Matric suction and stiffness measurement on soil containing fines at low stress state

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ABSTRACT

Matric suction significantly attributes on both strength and stiffness of the geomaterials. Earthen structures constructed by soil containing fines are profoundly found to be at an unsaturated condition. The unsaturated soil is often subjected remarkably and continuous changes in matric suction with variation in moisture content. This study focuses on an experimental investigation of Matric suction variation and its attribution on stiffness by means of elastic wave measurement on fine sand (Toyoura sand) with two types of fines; kaolin and non-plastic silt as well as natural soil containing fines (Edosaki sand). The small-scale triaxial apparatus equipped with disk transducer for measuring elastic wave and pressure membrane technique for evaluating matric suction is employed. A cylindrical specimen is prepared by sandy soil with several amounts of fines and subjected to change in moisture content by injecting water inside the specimen. Both compressional and shear waves velocities are measured in conjunction with an associated matric suction at low stress level that replicates the soil behavior of the shallow depth. This investigation reveals that the presence of fines in soil appears to play an important role in mechanical behavior of sandy soil. The small strain stiffness as well as dynamic properties seems to be affected by the moisture condition in the soil.

Keywords: elastic wave, collapse behavior, matric suction, sandy soil, laboratory test

1 INTRODUCTION

The collapse of earthen structures is ubiquitously known as additional deformation within the short time span at constant total stress that might cause the damage or fail of numerous infrastructures; embankments, earthen dams, levee and structures founded on not well-compacted soil. It is well recognized problems for geotechnical engineers and indicates the thorough understanding of the theory of unsaturated soil is crucial to resolve this phenomenon which provides the relationship between changes in volume mass properties and changes in stress states of the soil (Fredlund and Morgenstern 1978). Generally, collapsing behaviour consists of saturation process of unsaturated meta-stable soil that leads to varying moisture content in the soil system with vanishing matric suction. Therefore, soil suction is not only well descriptor of the moisture condition of unsaturated soils but also an important parameter used to analyse the collapse potential. Several studies have revealed the paramount role of matric suction on collapse of geo-infrastructures (Maswoswe 1985, Lawton, Fragaasy and Hetherington 1992, Jennings and Burland 1962, Barden, Mc Guar and Collins 1973, Houston, Mahmoud and Houston 1993) and urge the necessity of suction measurement in soil. Several studies speculate soil structures of collapsible soil that show the bulky grains of soils are held together in a honeycomb type of fabric by some type of bonding material or force at the points of contact. Water plays as agent that causes the bonding or cementing agent to be decreased and inter particle or inter granular contact to be vanished. Due to wetting, Matric suction at the contact decreases, resulting grain slippage and irrecoverable distortion which causes the volumetric strain variation (Larionov 1965, Burland 1965, Barden et al. 1973).

Sandy soils are abundantly used construction materials in earthen structures. The enough degree of compaction is rarely achieved in the vicinity of the several structures such as retaining wall, buried structures, abutment wall etc. The engineering properties of sandy deposits are strongly influenced by an array of parameters such as quantity of fines, type of fines, void ratio, water content and saturation degree etc. and it possesses a very low range of soil suction as compared to clayey or sily soils. Matric suction might be a dominant component of the total suction in the sandy soil when deionised water is a liquid constituent in the soil.

While concerning to the laboratory based researches that regards to matric suction measurement, numerous techniques, for instance, relative humidity

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measurement, filter paper method, tensiometer, axis translation, pressure plate have been developed for testing unsaturated soils (Beddoe, Take and Rowe 2010, Houston et al. 1993, Richards 1941, Hilf 1956, Bishop and Donald 1961, Bishop and Henkel 1962) and those studies had dealt with mainly silts, clays and clayey soils. Few years back, micro porous membrane technology for matric suction measurement of soils has been introduced by Nishimura (Nishiumura et al. 2012) which is mainly dedicated for measuring lower range of matric in sandy soils. Recently this technique is integrated enabling to measure elastic waves; both compression and shear waves in triaxial apparatus (Suwal and Kuwano 2018) and use in this study which focuses on an investigation of matric suction variation and its attribution on stiffness by means of elastic wave measurement on fine sand (Toyoura sand) with two types of fines; kaolin clay and non-plastic silt as well as naturally fine content geomaterial (Edosaki sand). The triaxial apparatus has been modified enabling to measure both elastic wave and matric suction. For this purpose, the elastic wave measurement technique, disk transducer method and pressure membrane technique for suction measurement are merged. A cylindrical specimen is prepared by sandy soil with several amounts of fines and subjected to change in moisture content by injecting water inside the specimen. Both compressional and shear wave velocities are measured in conjunction with an associated matric suction. It is noticed that the presence of fines appears to play an important role in mechanical behaviour of sandy soil. The small strain stiffness as well as dynamic properties seems to be affected by the moisture condition.

