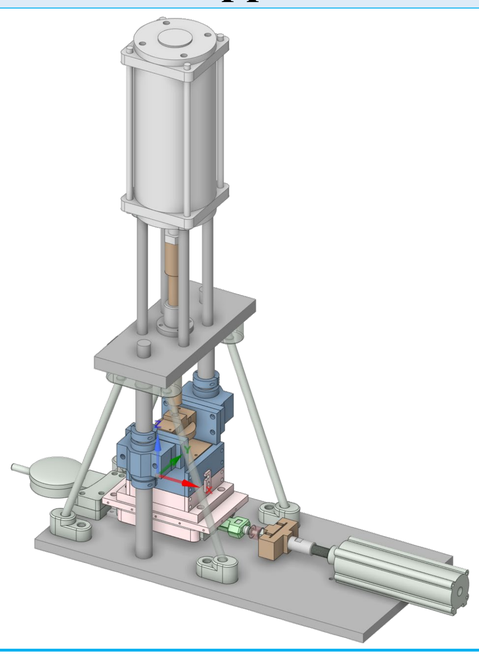
The mechanical behavior of foam-treated soil

気泡混合処理土の力学特性

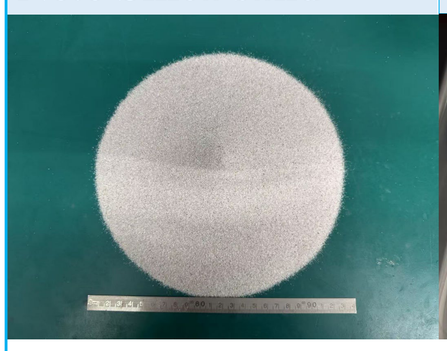
Foam-treated soil is soil that mixed with a foaming agent to alter its properties. In geotechnical engineering, foam treatment is widely used in Earth Pressure Balance (EPB) shield tunnelling. Injecting foam into the ground or excavated muck can transform the soil from a solid or granular state into a soft, plastic paste with fluid-like behavior. In this study, a direct shear apparatus was used to perform the monotonic and cyclic direct tests on foam-treated soil, considering the influencing factors such as foam content, mixing degree and stress level. The objective is to determine the optimal foam content range for foam-treated soil.

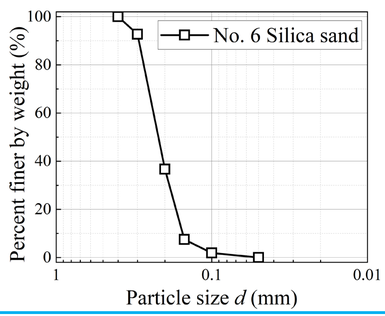
気泡混合処理土は、土に発泡剤を混合しその物理的性質を改良した材料である。地盤工学分野では、土圧バランス型シールド工法（EPB工法）において広く用いられている。発泡剤を地盤または掘削土に注入することで、土の状態は固体または粒状から、流動性を有する軟らかく塑性のあるペースト状に変化する。本研究では、改良型の一面せん断試験装置を用いて、気泡処理土の力学特性を評価した。気泡含有量、混合均一性、応力条件などの影響因子を考慮し、最適な気泡含有量の範囲を明らかにすることを目的とした。

Direct shear apparatus

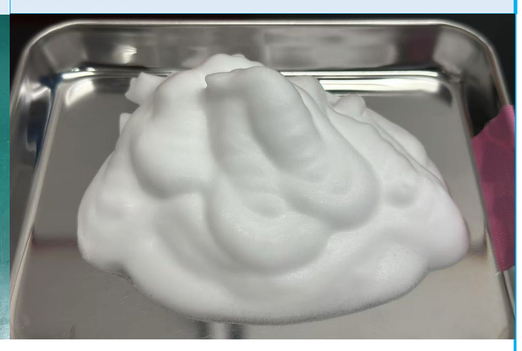


No.6 Silica sand





Foam



Foam property:

Foam solution concentration (C_f): 5%

Foam expansion ration (FER): 13.2

The half-life of foam: 60 ~ 90 mins

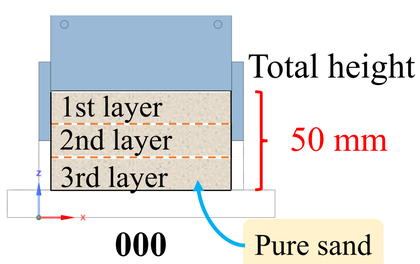
Foam-treated sand with different content



Foam injection ratio (FIR)

By mass fraction	1.0%	1.5%	1.6%	1.7%	1.8%	2.0%
By total volume fraction	19.8%	29.7%	31.7%	33.7%	35.6%	39.6%
By pore volume fraction	35.0%	52.5%	56.0%	59.5%	63.0%	70.0%

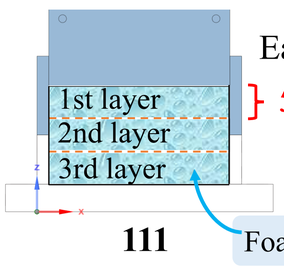
Results of simple shear



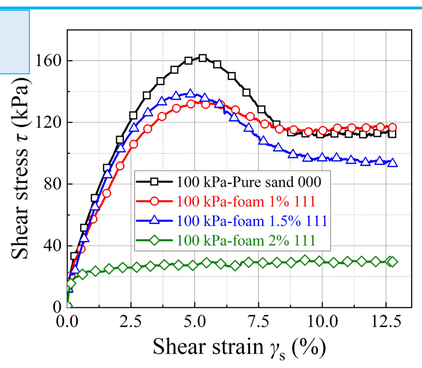
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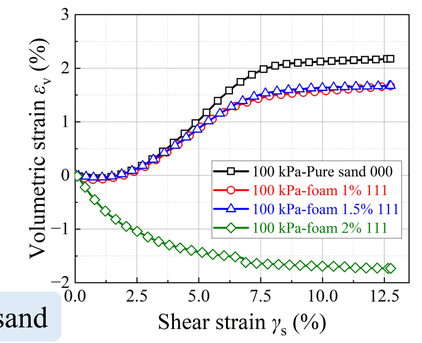
0: Pure sand

1: Foam-treated sand

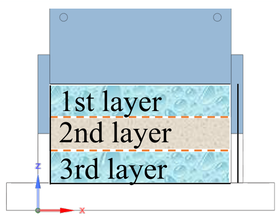


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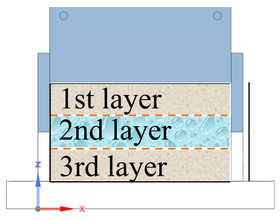




Mixing degree

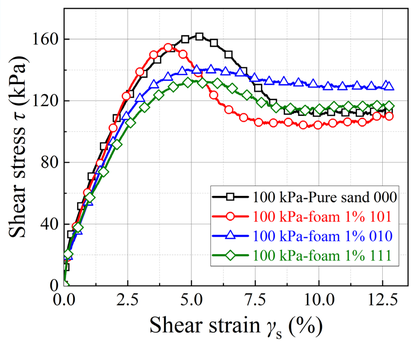


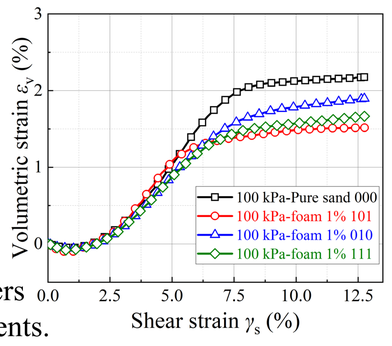
101

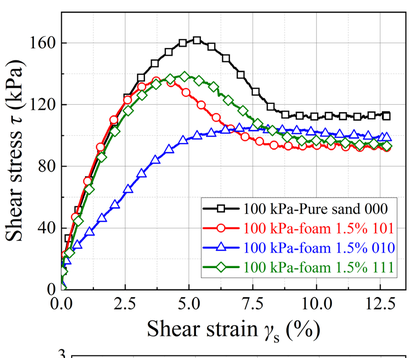


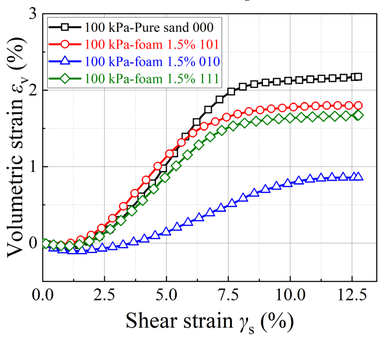
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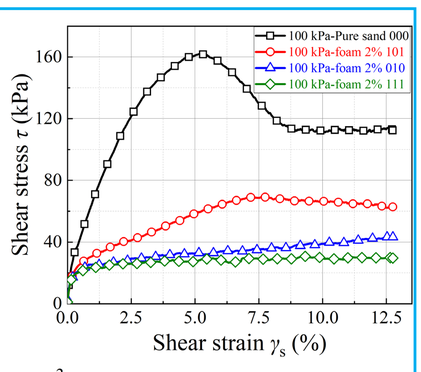
It is divided into three layers but with different components.

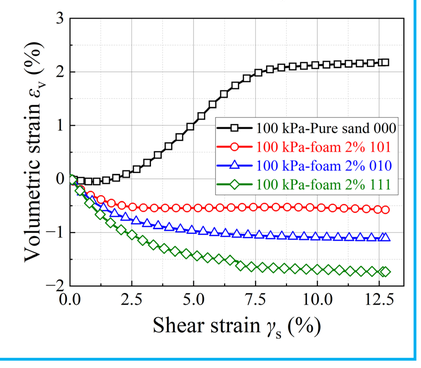




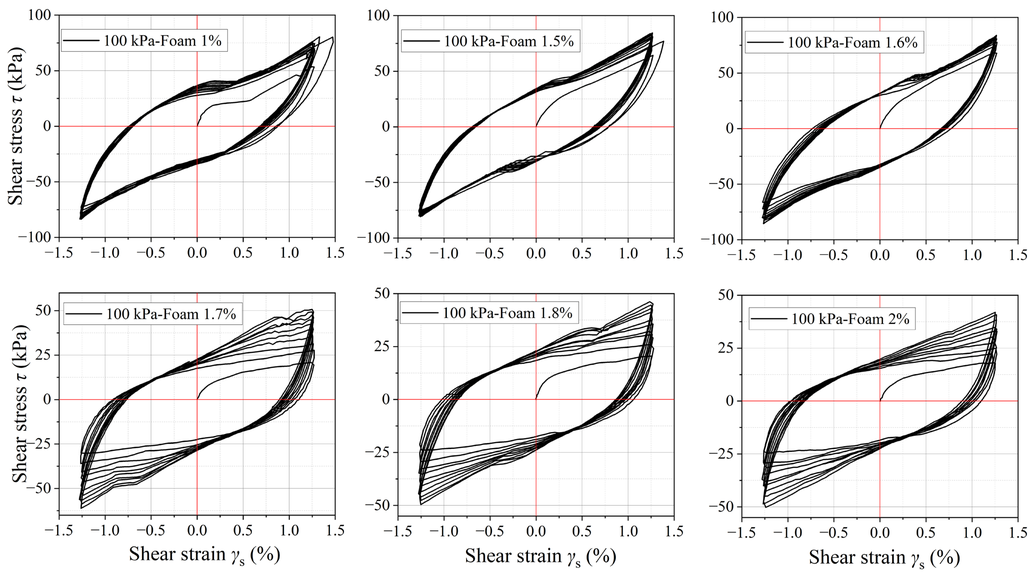


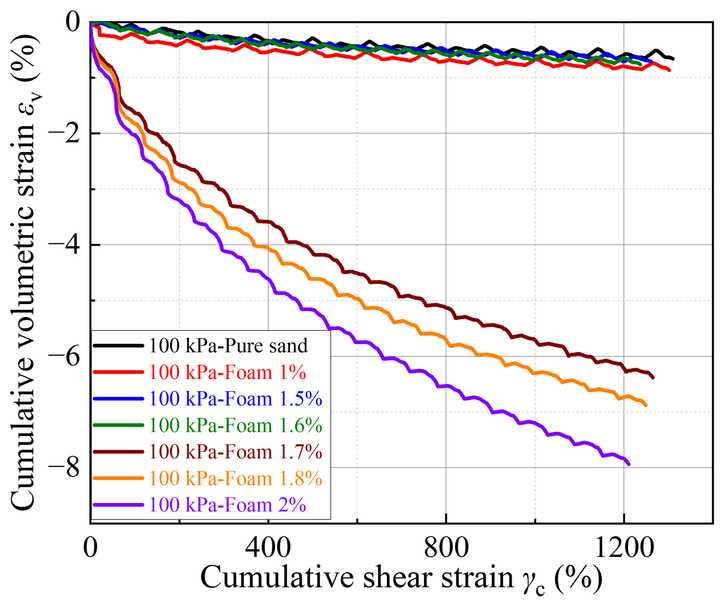






Results of cyclic direct shear test





A significant increase in the cumulative volumetric strain.

Conclusion

1. Foam can significantly reduce soil strength and increase the compressibility.
2. Foam-treated soil behaves differently with different foam mixing degree.
3. Static direct shear tests showed that shear stress decreased significantly when foam content was 2%.
4. Dynamic direct shear tests showed that an obvious jump occurred in the cumulative volumetric strain when foam content exceeds 1.6%.
5. There is an optimal foam content threshold range for the foam-treated soil.

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Geotechnical interpretation of the interlayered structure adopted in the construction of ancient tomb mounds “Kofun”

古墳盛土構築に用いられた細･粗粒土互層構造の地盤工学的解釈

６世紀半ばから全国の古墳盛土に見られる構造として、目の粗い土と細かい土とを交互に薄く積む構造があります。この構造の役割は長らく謎でしたが、本研究ではこの互層構造をケイ砂を用いて再現し、力学特性、浸透特性の２つの観点で実験し、その結果を元に現代地盤工学的な説明を加えました。

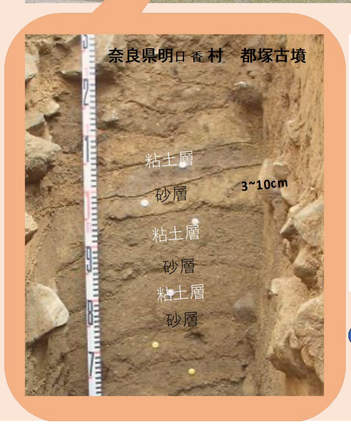
One structure that has been seen in Kofun mounds throughout Japan since the mid-6th century is alternating coarse and fine soil. And its role has been a mystery. In this study, this alternating layer structure was reproduced using silica sand and tested from two viewpoints, mechanical properties and infiltration properties, and a modern geotechnical explanation was made.

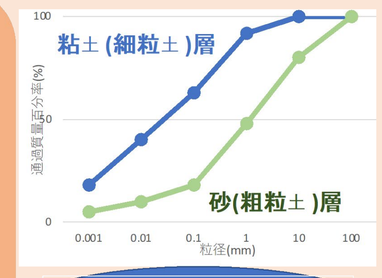
古墳とは？

日本を代表する歴史遺産である古墳は、今から約1800年前～1400年前に築かれた古代のお墓です。日本全国で約15万基築かれました。古墳は単なるお墓だけでなく権力の象徴でもあり、壮大に魅せ、後世に残すための数々の工夫がなされています。例えば、自然災害に耐えうる頑丈な盛土を築くため、寺院などの基礎に用いられた版築という突固め技術が応用されました。古墳の盛土構造や遺構を調査すると、当時の技術力の高さを垣間見ることができます.

Kofuns, are ancient tomb mounds built about 1400-1800 years ago. 150,000 Kofuns were built throughout Japan. Kofuns are not just graves, but also symbols of power, and numerous efforts have been made to make them grandly fascinating and to preserve them for future generations. For example, in order to build a sturdy mounds, the method that used for the foundations of temples, was applied.







細かい粘土と目の粗い砂を交互に積む構造

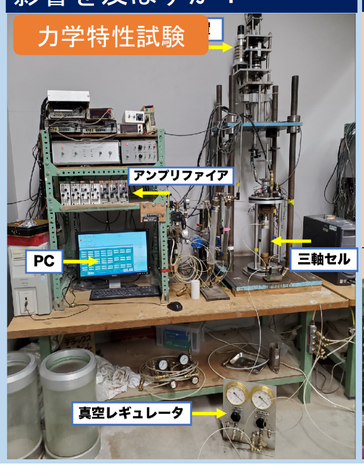
実験結果

力学特性の試験では、互層構造は細粒土のみと比べ盛土強度はほとんど変わらない結果であり、盛土の強度増加の意図はなかったと示唆されました。一方、浸透特性実験では、細粒土層が墳丘内に雨水が浸透するのを抑制し、粗粒土層が浸透した雨水を傾斜に沿って墳丘外に排出する構造をもつことが示唆される結果となりました。

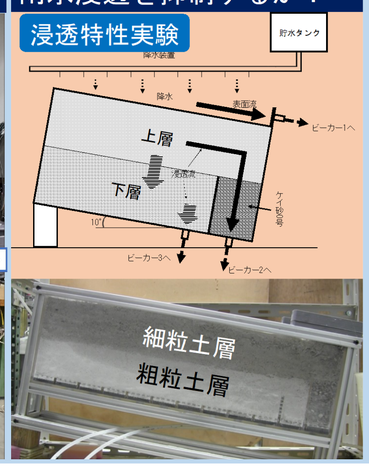
Testing of mechanical properties showed that the alternating layer structure resulted in almost no change strength compared to the fine-grained soil alone, suggesting that there was no intention to increase the strength of mounds. On the other hand, infiltration tests suggested that the fine-grained soil layer inhibits rainwater infiltration into mounds, while the coarse-grained soil layer drains the infiltrated rainwater along the slope to the outside of mounds.

古墳盛土に用いられた細・粗粒土互層構造

仮説1
互層構造は盛土の強度に影響を及ぼすか？



仮説2
互層構造は墳丘内の雨水浸透を抑制するか？



現代の地盤工学の視点から解釈

盛土内に粘性土と砂質土で互層構造を設けることは、墳丘内部への水の侵入を防ぐ工夫であったと思われます。特に墳丘中心部に横穴式石室を構築する後期古墳では、墳丘盛土内の浸透抑制構造は石室内が雨水浸透により劣化することを防ぐ役割があったのでしょう。古墳時代中期～後期における古墳の盛土構築技術は現代の地盤工学的に見ても合理的であり、盛土の密度や強度、排水機能を最適化するような設計であったと解釈できました。

Creating a fine-coarse alternating layer structure of clay and sandy soil within the mound fill, was probably a device to prevent water from penetrating into the interior of the mound. Especially for the Late Kofun tumuli, which had a horizontal stone chamber built in the center of the mound, the infiltration control structure within the mound fill probably played a role in preventing deterioration of the interior of the stone chamber due to rainwater infiltration. The construction technique of the mound was rational from the viewpoint of modern geotechnical engineering.

強度面では
互層構造≒細粒土単層

細粒土層→遮水
粗粒土層→排水

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Estimation of Internal Structure of Shiroitsuka Kofun by Seismic Survey

弾性波探査による白井塚古墳内部構造の推定

要旨
Abstract

東京都狛江市に位置する白井塚古墳は、今から約1700年前に築造された直径約40mの円墳である。本研究は、東京都狛江市白井塚古墳の内部構造を明らかにするため、弾性波探査を実施した。墳丘頂上で行った反射法弾性波探査について、CMP重合とNMO補正によりデータを分析したところ、地中深度4mと2mにある反射断面が観測され、これらが墳丘の築造時の層境界や未発掘の埋葬施設である可能性が示された。

This study summarizes the results of a seismic survey conducted to reveal the interior structure of the Shiroitsuka Kofun in Komae City, Tokyo. Data analysis of the seismic reflection survey conducted at the top of the mound, using CMP gathering and NMO correction, revealed reflection cross sections at 4m and 2m depth from the surface. It indicated that these reflections could be layer boundaries at construction of the mound, or unexcavated burial facilities.

