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Direct shear testing on unsaturated silty soils to investigate the effects of drying and wetting on shear strength parameters at low suction

Chaminda Pathma Kumara Gallage[i] and Taro Uchimura[ii]

[i] Lecturer, School of Urban Development, Queensland University of Technology, Brisbane, QLD 4001, Australia, chaminda.gallage@qut.edu.au

[ii] Associate Professor, University of Tokyo, Department of Civil Engineering, 7-3-1, Hongo, Bunkyo-Ku, Tokyo 113-8656, Japan, uchimura@geot.t.u-tokyo.ac.jp

Abstract

The unsaturated soil mechanics is receiving increasing attention from researchers and as well as from practicing engineers. However, the requirement of sophisticated devices to measure unsaturated soil properties and time consumption have made the geotechnical engineers keep away from implication of the unsaturated soil mechanics for solving practical geotechnical problems. The application of the conventional laboratory devices with some modifications to measure unsaturated soil properties can promote the application of unsaturated soil mechanics into engineering practice. Therefore, in the present study, a conventional direct shear device was modified to measure unsaturated shear strength parameters at low suction. Specially, for the analysis of rain-induced slope failures, it is important to measure unsaturated shear strength parameters at low suction where slopes become unstable. The modified device was used to measure unsaturated shear strength of two silty soils at low suction values (0 ~ 50 kPa) that were achieved by following drying path and wetting path of soil-water characteristic curves (SWCCs) of soils. The results revealed that the internal friction angle of soil was not significantly affected by the suction and as well as the drying-wetting SWCCs of soils. The apparent cohesion of soil increased with a decreasing rate as the suction increased. Further, the apparent cohesion obtained from soil in wetting was greater than that obtained from soil in drying. Shear stress-shear displacement curves obtained from soil specimens subjected to the same net normal stress and different suction values showed a higher initial stiffness and a greater peak stress as the suction increased. In addition, it was observed that soil became more dilative with the increase of suction. A soil in wetting exhibited slightly higher peak shear stress and more contractive volume change behaviour than that of in drying at the same net normal stress and the suction.

Key words: unsaturated soils, box shear tests, suction, hysteresis of suction, shear strength, dilatancy

Introduction

Conventional testing equipment such as triaxial and direct shear testing apparatus used for saturated soil testing have been modified and extensively used in the determination of the shear strength of unsaturated soils (Bishop and Donald 1961; Ho and Fredlund 1980; Gan et al. 1988; Ridley 1995, Vanapalli et al. 1996; Caruso and Tarantino 2004, Sedano et al. 2006). The modified direct shear apparatus is particularly convenient for determination of shear strength of unsaturated soils (Fredlund and Rahardjo 1993). This apparatus offers an advantage over the triaxial tests because the drainage path in the soil specimen is relatively much shorter. The time required to reach equilibrium conditions under applied matric suction could be about 1 ~ 2 days which is relatively much lower compared to that of required for a triaxial test (about 7 ~ 15 days depending on the sample height). The design of modified triaxial apparatus for unsaturated soils is complicated and the experimental set-up for a triaxial test is tedious. However, in triaxial apparatus, it is possible to apply a variety of confining pressures to the specimen allowing it to undergo different types of stress paths. Therefore, the data obtained from the triaxial apparatus can be used for critical state analysis of shear strength. In direct shear tests, the failure plane is pre-defined and the shear strength and deformation behaviour of unsaturated soils can be studied only over a limited range of displacement. However, some field-loading and failure conditions for unsaturated soils (landslides) can be modeled by simple shear test (Rahnenma et al. 2003) which is less time- consuming, east to set-up and less complicated.

It is necessary to modify the conventional direct shear apparatus in order to conduct tests on unsaturated soils. Donald (1956) conducted a series of direct shear tests on fine sands and coarse silts subjected to a negative pore-water pressure. The soil specimens were exposed to the atmosphere to maintain pore-air pressure, u_a, at zero. The negative gauge pore-water pressure was controlled by applying a constant negative head to water phase through a membrane at the base of the specimen. This apparatus limited the applied matric suction, (u_a-u_w), to 101 kPa (i.e., 1 atm) because water cavitates in the measuring system at a negative gauge pressure approaching to 101 kPa.

Hilf (1956) suggested that pore-air and pore-water pressures could both be raised to positive pressure in order to apply matric suctions higher than 101 kPa without cavitation in the measuring system. This proposed procedure is referred to as the axis-translation technique. This procedure is performed with the use of a high air entry disk that allows a passage of water but prevents the passage of air. Gan et al. (1988) used a modified conventional direct shear apparatus by which the sample could be subjected to matric suction greater than 101 kPa by employing the axis-translation technique. The high air entry ceramic disk is embedded in the sample base. Therefore pore-air and pore-water pressures can be controlled or measured independently as long as the matric suction of the soil does not exceed the air entry value of the ceramic disk.

The most commonly used shear strength equation for an unsaturated soil in which two independent stress state variables are used was proposed by Fredlund et al. (1978).The two stress state variables used in the equation are the net normal stress, $(\sigma_n - u_a)$, and the matric suction, $(u_a - u_w)$, where σ is total normal stress, u_a is pore-air pressure, u_w is pore-water pressure. The proposed shear strength equation has the following form:

$$\tau = (\sigma_n - u_a)\tan\phi' + c \qquad [1]$$

$$c = c' + (u_a - u_w)\tan\phi^b \qquad [2]$$

where τ is shear strength of unsaturated soil, c is apparent cohesion, c' is effective cohesion of saturated soil, ϕ' = is the shearing resistance angle which is assumed to be constant for all values of matric suction and is equal to that of saturated condition, ϕ^b is the angle of shearing resistance with respect to suction.

In this interpretation, the relationship between τ and (u_a-u_w) is assumed to be linear. However, (Escario & Saez 1986) determined that this relationship is actually non-linear. Later several other researchers observed the non-linear relationship between apparent cohesion and matric suction (Fredlund et al. 1987; Wheeler 1991; Ridley 1995; Ridley et al. 1995).

Although numerous experimental results can be found for the hysteresis between the drying and the wetting SWCCs, not much experimental evidences are available for the effects of the drying and the wetting on unsaturated shear strength. Prediction of rain-induced landslides is concerned, it is important to know unsaturated shear strength of soils for low suction where slopes become unstable. Therefore, this paper presents the results of modified direct shear test conducted on two silty soils for a low suction range (0~50 kPa). To obtain shear strength parameters with less time consumption compared to triaxial tests, a conventional direct shear apparatus was modified. The modified apparatus is similar to the device used by Donald (1956) and therefore it can be used to apply maximum suction of 101 kPa. Further, the test results obtained from the modified direct shear apparatus were used to investigate the effects of suction and dying-wetting hysteresis on the shear strength, the stiffness, the internal friction angle, and the apparent cohesion of test materials.

Test device

A modified direct shear apparatus which was employed in this study is shown in Figs.1 and 2. A ceramic disk with an air entry value of 100 kPa is embedded in the circular sample base. A specimen with a diameter of 60 mm and a height of 20 mm is prepared by wet-compaction on the saturated ceramic base to achieve pre-determined density.

The compartment below the ceramic disk is connected to a water tank that maintained its water level at the mid-height of the sample. The water in the tank can be subjected to negative pressure and the applied pressure can be measured by the pressure transducer which is connected to the bottom of the water tank (Figs. 1 and 2). The negative pressure measured by the pressure transducer is applied to the water phase in the sample through the saturated ceramic disk at the base of the sample. The soil specimen is exposed to the atmosphere through the gap (1 mm) between the two shear boxes and the porous stone at the sample top to maintain the pore-air pressure, u_a, at zero pressure. The constant matric suction, $(u_a\text{-}u_w)$, in the sample is equal to the applied negative pressure in to the water tank. This apparatus can be used to apply the maximum suction of 100 kPa.

The water tank is placed on an electronic balance which can be used to measure the weight up to 4.2 kg with an accuracy of 0.01g. The balance reading is used to calculate the movement of water into and out from the soil specimen. A thin layer of silicon oil is placed on the water surface in the tank to avoid water evaporation. It is assumed that equalization of the pore-water pressure in the sample is achieved when the balance reading is approximately constant.

The total vertical stress, σ_n, is applied by a double action bellofram cylinder mounted with a loading piston, which in turn is connected to the vertical loading shaft of the direct shear apparatus. The vertical loading shaft is connected to the base of the sample as shown in Figs. 1 and 2. In this system, the vertical load is applied by air pressure which is controlled through electro-pneumatic (E/P) transducer and an air volume booster. When the vertical load is applied, the load is transmitted through the sample base, the sample, and the top cap to the load- receiving plate. The vertical load is then measured by two load cells (Wu, 2003) attached to the load-receiving plate. The summation of the reading of two load cells is equal to the applied vertical load. This loading system can adjust the vertical load very quickly in order to maintain the constant vertical normal stress condition during shearing by taking into account the change in the sample cross section area.

A horizontal shaft coming from the motor can drive the upper shear box for the application of horizontal shear load to the specimen. As shown in Fig. 2, a load cell is connected to the horizontal shaft to measure the applied horizontal shear load. The minimum possible constant shear displacement rate that the motor can generate is 0.0008 mm/sec. Gan et al. (1988) found that the shear displacement rate of 0.00022 mm/sec or less is necessary to maintain the equilibrium pore-air pressure during shearing of clayey soils. Therefore, the minimum possible shear displacement rate of 0.0008 mm/sec was used in this study for silty sand.

Two linear voltage displacement transducers (LVDT) with a capacity of 10 mm are used to measure vertical and shear displacements. The analog-to-digital (A/D) converter used in this apparatus is one board of 12bit (4.9mV) with 8 channels in which a total of 6 channels were used. All analog output signals of transducers (three load cells, two LVDTs, one pore-water pressure transducer) are first amplified before sending to the A/D converter. The digital signals of the transducers can be converted in to physical values using relevant calibration factors and stored in the computer

Test materials

Two silty soils, namely Edosaki sand and Chiba soil, were employed in the experimental work of this study. Edosaki sand was procured from a natural slope in Ibaraki (Japan) and Chiba soil was excavated from a railway embankment in Chiba prefecture (Japan).

Wet sieving analysis and hydrometer tests were performed on Edosaki sand and Chiba soil as these materials contain fines (particles finer than 0.075 mm) contents of 17.1 and 36%, respectively. The grain-size distributions of test materials are shown in Fig. 3. Other basic soil properties such as specific gravity, maximum void ration, minimum void ratio, and plasticity index measured for two soils using JGS standard test methods are shown in Table 1. According to the Unified Soil Classification System, it was found that both soils were silty sand.

Fig. 4(a) and (b) depict the soil-water characteristic curves (SWCCs) for Edosaki sand and Chiba soil, respectively, obtained in the laboratory using a Tempe pressure cell. Both the drying and the wetting SWCCs were obtained for Edosaki sand using a sample with dry density of 1.35 g/cm^3 and while it was 1.25 g/cm^3 for Chiba soil. Direct shear tests were conducted on soil specimens of Edosaki and Chiba soils with dry density of 1.35 and 1.25 g/cm^3, respectively. Since the air-entry value of the ceramic disk used in Tempe pressure cell is 300 kPa, the measured SWCCs were restricted to the maximum suction of 200 kPa. As shown in Figs. 4(a) and (b), the equation proposed by Fredlund and Xing (1994) was used to fit the laboratory measured SWCC data. The fitting parameters used for Figs.4(a) and (b) are shown in Table 2.

The equation proposed by Fredlund & Xing (1994) is given in Equation [3]

$$\theta(\psi, a, n, m) = C(\psi)\frac{\theta_s}{\left\{\ln\left[e + (\psi/a)^n\right]\right\}^m} \quad [3]$$

where $C(\psi)$ is a correction function defined as

$$C(\psi) = 1 - \frac{\ln(1 + \psi / \psi_r)}{\ln[1 + (1000000 / \psi_r)} \qquad [4]$$

and $\theta =$ Volumetric water content, $\psi =$ Suction (kPa), ψ_r = Residual suction (kPa), θ_s = Water content at zero suction, *a, m, n* = Fitting parameters (*a* has the unit of pressure (kPa))

Method of testing

To obtain unsaturated shear strength parameters for Edosaki sand with an initial dry density of 1.35 g/cm^3, a series of constant suction consolidated drained direct shear (CSCDDS) tests were conducted by achieving the predetermined low suction values (i.e., 0, 10, 20, 50 kPa) following the drying or the wetting path. For each suction value, four tests were conducted under different net normal stress (σ_n-u_a) values (i.e., 34, 84, 135, 185 kPa). All specimens were prepared with an initial gravimetric water content of 8% in order to obtain the initial matrix suction greater than 50 kPa.

Another series of CSCDDS tests were conducted on Chiba soil to obtain its unsaturated shear strength parameters for an initial dry density of 1.25 g/cm^3. The constant suction values (i.e., 0, 10, 20, 50 kPa) were achieved following the drying or the wetting path. For each suction value, four tests with different net normal stress (σ_n-u_a) values (i.e., 25, 50, 100, 200 kPa) were conducted. All test specimens in this series were prepared with the initial gravimetric water content of 10% in order to obtain initial matrix suction greater than 50 kPa.

The test procedure for measuring unsaturated shear strength parameters in wetting and drying using the modified direct shear apparatus involves the sample preparing and setting-up of the test specimen, achieving the pre-determined suction following wetting or drying, and shearing the sample under the controlled suction. To obtain the saturated shear strength, the prepared sample is left under zero suction for saturation before shearing.