2 TESTED MATERIALS

Natural fine content sandy soil and sandy materials derived mixing clean sand with specific amounts of fines are tested. Two sorts of fine; non-plastic silt and kaolin clay are used. The properties of those materials are briefly described here;

2.1 Edosaki sand

Edosaki sand is natural sand collected from the Ibaraki prefecture, Japan. Grains are mostly round with yellowish orange color. It is mostly used in earthen infrastructures as filling materials in Japan. The photograph taken from optical microscope of the sample of Edosaki sand and gradation curve are shown in Fig. 1(a) and 2(a).

2.2 Toyoura sand

Toyoura sand is the major constituent of the sandy soil derived for testing which is fine-grained, uniformly graded sand. It is derived from the siliceous rocks and shale. It looks light yellowish-brown in color and well sorted with rounded quartz particles. The photograph taken from the optical microscope of the sample of Toyoura sand and gradation curve are shown in Fig. 1(b) and 2 (a).

2.3 Non-plastic silt

Commercial non-plastic silt available in Japan with brand name “DL-clay” is used in the current study. The appearance of freshly and freely deposited DL-clay looks yellowish brown. The photograph taken from the optical microscope of the sample of DL-clay is shown in Fig. 1(c) and gradation curve is shown in Fig. 2 (b).

2.4 Kaolin clay

Kaolin (hydrated aluminum silicate, [Al₂Si₂O₅(OH)₄] is soft white powder consisting principally of the mineral kaolinite, which, under the electron microscope, is seen to consist of roughly hexagonal, platy crystals ranging in size from about 0.1 micrometers to 10 micrometers or even larger. The photograph taken from the optical microscope of the sample of kaolin clay is given in Fig. 1(d) and gradation curve in Fig. 2 (b).

2.5 Mixing Toyoura sand with fines

Toyoura sand and fines (non-plastic silt and kaolin clay) are mixed at dry state by weight proportion. Initially mix are stirred manually well, then stirred by mechanized stirrer with adding water a little and stirred well for enough time to make homogeneously mixed soil. In this study, initial water content is found approximately 2% - 4%. Then after this, the mixed soil is packed in air tied plastic bags and leaves at least for more than one day for eventual distribution of moisture throughout the whole soil.

3 TESTING APPARATUS AND ACCESSORIES

A small triaxial apparatus equipping with various transducers/sensors for strain, moisture, matric suction and elastic wave measurement is employed in this study.

3.1 Triaxial machine

The displacement controlled triaxial testing machine is utilized which consists of an AC servo-motor and a reduction gear system, electro-magnetic clutches and brakes for precise loading and unloading. The stress states are controlled using a closed loop feedback system with the aid of the analog-to-digital and digital-to-analog converters.

3.2 Top and Bottom platens

Top cap and pedestal as depicted in Figure 4 are employed in test. It is customized to encapsulate the disk transducers for elastic wave measurement and integrate the matric suction measurement system by micro porous membrane technology. Pore-water pressure is measured at pedestal where air pressure is recorded at top cap as schematically shown in Fig. 3.

3.2 Strain measurement transducers

Axial deformation is measured by Local Deformation Transducer (LDT), which is developed...
following to (Goto et al. 1991) and it can measure local strain with higher precision. Radial deformation is evaluated with the aid of clip gauge which is modified from industry manufactured clark gauge. A pair of LDT was employed to measure axial strain and three clip gauges were attached onto the specimen.

Fig. 1. Photograph of Tested materials; a. Edosaki sand, b. Toyoura sand, c. non-plastic silt and d. kaolin clay

Fig. 2. Gradation curve of Tested materials.

Fig. 3. Schematic of Top and Bottom Platen

3.3 Elastic wave measurement system

The wave measurement system consists of transducers and a chain of instruments; signal generator, amplifying agent and recording instrument.

Smooth and flat surfaced disk transducer, developed at the University of Tokyo (Suwal and Kuwano 2013a) is employed for elastic wave measurement. It has ability to acquire both compressional and shear waves
simultaneously (Suwal and Kuwano 2013b). A digital function generator enabling to generate twelve kinds of different waveforms at frequency ranges from 0.001 Hz to 25 MHz with the maximum peak-to-peak voltage of 10 V is used. An amplifier is employed to amplify the input signal generated by the function generator before feeding it into the transducer. The multi-channels oscilloscope having 1 µsec resolution was used to record and display waveforms of the transmitted and received signals. Photographs of the function generation, the amplifier and the oscilloscope are shown in Fig. 4.