白井塚古墳について
Shiroitsuka Kofun

About Shiroitsuka Kofun

- Shiroituka Kofun is a round shape burial mound about 36 m in diameter and 4 m high, located in Komae City, Tokyo, Japan.
- 1978 excavations unearthed a portion of earthenware, suggesting that it was built in the 4th to 5th centuries.
- In a survey conducted in 2022, three new gravel layers were discovered that were thought to be burial facilities, and iron, straight swords, and iron arrowheads were excavated. [1]

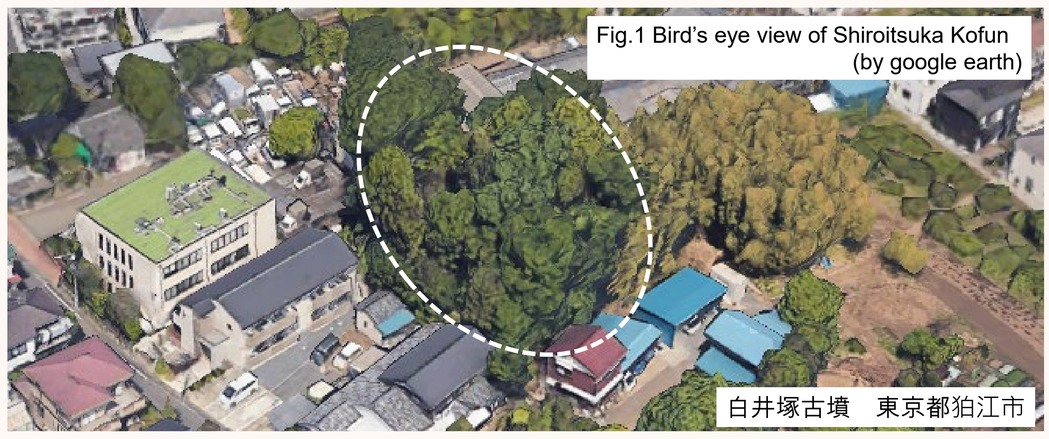


Fig.1 Bird's eye view of Shiroitsuka Kofun (by google earth)

これまでの調査結果
Previous Research

Previous Research

- The investigation of the mound cross section (See Fig.3) showed that black, brown, and loam soils were layered in this order on top of a black soil base, a method similar to plate construction [2] .
- Generally, the main remains of a burial mound are located in the center of the mound. However, in the Shiroitsuka Kofun, the burial facilities discovered in previous surveys were located off-center. **It is possible that the main burial facility exists in the central part of the mound.**

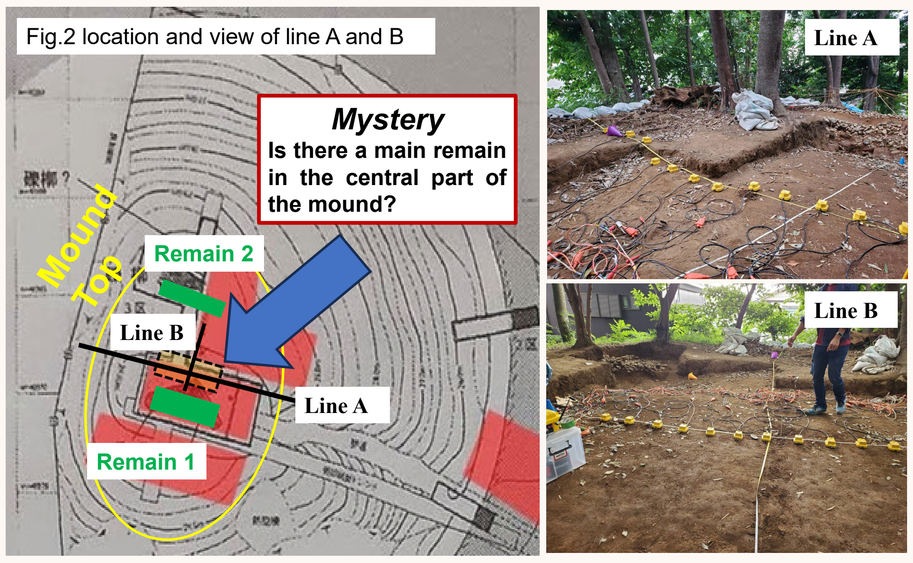
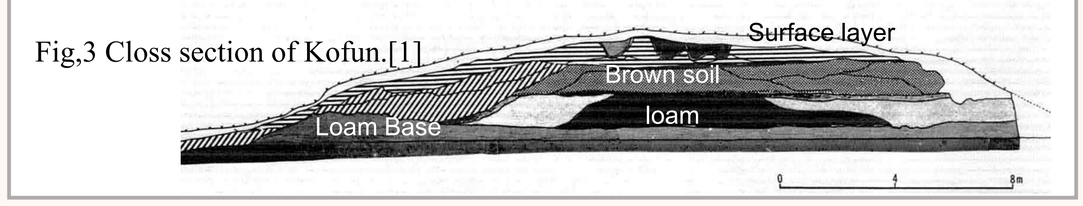


Fig.2 location and view of line A and B



Fig,3 Closs section of Kofun.[1]

調査手法
Survey Methodology

Seismic Survey Method

- This survey was conducted on two lines A, B (see Fig.2) , sealed with 20 cm of soil.
- The sensors were a geophone with a natural frequency of 4.5 Hz, and the placement interval was 0.3 m. 24 geophones were placed on A and 12 on B. Both excitation and reception were in the vertical direction, and artificial excitation using a hammer was used.
- Common Mid-Point gathering and Normal Movement Out Correction were performed after deconvolution process and correction of wave amplitude scattered by propagation distance based on the reflection seismic survey method. (see Fig.4) Reflected waves at each point were integrated to produce a reflection cross section of the line.

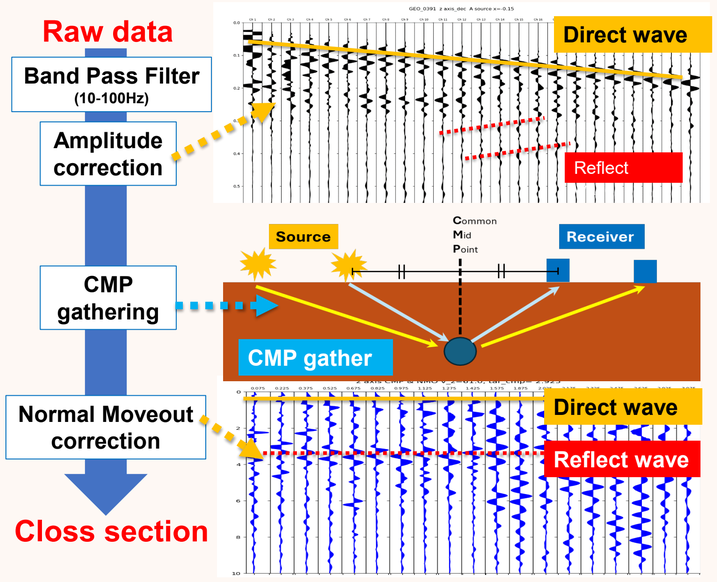




Fig.4 Survey Flow and view of research

結果と考察
Result and Discussion

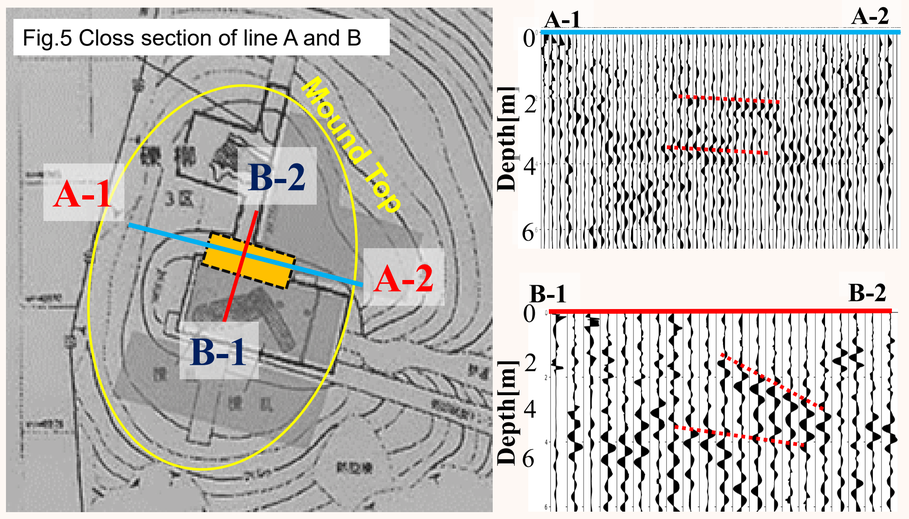


Fig.5 Closs section of line A and B

Result and Discussion

- The dominant wave velocity was about 60.0 m/s for both lines A and B,
- In both line A and B, two reflection surfaces were observed at depths of 4 m and 2 m.
- Reflection cross section at 4 m depth was observed throughout the line, assumed to be the boundary surface between the earthen platform and artificial mound.
- Reflection cross section at 2m depth was seen at 2.6 m to 4.9 m in line A and at 1.0 to 1.5m in line B. It may be the boundary with the loam/brown soil layers or some buried remains, such as a gravel layer (See Fig.5).

結論
Conclusion

Conclusion

- This study summarizes the results of a seismic survey of the top of the Shiroitsuka Kofun in Komae City. In accordance with the reflection seismic survey method, reflection cross sections were created by CMP gathering and NMO correction for the measured data. As a result, two reflection cross sections were observed at depths of 2 m and 4 m.
- Comparing the results of the reflection cross-sections with those of the literature [2], the cross section at 4m depth was considered to be the layer boundary between the ground and the mound fill, while the cross section at 2m depth may be the layer boundary at the time of mound construction or an unexcavated burial facility.

References: [1] 20220812-103659.pdf (city.komae.tokyo.jp), [2]狛江市の古墳 (I) (1979). 狛江市文化財調査報告書 第2集. pp51-63

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Seismic and resistivity surveys to the Sakuradani Kofun tumuli after the Noto earthquake

能登地震による櫻谷古墳の被害状況把握のための比抵抗・弾性波探査を組み合わせた複合非破壊探査

2024年1月1日、能登半島を襲った大地震は、富山県屈指の規模を誇る櫻谷古墳に甚大な被害を与えた。1号墳では亀裂や陥没、2号墳では深さ6mにもおよぶ大陥没が生じ、復旧のための第一歩として、地震による盛土被害状況の把握のため、比抵抗と弾性波を組み合わせた複合的な非破壊探査を実施した。その結果、1号墳では陥没抗付近の斜面近くが高比抵抗、と後方部中央の1m深度が高比抵抗値・低弾性波速度であると観測され、緩み領域である可能性が示された。また、墳丘底部(深さ4m～)は低比抵抗・低速度であり、雨水等が帯水している可能性が示唆された。2号墳では陥没孔付近が高比抵抗・高弾性波速度と観測され、緩み領域で低い弾性波速度として解釈される一般的な地盤内空洞の解釈とは異なる結果となった。また、北側斜面の浅い部分は高比抵抗、深い部分は低比抵抗・低弾性波速度と観測され、1号墳と同様帯水層となっている可能性が示唆された。

Introduction

The Noto Earthquake of January 2024 caused substantial damage to the Sakuradani Kofun Tumuli in Takaoka City, Toyama Prefecture, resulting in notable sinkholes and cracks across Tumulus No. 1 and Tumulus No. 2. To accurately assess this damage and consider future remedial measures, we conducted a comprehensive, non-destructive investigation using both seismic exploration and electrical resistivity tomography (ERT).



Fig.1 bird-eye view of Sakuradani Kofun Tumuli

Seismic & ERT Survey

In the two-dimensional resistivity survey, a portable dynamic cone penetration test (DCPT) was performed to measure ground strength and to investigate a method currently under development that utilizes the DCPT device to complement the traditional resistivity survey.
In seismic explorations, 24 geophones spaced 0.5 meters apart were used. A chirp signal generated by a portable vibration-speaker source, with a high-frequency range of 20-300 Hz, and cross-correlation signal processing were employed to improve the signal-to-noise ratio and enhance the accuracy of investigating the shallow layer at a depth of approximately 10 meters.

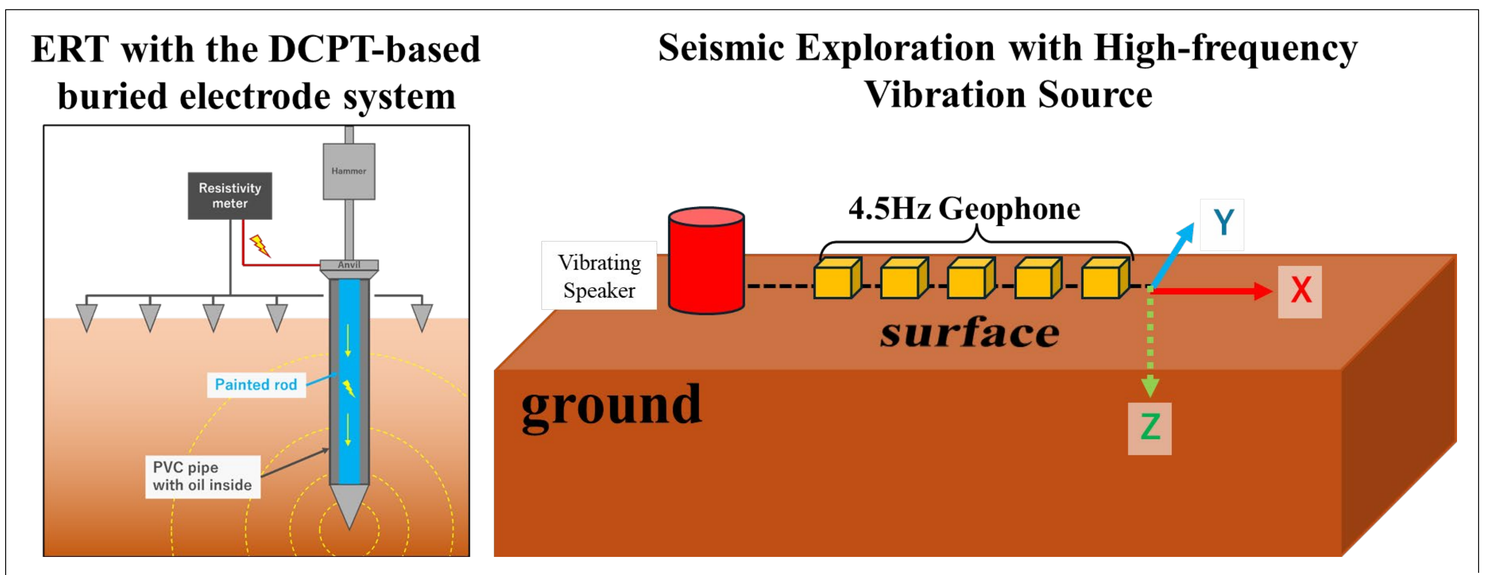


Fig.2 Overview of Electric resistivity Tomography(ERT) and Seismic survey

Results

Fig. 3 shows the results of the ERT survey and Vs inversion using the Rayleigh wave survey. Both Tumulus No. 1 and No. 2 had an average Vs velocity of 190 m/s and a resistivity of 700 Ω·m. In Tumulus No. 1, a low-Vs and a high-resistivity area were observed at a depth of approximately 1–2 m in the central part (a-1) of the line A2-A3. Additionally, a low-Vs area and a low-resistivity area were observed throughout the area at depths of 4 m or deeper (a-2). The former was a relaxation area. Meanwhile, the latter is believed to be a water-saturated layer caused by rainwater infiltration, both of which are considered vulnerable areas. In Tumulus No. 2, a sinkhole with a depth of 6 m on the southern slope was observed as a high-Vs and a high-resistivity area (b-1). Additionally, a high-resistivity area was observed on the surface of the northern slope (b-2). A low-Vs and low-resistivity area (b-3) was observed at a 4m deep of the mound, considered vulnerable area.

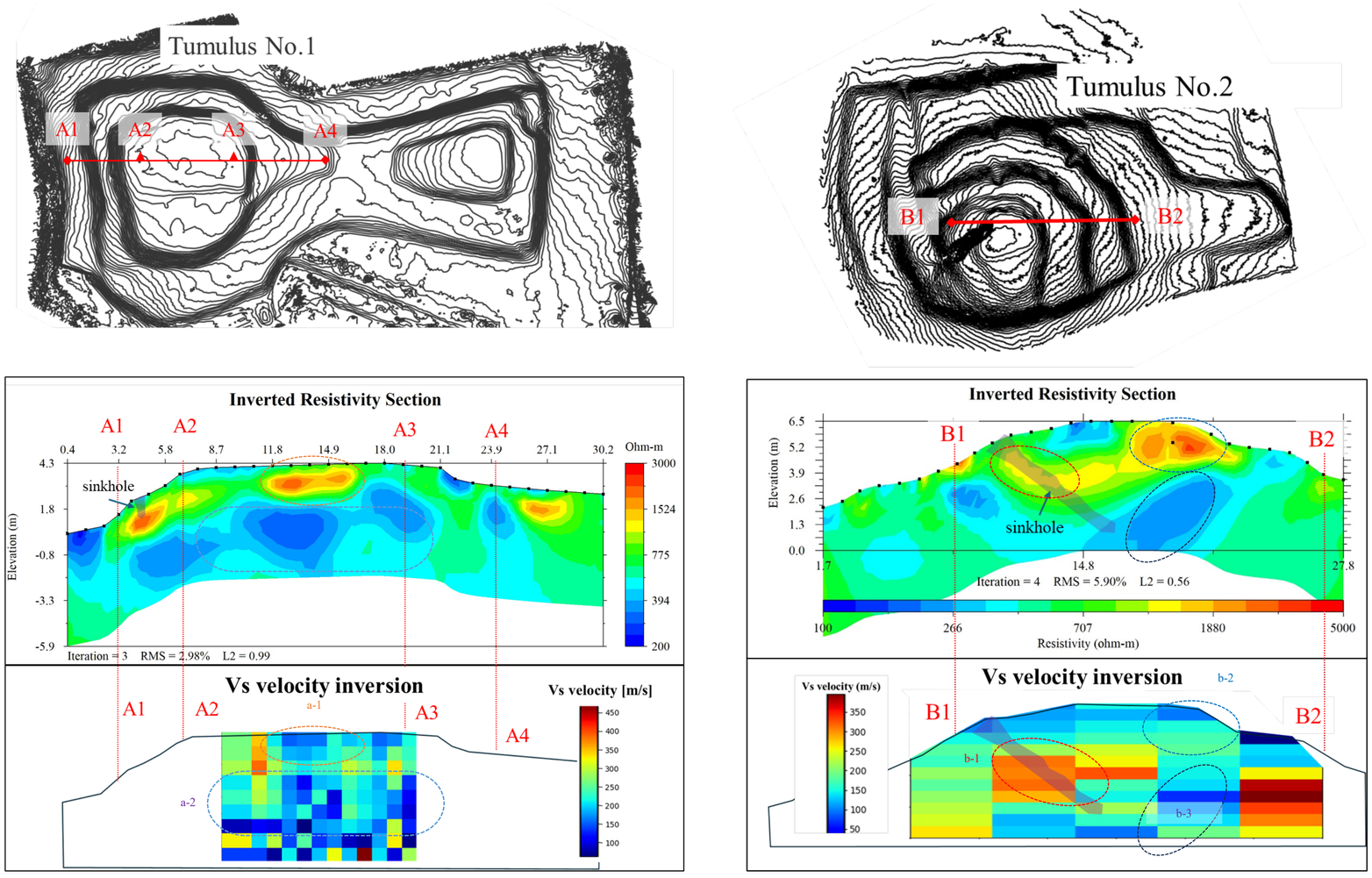


Fig.3 The result of ERT resistivity inversion and Vs inversion of Tumulus No.1 (left) and No.2 (right).

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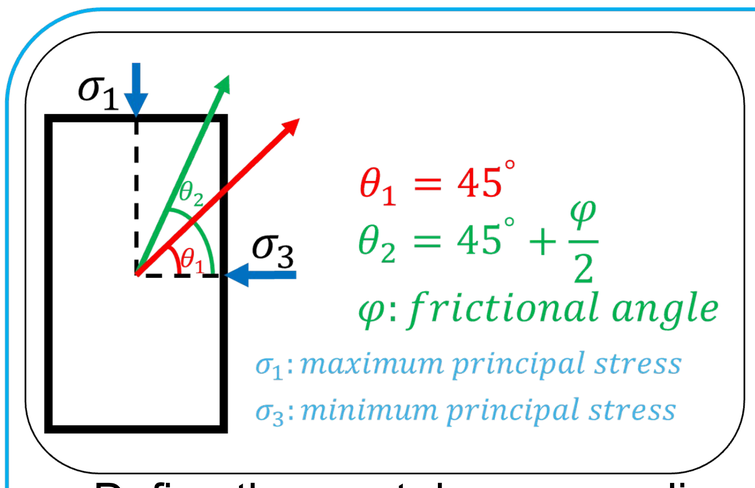
Numerical Investigation of Three-Dimensional Effects in Slope Stability

斜面安定性における三次元効果の数値的検討

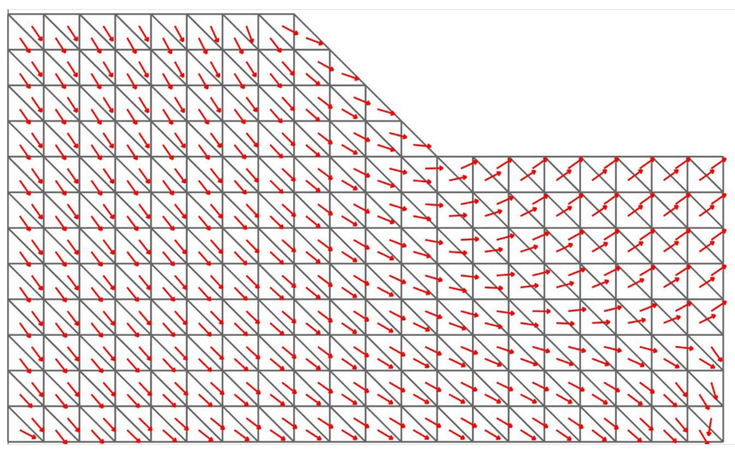
斜面の三次元的特性は、斜面崩壊の一因としてしばしば指摘されている。しかしながら、従来の二次元解析や、破壊面形状を事前に仮定する三次元分析手法では、斜面の三次元効果を適切に評価することは困難である。本研究では、斜面内の土要素が破壊に至る際の「最も危険な滑動方向」に基づき、形状の仮定を要しない破壊面を生成する手法を提案する。さらに、同一の二次元断面を有する複数の三次元斜面モデルに本手法を適用し、斜面の三次元ジオメトリーが破壊面に及ぼす影響を分析した。

The three-dimensional effects of slopes are often regarded as a contributing factor to slope failures. However, conventional 2D analyses and 3D methods that require prior assumptions about the failure surface shape have difficulty capturing such 3D effects. This study proposes a method to generate slope failure surfaces without any shape assumptions, based on the most dangerous slip directions observed at the point of failure in soil elements. The method is applied to various 3D slope models with identical 2D cross-sections to investigate how 3D slope geometry influences the resulting failure surface shape.