Preparing and setting-up of the test specimen

After saturation of the ceramic disk, a check was then made to ensure the saturation of the associated system following the procedure described by Huang (1994). To do the check, the fully saturated system (the ceramic disk, the compartment below the ceramic disk, and the tube connected to the base plate) was connected to a pore pressure transducer by the tube connected to the base plate. The surface of the ceramic disk was then wiped using a soft dry paper and the reading of the pressure transducer was observed with time. The saturation of the ceramic disk and the associated system was considered perfect when a negative pore-water pressure of about 60~70 kPa was observed after drying the surface of the disk by a soft dry paper (Huang, 1994). Otherwise, the described process of saturation was conducted again. Fig. 5 shows the typical result of saturation check of the ceramic disk and the associated system. After confirming the saturation, the water was flushed through the bottom of the ceramic disk in order to saturate the upper portion of the disk which dried-up during the saturation-check.

The base of the sample (surface of the ceramic disk) was brought 1 mm above the bottom edge of the lower shear box by adjusting the regulator of the air supply to the double action bellofram cylinder and then the vertical shaft was then clamped. The above procedure was aimed at preparing a sufficient space to allow the specimen to freely expand (dilate) during shearing. Thereafter, the upper and lower shear boxes were clamped placing spacers in between them to create a gap which would avoid the effect of frictional resistance between two shear boxes during shearing. The water tank was placed on the electronic balance and the water level was brought to the mid-height level of the specimen by adding or removing water. The LVDT for measuring vertical displacement was set at the specified position. Then all the readings of instruments were initialized as zero. The valve connecting the water tank and the compartment below the ceramic disk (both the ceramic disk and the compartment below it were saturated with water) was closed. The pore-water pressure transducer was then connected with the compartment to measure initial suction (negative pore-water pressure) of the sample.

The sample was directly prepared on the ceramic disk. The soil with initial gravimetric water content of 8% and 10% for Edosaki and Chiba soils, respectively required to achieve predetermined sample density was then poured into the mould and compacted by a metal rod until the soil surface leveled with the top surface of the upper shear box. This method of sample preparation has an advantage of controlling specified void ratio of the sample.

The assembly of the reaction frame and the modified load cells (Wu, 2003) was bolted to the cross roller case. The spacers between shear boxes were carefully pulled out without imposing any disturbance on the specimen and the LVDT for measuring shear displacement was set.

After starting storing data in the computer, it was allowed to stabilize the initial suction measurement. The clam of the vertical loading shaft was then released and predetermined vertical stress was applied with a constant rate of 2 kPa/min. At the same time, the water subjected to a predetermined pressure (0 or negative) was allowed to flow into the specimen through the ceramic disk at the bottom of the sample.

Suction in the sample before shearing

The specimen in the wetting path

The initial water content of soils (8% or 10%) was determined in order to achieve the initial suction greater than 50 kPa, and the suction was then reduced to predetermined value which was less than 50 kPa by wetting the soil sample. The negative air pressure was first applied to the water tank until the predetermined negative water pressure was read by the pressure transducer. The valve was then opened allowing water to flow into the specimen through the ceramic disk. During this water supply, the normal stress was gradually increased to a predetermined value. The change in the weight of the water tank was monitored during the wetting process and the pore-water pressure equalization in the specimen was assumed when there was no water flow into the specimen (the reading of the electronic balance was approximately constant). It generally took about 24~30 hours to obtain the pore-water pressure equalization in the sample. Fig. 6 shows the typical time histories of (measured and controlled) sample pore-water pressure, and the change in the weight of the water tank until the pore-water pressure equalization was achieved.

The specimen in the drying path

After preparing the specimen on the ceramic disk and setting up the apparatus, the specimen was first saturated allowing water to flow into the specimen through the ceramic disk embedded in the sample base. The saturation of the specimen was assumed when the change in the weight of the water tank was negligible. During sample saturation, the water tank was vented to the atmosphere and the pore-water pressure by the transducer was approximately equal to zero. At the same time, the normal stress was gradually increased to a predetermined value.

After sample saturation, negative air pressure was applied to the water tank until the pressure transducer reading became equal to the predetermined negative pore-water pressure value. When the valve between the tank and the sample base was opened, water flowed into the tank from the specimen until pore-water pressure equalization was achieved in the sample. Generally, it took about 12~24 hours for saturation and 24~30 hours for de-saturation. Fig. 7 shows the typical time histories of the pore-water pressure and the change in the weight of the water tank until the pore-water pressure equalization was achieved.

Shearing the specimen

After achieving the pore-water pressure equalization in the specimen under the predetermined constant suction (i.e., 0 ~50 kPa) and the predetermined vertical normal stress, the specimen was sheared with the shear displacement rate of 0.0008 mm/sec. Before shearing the specimen, the two LVDTs were initialized as zero and the reading of the shear load cell was made zero.

During shearing, the vertical normal stress was controlled at constant value by the feed back system taking into account the change in cross section area. The vertical and shear displacements were measured in mm. Negative and positive values of the vertical displacement were represented as contraction and dilation of the sample volume, respectively. The shear stress was calculated by using the measured shear force and corrected cross sectional area of the specimen. The output data from the measuring system was saved in the computer with the time interval of 2 sec. After the test was completed, the final water content of the specimen was measured by oven drying the specimen.

To obtain saturated shear strength properties of test materials, the sample was saturated by following the procedure explained in the section of “the specimen in the drying path” while increasing the normal stress. After achieving the saturation and the predetermined normal stress, the specimen was sheared maintaining the zero pore-water pressure measured by the transducer.

Test data analysis

The shear stress, τ, and the normal stress (vertical stress), σ_n, are calculated as follows:

$$\tau = SF/A_c \quad [5]$$

$$\sigma_n = NF/A_c \quad [6]$$

where SF is the shear force, NF is the normal force to the specimen, and A_c is the corrected area of the sheared specimen. For the cylindrical specimen of internal diameter D,

$$A_c = \frac{D^2}{2}\left(\theta - \frac{\delta}{D}\sin\theta\right) \quad [7]$$

Where $\theta = \cos^{-1}\left(\frac{\delta}{D}\right)$ in radians and δ is the relative displacement between the lower and upper shear boxes. δ is equal to shear displacement, d, as the lower shear box is fixed.

During shearing, the pore-air pressure, u_a, of the specimen was maintained zero as the specimen was exposed to atmosphere and the negative pore-water pressure, u_w, which was measured by the pore-water pressure transducer was maintained constant. Hence, the constant suction (u_a-u_w) of the specimen was equal to the absolute value of the applied negative pore-water pressure.

Results and discussions

The results of series of unsaturated direct shear tests on Edosaki and Chiba soils are presented and discussed in this section.

Effects of the net normal stress ($\sigma_n - u_a$) on the shear stress-shear displacement and volumetric behaviors

Figures 8(a) and (b) shows the effects of the net normal stress ($\sigma_n - u_a$) on shear stress-shear displacement and volume change behaviors of saturated (zero suction) Edosaki sand. It can be seen from the test results that the increase in the net normal stress ($\sigma_n - u_a$) increases the shear strength and the initial stiffness of saturated soils. Further, the volume of unsaturated soils becomes contractive (in figures, the negative vertical displacement represents the volume reduction of the specimen) as the net normal stress increases. Similar results can be observed from the four tests conducted under constant suction of 20 kPa which was achieved by following the wetting path (Figs. 9(a) and (b)). The effects of net normal stress on shear stress-shear displacement and volume change behaviors were further verified by conducting four tests with different net normal stress (i.e., 34, 84, 135, 185 kPa) under constant suction of 20 kPa which was achieved by following the drying path (Figs. 10(a) and (b)). Also the results of the four tests (different net normal stress, i.e., 25, 50, 100, 200 kPa) conducted on Chiba soil under constant suction of 20 kPa which was achieved by following the drying path exhibit the same behavior (Figs. 11(a) and (b)).

It can be seen from the results shown in Figs. 8 to 11 that the shear strength and the initial stiffness of unsaturated soils increase and the volume of soils becomes contractive as the net normal stress increases. These behaviors are independent of the degree of saturation, the method of suction achievement (drying or wetting), and soil type. Further, similar results have been observed by Huang (1994), Blight (1967), Gan and Fredlund (1995), and Mashhour et al. (1995). The increase in the net normal stress (or net confining stress) may force soil particles to closed-pack arrangement (volume contraction) during shearing. This volume contraction makes the sample denser. Eventually the shear resistance and the initial stiffness increase.

Effects of suction (u_w–u_a) on the shear stress-shear displacement and volume change behaviors

Figs. 12(a) and (b) show the shear stress-shear displacement and the volumetric behaviors, respectively, of four tests conducted on Edosaki sand specimens subjected to the same net normal stress of 34 kPa and different suction values (i.e 0, 10, 20, and 50 kPa) which were achieved by the wetting. Similar results obtained from four tests conducted with the same net normal stress of 135 kPa are shown in Figs. 13(a) and (b). Figs. 14(a) and (b) depict the shear stress-shear displacement and the volumetric behaviors, respectively, of four tests conducted on Edosaki sand specimens subjected to the same net normal stress of 34 kPa and different suction values (i.e 0, 10, 20, and 50 kPa) that were achieved by the drying. Further, Figs. 15(a) and (b) show the effects of suction (i.e. 0, 10, 20, and 50 kPa), which was achieved by wetting, on the shear stress-shear strain and volumetric behaviors of Chiba soil specimens subjected to the same net normal stress of 50 kPa.

The test results shown in Figs. 12 to 15 strongly demonstrate that suction has a great influence on the shear characteristic of unsaturated soil. The shear resistance of unsaturated soils increases as the suction increases. Moreover, it is evident from these figures when the shear stress is greater than 15 kPa, the stiffness of the shear stress-shear displacement curves increases as suction increases. This fact implies that the suction has a contribution to the stiffness of unsaturated soil so that the stiffness increases as the suction increases. These phenomena are consistent with the fact that inter-particle forces in soils increases as suction increases.

To clarify the physics of unsaturated particulate media, two spherical particles of radius R in contact are considered as shown in Fig.16. The water meniscus between them is bound by the two particles and by an imaginary torus. The small radius of this doughnut-shaped torus is r_1 and the distance from the centre to the inside wall of the torus is r_2. Therefore, the local contact force, F, which the meniscus imposes on the particles, contributing by the pressure of the fluid acting on the cross-sectional area of the meniscus and the surface tension (T_s) acting along the perimeter of the meniscus, can be expressed as (Cho and Santamarina 2001):

$$F = (u_a - u_w)(\pi r_2^2) + T_s(2\pi r_2) \quad (8)$$

This force is the only one arising from meniscus water and increases as suction increases. Therefore, the effects of matric suction result in a greater normal force holding the particles together and limiting slippage strength (Sawangsuriya 2006). As the results, the stiffness and the strength of unsaturated soils increase with increasing matric suction. However, this effect does not increase infinitely since the contact force (F) tends toward a limiting value due to progressive reduction in the meniscus radius as suction increases (Mancuso et al. 2002).

Another effect of suction on the unsaturated soil behavior can be clearly seen in the volumetric deformation during shearing. As shown in these figures, the soil is more contractive at zero suction and becomes less contractive with the increasing the value of suction prior to shear, regardless of the value of the net confining pressure. As soil structures become stronger and less deformable with the increase in suction, it is expected to exhibit dilative (less contractive) behavior with the increase in suction. However, it is noteworthy to mention that the effect of suction on volumetric behavior of unsaturated soil reduces as the net confining stress increases. Similar effects of suction on stress-strain and volumetric behaviors have been reported by Huang (1994), Blight (1967), Gan and Fredlund (1995), and Mashhour et al. (1995).

Effects of the drying and the wetting on shear stress –shear displacement and volume change behaviors

The results shown in Figs. 17 (a) and (b) were obtained by shearing two Edosaki sand specimens subjected to the same value of constant suction of 10 kPa and an identical net normal stress of 84 kPa. The only difference was the method used to achieve the suction: one was achieved by wetting and the other was by drying. It can be observed from the results that the specimen in wetting exhibits slightly greater peak (or failure) shear stress than the specimen in drying. Further, the specimen in wetting is more contractive than that of in drying. These findings were further verified by Figs. 18 (a) and (b) where two Edosaki sand specimens were sheared with the same suction value of 20 kPa and the same net normal stress of 84 kPa. Fig. 19 (a) and (b) depict shear stress-shear displacement and volume change behavior of two Chiba soil specimens sheared under the same constant suction values of 10 kPa and an identical net normal stress of 50 kPa. It can be seen that the results shown in Fig. 19 is consistent with those in Figs. 17 and 18. Though, the difference between wetting and drying stress-strain behavior is small, a significant difference in volume change during shearing can be observed.

The results shown in Figs. 17(a), 18(a), and 19(a) suggest that the specimen in wetting process (lower water content) has slightly higher peak shear strength than that in drying process (higher water content). These results contradict the previous funding that the higher water content in drying process results in the higher strength in the soil sample (Lamborn 1986; Vanapalli et al. 1996; Oberg and Sallfors 1997). Therefore, to investigate the possible reasons for the author's contradictory results, the detailed analyses were conducted on data of two identical specimens (one in drying and the other in wetting) measured during shearing.