3.4 Moisture content measurement
The used triaxial system equips the accessories to supply and deplete water to reproduce wetting and drying cycles. Water is supplied through the pedestal. The upper tank with load cell is hung in elevated place connecting with pedestal. The decrease of water in upper tank is calculated monitoring weight of water via load cell. By means of weight of the soil and weight of water inside the specimen, the moisture content is computed.

3.5 Matric suction measurement
Following to (Nishiumura et al. 2012) the micro porous membrane technology has been enhanced in the triaxial apparatus. Both the pedestal and top cap are improved intending to measure the matric suction via monitoring pore-water and pore-air pressure. The micro porous membrane with pore diameter of 0.45µm having an air entry value of 250 kPa and a thickness 140 µm; manufactured is used. The micro porous membrane is fixed at the pedestal connecting with the pore water pressure measuring transducer, located outside the chamber of triaxial cell. The Polyflon filter (PF100) is used in top cap since it is hydrophobic and high air permeability with minimal pressure drop. It is mostly used for separation of aqueous and non-aqueous phases.

4 TESTING PROCEDURE AND PROGRAM

4.1 Specimen preparation
The specimen of 75mm diameter and 75 mm height is prepared on the pedestal by tamping method with the aid of the mould. The total soil is divided in 8 parts and each part is compacted within 10 mm. The specimen of 80 mm height is trimmed at the top by 5mm remaining the erected specimen by 75 mm in height. In this way, the density of the specimen is controlled.

4.2 Experimental program
The tested materials are tamped at atmospheric pressure and around 25 kPa isotropic stress is applied before removing the mould applying vacuum. With setting cell cover, the cell pressure is gradually increased up to 25 kPa with releasing vacuum at the same rate. These reflect that the specimen is prepared in isotropic stress state of 25 kPa. (Nishiumura et al. 2012) used a microporous membrane for measurement of the SWCC with matric suction of up to 25 kPa. The reason behind measuring matric suction up to 25 kPa was minimizing the errors in measurement due to water vaporization. It is confirmed that the water starts to vaporize forming air bubbles inside pipe connecting with pressure transducer after 3- 4 hours at suction (negative pressure) value greater than 25 kPa. To cope with this problem, back pressure of 50 kPa inside the specimen is applied with maintaining an effective stress equivalent to 50 kPa as shown in Fig. 5.

5 RESULTS

5.1 Test cases
The result of ten experiments, as given in Table 1, including two tests on reconstituted natural Edosaki sand are discussed here. The Edosaki sand is compacted in very dense state in one test where very loose state is achieved in another test. 10% and 20% fines; non-plastic silt and kaolin clay are mixed with Toyoura sand and performed an experiment in dense and loose states.

5.2 Matric suction and degree of saturation
Enough time is allowed after the specimen is subjected to the effective confining stress of 50 kPa to

Fig. 4. Schematic of specimen and elastic wave measurement system

Fig. 5. Experimental sequences
get eventual distribution of moisture (Matric suction) then very small amount of water (10 – 20 ml) is supplied through pedestal and waits in creep condition to achieve stabilized moisture throughout the specimen. Amount of water is gradually increased step by step and elastic waves are measured in each step upon the stabilization of pore water pressure.

| Experiment No. | Fine content | Initial dry density | Initial saturation degree |
|----------------|--------------|---------------------|--------------------------|
| Edosaki-1      | -            | 1.65                | 29.7                     |
| Edosaki-2      | -            | 1.31                | 27.2                     |
| DL-10-1        | 10           | 1.53                | 6.8                      |
| DL-10-2        | 10           | 1.43                | 5.3                      |
| DL-20-1        | 20           | 1.43                | 14.1                     |
| DL-20-2        | 20           | 1.54                | 5.6                      |
| K-10-1         | 10           | 1.43                | 12.4                     |
| K-10-2         | 10           | 1.45                | 12.9                     |
| K-20-1         | 20           | 1.43                | 19.2                     |
| K-20-2         | 20           | 1.45                | 18.0                     |

Fig. 6. Degree of saturation and Matric suction in time domain obtained on Edosaki sand

Fig. 7. Relationship between matric suction and degree of saturation obtained in Edosaki sand

Fig. 8. Relationship between matric suction and degree of saturation obtained in Edosaki sand and fine content Toyoura sand