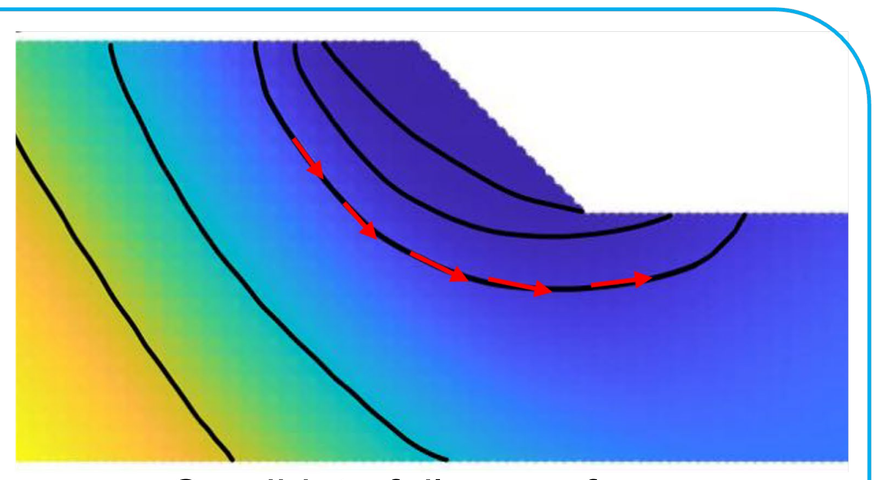
Methodology



Define the most dangerous slip direction vector



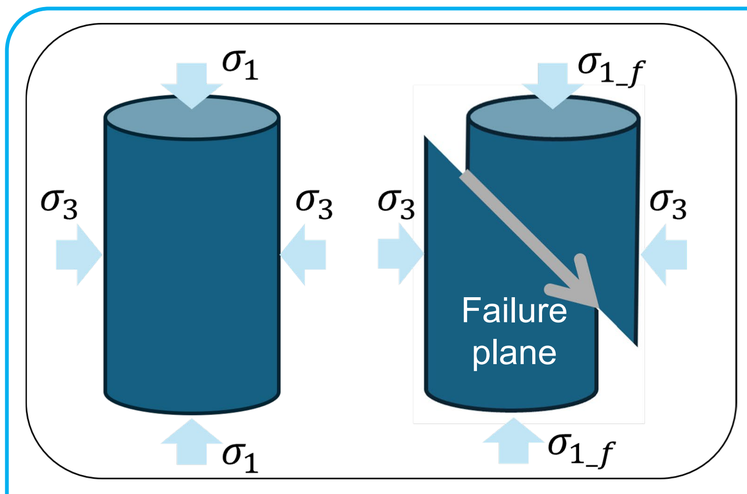
Vector field in the slope



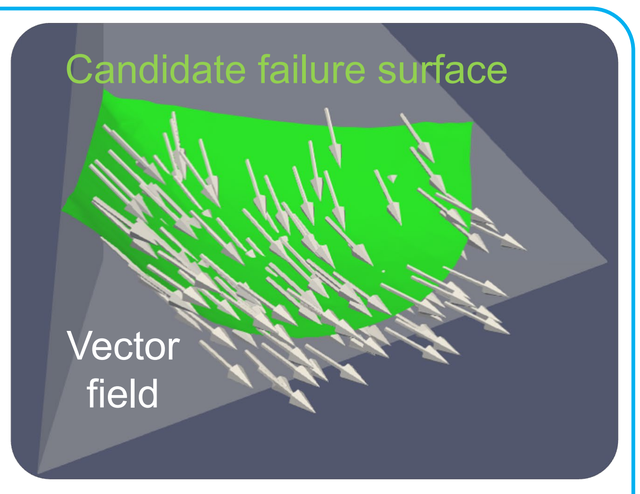
Candidate failure surfaces tangential to the vector field

The most dangerous slip direction is defined based on the related factors like material properties. Based the resulting vector field, surfaces whose tangential directions align with the vector field are generated. This allows for the generation of candidate failure surfaces without assuming their shape in advance.

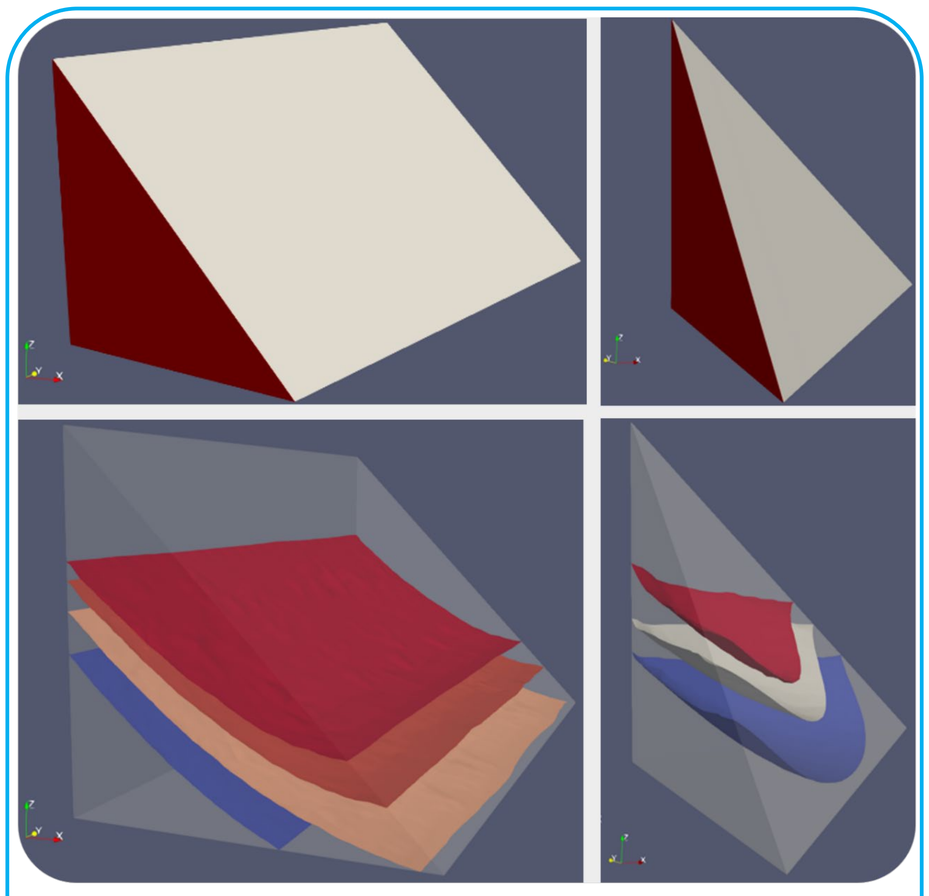
Application and Discussion



Failure plane of triaxial test



Surface tangential to vectors



3D slopes with identical 2D section and their different failure surface shape

The most dangerous slip direction vectors can be determined through geotechnical tests such as triaxial tests, where the orientation of the failure plane provides a basis. Two 3D slopes with identical 2D cross-sections exhibit different candidate failure surface shapes. The left-side slope shows a shape more consistent with traditional 2D analysis results, which validates the proposed method. In contrast, the sharp geometry of the right-side slope leads to a concave failure surface shape from the boundary inward, demonstrating the influence of 3D slope geometry on failure surface shape.

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From Falling Mass to Flow: Landslide Transition Mechanisms

落下する土塊から流動へ：地すべりの遷移メカニズムの解明

Background

Even in dry conditions, granular materials can display flow-like behavior due to dilation, shearing, and inter-particle dynamics. However, the presence of water introduces complex effects:
In fine soils, water can generate suction that increases shear strength and suppresses flow.
In medium sands, moderate suction and low interlocking allows flow like behavior.
In coarse materials, water often promotes instability and transforms collapse into debris flow.
Understanding these interactions is crucial for improving hazard prediction models.



Source: Jon White/Colorado Geological Survey

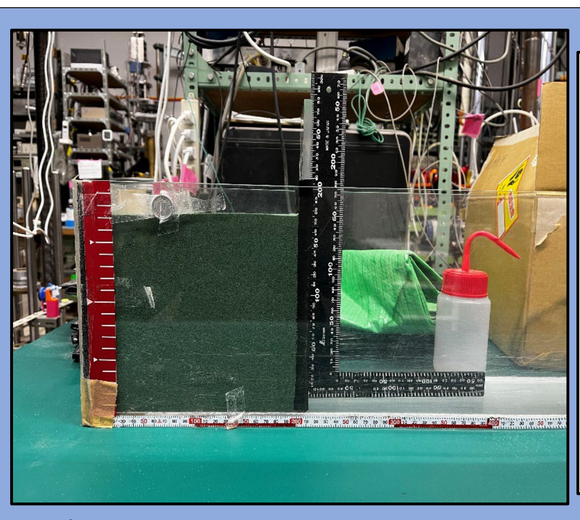
Research Motivation & Hypothesis:

- Key Question: Why do some landslides flow while others collapse?
- Key Factors: Water content, particle size, and compaction.
- Hypothesis: These factors govern the transition from static mass to movement, determining whether the material flows or collapses.

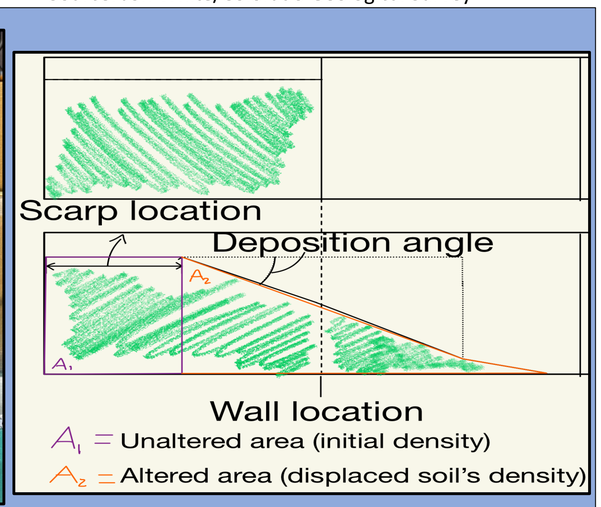
Experimental Setup:
Flume Dimensions:
10 cm (W) × 20 cm (H) × 200 cm (L) transparent plexiglass.
Soil Types Tested:
fine sand (0.425 - 0.1 mm)
medium sand (2.00 - 1.18 mm)
coarse sand (19 - 13.2 mm)

Variables:
- Dry vs. Wet conditions
- Loose vs. Compacted states
- Particle size variation

Measurements:
- Initial and deposition angles
- Density (before and after failure)
- Type of movement (collapse, flow, erosion)

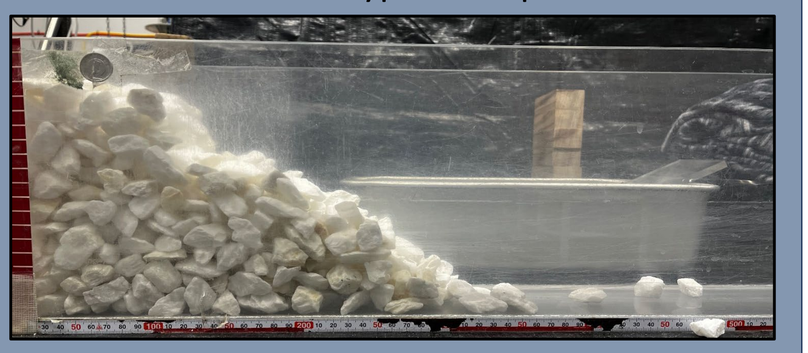


Flume front view



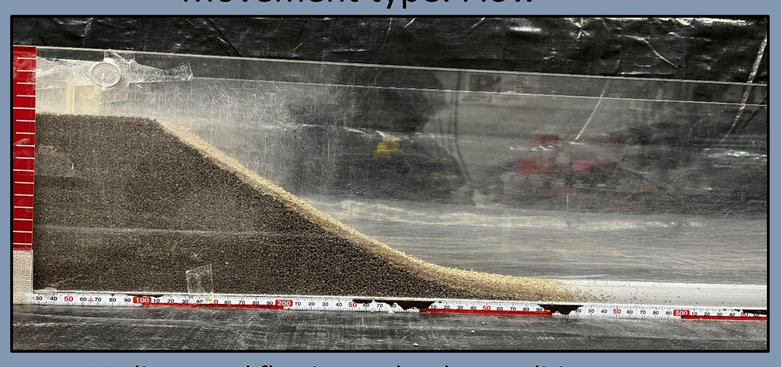
drawn schematic of flume

Movement type: Collapse



Coarse sand collapsing under dry conditions

Movement type: Flow



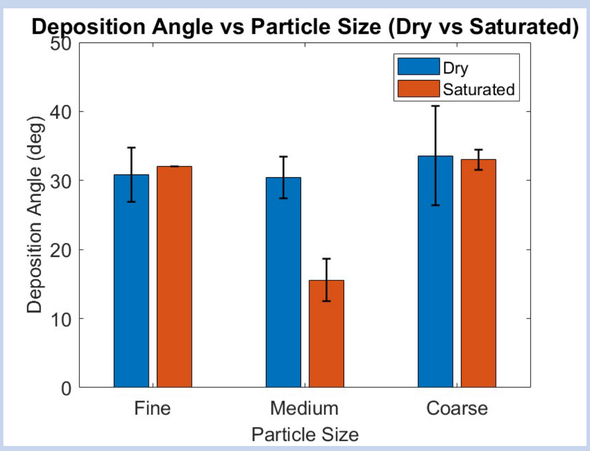
Medium sand flowing under dry conditions

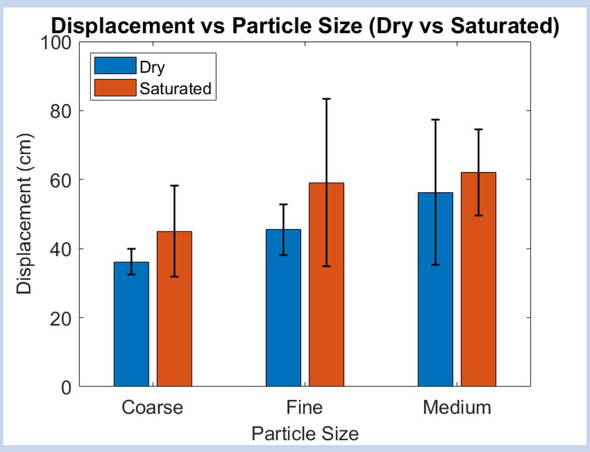
Measurement Focus:
Measure and analyze the influence of initial angle, particle size, compaction, and water on density, deposition angle, and overall soil strength.

Role of Water & Suction:

- Water increases pore pressure and can eliminate inter-particle contact in non-cohesive materials.
- In fine soils, capillary suction increases shear strength, inhibiting flow.
- In medium soils, water gives additional shear strength but not enough to avoid flow.
- In coarse soils, water does not add shear resistance but promotes fluidization and enhances distance travelled

the effect of Dry and Saturated conditions





Preliminary Results:

Particle Size	Dry Behavior	Wet Behavior	Notes
Fine (0.425 - 0.1 mm)	Flow	Collapse + Erosion	Suction increases resistance
Medium (2.00 - 1.18 mm)	Flow	Flow	Low suction
Coarse (19 - 13.2 mm)	Collapse	Collapse + Debris Flow	Water aids fluidization

1) In fine soils, water-induced suction prevents early flow, favoring collapse + erosion.
2) When flow is triggered, a basal horizontal flow appears almost immediately after shearing—indicating a translational mechanism.
3) The transition from collapse to flow is not binary. It results from a complex interplay of suction, particle interaction, and basal mechanics.

Key takeaways:

- Understanding early-stage flow mechanisms (e.g., basal flow) is critical to predicting flow-type landslides.
- Suction dynamics in fine soils may explain why some slopes appear stable yet collapse with little warning.
- These insights can improve landslide hazard mapping and early-warning models, especially under changing climatic conditions

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Making Parts & Jigs for Apparatus by Using 3D Printer

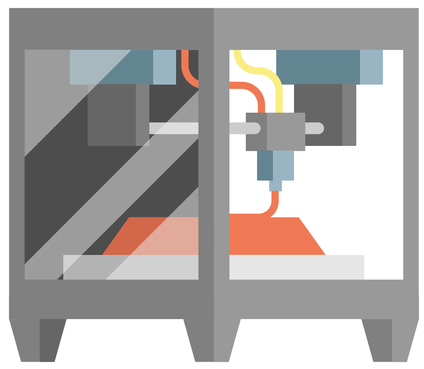
3Dプリンタを利用した試験機用パーツ/治具の作成

The 3D printer market developed a lot by a project called RepRap in the past few year. Many parts that constituted the apparatus are made of Aluminium/Steel/Stainless/Acrylic. When we make new parts/jigs, In the case of handcraft, it can be lower accuracy than requirement. But the drawing and outsourcing to manufacture needs too much cost. Then, this poster will show you some solutions that solved this conflict by using the 3D printer.

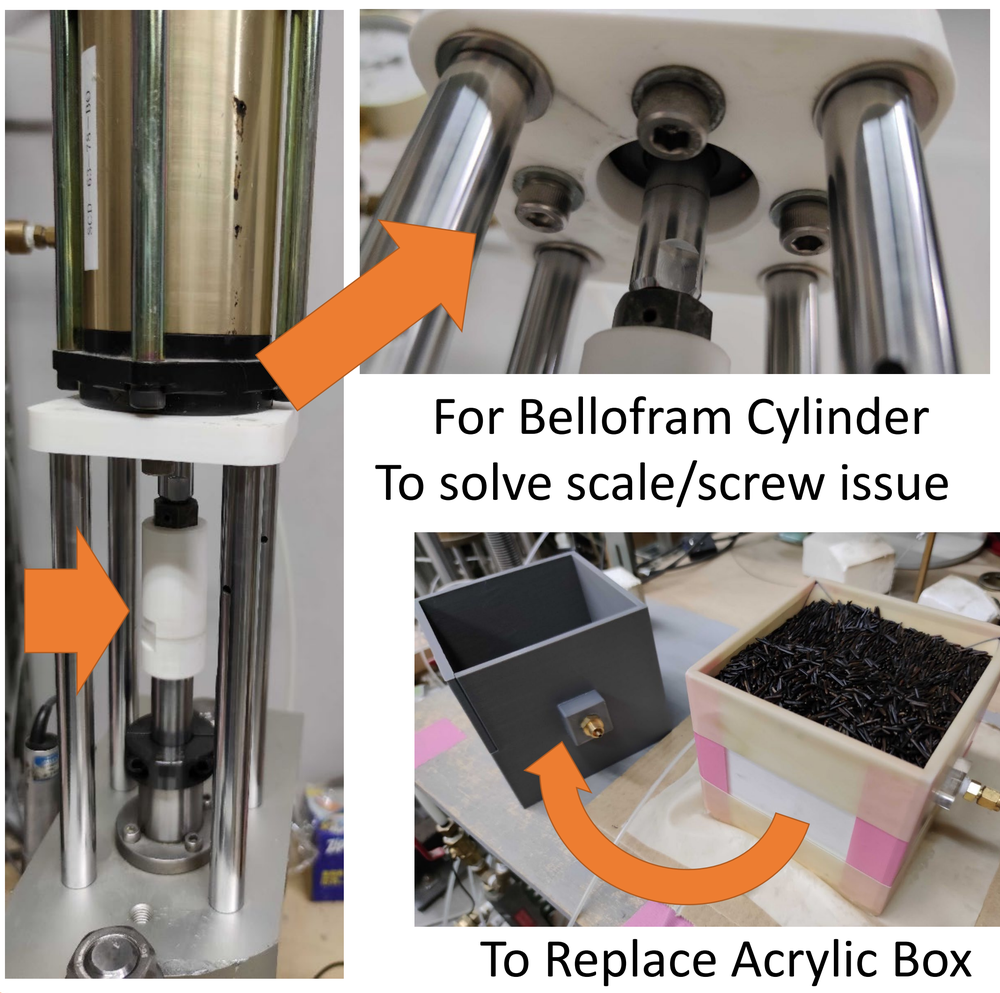
この数年、RepRapプロジェクトにより3Dプリンタ市場は急速に発達した。実験室の試験機で用いられるパーツの多くが、アルミ/鉄/ステンレス/アクリルで作られている。新規に部品を作成する際、手製では精度が足りないが、図面を引いて製作を外注するほどでもない機会が数多く存在する。ここではそのような3Dプリンタを用いた解決策について紹介する。

About 3D Printer

The 3D Printer is categorized into **Self-replicating machine**. But this is based on same technology as normal printer, not brand-new tech. The normal one can print **COLOR** layer by **INK**. The 3D one can print **PLASTIC** layer by **MATERIAL** filament. This material called “PLA”. It’s cheap and easy to procure, **1kg** PLA = **20 ~ 30 USD**. The **body** is from **100 USD**. It makes your workshop **easily**, **cheaper** and **creativity**.



Solutions for Apparatus

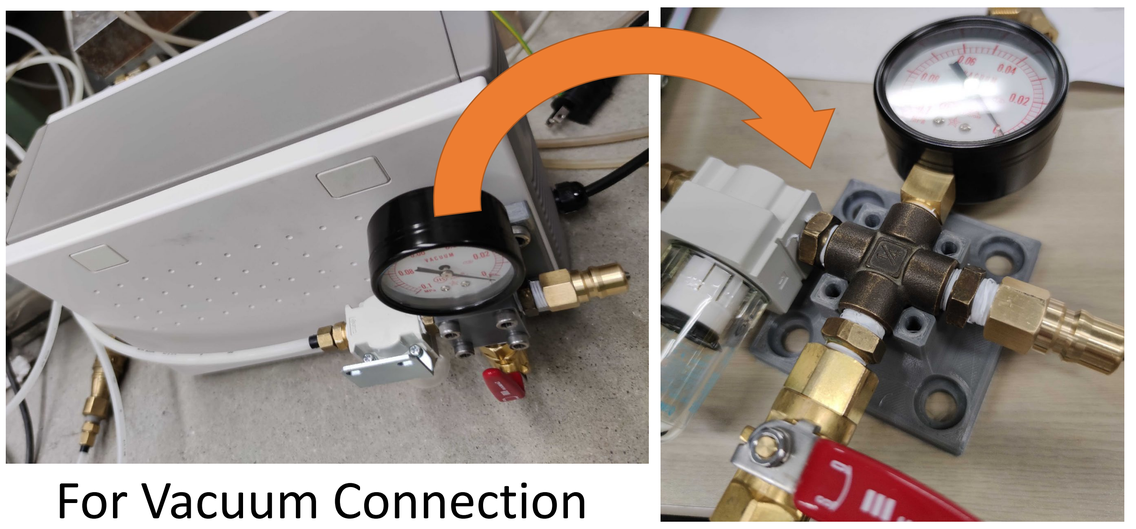


For Bellofram Cylinder
To solve scale/screw issue



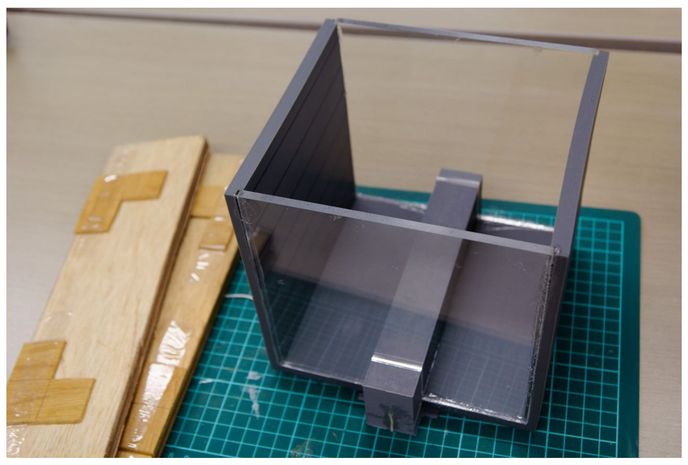
For Displacement Gauge, To Hold and Protect

To Replace Acrylic Box



For Vacuum Connection

Others



Box, Combine with Acrylic



3D Logo, To Promo



The Food of thermo-camera
To prevent unnecessary light

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Point Cloud Observation Device that can be Inserted into a Cavity Observation Hole Under the Road Surface

路面下空洞観測孔に挿入可能な点群観測装置

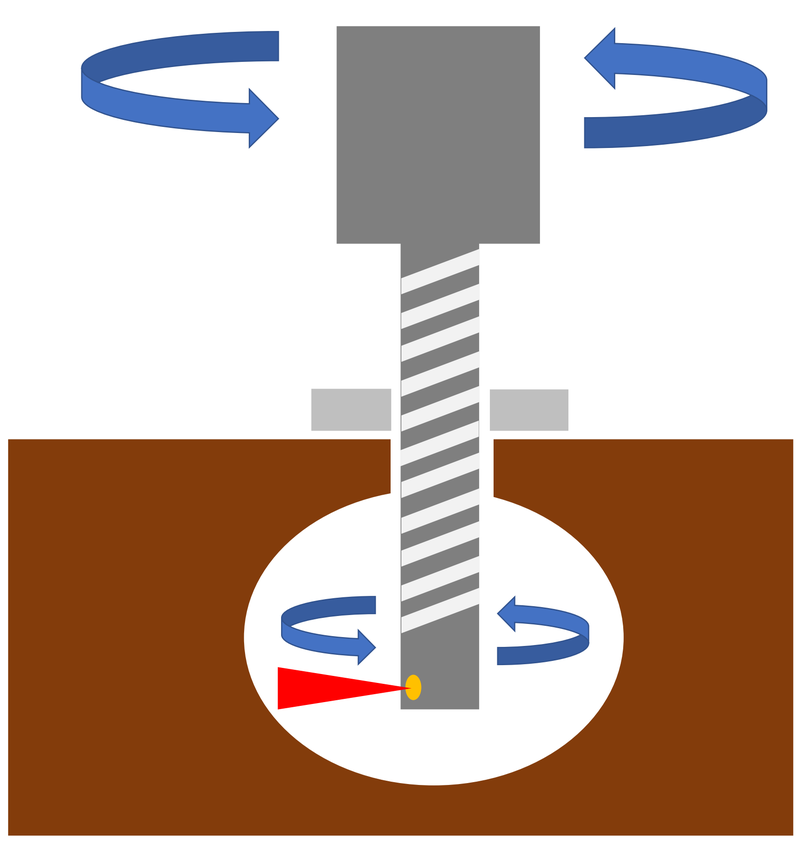
This several year, the problems by the under-road-cavity keep increasing. We wanted to know the figure and capacity about the cavity in order to filling the it. The MHz radar is good way to find it, but it is not good way to figure out the capacity. Because this observation device can 3d-imagenize the inside of the cavity, now we can get the figure and capacity by using this, just rotate this by your hands..