Figure 20 shows the vertical displacement, degree of saturation, and suction change during shearing of two identical soil samples of Chiba soil samples re-compacted to initial dry density of 1.25 g/cm^3 at the initial gravimetric water content of 10%. Though, the both specimens were subjected to the same suction of 10 kPa, one was in drying process and the other was in wetting process. The both specimens were sheared under the constant vertical net stress of 50 kPa. As shown in Fig. 20(a), the vertical displacement suggests that the specimen in wetting is more contractive than the specimen is in drying. No water content change in the sample was observed in both the specimens during shearing and the final water contents (just after the test) were measured as 20.9 % and 18.7% for the sample in drying and wetting, respectively. The change in degree of saturation of the specimens during shearing was calculated using the final water content and the sample volume change. The sample volume change was calculated using the measured vertical displacement and assuming a constant cross section area which is equal to the cross section area of a shear box. Figure 20(b) shows the change in degree of saturation of the two specimens during shearing. As the both specimens exhibited contractive volume change, the degree of saturation increased as show in Fig. 20(b). Since the specimen in drying is more contractive than the one in wetting, the difference between the degree of saturation of the specimen in drying and the specimen in wetting decreased as shown in Fig. 20(b). It was observed by Wu et al. 2007 and Airey (1987) that the volumetric strain in the shear band in the direct shear test is significantly greater than the average volumetric strain of the specimen. Hence, the volume change in the shear band of the specimen in wetting and in drying could be more contractive and dilative, respectively, than the calculated values. Specially at peak stress, this volume change behaviour could make the degree of saturation of the shear band of the specimen in wetting to be greater than that of in drying. This phenomenon may give higher strength to the specimen in wetting than to the one in drying. The authors' experimental results may then agree with the results of Lamborn (1986), Vanapalli et al. 1996, and Oberg and Sallfors (1997).

The suction in the specimens was controlled by applying negative pressure to the water supplying tank and therefore, no change in suction was observed in the specimen during shearing (Fig. 20(c)).

It is worthy to note that the difference between drying and wetting shear strengths presented in this paper is rather small and therefore, this difference could be within the accuracy of the measuring instruments such as LVDTs and load cells associated with the modified direct shear apparatus which was employed in this study.

Effects of suction (u_w–u_a) and wetting-drying on shear strength parameters (*c* and ϕ')

The direct shear test results on unsaturated soils demonstrated the significant effect of suction on the shearing resistance on which a more detailed and quantitative analysis will be made in this section. In this analysis, the failure of a specimen refers to its peak shear stress. The correction for the dilatancy effect was not made on the measured shear stresses at failure since the majority of direct shear tests exhibited contractive behavior.

To obtain the shear strength parameters (the apparent cohesion (*c*) and the internal friction angle (ϕ')) corresponding to a particular suction value, four soil specimens subjected the same suction and four different net normal stresses (i.e. 34, 84, 134, and 184 kPa) were sheared. Implying the mentioned failure criterion, the failure shear stress for each test was then obtained. Plotting these failure shear stresses with the corresponding net normal stress and performing best linear-fitting on the plotted data, the apparent cohesion(c) and the internal friction angle(ϕ') corresponding to the particular suction value were obtained as shown in Fig. 21.

Figs. 22 (a) and (b) depict, respectively, the variation of ϕ' and c with the increase in suction for Edosaki sand. Furthermore, these figures demonstrate the effect of wetting–drying on ϕ' and c. Figs. 23 (a) and (b) illustrate similar effects of suction on ϕ' and c obtained from the direct shear tests on Chiba soil at the initial dry density of 1.25 g/cm^3.

It can be seen from the Figs. 22 (a) and 23 (a) that the effects of the suction and the drying-wetting hysteresis of the SWCCs on ϕ' are insignificant. The ϕ' represents the frictional resistance at inter-particle contacts. This may be affected by particles' surface roughness (Christopher et al. 2008), particle crushing during loading (Hamidi et al. 2009; Bolton 1986), and the density (dilatancy effect) (Bolton 1986), but not the suction or water content (Cokca et al 2004; Mouazen et al. 2002).

Figs. 22 (b) and 23 (b) show that the apparent cohesion (c) increases with a decreasing rate as the suction increases. This result is consistent with the findings of Escario & Saez 1986; Fredlund et al. 1987; Wheeler 1991; Ridley 1995; Ridley et al. 1995.The increase in suction may increase the inter-particle bonding force which can be attributed to the cohesive force between particles. Furthermore, these figures reveal that the c at wetting is greater than that of in drying and this is consistent with the finding of Han et al. (1995). A possible reason for this behavior is discussed under the sub-topic of "Effects of the drying and the wetting on shear stress –shear displacement and volume change behaviors"

Conclusions

The shear behavior of unsaturated silty soils subjected to low suction (0 ~50 kPa) and low net normal stress was investigated in this study by using a modified direct shear apparatus. A series of shear tests was conducted on Edosaki and Chiba soils under various combinations of the net normal stress and the suction. The suction was achieved by either wetting or drying in order to investigate the effect of wetting-drying (the hysteresis of SWCC) on the shear behavior of unsaturated soils. The main conclusions of this study are follows:

- The shear resistance and the initial shear stiffness increase with the increase in the net stress (net confining or net normal). The volume change of the specimen becomes more contractive as the net stress increases.
- It was observed that soil subjected to a higher value of suction exhibits a stiffer shear stress-shear displacement curve and a greater peak shear stress as compared to the one subjected to a lower value of suction. Further, a soil having a higher suction shows less contractive volume change during shearing.
- The internal friction angles of tested materials are independent from the suction and the wetting-drying hysteresis of SWCC.
- The remarkable non-linearity between the apparent cohesion and the suction was observed in the test results. The test data indicated that the apparent cohesion increases generally at a decreasing rate with the increase of suction.
- Soil in wetting exhibited higher apparent cohesion than soil in drying at the same suction.
- The direct shear test results revealed that soil in wetting is more contractive than the soil in drying at the same suction and the net normal stress.

Acknowledgement

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Table 1:

Properties	Edosaki sand	Chiba soil
Specific gravity, G_s	2.75	2.72
Mean Grain size, D_{50} [mm]	0.22	0.14
Coefficient ofuniformity, $C_u= D_{60}/D_{10}$	16.40	54.40
Coefficient of gradation, $C_c=(D_{30})^2/(D_{10}*D_{60})$	3.97	1.95
Sand content, [%]	83.60	64.00
Fines content, [%]	17.10	36.00
Maximum void ratio, e_{max}	1.59	1.74
Minimum void ratio, e_{min}	1.01	1.11
Liquid limit [%]	NP	25.78
Plastic limit [%]	NP	23.52
Plastic index	NP	2.26

Physical properties of test materials

Table 2. Fredlund and Xing (1994) fitting parameters used in Figs. 4 (a) and (b)

Fredlund & Xing fitting parameters	Edosaki sand (ρ_d = 1.35 g/cm^3)		Chiba soil (ρ_d = 1.25 g/cm^3)	
	Drying	Wetting	Drying	Wetting
θ_s	0.412	0.370	0.530	0.425

a [kPa]	3.320	1.674	3.696	0.642
m	0.403	0.400	0.195	0.163
n	5.453	5.512	10.729	6.406
Ψ_r [kPa]	10.130	6.086	11.913	3.039