With aid of the recorded data of pore air pressure at top cap and, pore water pressure at pedestal, the matric suction is computed. Similarly, degree of saturation is derived from the data of the changes in water inside the specimen accounting both axial and radial strain. Typical plots of the degree of saturation and matric suction in time domain series, achieved on Edosaki sand is given in Fig.6. The remarkable variation in matric suction upon little increase in degree of saturation is evidenced. The variation of matric suction and corresponding degree of saturation are found out in each experiment. The relationship between the matric suction and degree of saturation obtained in Edosaki sand and fine content Toyoura sand are plotted in Fig. 7 and 8 respectively which give the clear trend of varying matric suction with respect to the saturation degree for these materials. It is noticed that regardless of density, the water retention curve is found to be an identical for Edosaki sand where, the higher amount of fine in Toyoura sand attributes to develop the higher value of matric suction. It is also evident that Toyoura sand containing kaolin clay has possessed higher matric suction than that of containing non-plastic silt.

5.3 Elastic wave

As prior mentioned, disk transducer method can be used for measuring both compressional and shear waves. Both compressional and shear waves are propagated in each step. The typical traces of compressional and shear wave signals retrieved in Toyoura sand containing non-plastic silt are drawn in fig. 9 and the arrival of both compressional and shear waves are estimated accordingly as depicted in the fig.9 (Suwal and Kuwano 2013b) and travel time for signal propagation is calculated.

Fig. 10 and 11 are the waveforms obtained while propagating compressional and shear waves on the dense Edosaki sand specimen. The variation on the travel time for propagating signals are observed at
several degree of saturation. The time to propagate the signals are tending to be increased with higher degree of saturation. Similarly, the travel time for propagating elastic waves are achieved in all experiments then velocity of those propagated signals is calculated adopting simple mathematical relation the height of specimen at the time of measurement is divided by the travel time.

![Toyoura sand with 10% non-plastic silt, Input: Sine, 10 kHz](image)

**Fig. 9.** Typical waveform; a. received compressional wave signal and b. received shear wave signal

5.4 Stiffness

The information of elastic wave velocity is crucial in evaluating the stiffness since it has a clear relation. The values of the stiffness are achieved adopting the following equations;

\[
M = \rho V_p^2 \tag{1}
\]

\[
G = \rho V_s^2 \tag{2}
\]

\[
M = \frac{E(1-\nu)}{(1-2\nu)(1+\nu)} \tag{3}
\]

\[
G = \frac{E}{2(1+\nu)} \tag{4}
\]

Where; \(V_p\) compressional wave velocity  
\(V_s\) shear wave velocity  
\(M\): constrained modulus  
\(G\): shear modulus

The injection of water leads not only to changing the matric suction, but also causes the deformation of the specimen that attributes to vary the density of specimen. The void ratio function (Eqn. 5) proposed by (Hardin and Richart 1963) is used to eliminate the effects of density variation. This function is primarily derived for granular materials however it is used here considering that major constituent of the soil is granular, and it shows better nullification effect as compared to other void ratio functions.

\[
F[e] = \frac{(2.17-e)^2}{(1+e)} \tag{5}
\]

![Edosaki sand, \(\rho_{mi} = 1.65\text{g/cm}^3\), \(\sigma_1 = \sigma_3 = 50\text{kPa}, Input: 15\text{kHz}, Sine Compression wave](image)

**Fig. 10.** Traces of compressional waves at several degree of saturation obtained at the Edosaki sand specimen

Fig. 12 and 13 show the variation young’s moduli and shear moduli observed in the tested geomaterials with respect to the measured matric suction. The moduli are normalized using Eqn. 5 to minimize the influence of variation of void ratio. So that the effect of matric suction on the stiffness can be seen effectively. It is clearly seen that the higher values of stiffness are obtained at the soil which possesses the higher amount of matric suction.
CONCLUSIONS

This study demonstrates the experimental evidence of successful measurement of matric suction as well as stiffness on the sandy soil. It also shows that the small values of matric suction that possesses in the sandy soil might attribute in varying several engineering parameters including stiffness. In addition, the higher value of the matric suction is achieved in the specimen that content the higher amount of fines and kaolin clay content Toyoura sand has attributed higher matric suction as compared to the non-plastic silt content Toyoura sand. In case of Edosaki sand, a natural sandy material, the unique relationship between the matric suction and degree of saturation has been shown despite of varying density.
Fig. 13. Shear moduli obtained in (a.) Edosaki sand; (b) non-plastic silt content Toyoura sand and (c.) kaolin content Toyoura sand

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