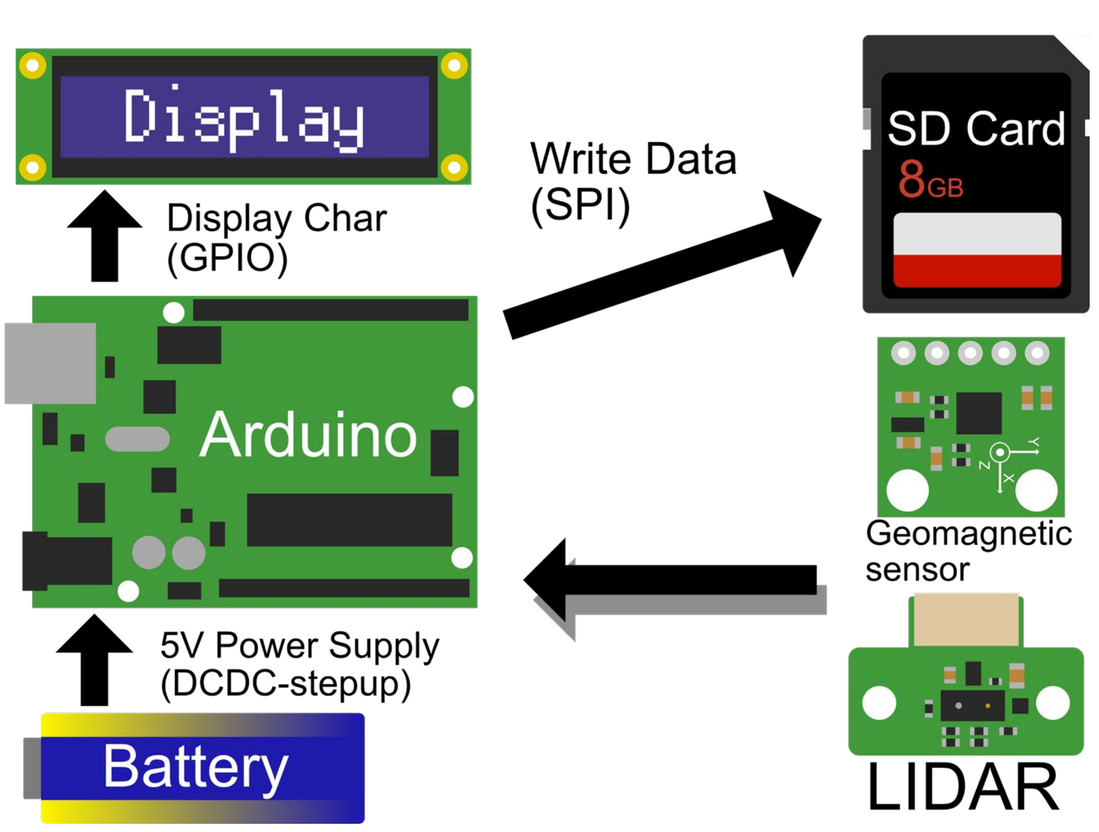
この数年、都市成熟型の路面下空洞を原因とする問題が増え続けている。そこで、空洞を充填するために形状や容量を知っておきたいという要望があった。MHz帯のレーダは空洞の発見には有用なものの、空洞の詳細な形状を把握するにはあまり良い方法ではなかった。この観測機器は空洞内部を3Dイメージ化できる為、この機器を手で回すだけで、空洞の容量と形状を把握することができる。



What is Point Cloud and LIDAR

The **point cloud** is one of the technology that **detect the figure**. For example, used for the face recognition in case of unlocking your device. This system is used sensor, called “LIDAR”. By the way, this sensor is used the automatic driving system or the drone. The LIDAR has two method by broadly divided, 2D or 1D. The 2D one use grid pattern exposure or another way, but it’s expensive. The 1D is only single point distance.



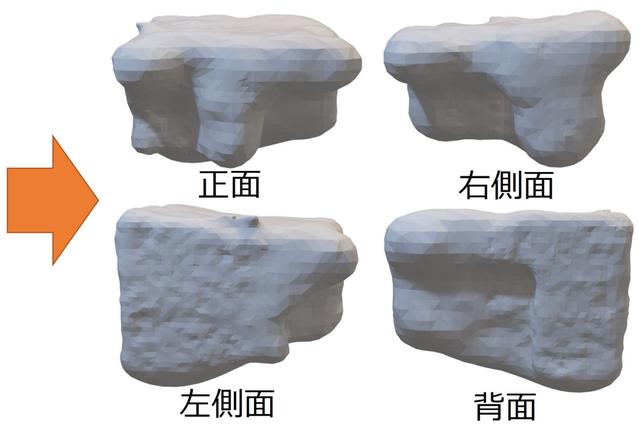


Test Result

Here is two example. The top one is the cardboard box that has some various objects (cardboard boxed, can, ball). The second is the handmade cavity under road surface. As you can see, the top result has **good details**, **works well**. The second result doesn’t look quite good. It seems that this cavity had many unexpected object inside, because this cavity was handmade. LIDAR is just laser, **so it is not good at an obstacle that is between sensor to the target object**.

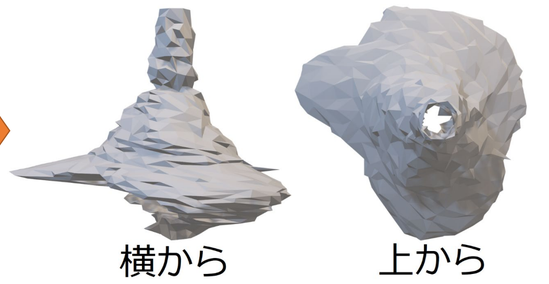


Various objects in cardboard box





Simulated cavity under road surface



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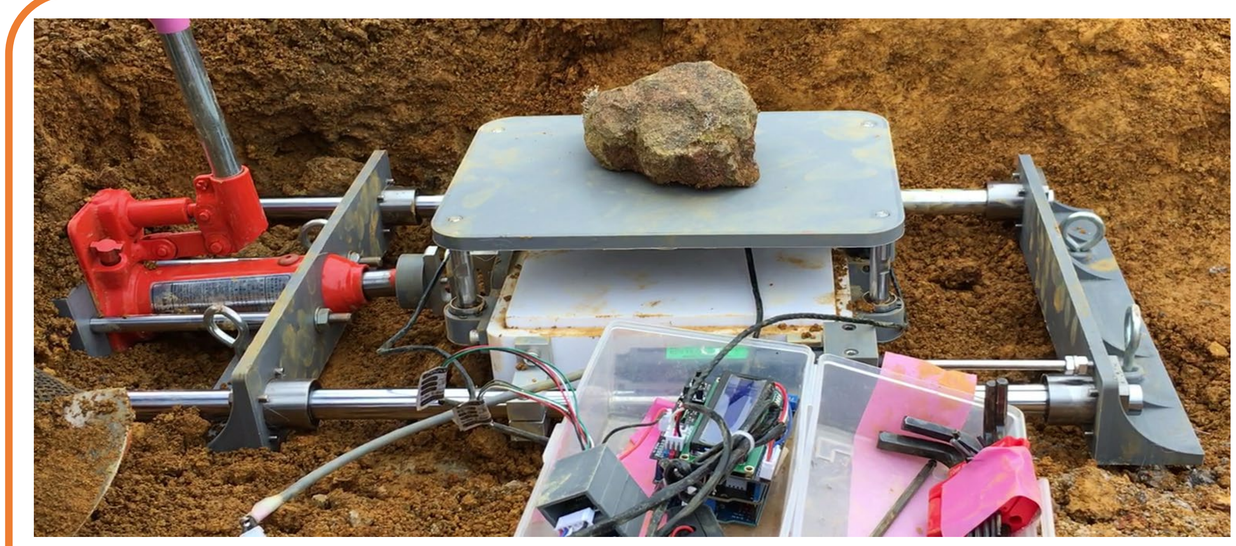
Production of Insitu Direct Shear Test Equipment by using 3D Printer and Microcontroller

3Dプリンタとマイコンを利用した原位置一面せん断試験装置の試作

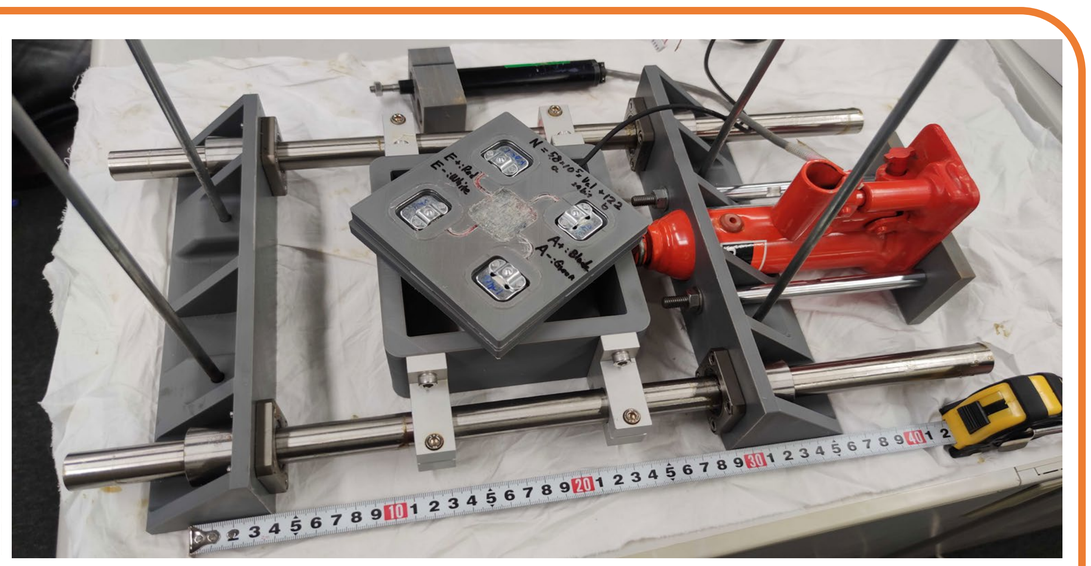
The direct shear test is very basically and generally in the soil-testing-method. But the general one has the portability, accuracy and anchoring-to-the-ground problems when we use it insitu. On the occasion of developing, we need to pick it up to top of mountain in order to test, so we should make it more lightweight. This device could resolve this problem by using the 3D-printer and the microcontroller board.

一面せん断試験は、土質試験の中ではとても一般的かつ基本的な試験です。しかし現地でこれを行うとなると、可搬性、データ精度、固定方法等の制約が出てきます。この機器の開発では更に、試験機を山頂まで運んで試験する必要があったため、なるべく金属を減らし、軽く作成することが求められました。この機器は3Dプリンタ及びマイコンを用い、その問題を解決しています。

Photo of the Whole Equipment



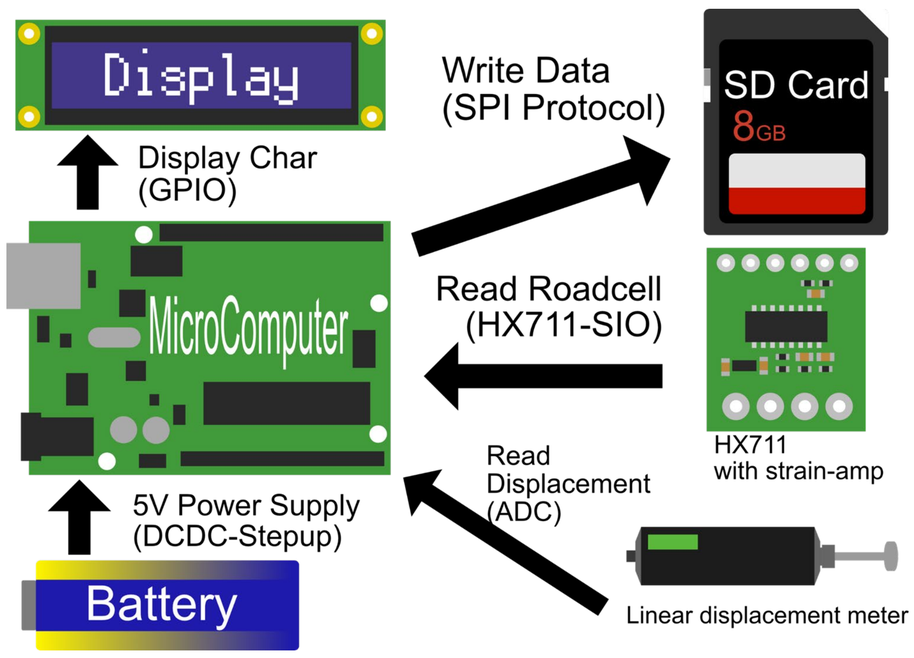
Large(30x30x5cm) Shear Box version
Testing at nearly top of 1600m mountain

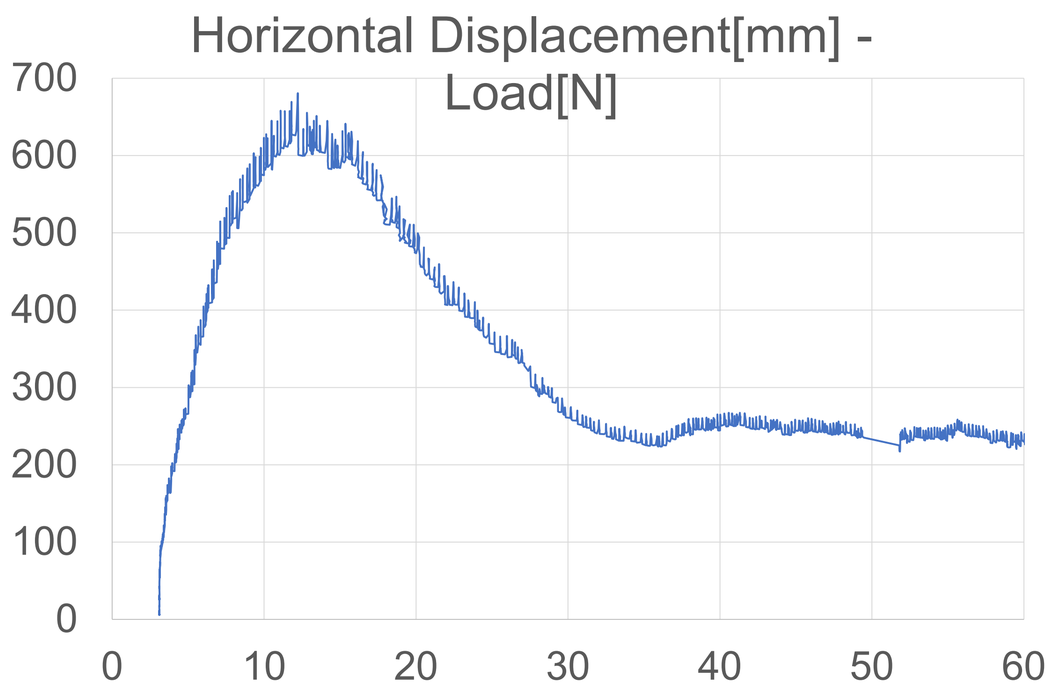


Small(20x20x5cm) Shear Box version, Developing

About System

This equipment created by using the **3D-Printer** and the **microcontroller board** is basically same as general **direct shear equipment** that can get the **soil strength against the shear slip**. This is. The software can run on **even Arduino**, because standalone and small footprint. The hardware is also small footprint, because of can be structed by several stackable shields. In addition, this equipment can run by **AA/AAA battery** and the equipment body **made by PLA** (3D printer material). So, the portability is quite good.





Test Result Sample

This result is the sample in case of **111Pa(10N) loading pressure**, for the volcanic soil include gravel and using handy oil jack, **large(30cm) shear box**. The jack can be moved only little bit by one paddling. And the many small pulse that you can see in the left graph means the timing that the jack started moving. As you can see, we can easily get the **residual strength** (around 250N) and the **peak strength** (around 630N) from the graph.

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STUDY ON HEALING CAPABILITY OF BIO-CEMENTED SANDY SOIL

微生物機能により固化した砂質土の潜在的修復性に関する検討

A new technique of ground improvement by microbial function has been recently proposed, as more eco-friendly technique than conventional one. Metabolic function of microbes produces carbon dioxide, which helps to generate calcium carbonate. In this study, a series of triaxial test was conducted in order to evaluate the degree of soil cementation generated by those function in Toyoura sand.

環境への負荷の少ない地盤固化技術として、微生物の保持するウレアーゼによる尿素分解効果を用いた地盤固化が試みられています。本研究では、微生物の作用により固化させた豊浦砂供試体にせん断による損傷を与え、再度微生物の作用を促す固化促進グラウトを注入して、強度や剛性の回復度合いを検討しました。

また、SEM-EDSを用いて固化した砂の観察、および豊浦砂の主要元素であるケイ素（Si）およびカルシウム（Ca）の元素マッピングを行いました。

炭酸カルシウムによる粒子の固結
Bonding of soil particles due to calcium carbonate

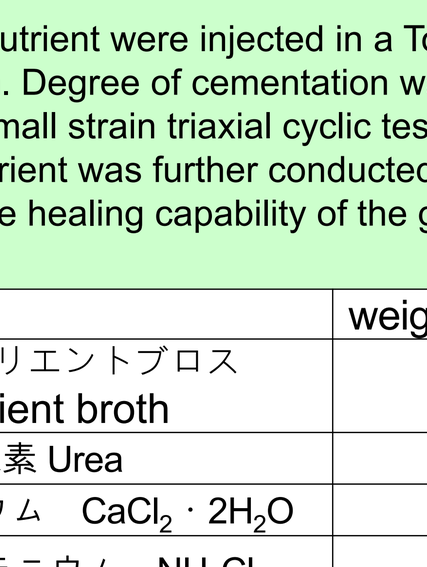
Bacillus pasteuriiは尿素を分解し、関連する化学反応で炭酸カルシウムを析出します（Eq.1, 2, 3）。間隙中に析出した炭酸カルシウムは土粒子同士を結合し、地盤を固化します。

Bacillus pasteurii can precipitate calcium carbonate through the chemical process (Eq.1, 2, 3). Calcium carbonate bridges between soil particles.

$$NH_2 - CO - NH_2 + 2H_2O \rightarrow 2NH_3 + CO_2 \quad \text{Eq. 1}$$

$$CO_2 + H_2O \rightarrow CO_3^{2-} + 2H^+ \quad \text{Eq. 2}$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \quad \text{Eq. 3}$$



三軸試験による剛性・強度測定
Strength and stiffness obtained from triaxial test

砂供試体にPasteuriiを混入した後、栄養塩（固化促進グラウト）を浸透させ、固化の進度を三軸微小繰返し試験により推定しました。さらに、せん断を加えて供試体に損傷を与えた後、固化促進グラウトを再度注入し損傷の回復度合いを評価しました。

Pasteurii and nutrient were injected in a Toyoura sand specimen. Degree of cementation was evaluated by small strain triaxial cyclic test. Grouting of nutrient was further conducted after the shear to see healing capability of the grout.