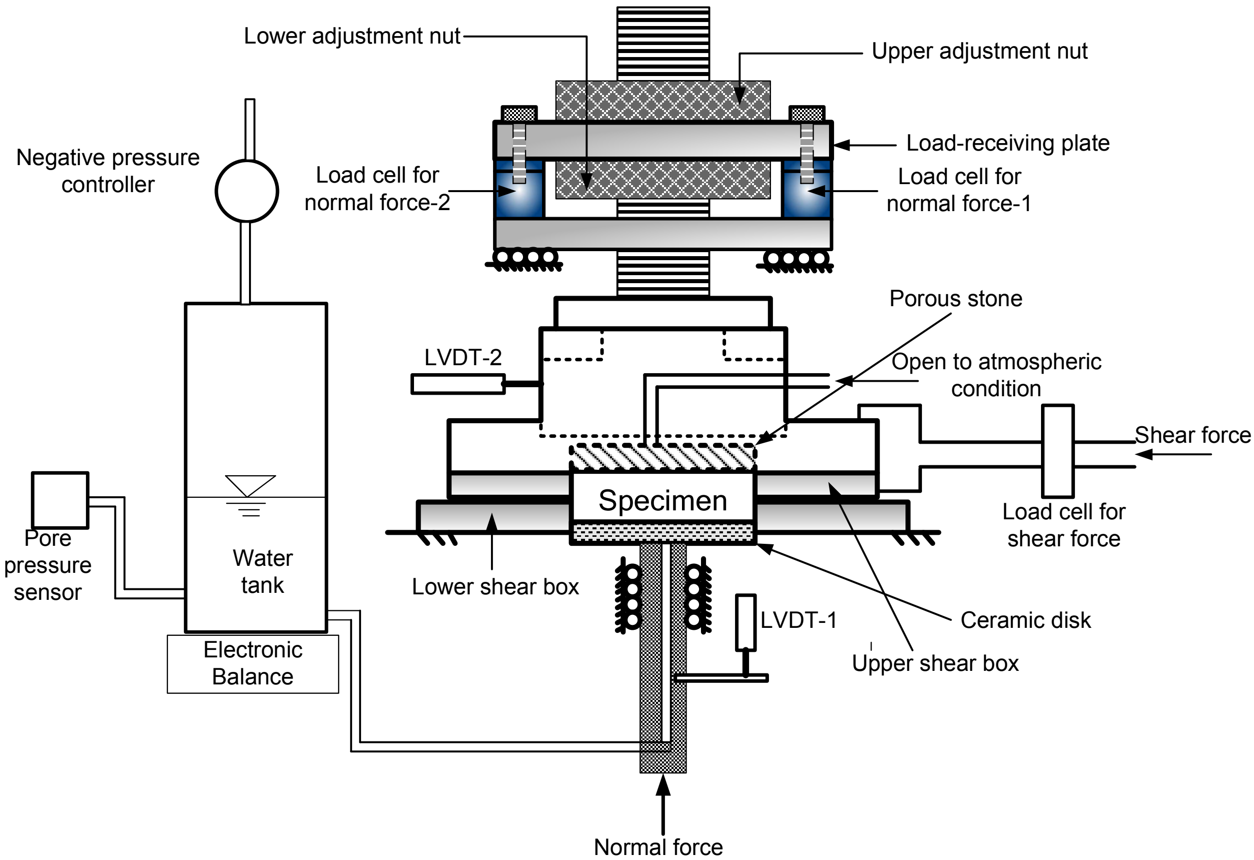

Fig. 1: Schematic diagram of modified direct shear apparatus

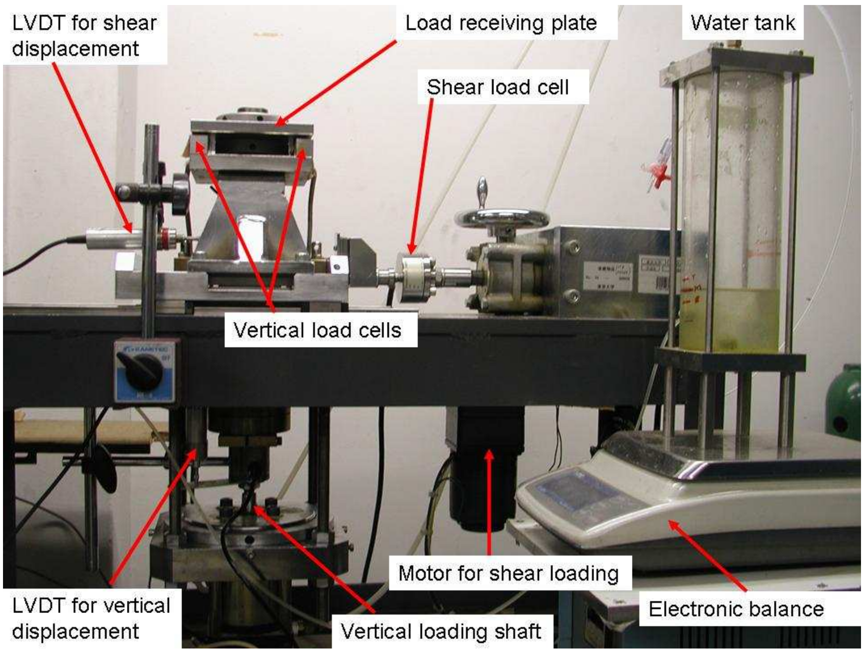

Fig. 2: A photo showing the components of modified direct shear apparatus

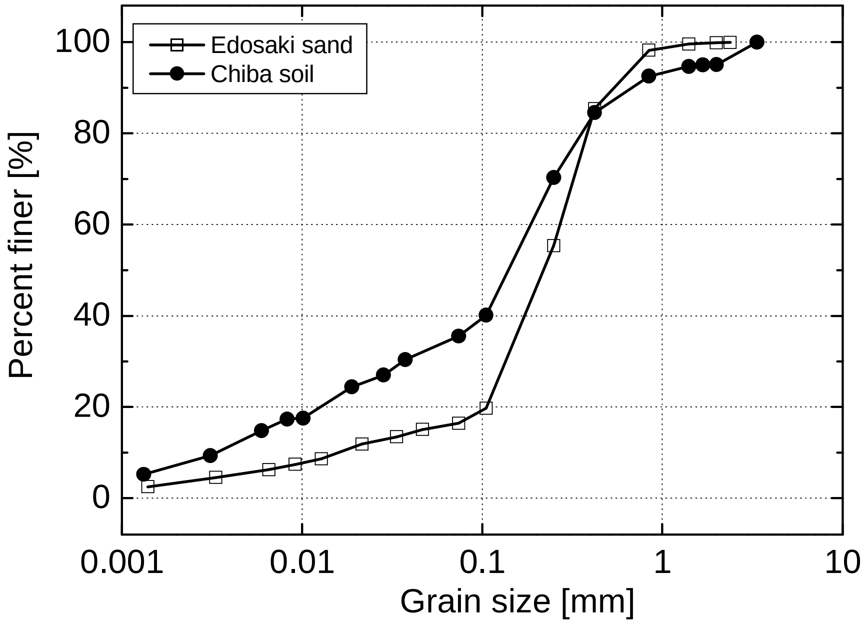

Fig. 3: Grain size distribution curves for test materials

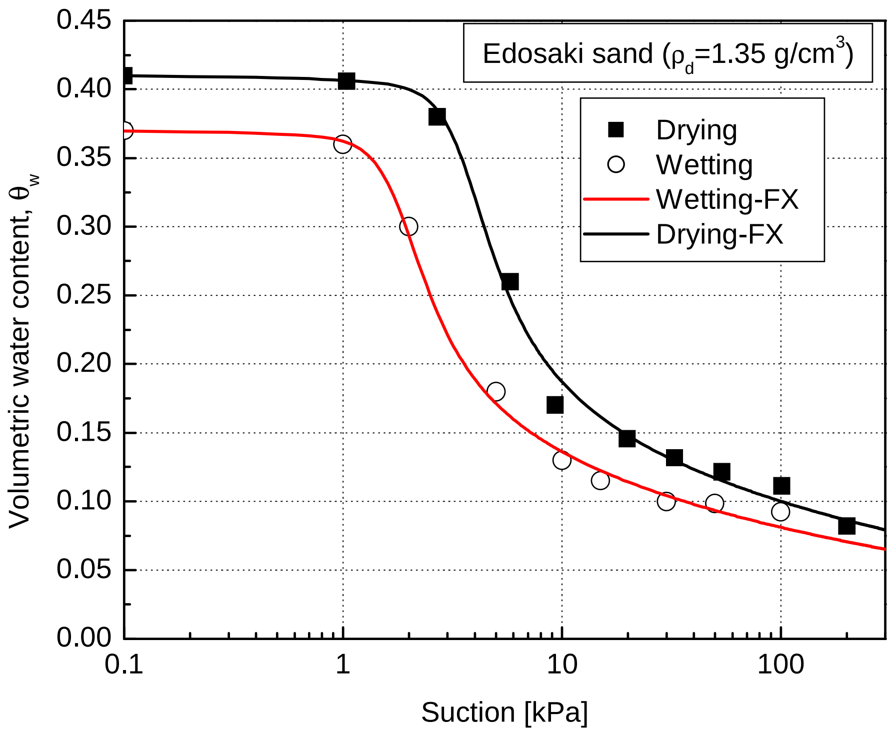

Fig. 4 (a): Soil-water characteristic curves for Edosaki sand

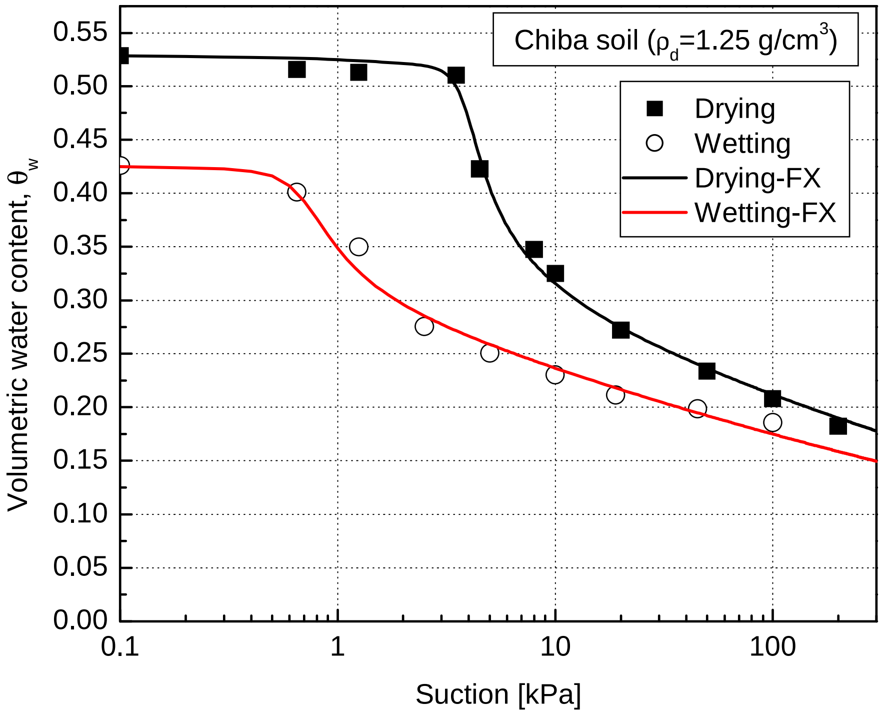

Fig. 4 (b): Soil-water characteristic curves for Chiba soil

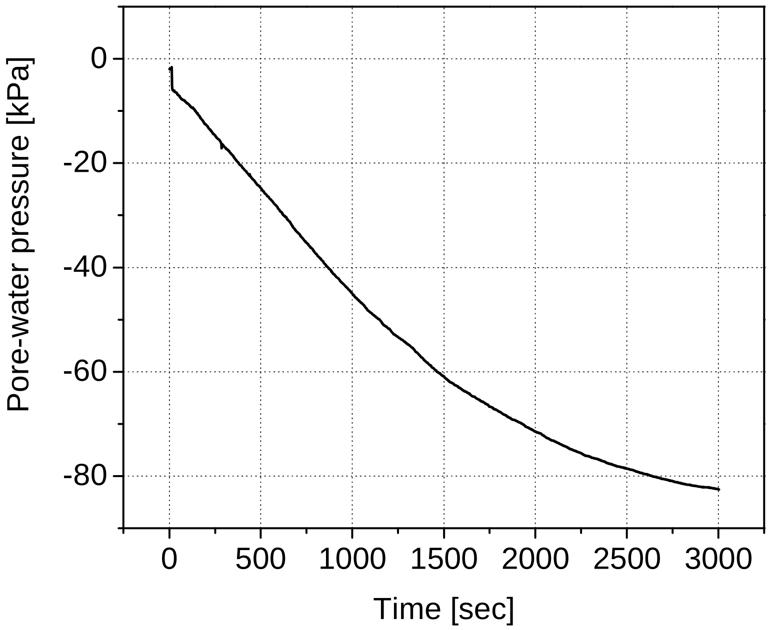

Fig. 5: The time-history of pore-water pressure measurement after wiping the ceramic surface

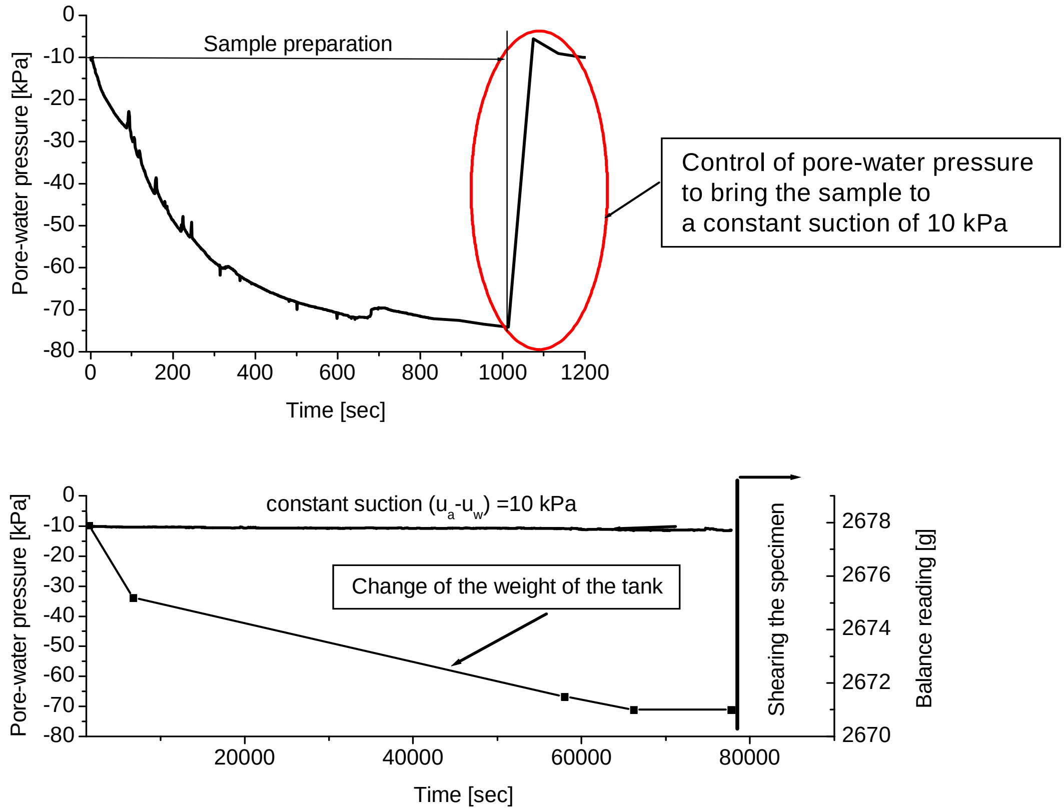

Fig. 6: Sample preparation and bringing the sample to 10 kPa suction following the wetting

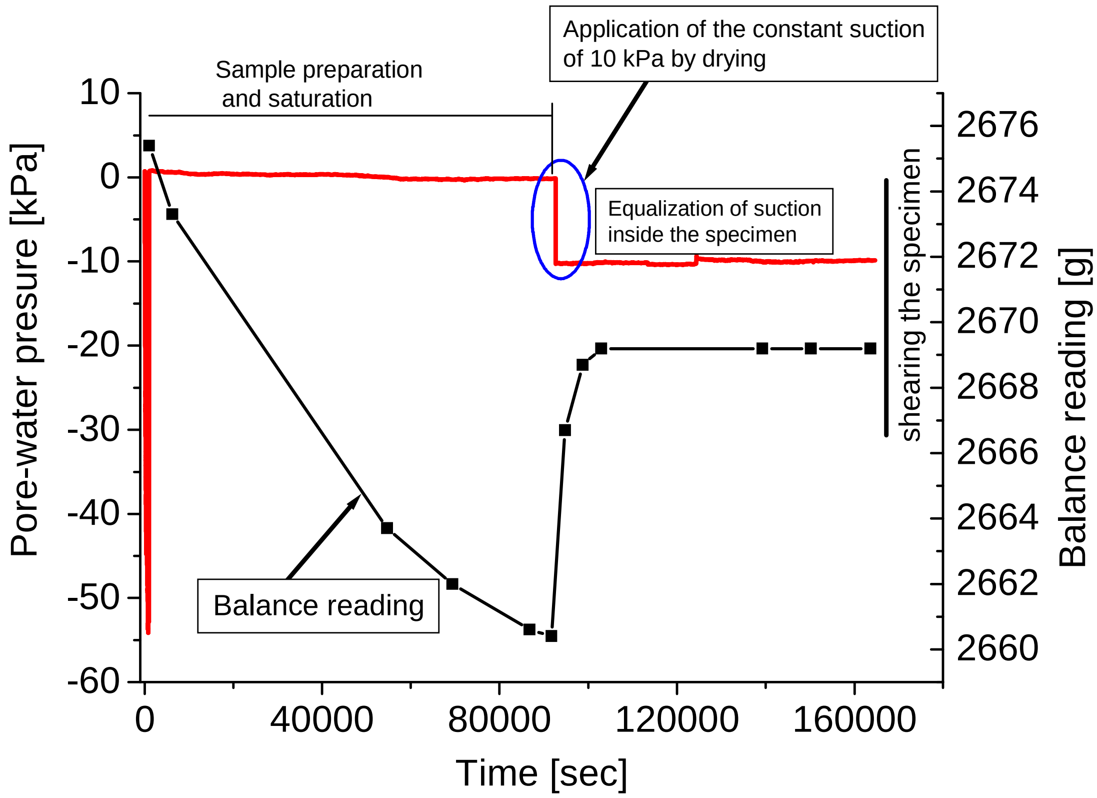

Fig. 7: Sample preparation and bringing the sample to 10 kPa suction following the drying

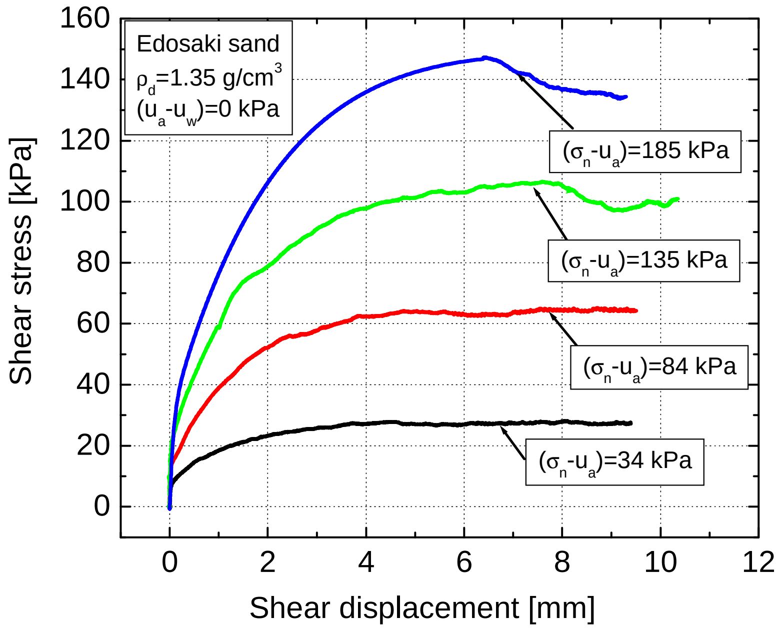

Fig. 8(a): Effects of the net normal stress on shear stress-shear displacement behaviour of saturated Edosaki sand.