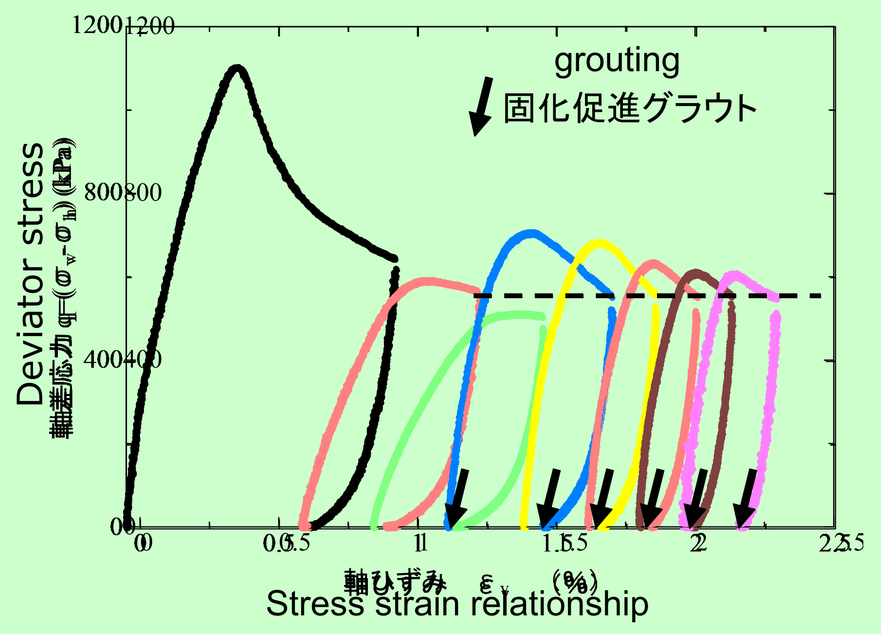
	weight (g/L)
ニュートリエントブロス Nutrient broth	3
尿素 Urea	30
塩化カルシウム $CaCl_2 \cdot 2H_2O$	70
塩化アンモニウム NH_4Cl	10
炭酸水素ナトリウム $NaHCO_3$	2

栄養塩の組成
Composition of nutrient

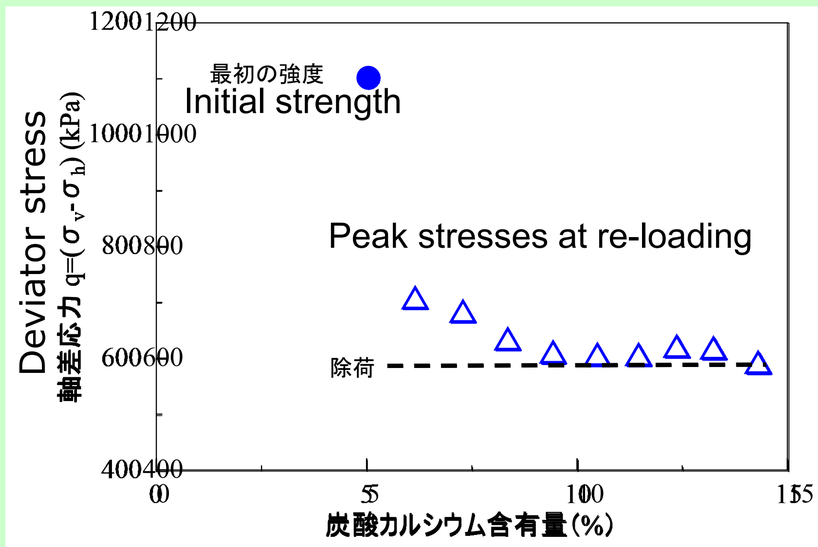
せん断により損傷した供試体の強度・剛性回復
Restoration of strength and stiffness of shear-damaged specimen

固化促進グラウトの注入（供試体内の炭酸カルシウム含有量の増加）に伴い供試体の強度や剛性が増加しました。せん断により損傷が生じた供試体の剛性は低下しますが、その後のグラウト注入によりある程度の回復が見られました。

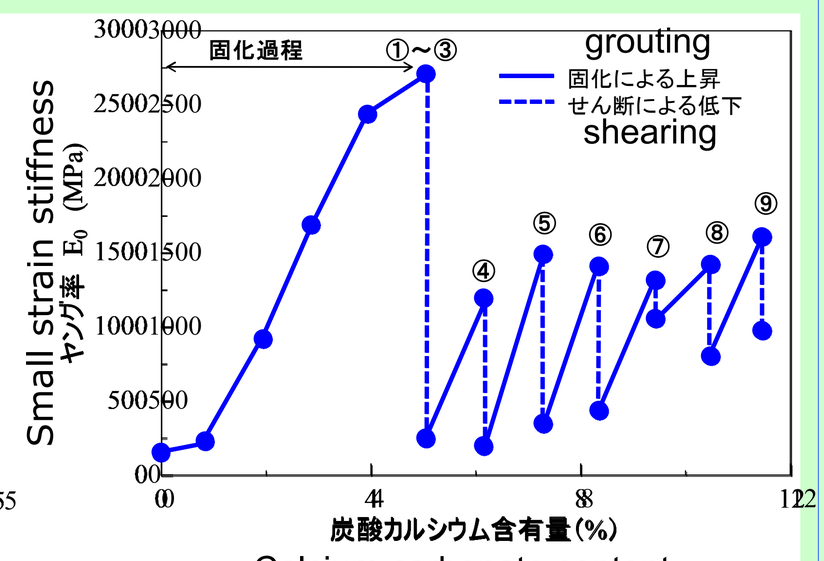
Strength and stiffness of the specimen increased as the calcium carbonate content increased due to grouting. Small strain stiffness decreased when the specimen was damaged by shearing. Further grouting seemed to restore the mechanical properties of the specimen to some extent.



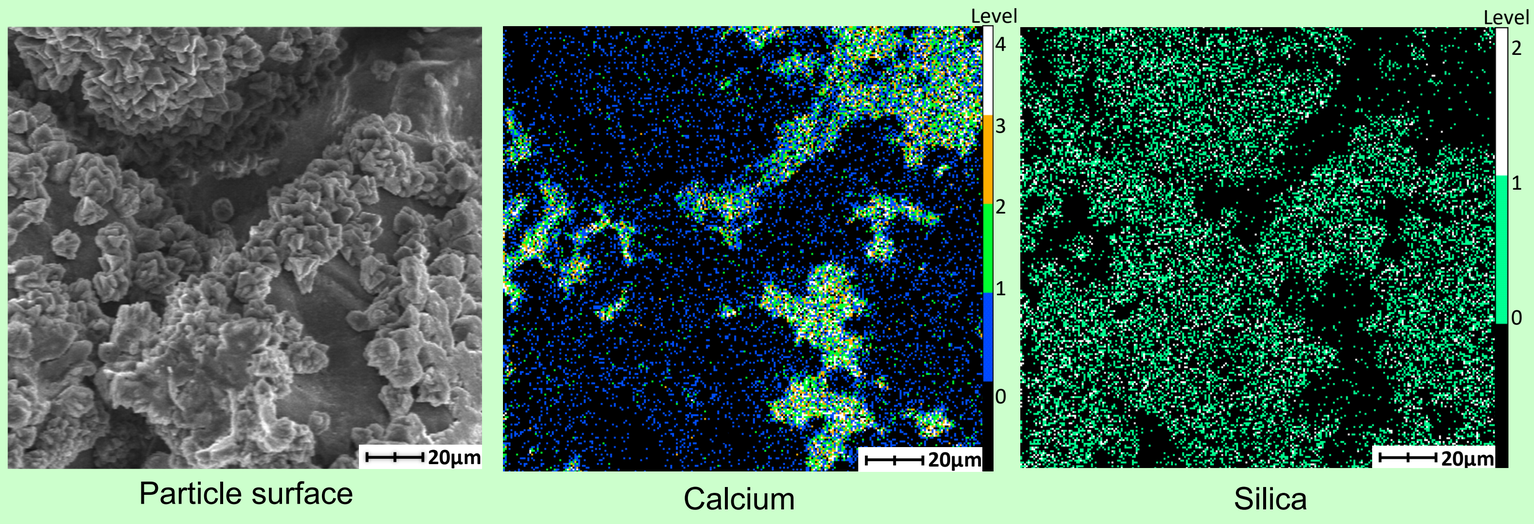
Stress strain relationship



Calcium carbonate content



Calcium carbonate content



Particle surface　Calcium　Silica

SEM による粒子表面の観察および元素分析
Observation and compositional mapping by SEM-EDS

栄養塩濃度に応じた固化が発現し、固化部分の土粒子表面には多量のカルシウム鉱物が析出していることがSEM-EDSより確認されました。

Cementation appeared on the surface of sand grains. Compositional mapping indicate presence of calcium carbonate.

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細尾誠 (2011)

Microbial Precipitation of Calcium Carbonate for Liquefaction Mitigation of Sand with Fines

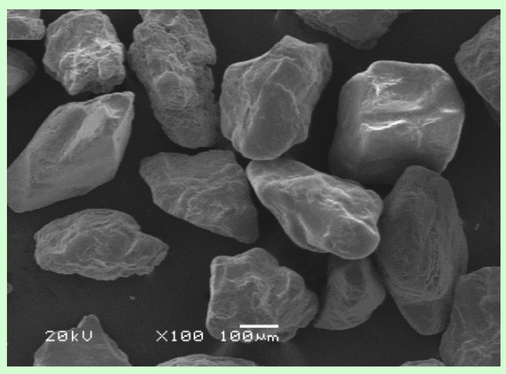
液状化対策としての微生物を利用した細粒分混じり砂の固化

Microbial precipitation of calcium carbonate was carried out to soils with varied fines content, and the changes of the liquefaction resistance were measured by conducting undrained cyclic triaxial testing. The focus is on how fines of soils affect the increase of liquefaction resistance by calcium carbonate precipitation. It was found that fine grains influence the improvement of liquefaction resistance adversely, inhibiting the generation of large calcium carbonate bridges between particles. Moreover, fines seem to help trapping bacteria to cause uneven precipitation. Further research needs to be performed to overcome these shortcomings, in order to allow for an inexpensive and environmentally friendly soil improvement.

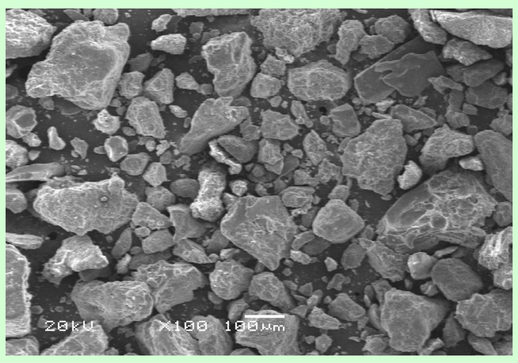
本研究では種々の細粒分含有率を有する砂を微生物機能による炭酸カルシウム析出を利用して固化し、液状化抵抗の増加具合を非排水繰返し三軸試験により測定した。砂に含まれる細粒分が微生物による炭酸カルシウムの析出に及ぼす影響と、それによる液状化抵抗の変化を評価することが研究の目的である。研究結果より、細粒分が微生物機能により析出する炭酸カルシウムの成長を阻害し、土粒子接着による液状化抵抗の上昇を妨げる可能性があることが分かった。また、細粒分が砂中の微生物の移動を妨げ、それにより不均一な炭酸カルシウムの析出が発生することが示された。これらの点を踏まえ、微生物を利用した安価で環境にやさしい液状化対策を実現するためにさらなる研究が必要である。

実験試料
Tested Materials

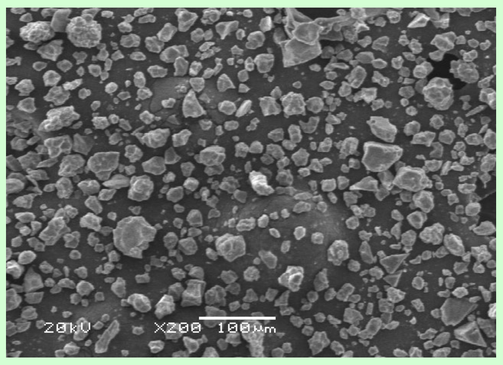
実験試料として、豊浦砂、浦安砂そして豊浦砂+DLクレーの三種類を用いた。
Toyoura sand, Urayasu sand and Toyoura sand mixed with DL clay were employed as test materials.



豊浦砂（細粒分0%）
Toyoura sand (Fine content 0%)

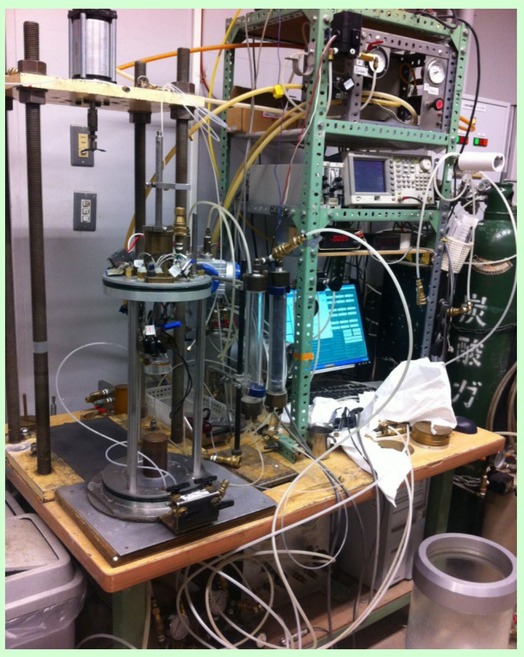


浦安砂（細粒分30%）
Urayasu sand (Fine content 30%)

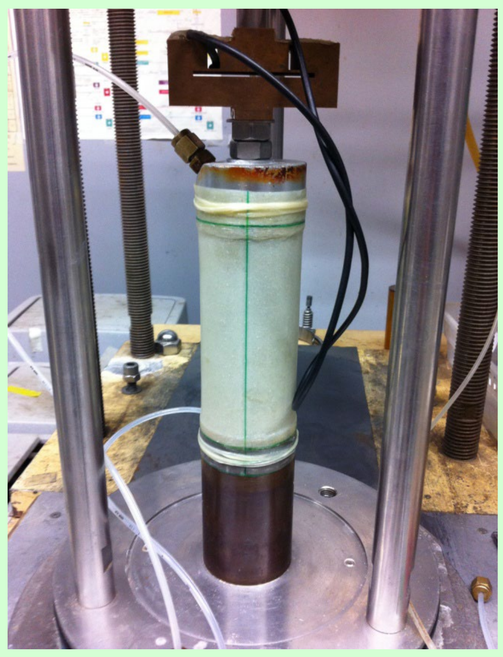


DLクレー（細粒分100%）
DL clay (Fine content 100%)

実験装置
Apparatus

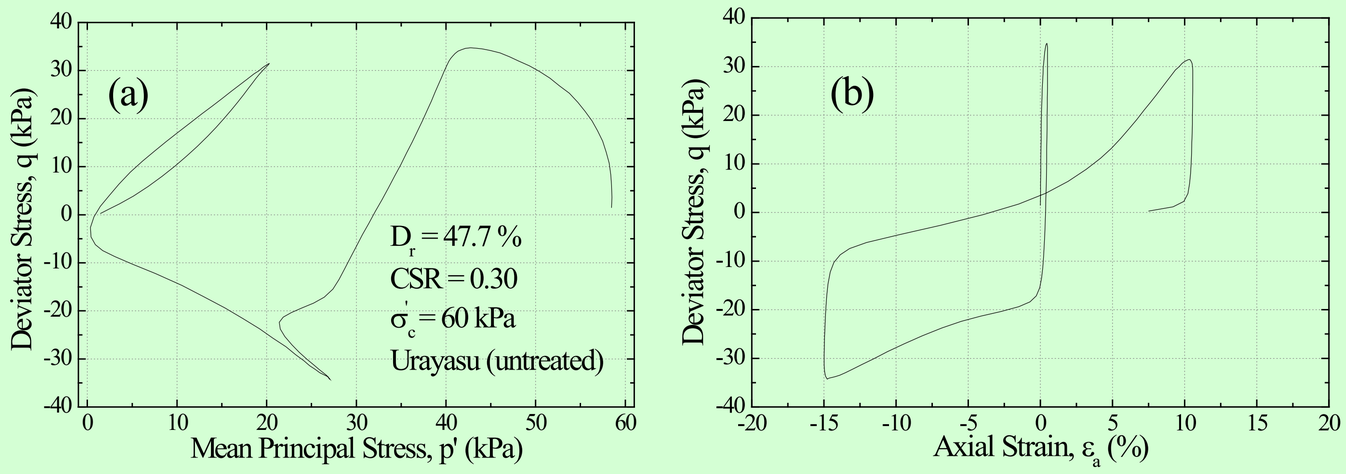


三軸試験機
Triaxial Apparatus

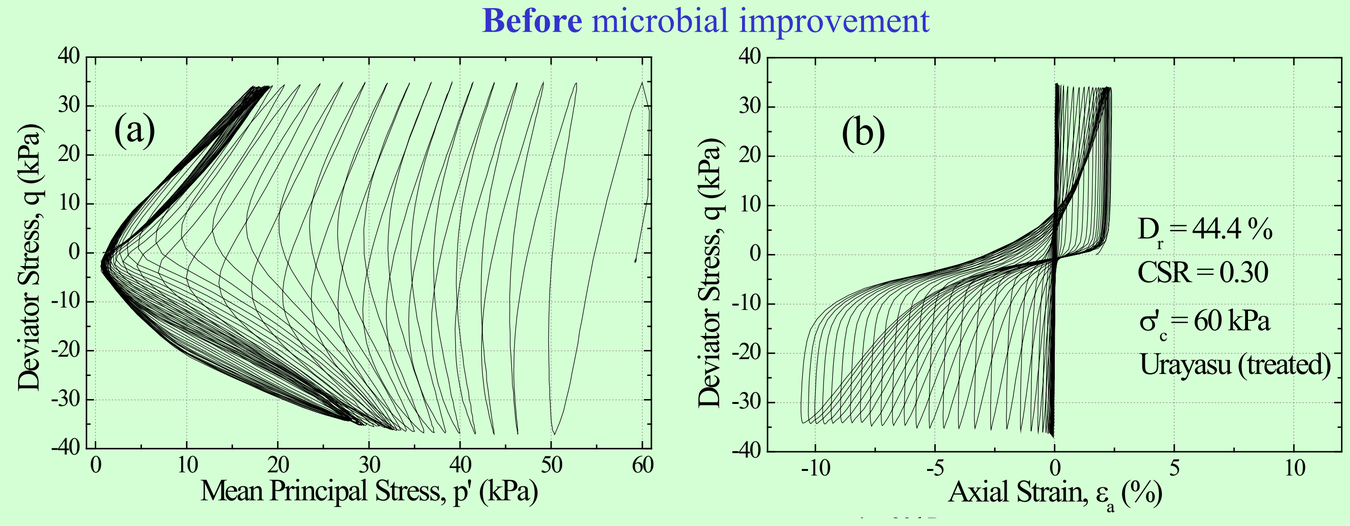


三軸供試体
Specimen for the Apparatus

非排水繰返し三軸試験結果（浦安砂）
Liquefaction test results for Urayasu sand

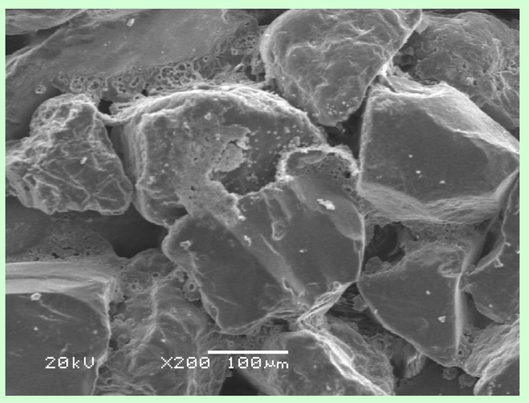


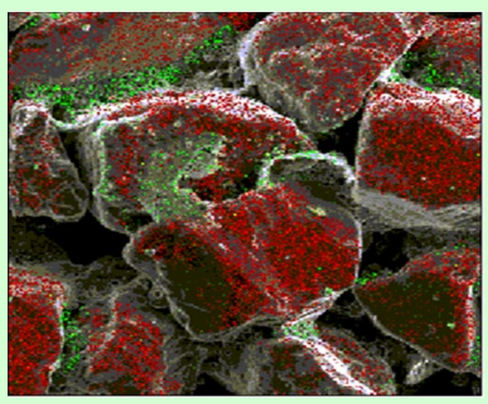
微生物による**改良前**
Before microbial improvement



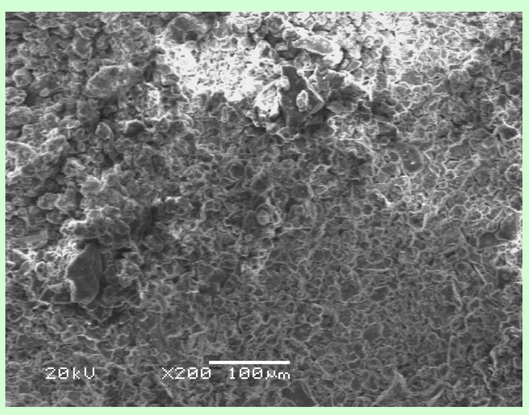
微生物による**改良後**
After microbial improvement

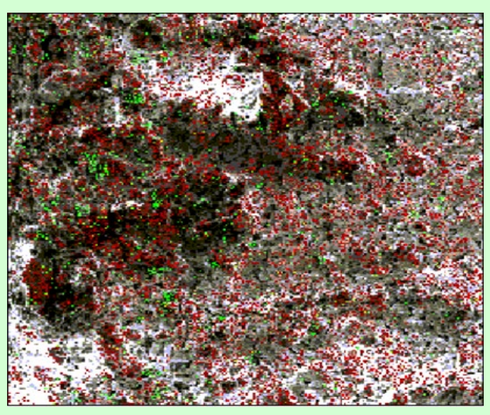
改良後試料のSEM画像（豊浦砂、豊浦砂+DLクレー）
SEM images of treated specimens
(Toyoura sand, Toyoura sand + DL clay)





豊浦砂（緑：炭酸カルシウム　赤：土粒子）
Toyoura sand (Green: Calcium carbonate, Red: Soil particles)





豊浦砂+DLクレー （緑：炭酸カルシウム　赤：土粒子）
Toyoura sand+DL clay
(Green: Calcium carbonate, Red: Soil particles)

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佐々木翼 (2014)

SAND BOILING AND ERUPTED SAND FROM THE LIQUEFIED GROUND

液状化地盤の噴砂と砂脈

A number of sand boiling occurred in the coast of Tokyo Bay at Great East Japan Earthquake. A series of model tests was conducted to simulate the phenomenon of sand eruption from the crack of pavement. A model sand layer was prepared in the small soil chamber and the surface was covered by an acrylic lid with a slit opening. Water penetrated into the model sand ground from bottom to top. When the hydraulic gradient well exceeded critical hydraulic gradient, sand eruption has started. In this study, liquefaction was generated by the 1G shaking table test. It was observed that pavement subsidence with liquefied ground settlement was necessary for the sand eruption. Horizontal movement of sand grains at the surface of liquefied layer was observed in the early stage of sand boiling.

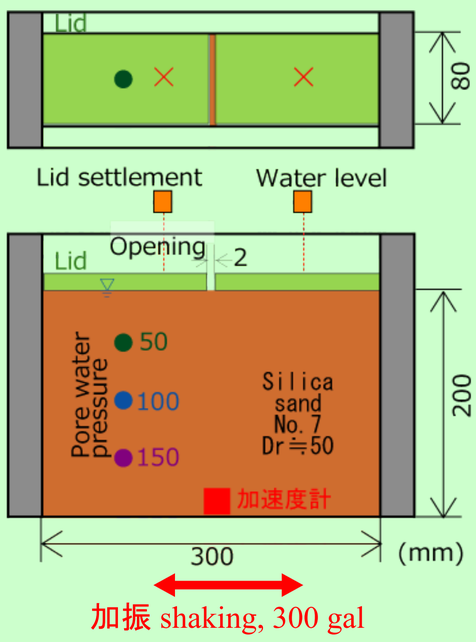
A trench excavation was conducted at Itako City, Ibaraki prefecture, to observe the trace of boiled sand which elevated along cracks in the silt layer. Undisturbed soil samples were taken from the sand and silt layers of about 2 to 3 m deep. X ray CT scanning was conducted for the undisturbed specimens to observe the micro structure of liquefied soil. The image obtained from X ray CT indicated the path of boiled sand erupted from liquefied sand layer. The overall structure of liquefied layer is mostly disturbed in contrast with laminar structures observed in a non-liquefied layer.

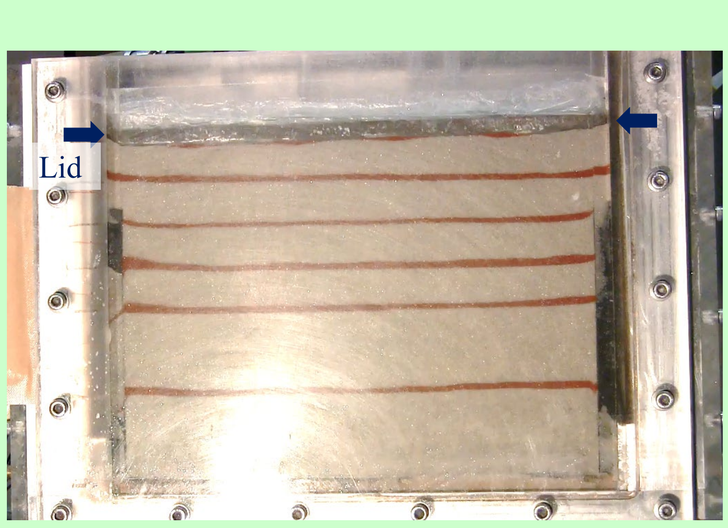
東日本大震災で発生した液状化地域には、大量の噴砂が生じました。既往研究として、水頭差による上向き浸透流により舗装亀裂からの噴砂発生を模擬した模型実験を行っています。本研究では、同様の模型を用いた1G場の振動台実験を行いました。その結果、液状化による地盤の沈下に舗装が追随することで噴砂が発生すること、既往研究と同様に地表面と舗装の隙間の水平流により砂が運ばれて噴砂が生じることを確認しました。

また液状化被害のあった茨城県潮来市においてトレンチ調査が行われ、液状化現象に起因するものと思われる砂脈が発見されました。砂脈形成のメカニズム解明を目的として、調査においてサンプルを採取し、X線CTスキャンによる内部観察を行った結果、砂脈を画像として捉えることができたと共に、液状化したと思われる砂質土において、液状化判定指標に用いられる幾つかの地質学的特徴が見られました。

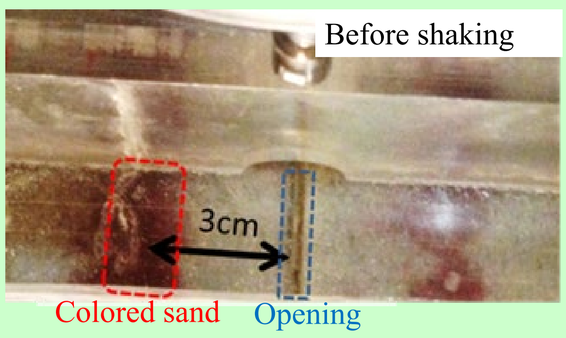
噴砂の振動台模型実験

Shaking table tests of sand boiling

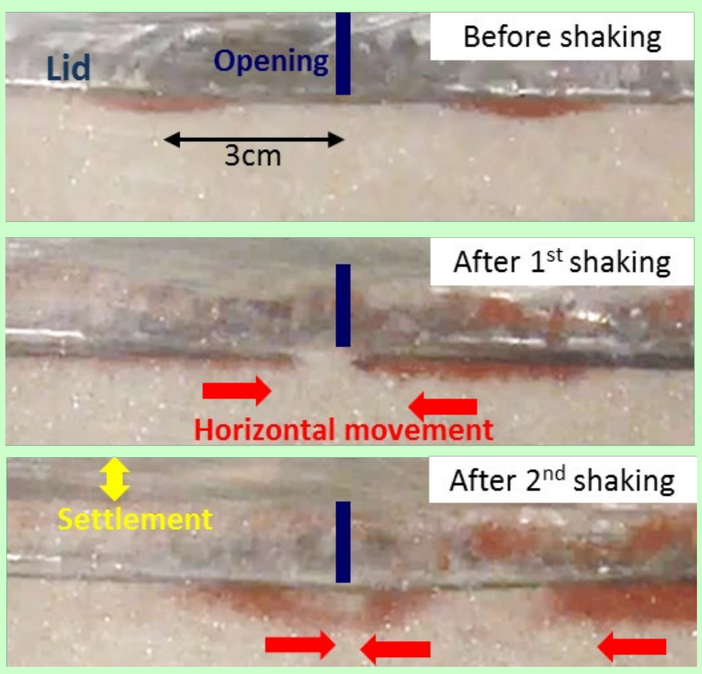




実験模型（加振前）
Model test, before shaking







地表付近の砂の動き
Movement of sand grains on the ground surface

液状化による地盤の沈下に舗装が追随することで噴砂が生じる。

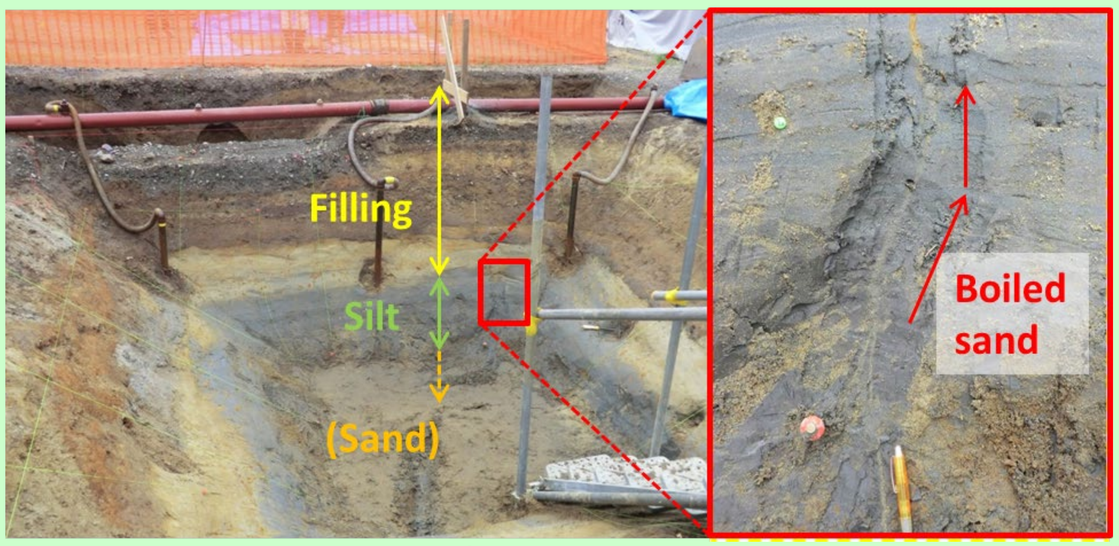
Pavement subsidence with liquefied ground settlement was necessary for the sand eruption.

地表面と舗装の隙間の水平流により砂が運ばれて噴砂が生じる。

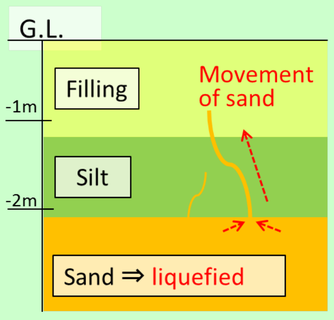
Horizontal movement of sand grains at the surface of liquefied layer was observed

液状化層からの砂脈の観察

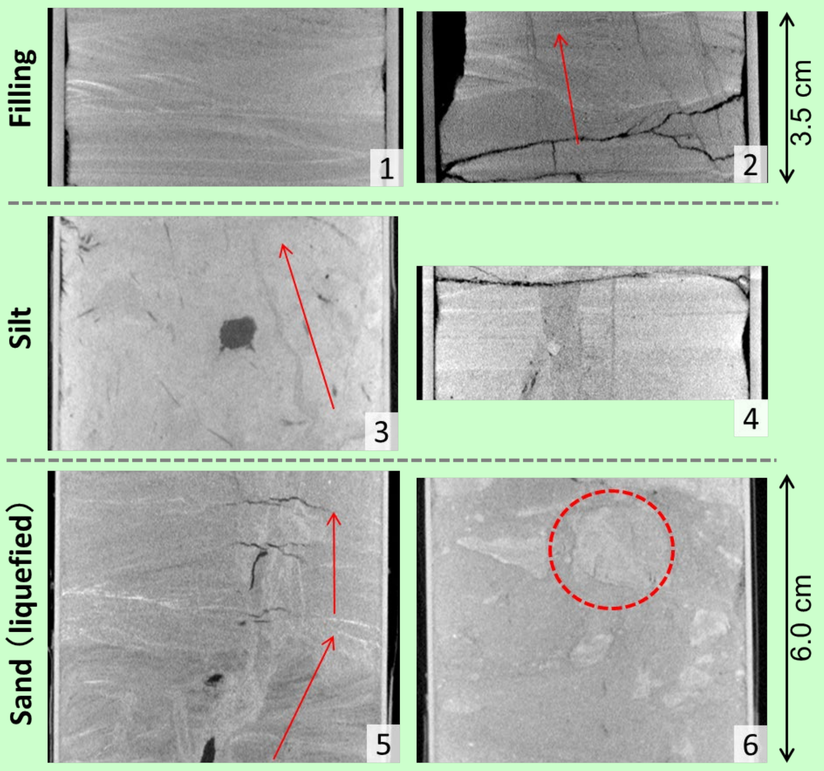
Observation of boiled sand erupted from liquefied layer



トレンチ調査 A trench excavation



地質構成
Geological structure



X線CTスキャン結果 X ray CT scanning

X線CTスキャンによる観察で砂脈を捉えることができた。

The image obtained from X ray CT indicated the path of boiled sand erupted from liquefied sand layer.

液状化したと思われる砂質土において、液状化判定指標に用いられる幾つかの地質学的特徴が見られた。

The overall structure of liquefied layer is mostly disturbed in contrast with laminar structures observed in a non-liquefied layer.

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堀内祐樹 (2015)

SUBSURFACE CAVITIES IN THE LIQUEFIED GROUND

液状化地盤の路面下空洞

Significant number of subsurface cavities were found in the liquefied ground after the Great East Japan earthquake. In this study, a series of model tests is conducted in order to understand the mechanism of underground cavity formation when liquefaction occurs. According to the results of field investigation in Urayasu-city, Shinkiba-area, and Narashino-city, cavities tended to form near man-holes and joints in pavement. Size/shape of the cavities are larger and thinner compared to those of cavities observed in the non-liquefied ground.

Liquefaction and sand boiling was simulated in the model test. Sand grains initially moved horizontally and then vertically, causing disturbance and loosening in the ground. Gaps and voids near the ground surface were eventually generated at the location of the boiled sand.

東日本大震災で発生した液状化地域には、大量の噴砂が確認されると共に多数の路面下空洞が生じました。本研究では、新木場、習志野、浦安などにおける路面下空洞調査の結果を踏まえ、液状化と空洞の発生形態を調べるために模型実験を実施しました。実態調査よると、液状化地盤ではマンホール脇や舗装施工目地付近に空洞が頻発し、通常の空洞と比べると薄く大きく広がり、舗装路面下の地盤が波打つような形状で空洞が連続しているという特徴が確認されています。小型模型土槽を用いて砂地盤の液状化、および噴砂を再現し、それによる路面下の空洞の生成状況について調べました。

まず、噴砂に伴い舗装面と地盤との隙間を砂が水平移動し、次に動水勾配の高い所や地中構造物脇の水みちなどに沿って土粒子が鉛直移動する様子がわかりました。土砂が地上に噴出すると地表面下には局所的に空隙が残り、調査で観察されたものと同様の形態の空洞生成が観察されました。

液状化地盤に多発する路面下空洞
Subsurface cavities generated in the liquefied ground

液状化地盤の空洞の特徴
Features in subsurface cavities in the liquefied ground

定常時よりも多くの空洞が発生し、特に生活道路では30倍近い発生率となる。
The number of subsurface cavities is found to be nearly 30 times.

広がりが大きく空洞厚が薄い。Thin and large in size.

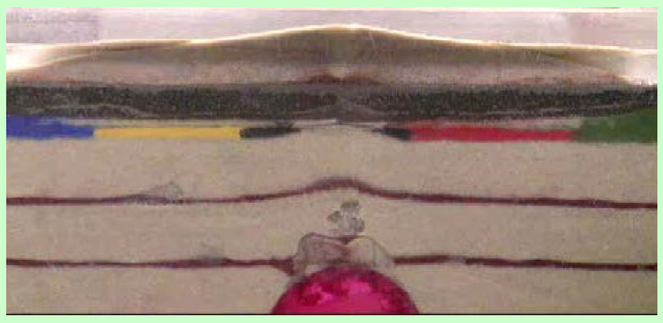
人孔脇、補修跡、舗装の施工目地付近に多い。
A lot of cavities were found near manholes and joints in pavement.

大規模な噴砂で路面沈下のみならず舗装下に空洞が発生する。この時、連続空洞であっても厚さが一様ではなく、舗装下で土砂が波打った状態であることが推測される。Sometimes, several cavities are connected, forming a large uneven cavity.

噴砂の発生と土砂の亡失
Sand boiling and formation of subsurface cavity



地表面近くの砂の水平移動
Lateral movement of sand grains below ground surface



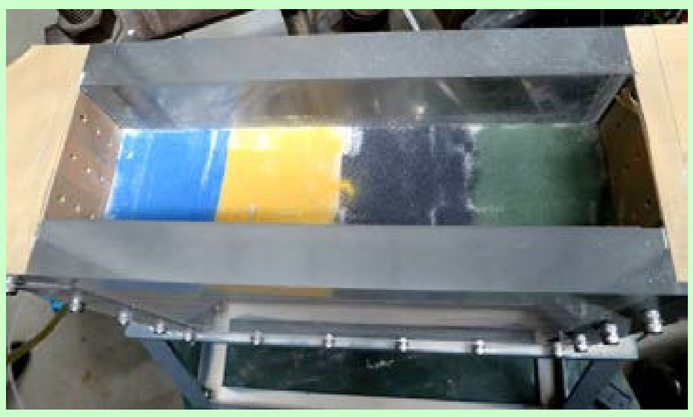
大規模噴砂時の液状化地盤の乱れと砂の鉛直移動
Disturbance and loosening of the liquefied ground



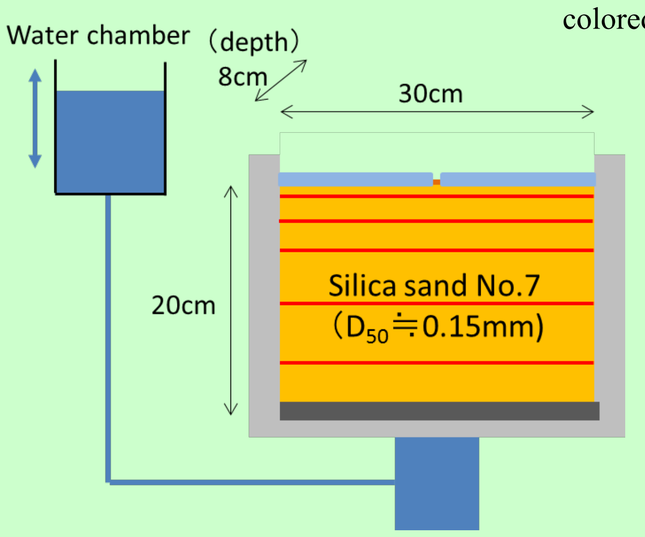
噴砂直下の土砂の亡失
Boiled sand and void in the liquefied ground

模型地盤における液状化・噴砂の再現
Simulation of liquefaction and sand boiling in a model test

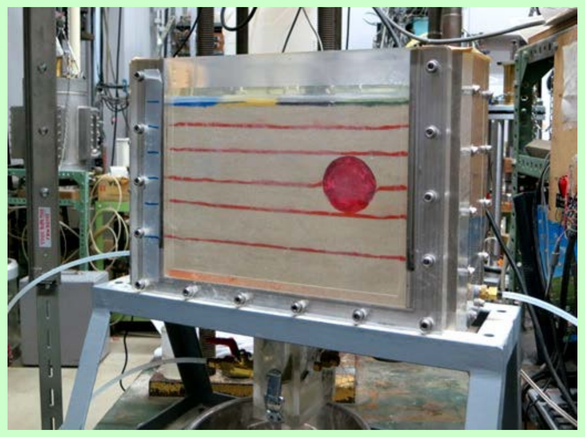
模型地盤の作製
Preparation of model ground



砂の移動の観測用に設けられた色砂
colored sand for the observation of grain movement



実験装置
Model test apparatus



模型地盤
Model ground

噴砂時には、開口部に向かって地表面付近の砂の水平方向の移動がまず生じた。さらに動水勾配が高くなった時に、砂の鉛直上向きの移動が見られた。
Sand near the surface move horizontally first, then later vertically.

小規模な噴砂の場合地盤深部への影響は少ないが、開口部下方に構造物模型を設置すると構造物壁に沿って水みちが発生し、砂の移動、および地盤のゆるみが促進された。地盤のゆるみの範囲も拡大する可能性がある。
When a model structure was put near the opening, water pathway tended to be generated along the model structure and sand movement was accelerated.

噴砂で生じる空洞は浅く広範囲なものとなり、空洞底面は波打つ傾向がある。これは、地震後の空洞調査で観察されたものと類似している。
A small scale sand boiling did not affect the penetration resistance deep in the ground. A buried structure sometimes enhanced the generation of water pathway and the extent of ground loosening.

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堀内祐樹 (2015)

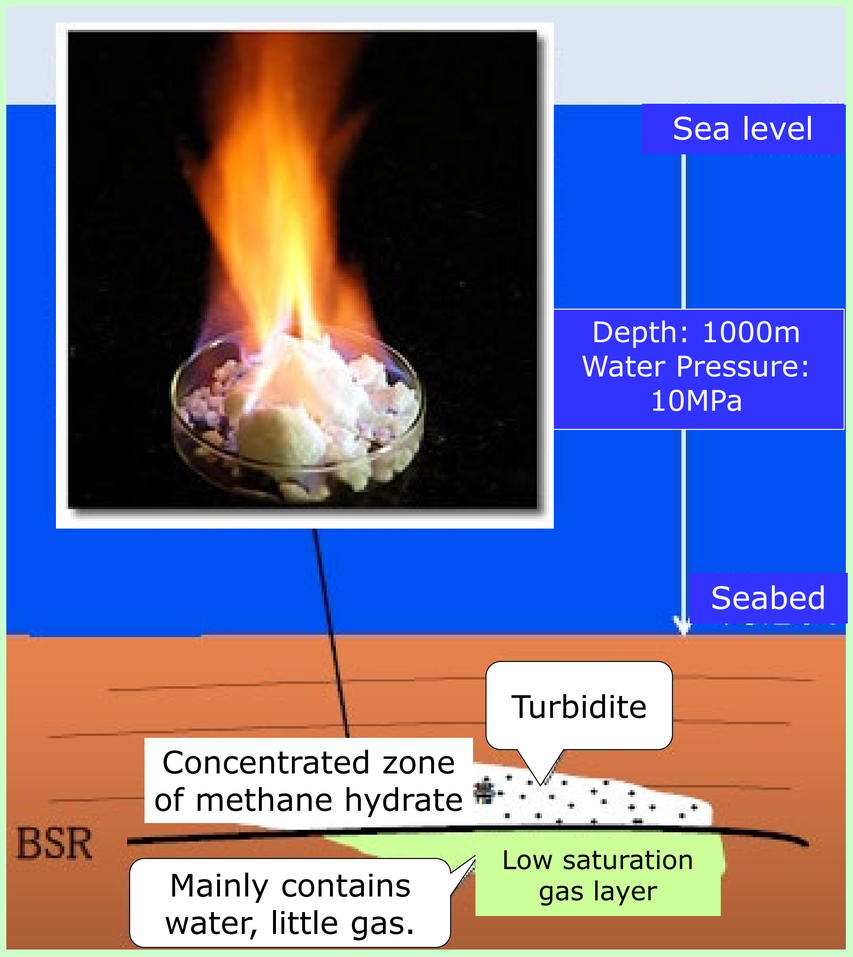
BASIC RESEARCH ON FINE PARTICLE EROSION IN MINING OF METHANE HYDRATE

メタンハイドレート採掘における出砂現象に関する基礎的研究

Recently Methane Hydrate(hereafter MH) as known as next-generation energy has got attention. It was identified that this natural resource called “combustible ice” is restored by filling the void of the seabed around Japan, such as Nankai Trough, which is high-pressure environment, the depth of the sea is about 1000m,10MPa in pressure. One of the problems to be solved for commercial production is sand production from MH layer to inside of the gas production well. The goal of this study is to clarify the cause of sand production in mining MH, and propose the effective solution.