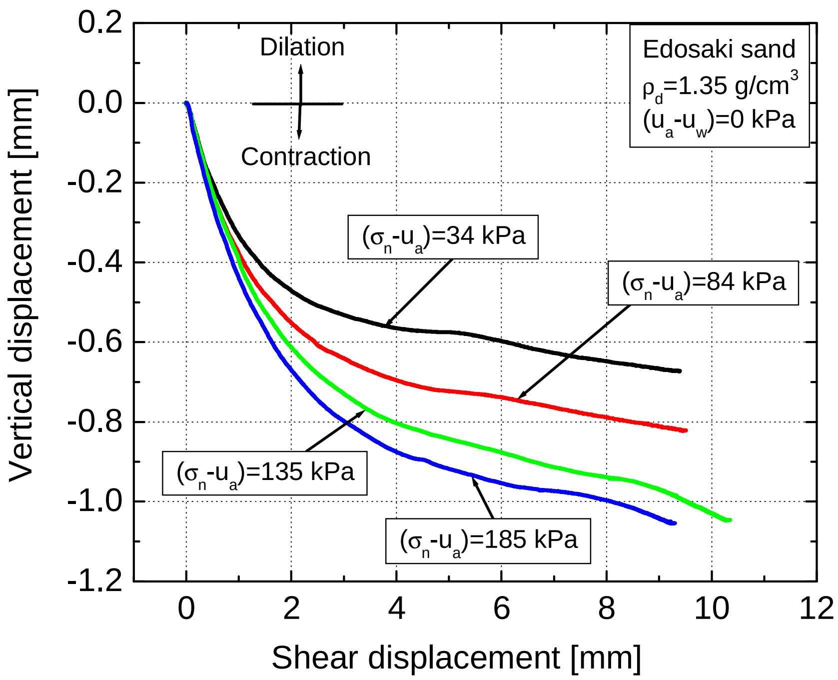

Fig. 8(b): Effects of the net normal stress on volumetric behaviour of saturated Edosaki sand.

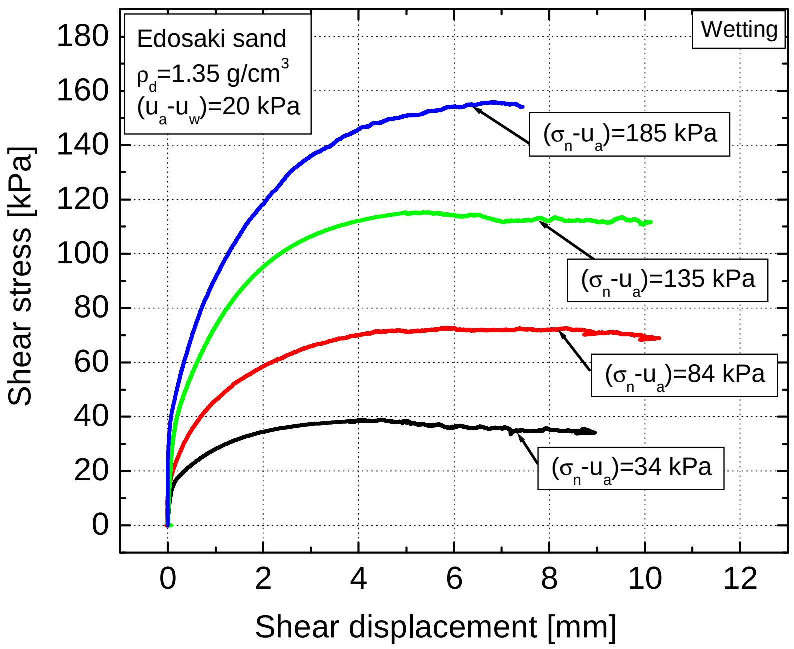

Fig. 9(a): Effects of the net normal stress on shear stress-shear displacement behaviour of unsaturated Edosaki sand (suction 20 kPa achieved by following the wetting)

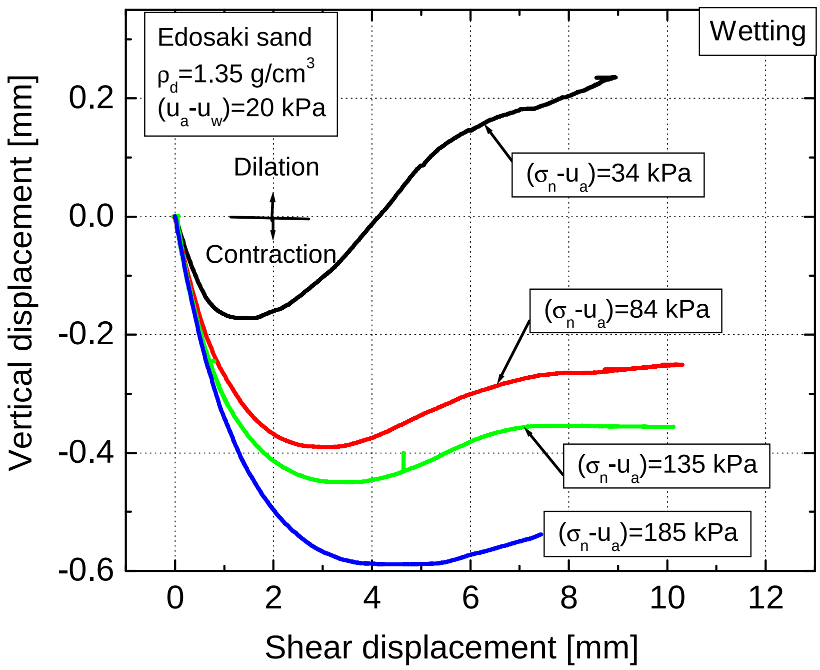

Fig. 9(b): Effects of the net normal stress on volumetric behaviour of unsaturated Edosaki sand (suction 20 kPa achieved by following the wetting)

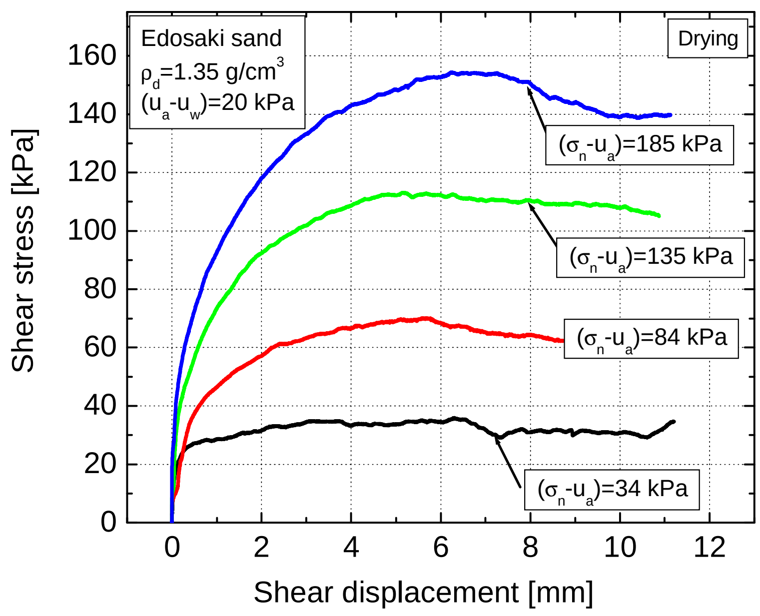

Fig. 10(a): Effects of the net normal stress on shear stress-shear displacement behaviour of unsaturated Edosaki sand (suction 20 kPa achieved by following the drying)

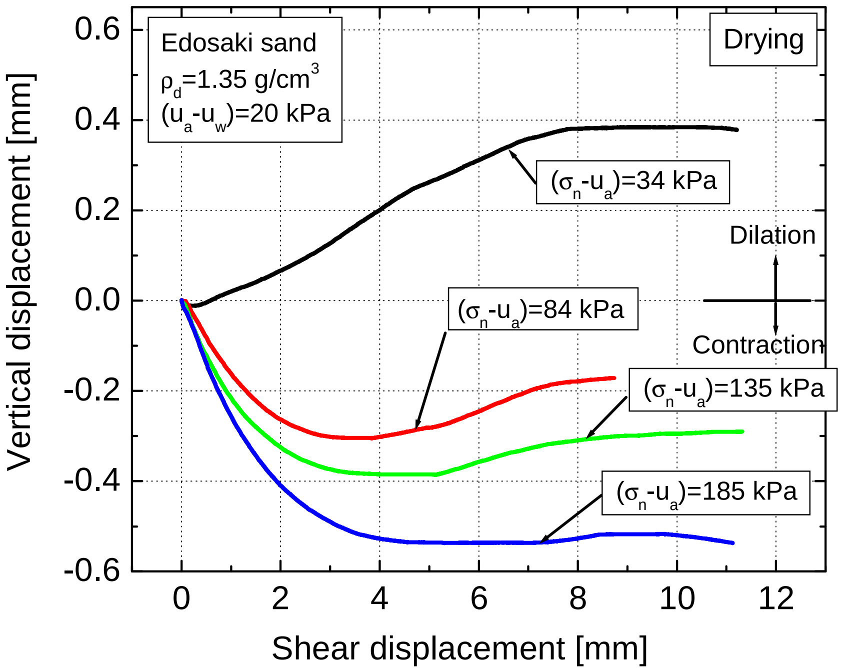

Fig. 10(b): Effects of the net normal stress on volumetric behaviour of unsaturated Edosaki sand (suction 20 kPa achieved by following the drying)

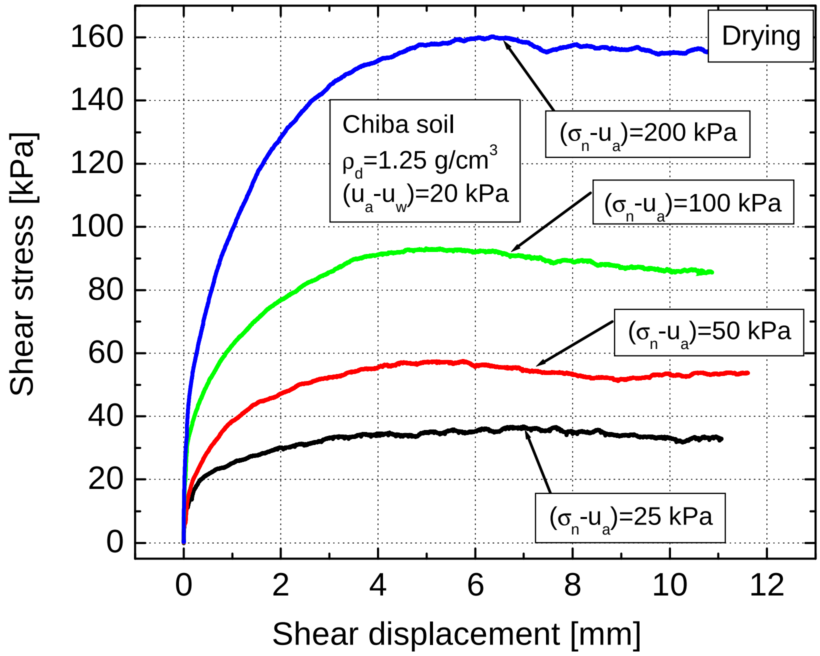

Fig. 11(a): Effects of the net normal stress on shear stress-shear displacement behaviour of unsaturated Chiba soil (suction 20 kPa achieved by following the drying)

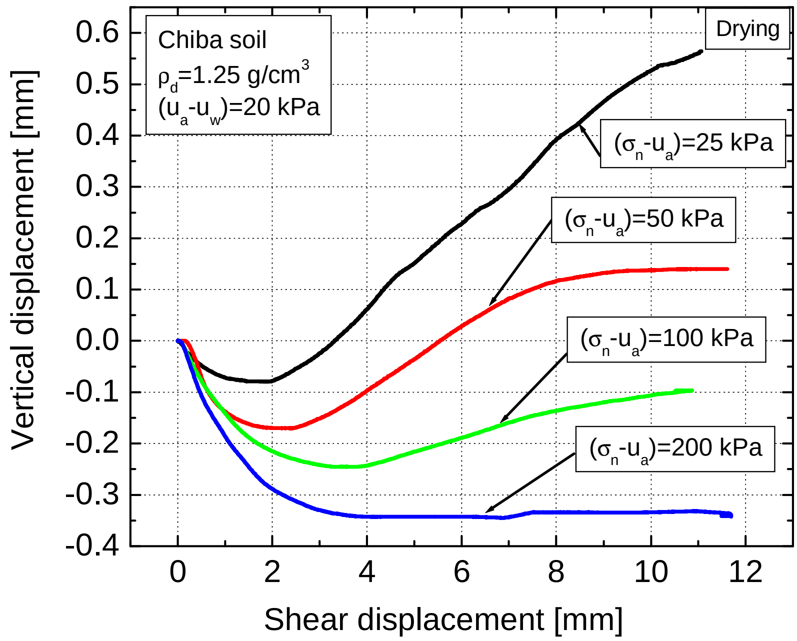

Fig. 11(b): Effects of the net normal stress on volumetric behaviour of unsaturated Chiba soil (suction 20 kPa achieved by following the drying)