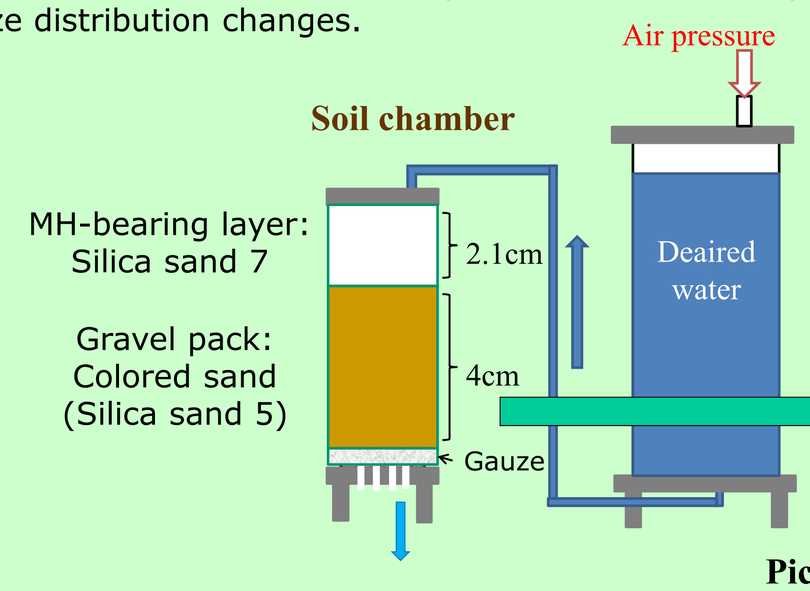
近年、次世代資源としてメタンハイドレート(以下MH)が注目されている。燃える氷とも言われるこの資源は日本周辺でも南海トラフなどにて、海底地盤の砂の間隙内を充てんする形で、水深およそ1000m程度、圧力レベル10MPa程の高圧環境下に貯留されていることが確認されている。このMHの商業生産に向けて解決すべき課題の一つに、MH層からガス坑井内への出砂現象が挙げられる。本研究ではMH採掘の際に観察された出砂の原因を明らかにし、出砂対策に有効な改善策を提示することを目標とする。

砂層型MHの存在環境
Environment where MH stored in the seabed



グラベルパックとMH層を模擬した一次元カラム透水試験
One dimensional column permeability test with simulation of gravel pack and MH layer

アクリル円筒内に作製したMH模擬層とグラベルパック層に水を浸透させ、一定時間透水した後グラベルパック層の粒度分布を調べ、MH層からどの程度細粒分が流入したかを調べる。
Water flows from fine sand layer to coarse sand layer to investigate how the grain size distribution changes.



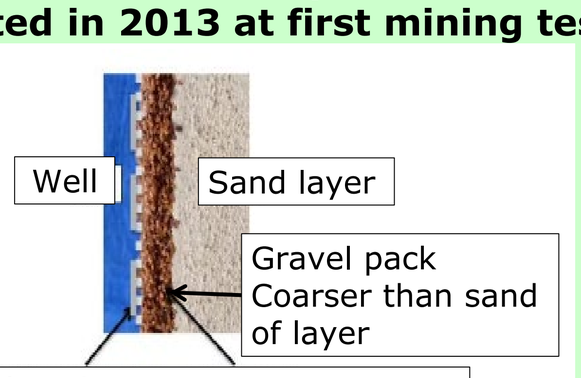
Sand to use	Grain size (mm)
Colored silica sand	0.1 ~ 0.8
Silica sand 7	0.08 ~ 0.3

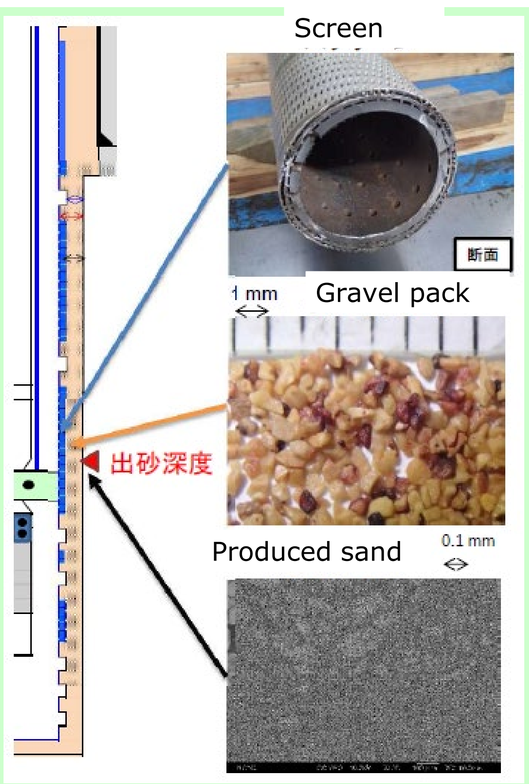


Pick up the gravel, divide it into 4 specimens, and conduct sieve test

粒度分布の変化によって細粒分の流入を観察する
Observe the inflow of fine sand
by checking the change of the grain size distribution

2013年第一回海洋産出試験における出砂対策
Measures on sand production conducted in 2013 at first mining test

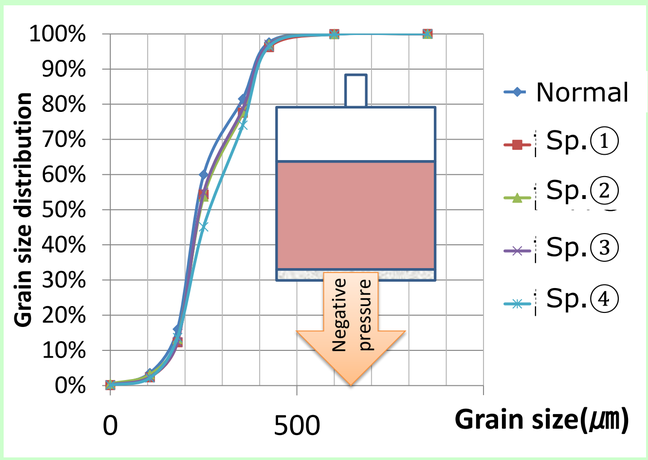




実験後得られた粒度分布
Grain size distribution acquired after the test

実験結果
Test Result

負圧で下部から0.1MPaで引いた場合
In case 0.1MPa negative pressure from bottom



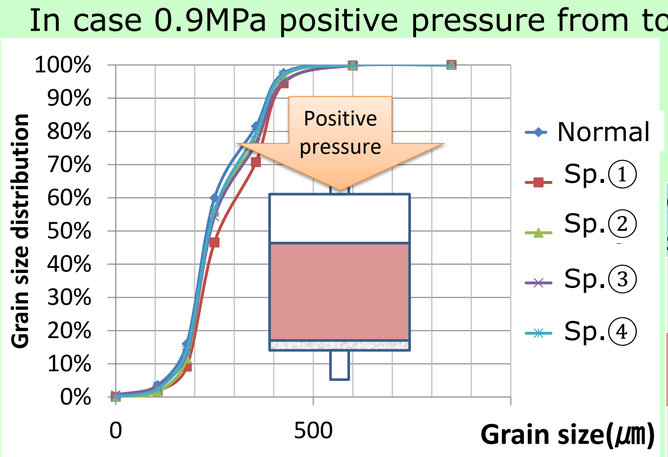
Test time: 14 minutes
Average flow rate : 11.6cm^3/s

Water flow direction: Top → Bottom

Grain size(μm)	Normal	Sp.①	Sp.②	Sp.③	Sp.④
Under 355	60.0%	54.3%	53.7%	54.9%	45.1%
Under 250	16.0%	12.3%	13.2%	12.4%	13.6%
Under 180	3.6%	2.3%	3.1%	2.4%	2.2%

・MH模擬層からの細粒分の移動、流出は観察できない。
・Haven’t been confirmed the inflow from the MH layer yet
・底部のみ流出が顕著。負圧で引いている事による影響を受けている可能性。
・outflow from bottom is apparent. Potentially be affected by use of negative pressure

正圧で上部から0.9MPaで押した場合
In case 0.9MPa positive pressure from top



Test time: 3 minutes
Average flow rate: 45.2cm^3/s

Water flow direction: Top → Bottom

Grain size(μm)	Normal	Sp.①	Sp.②	Sp.③	Sp.④
Under 355	60.0%	46.6%	55.8%	54.3%	56.1%
Under 250	16.0%	9.1%	11.6%	13.2%	14.0%
Under 180	3.6%	1.9%	1.6%	3.2%	2.5%

・上部の方が流出が顕著。特に250μm以下では上部から底部にかけて段階的。
・Clear outflow from the top. Especially grain size under 250 μm is gradually move from top to bottom
・グラベルパック層内で細粒分の移動が起きている可能性
・Possibility of sand moving inside of the gravel pack layer

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鈴木俊也 (2015)

BEHAVIOR OF BURIED DOUBLE-LAYERED PIPE BY TRENCHLESS RENEWAL

非開削更新による二層構造管の挙動研究

Buried pipes play an important role for transporting water, sewage, electricity, gas, communication cables, and etc. Their construction has been rapidly progressed as the development of city so far. Nowadays in urban area, management and renewal of existing old buried pipes become more serious issue than new construction of pipes.

In this research, trenchless renewal method for an old existing pipe, putting inner flexible lining without ground excavation, is mainly being investigated. A series of laboratory model tests have been conducted to examine effects of backfill soil condition and host pipe deterioration on the behavior of flexible liner of double-layered pipe by trenchless renewal.

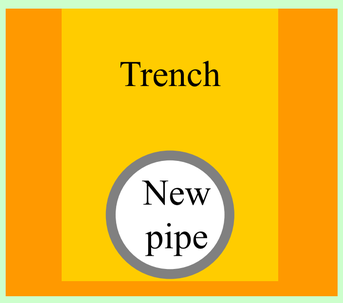
地中埋設管は上水・下水や電気、ガス、通信などを地中で輸送する役割を担う都市基盤施設であり、都市の発達と共に急速に整備が進められてきました。成熟した都市部では、既に新規建設が頭打ちとなり、老朽施設の合理的な維持管理・更新が重要な課題となっています。

本研究では、地中埋設管の老朽化に伴う問題を整理し、地中埋設管の効率的で合理的な更新・維持管理に資するよう、埋設管の長期挙動の解明、埋設管の非開削更新に関する検討を行っています。ここでは、内部ライニングの施工により地盤掘削することなく老朽管を更新する方法の、ライニングの合理的な設計を目指した基礎実験の経過や、埋設地盤の密度と更生管の劣化度による影響に関して報告します。

研究背景　Background of Study

非開削更新とは　Trenchless renewal

老朽埋設管を地盤掘削することなく内側からライニングを施すことにより更新が可能。コスト縮減の他、道路掘削による交通渋滞を避けることができ都市部でよく採用される。
Old deteriorated buried pipes could be renewed by inner lining without ground excavation. Trenchless renewal methods have been preferred in the congested urban cities.

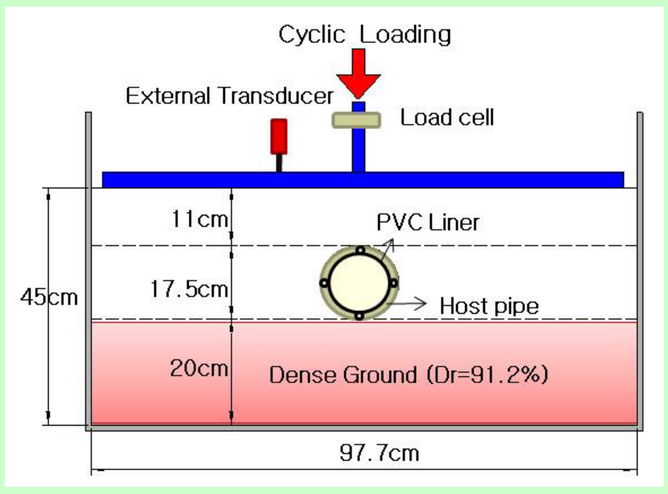


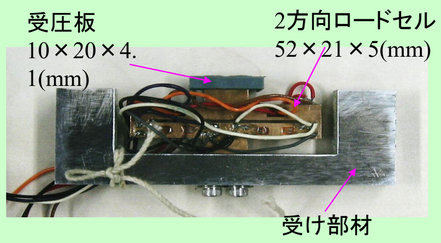
開削を伴う新管への取替による更新
Renewal by replacement with excavation



ライニング施工による非開削更新
Renewal by inner lining without excavation

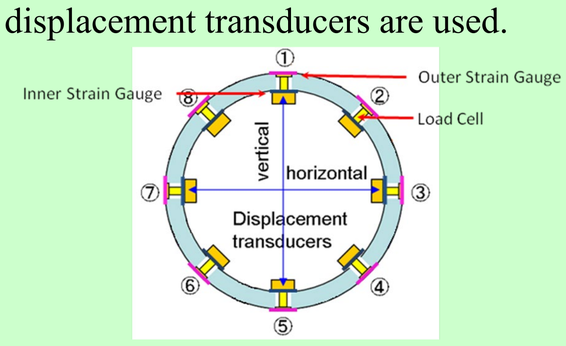
更生管ライニングに作用する土圧に関する模型実験
Behavior of flexible liner in rehabilitated pipe

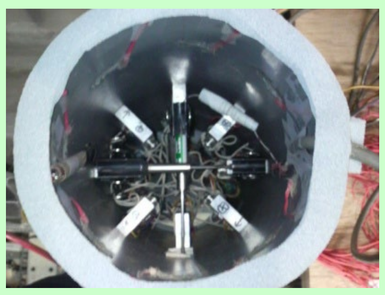




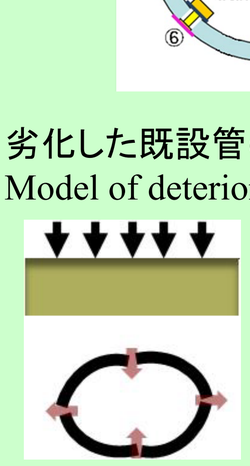
2方向ロードセル
2-way load cell

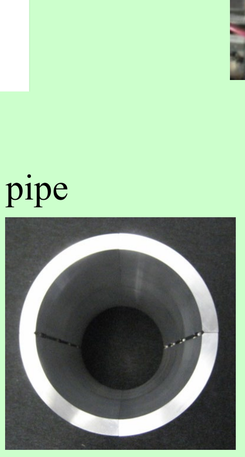
ライニング モデル（塩ビ管）
Model pipe of liner: 8 load cells, 8 strain gauges, 4 pressure cells and 2 displacement transducers are used.

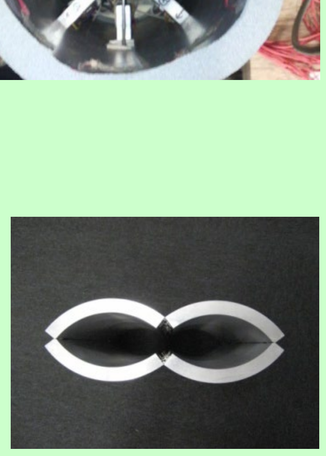




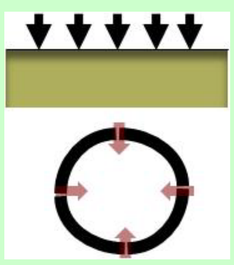
劣化した既設管のモデル
Model of deteriorated host pipe

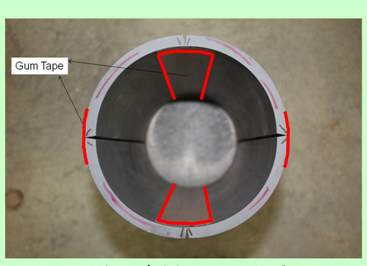


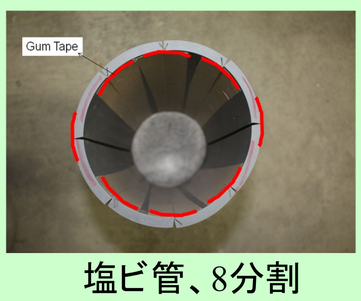




ジュラルミン、4分割



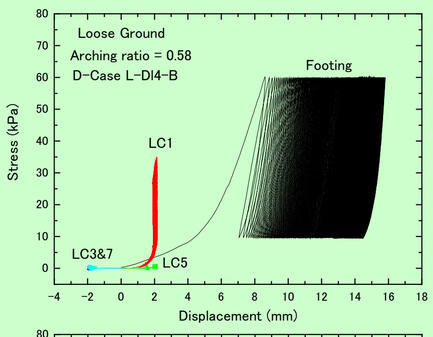




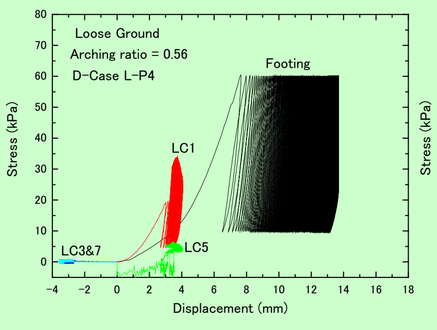
塩ビ管、4分割　　塩ビ管、8分割

既設管の劣化による実験結果
Result of Model Tests Using Deteriorated Host Pipe

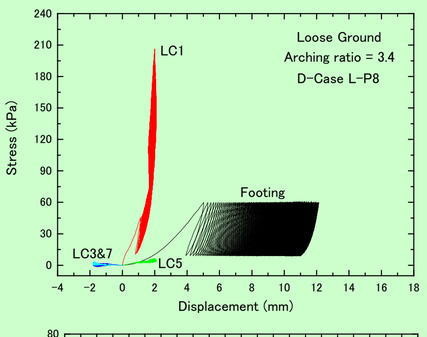
ジュラルミン、4分割
D-Case-Dl4-B

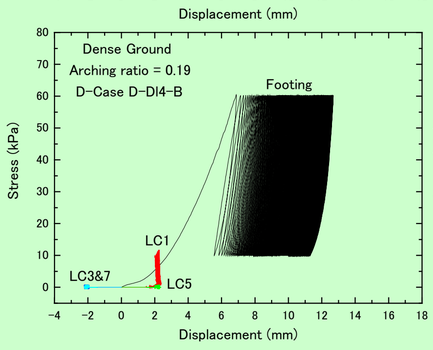


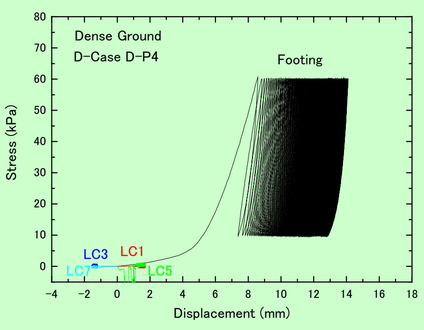
塩ビ管、4分割
D-Cas-P4

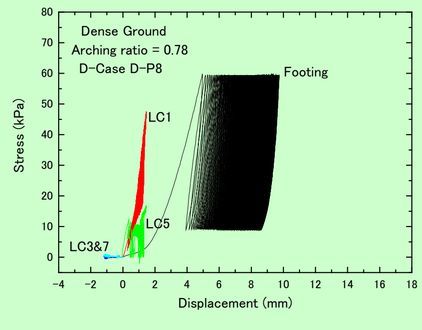


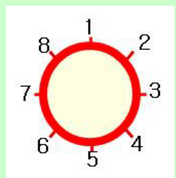
塩ビ管、8分割
D-Cas-P8











Arching Ratio =
$$\left(\frac{\text{Measured Normal Stress at LC1}}{\text{Arching ratio of single pipe}}\right)$$

Host pipe coefficient(α) =
$$\left(\frac{\text{Arching ratio of double-layered pipe}}{\text{Arching ratio of single pipe}}\right)$$

低減係数
(既設管の負担によるライニングにかかる土圧)
Host pipe coefficient

Case		*Host pipe coefficient*
Duralumin-4分割	Loose	0.317
Duralumin-4分割	Dense	0.268
Duralumin-4分割-**45**度回転	Loose	≈0
PVC-4分割	Loose	0.306
PVC-4分割	Dense	≈0
PVC-4分割	Partially loose	0.178
PVC-8分割	Loose	1.858
PVC-8分割	Dense	1.099

本研究に関する担当研究室は桑野研究室です.
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高東熙 (2010)

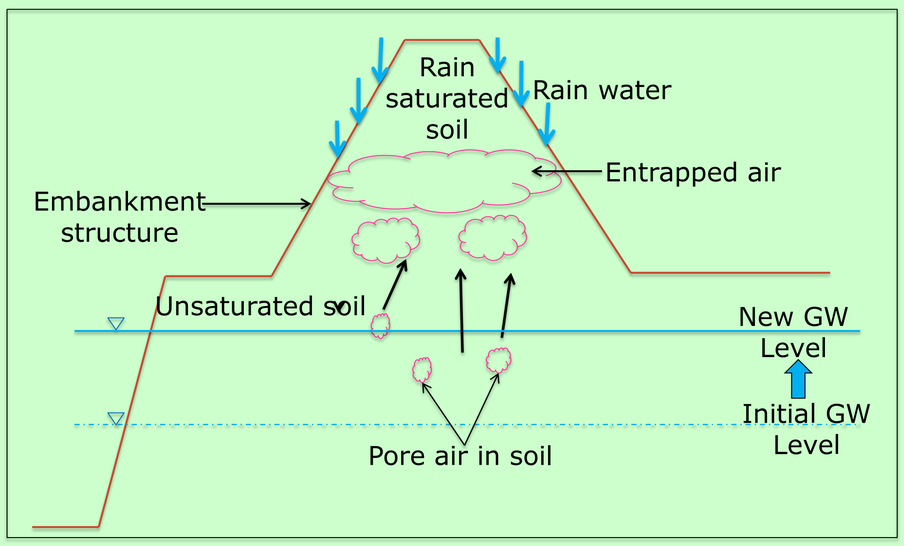
LOCAL FAILURE DUE TO ENTRAPPED AIR BETWEEN DL CLAY AND SILICA SAND NO.8

地盤内に閉塞された間隙空気圧による地盤の局所破壊

Entrapped air pressure development (and subsequent local ground failure) is investigated between wet DL clay overlaying unsaturated silica sand 8. During infiltration of water through the unsaturated soil, pore air pressure increased. Further infiltration led to upward displacement of the pore air by the infiltrating water causing air to be trapped just below the wet DL clay which had a relatively low air permeability. Displacement of the DL clay layer was observed. In this study, local failure occurred when the air entrapped between the wet DL clay and unsaturated silica sand no.8 uplifted the DL clay layer causing reasonable displacement.

地盤の表層が水で飽和しかつ地下水位が上昇する場合、地盤内に空気が閉じ込められ、水の侵入に伴い空気圧が上昇し、地盤が局所的に破壊されることがあります。地層下部からの水の浸入に伴い不飽和層内の間隙空気は上部へ追いやられていきます。飽和土は空気をあまり通さないため上昇した空気が閉じ込められることで空気圧が上昇し、表層を押しやって変位させる可能性があります。本研究では、地盤内の間隙空気が地盤の破壊に及ぼす影響を実験により検討しました。上層の飽和層にDL−clay(細粒土)を、下部の不飽和層に珪砂8号を使用し、動水勾配を変化させ、浸透水量・間隙空気圧・上層土塊の変位の関係を明らかにしました。

間隙空気による盛土崩壊のメカニズム
Hypothesis of failure mechanism in an embankment due to air entrapment

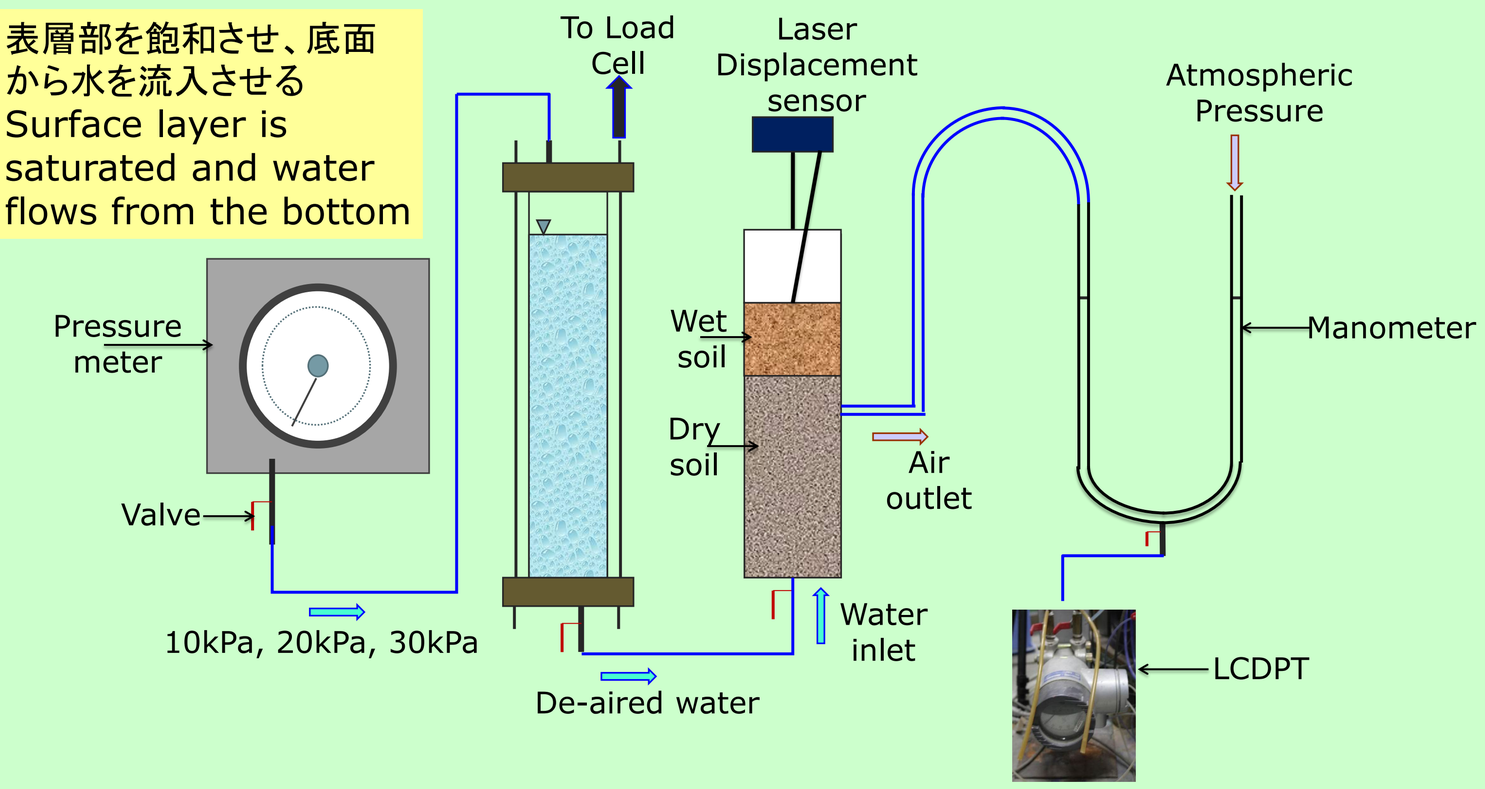


地下水位上昇と表層地盤の飽和により空気が閉じ込められ、空気圧が上昇。盛土内部にて局所破壊の可能性。

Air is trapped due to surface ground saturation and rise of ground water level. Increase in air pressure leads to local ground failure. Internal cracks develop in the embankment.

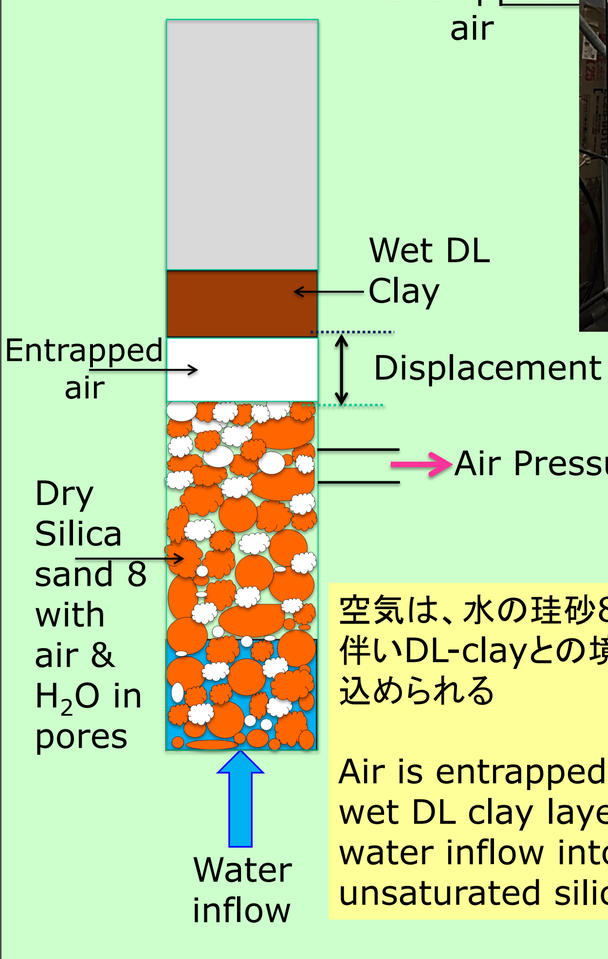
地盤内への水の浸入を模擬した円筒実験装置
Experiment set-up of one-dimensional column test

表層部を飽和させ、底面から水を流入させる
Surface layer is saturated and water flows from the bottom



試料内空気の挙動
Formation of entrapped air



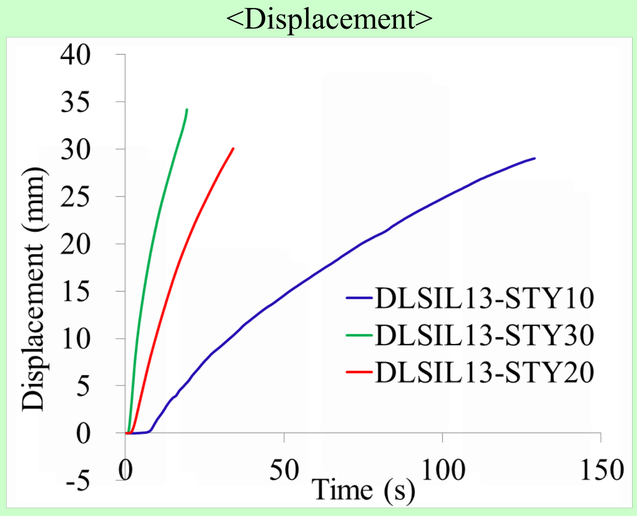


空気は、水の珪砂8号への侵入に伴いDL-clayとの境界付近に閉じ込められる

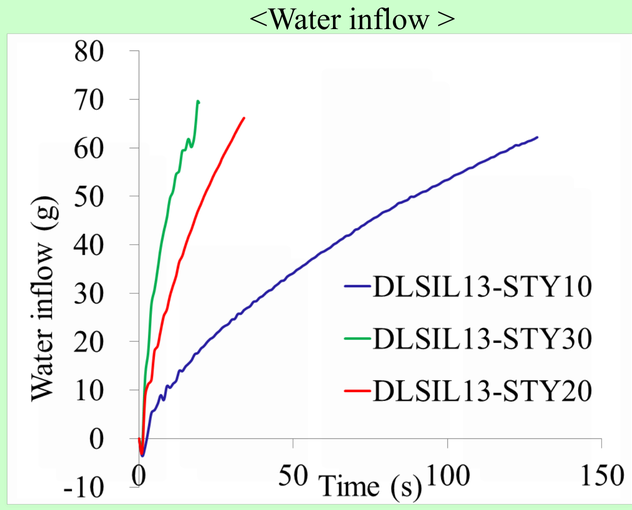
Air is entrapped below the wet DL clay layer due to water inflow into the unsaturated silica sand no. 8.

試験結果
Test Results

<Displacement>

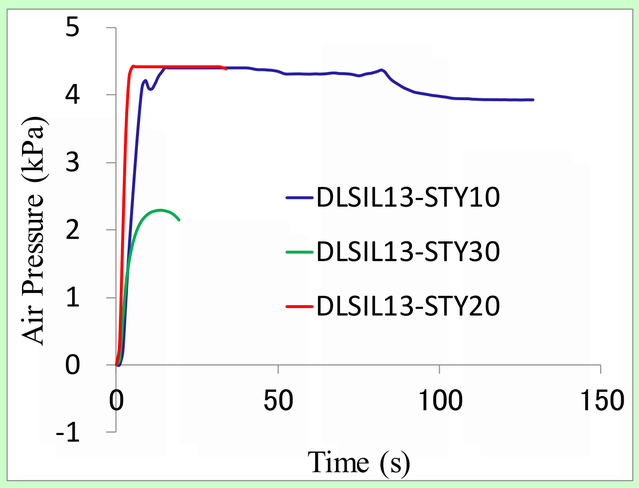


<Water inflow >



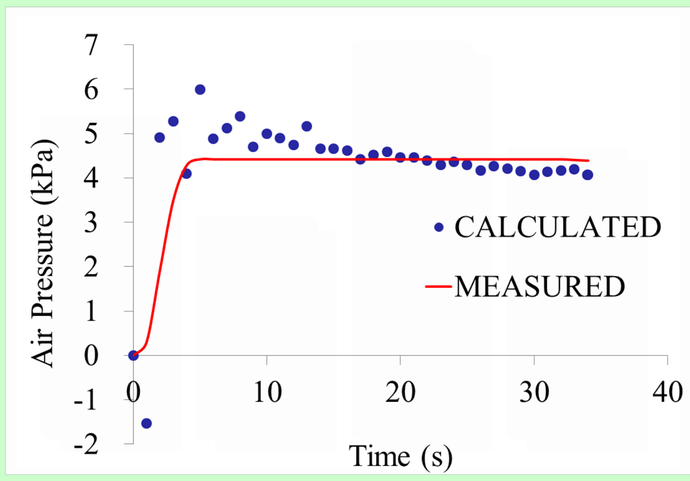
変位(空気層の厚さ)は侵入した水量と相関有
Displacement (thickness of air-layer) increases with water inflow

<Entrapped air pressure>



空気圧
計算結果と実験結果はほぼ一致した
Calculated (theoretical) air pressure ≒ Measured (experiment) air pressure

<Calculated air pressure ⇔ Measured air pressure for 20kPa water infiltration rate>



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Leah Musenero (2016)

Physical and Mechanical Properties of Plaster
- Soil Mechanics Perspective -
漆喰の物理・力学特性における土質力学的解釈

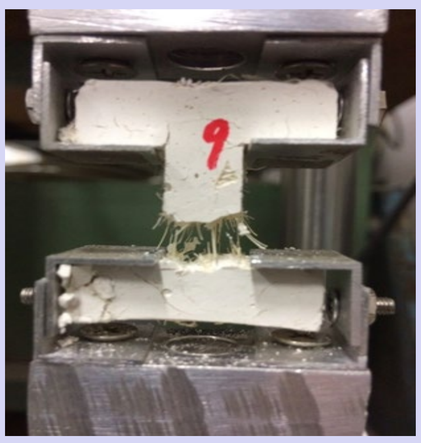
歴史的建造物の天井や壁の保護材料として広く使用されてきた漆喰だが、その強度発現・低下のメカニズムは不明瞭であり、文化財の保存作業における効率的な手法はまだ確立されていない。本研究では、漆喰の物理・力学特性に土質力学の観点から知見を与えることを目的に、天井に使用される漆喰の物性の測定及び引張強度の発現・低下の過程に関する分析を行った。漆喰の乾燥に伴う重量の変化及び一軸引張試験の結果から、施工後一週間が経過した漆喰は自重に対してとても高い安全率を誇る材料であることが確認された。また含水が引張強度の低下をもたらすことも確認され、含水比が40%を超える漆喰は剥落の危険性が高いことが明らかになった。

Efficient ways in preservation of plasters that are often used to protect ceilings and walls of traditional and historical buildings are not established yet. This is partially because engineering properties of plasters are still not clearly understood. In the present study, I measured physical properties of a plaster used for ceilings and analyzed how tensile strength of the plaster varies in the aim of getting knowledge based on soil mechanics. From the results of uniaxial extension test and variations of plaster's mass, it can be concluded that plasters are highly safe materials against plaster's own mass. It is also understood that water content makes plaster weak, and there is a high risk of fall of plasters when water content exceeds 40%.

材料と供試体 Material and specimen

漆喰＝石灰＋水＋糊（＋砂）
【化学反応式：$Ca(OH)_2+CO_2 \rightarrow CaCO_3+H_2O$】
→吸湿性、殺菌性を持つ

Plaster=Lime + water + bond (+sand)
【Chemical reaction formula : $Ca(OH)_2+CO_2 \rightarrow CaCO_3+H_2O$ 】
→Plaster has moisture absorbing and sterilizing effect

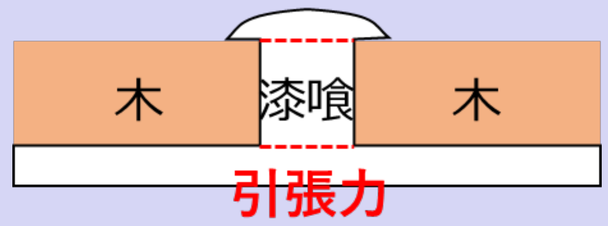


一軸引張試験後の供試体
中央の細い部分(10mm×10mm)で
破断するようにH型供試体を採用

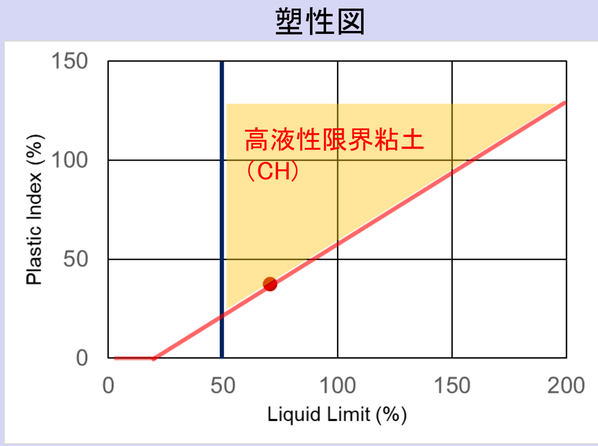
Specimen after uniaxial extension tests
We adopted 'H' shape specimen to break in the middle and thin part (10mm×10mm)

引張応力が作用する様子（漆喰天井の図）
How tensile strength works （Schematic of plater ceilings）





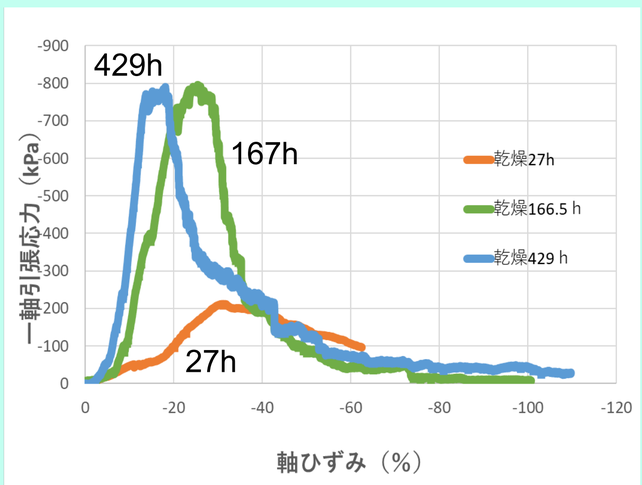
塑性図



フレッシュ漆喰の液性・塑性限界
液性限界：70.3％
塑性限界：32.5％
➢ 「高液性限界粘土」に分類される
→塑性が高く、圧縮性が大きい

Liquid and plastic limit of fresh plaster
Liquid limit:70,3%
Plastic limit:32.5%
This is classified as 'high liquid limit clay'
→High plasticity and compressibility

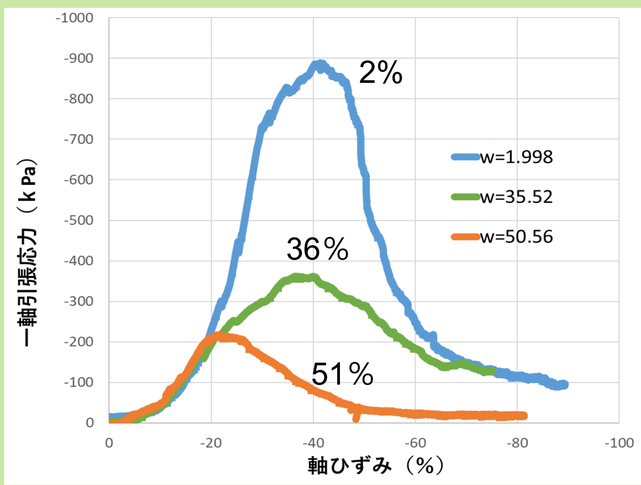
強度発現 Increase in strength



供試体作製後の経過時間に伴う
応力ひずみ曲線の変化
・時間経過に伴い最大強度が増加
ただし一週間を超えると増加量は減少
・時間経過に伴い剛性が増加

Variation of stress-strain curves with curing time
・Maximum tensile strength increases as time passes
However, there is no change in a week from they are made
・Stiffness increases as time passes

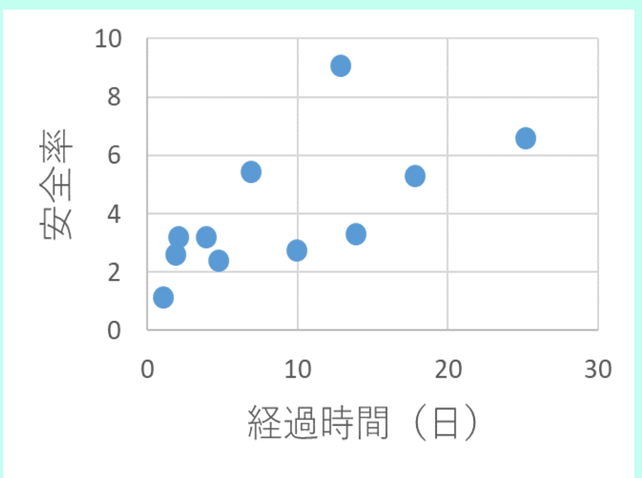
含水に伴う強度低下 Decrease in strength due to water content



含水比による応力ひずみ曲線の変化
・含水比の上昇に伴い最大強度が減少
・初期剛性は大きな変化なし

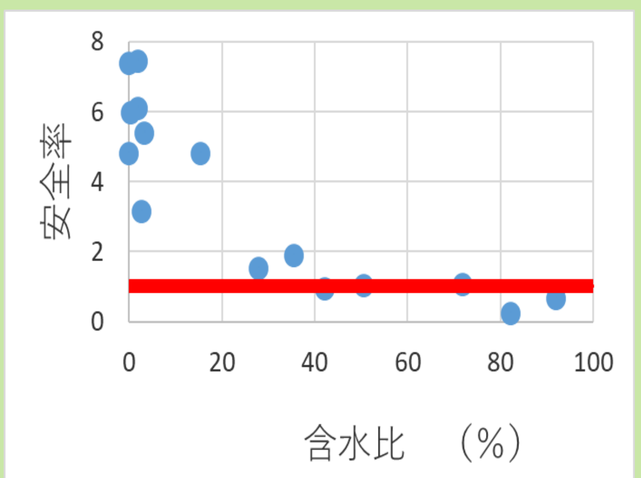
Effect of water content on variation of stress-strain curves
・Maximum tensile strength decreases as water content increases
・Small-strain stiffness is not influence due to water content

＜安全率の導入＞ 安全率＝最大引張強度/重量
＜Introduction of safety factor＞ Safety factor = Maximum tensile strength / weight



乾燥に伴う安全率の上昇
・施工から時間が経過し乾燥が進むにつれて、安全率は上昇する
・特に施工後一週間を超えると、高い安全率を誇る

Increase of safety factor with dry
・Safety factor increases with drying process
・Particularly, it becomes high within a week after the plaster was made



含水に伴う安全率の低下
・含水比が上がると安全率は低下
・40％を超えると安全率１を下回る
（＝自重を支えられなくなる）

Decrease of safety factor due to water content
・Safety factor decreases as water content increases
・Safety factor drops below 1 when water content exceeds 40%, i.e. plasters can not support their own weight

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平野裕 (2019)