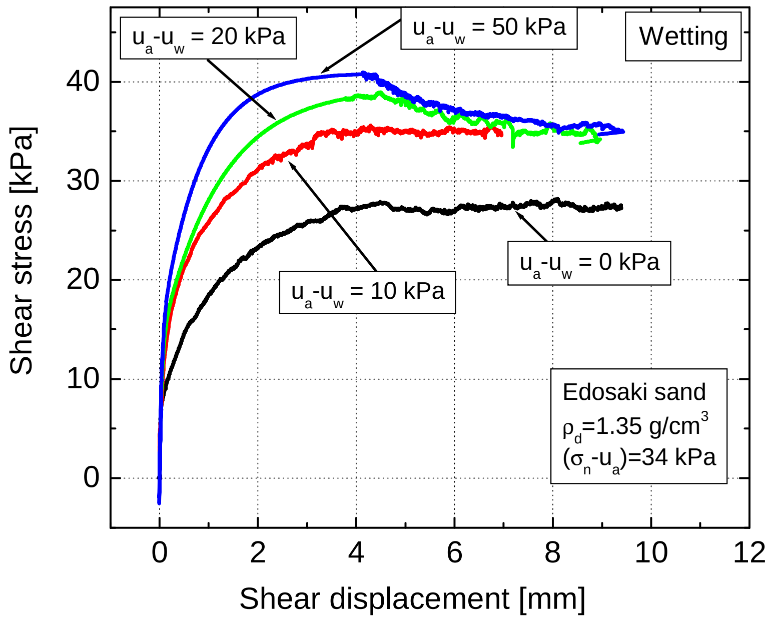

Fig. 12(a): Effects of the suction on shear stress-shear displacement behaviour of Edosaki sand (the net normal stress is 34 kPa for all tests and the suction was achieved by wetting)

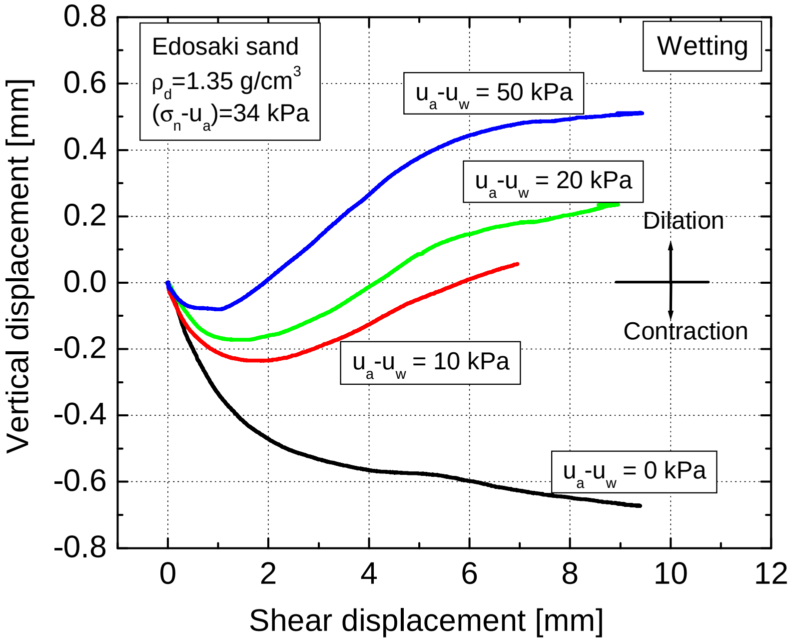

Fig. 12(b): Effects of the suction on volumetric behaviour of Edosaki sand(the net normal stress is 34 kPa, the suction was achieved by wetting)

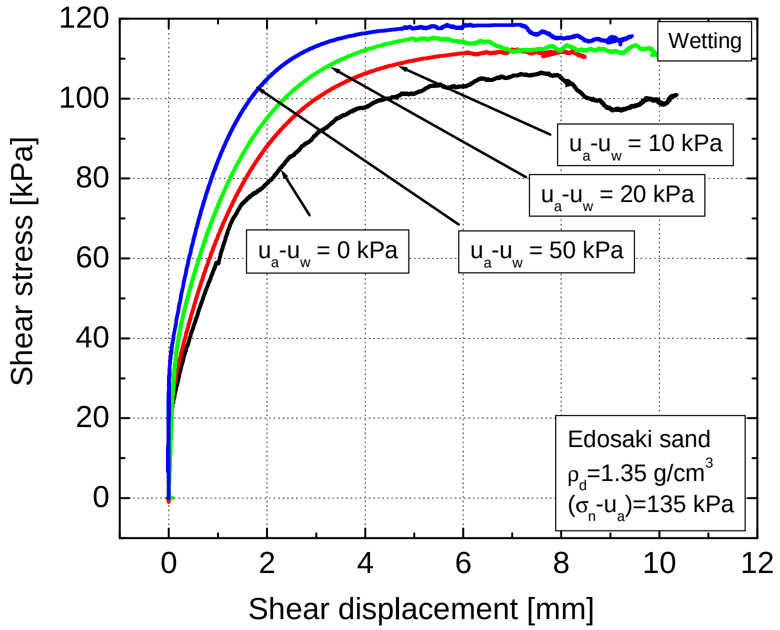

Fig. 13(a): Effects of the suction on shear stress-shear displacement behaviour of Edosaki sand (the net normal stress is 135 kPa for all tests and the suction was achieved by wetting)

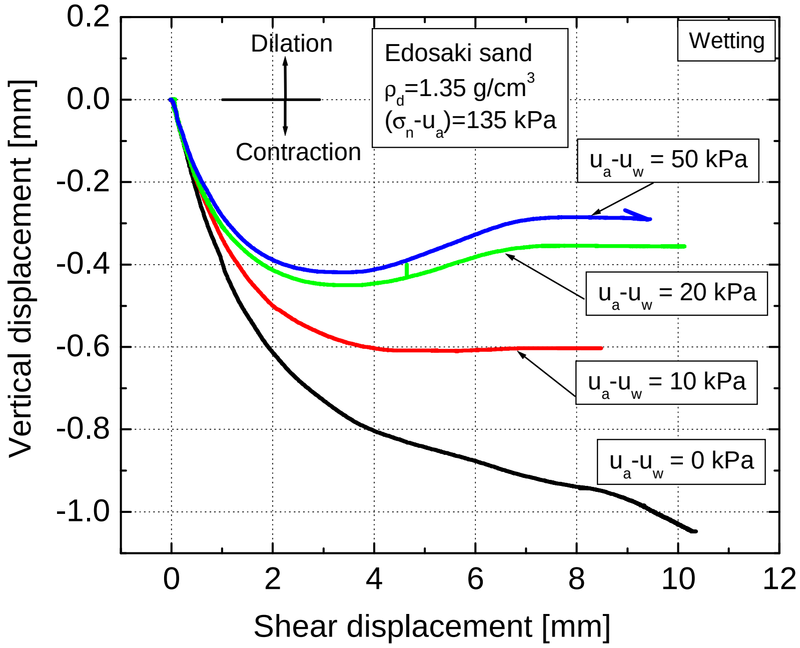

Fig. 13(b): Effects of the suction on volumetric behaviour of Edosaki sand(the net normal stress is 135 kPa, the suction was achieved by wetting)

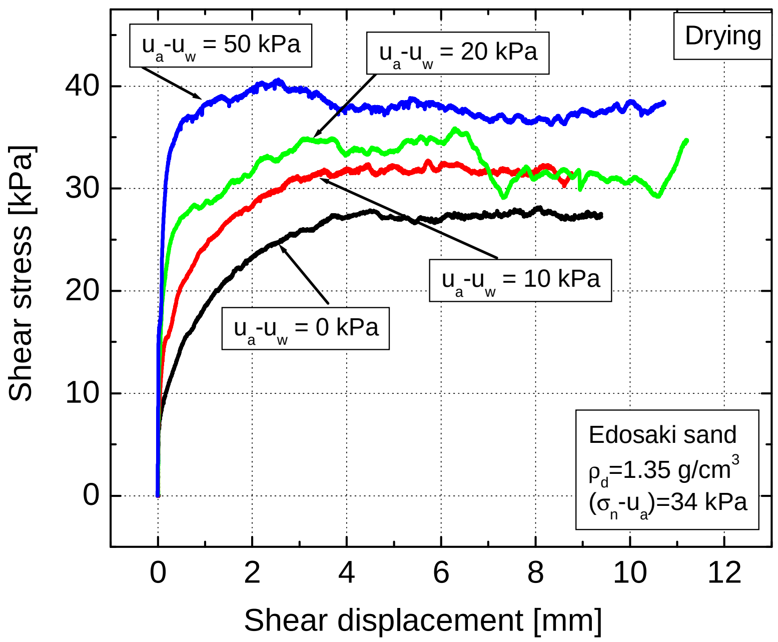

Fig. 14(a): Effects of the suction on shear stress-shear displacement behaviour of Edosaki sand (the net normal stress is 34 kPa for all tests and the suction was achieved by drying)

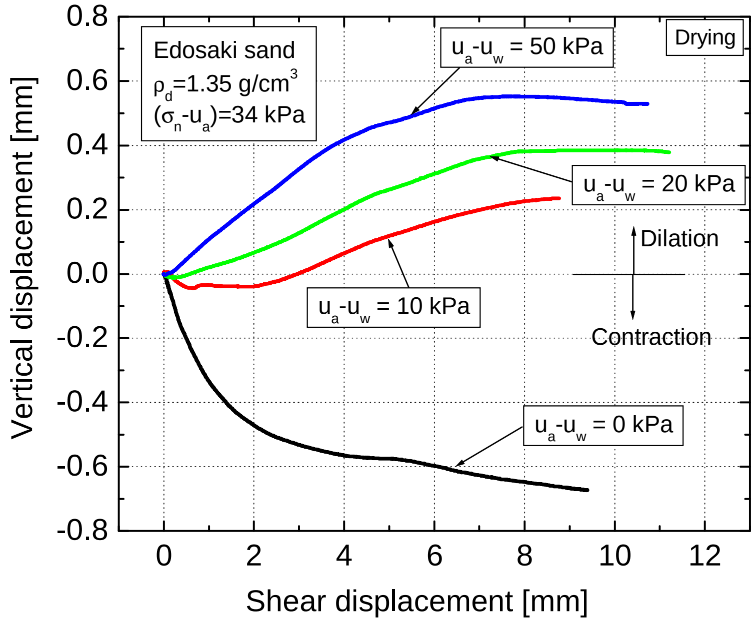

Fig. 14(b): Effects of the suction on volumetric behaviour of Edosaki sand(the net normal stress is 34 kPa, the suction was achieved by drying)

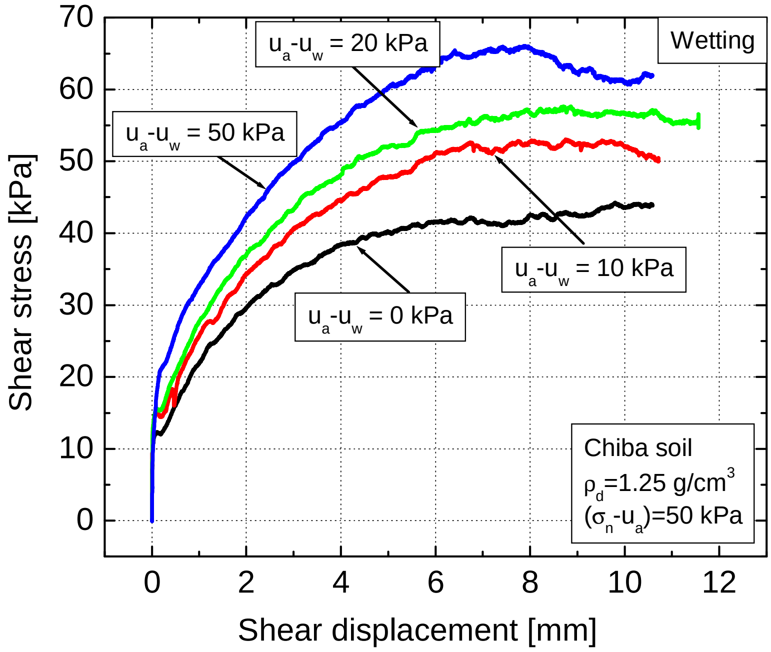

Fig. 15(a): Effects of the suction on shear stress-shear displacement behaviour of Chiba soil (the net normal stress is 50 kPa for all tests and the suction was achieved by wetting)

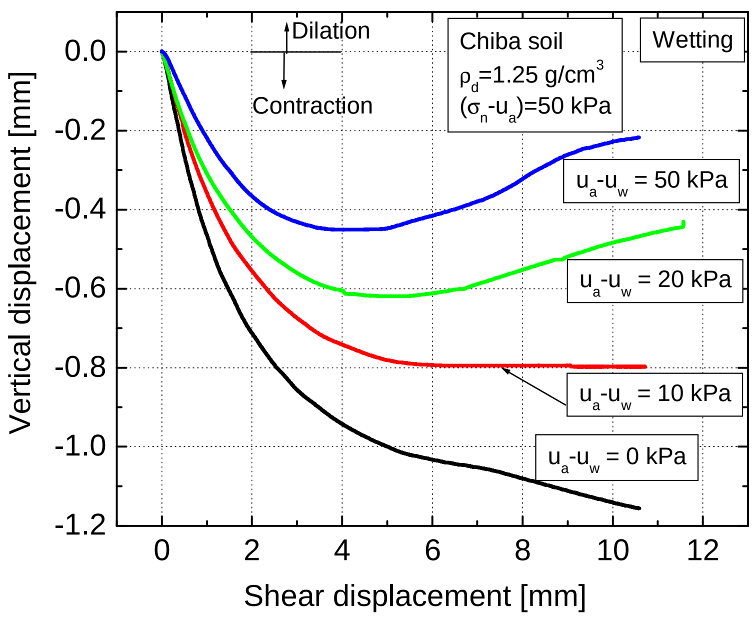

Fig. 15(b): Effects of the suction on volumetric behaviour of Chiba soil (the net normal stress is 50 kPa, the suction was achieved by wetting)

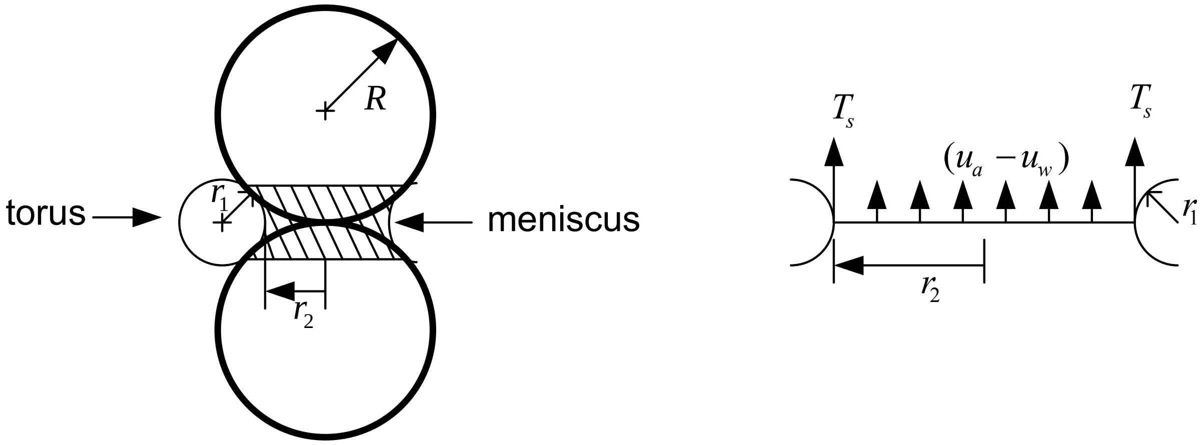

Fig. 16: Microscale model – schematic of unsaturated spherical particles (Cho and Santamarina 2001)

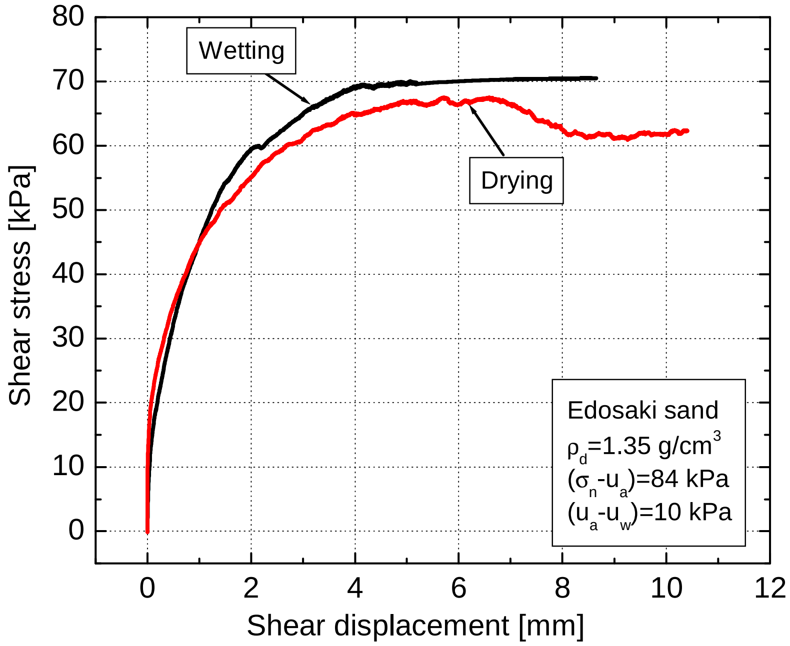

Fig. 17(a): Effects of drying-wetting on shear stress-shear displacement behaviour of Edosaki sand (the net normal stress is 84 kPa, the suction is 10 kPa)

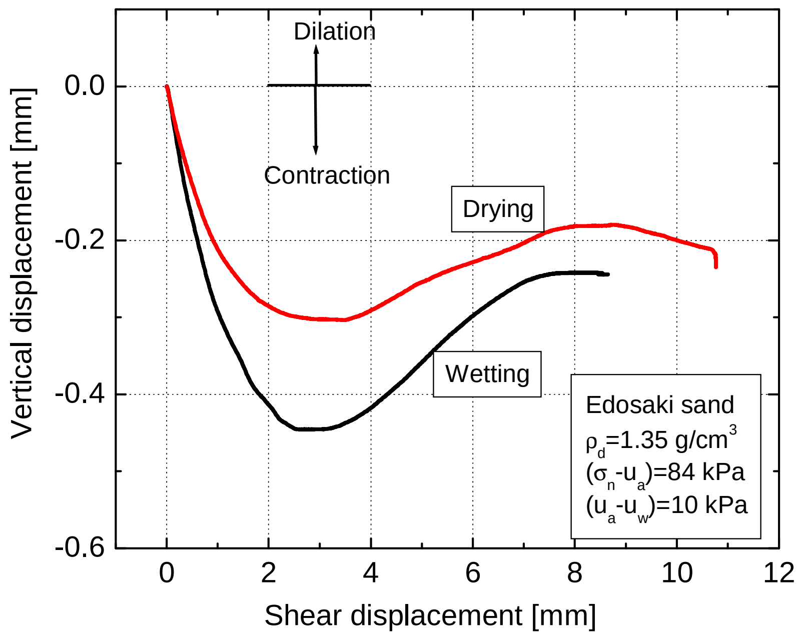

Fig. 17(b): Effects of drying-wetting on volumetric behaviour of Edosaki sand (the net normal stress is 84 kPa, the suction is 10 kPa)

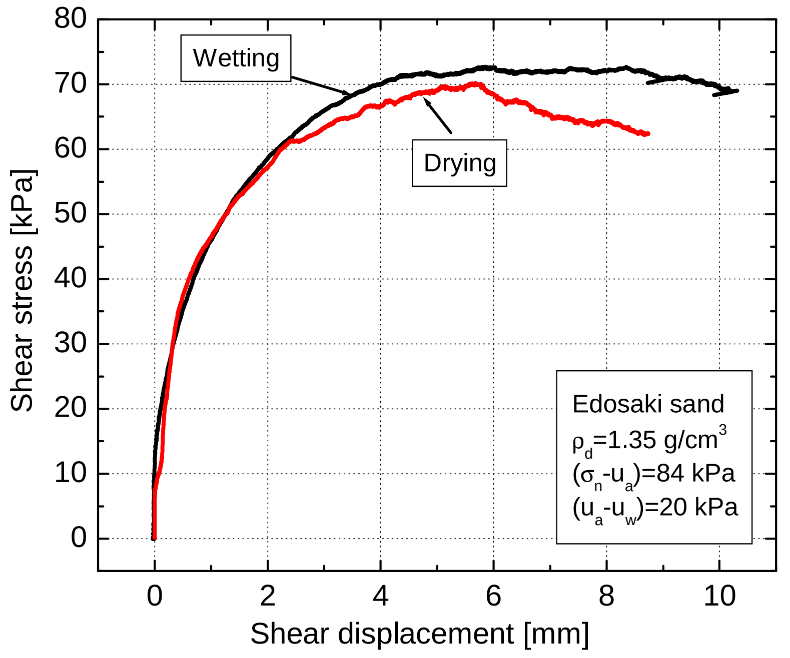

Fig. 18(a): Effects of drying-wetting on shear stress-shear displacement behaviour of Edosaki sand (the net normal stress is 84 kPa, the suction is 20 kPa)

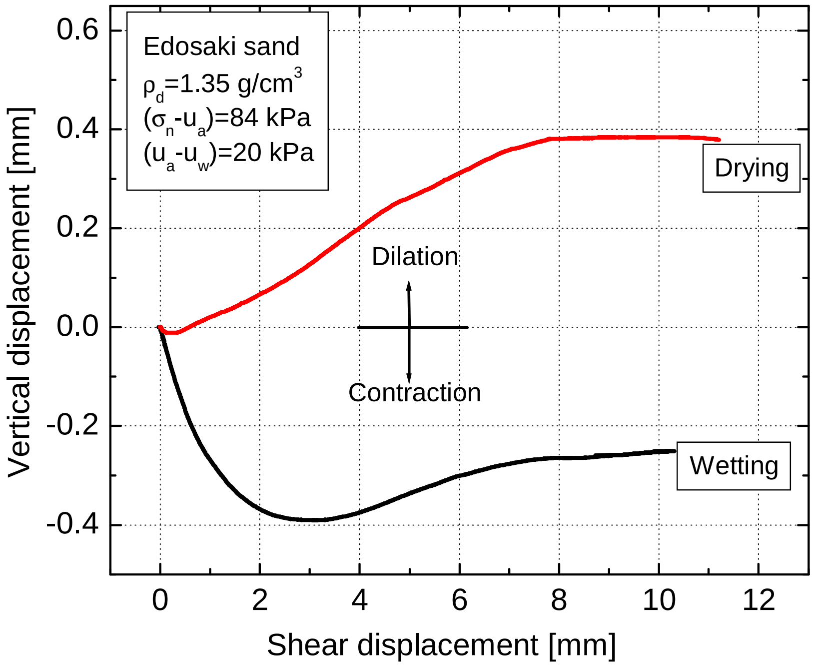

Fig. 18(b): Effects of drying-wetting on volumetric behaviour of Edosaki sand (the net normal stress is 84 kPa, the suction is 20 kPa)

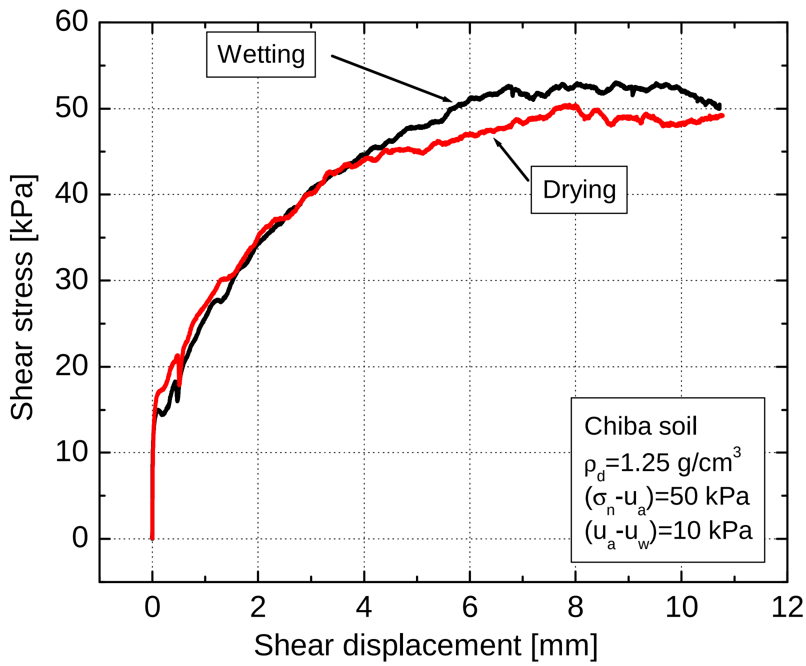

Fig. 19(a): Effects of drying-wetting on shear stress-shear displacement behaviour of Chiba soil (the net normal stress is 50 kPa, the suction is 10 kPa)

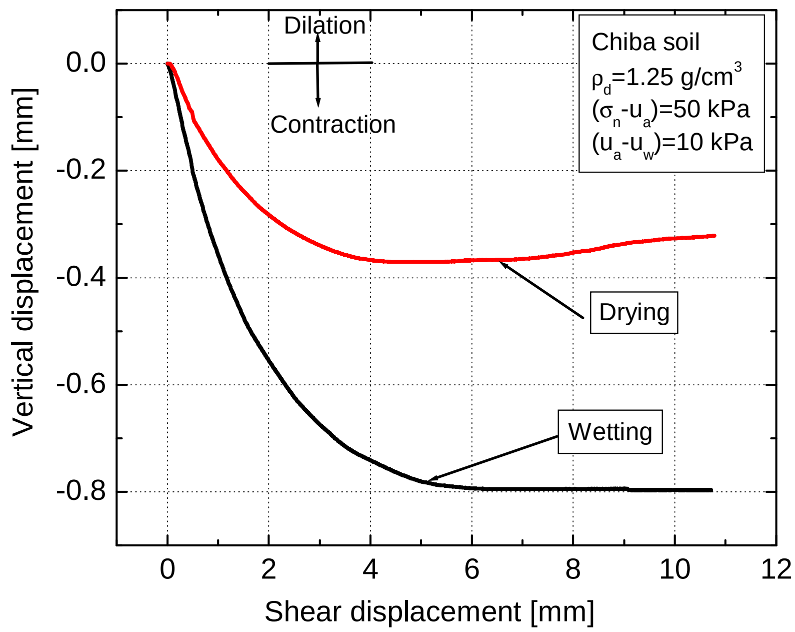

Fig. 19(b): Effects of drying-wetting on volumetric behaviour of Chiba soil (the net normal stress is 50 kPa, the suction is 10 kPa)

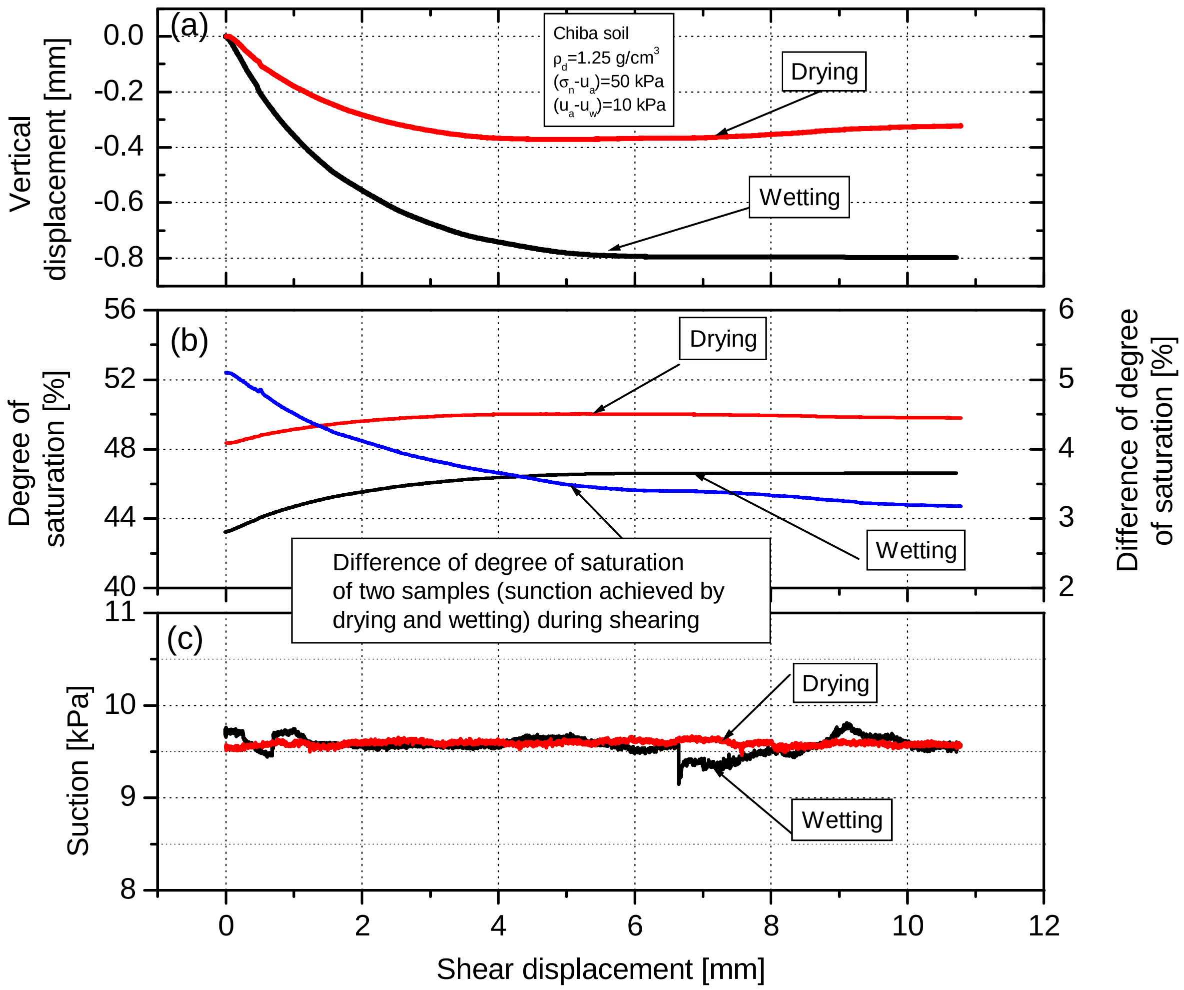

Fig. 20: Behaviour of volume change (vertical displacement), degree of saturation, and suction during shearing of two identical soil samples with 10 kPa suction achieved by drying and wetting

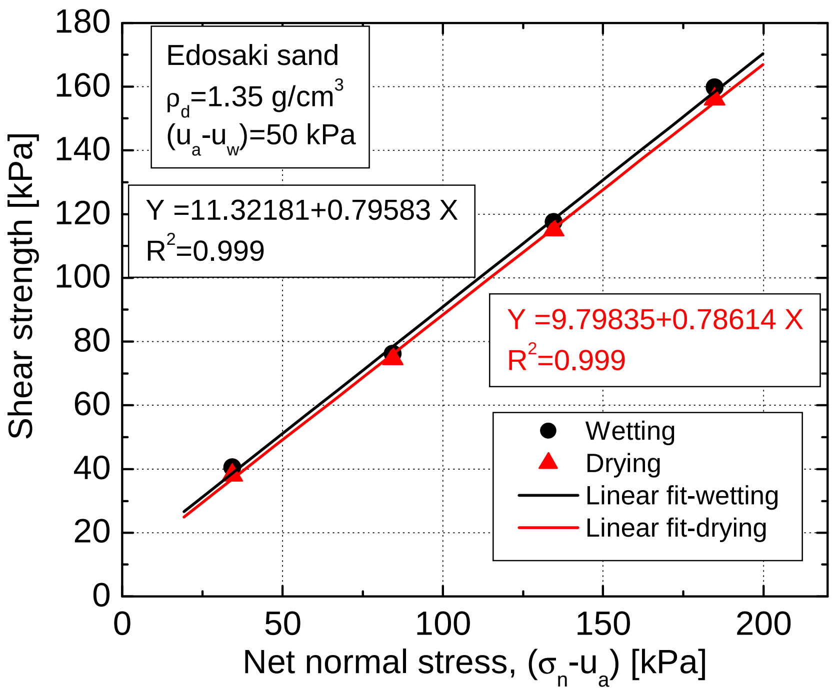

Fig. 21: The net normal stress vs the peak shear stress for the four tests conducted on Edosaki sand specimens subjected to the same suction of 20 kPa which was achieved by wetting

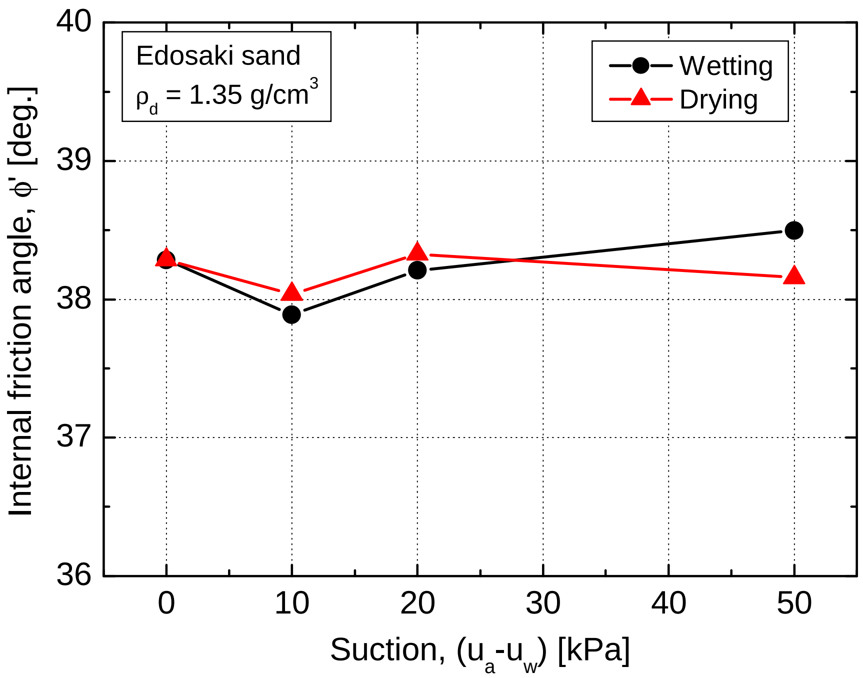

Fig. 22(a): Effects of the suction and drying-wetting on the internal friction angle of Edosaki sand

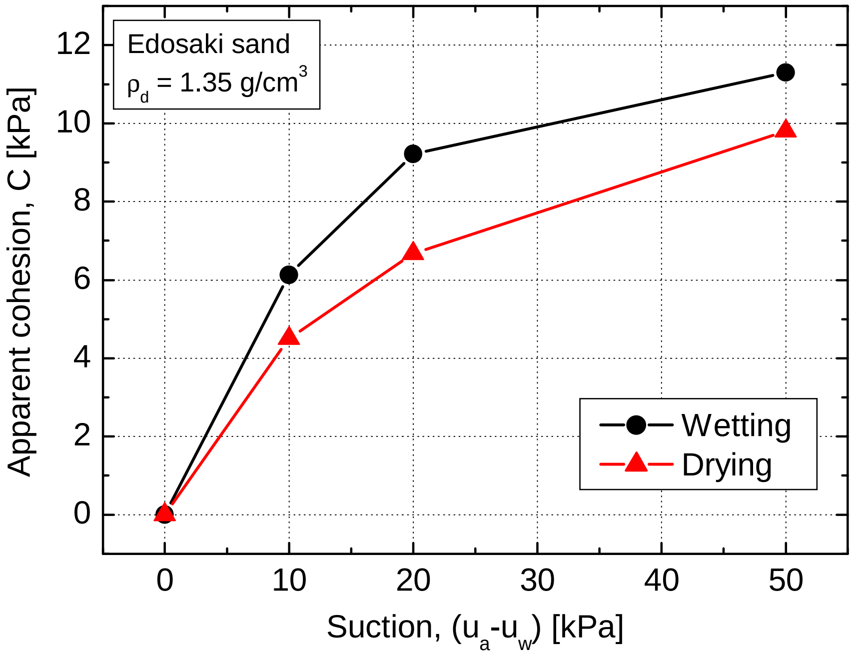

Fig. 22(b): Effects of the suction and drying-wetting on the apparent cohesion of Edosaki sand

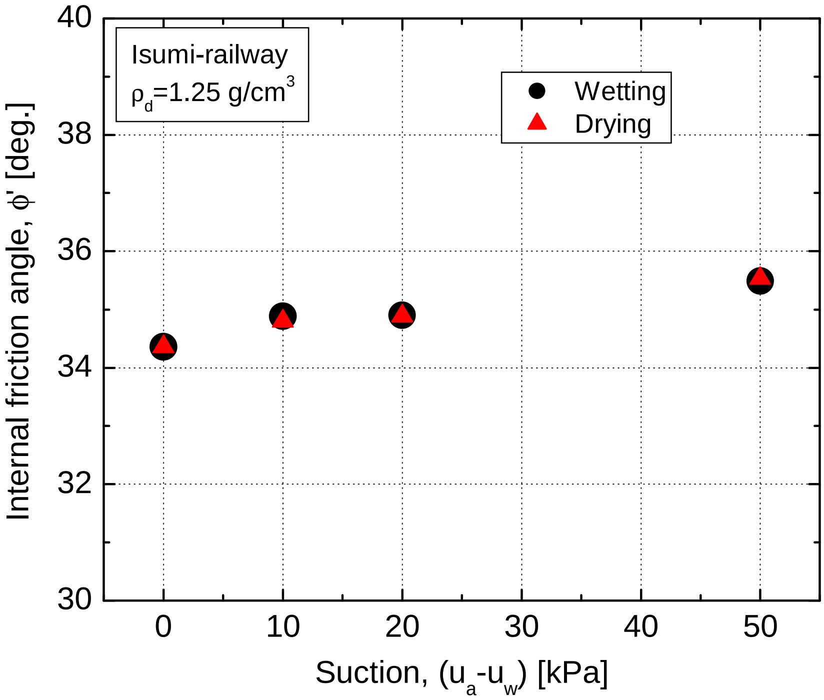

Fig. 23(a): Effects of the suction and drying-wetting on the internal friction angle of Chiba soil

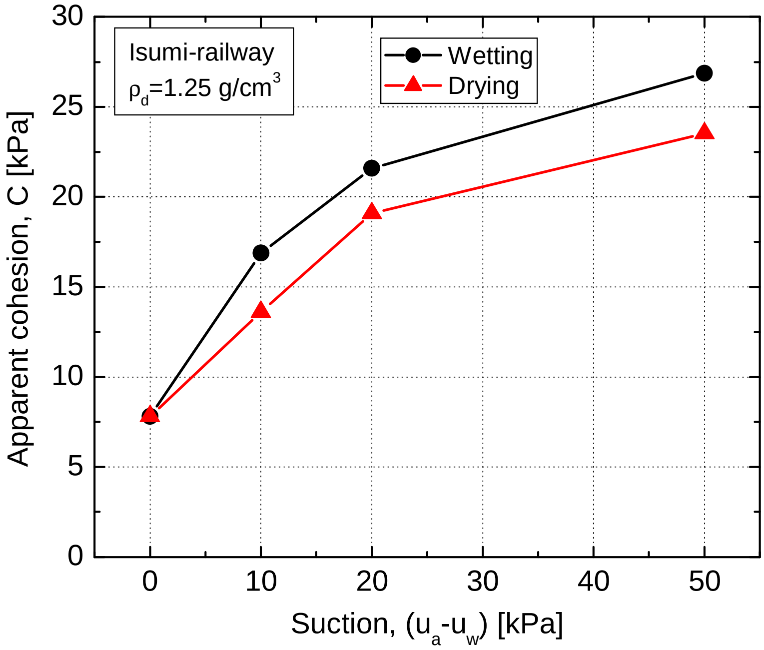

Fig. 23(b): Effects of the suction and drying-wetting on the apparent cohesion of Chiba soil