Comparative study on suction obtained using the membrane filter method from triaxial apparatus and pressure plate apparatus

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ABSTRACT

To investigate the stability of the earth embankments and slope failures during natural disasters, it is necessary to consider that soil is naturally unsaturated. Hence, it is essential to understand the variations of pore air pressure and pore water pressure, in terms of suction. The relationship between soil suction and soil moisture content is generally attained by soil water characteristic curve (SWCC), which is critically important in characterizing the mechanical behaviour of unsaturated soils. The SWCC is obtained from pressure plate apparatus by imposing the suction continuously by draining water from the saturated specimen and/or supplying water to unsaturated soil, which differs from the actual soil compaction process at the site. Therefore, the current study employs a methodology of suction measurement directly at a certain degree of compaction and degree of saturation using the membrane filter method in the triaxial apparatus, to meet the realistic conditions in the field. A comparative study has been done using SWCC with the imposed suction and the measured suction (Natural suction) at each compacted state. The results from both the methods exhibited an increase in the suction and air entry value with the increase in the degree of compaction, proving that an increasingly positive effect of suction contributed while increasing the density. Whereas the suction measured immediately after the compaction (Natural suction) in triaxial apparatus is more consistent with the suction imposed in the wetting process of SWCC. Further deep understanding of the microstructure behaviour of each compacted state and the SWCC is necessary.

Keywords: Unsaturated soils; SWCC; Natural suction; Degree of saturation; Compaction.

1. Introduction

Recent times have seen an increase in the sophistication of performance requirements for earthwork structures. Proper compaction during construction is an effective measure to reduce the maintenance and management costs of the structure. For effective and efficient compaction, there is a need to improve the conventional soil compaction procedure method. The conventional soil compaction procedure controls the dry density ρ_d and the water content w_c based on the compaction curve by laboratory compaction tests on the soil sample using a certain compaction energy level (CEL). However, in the recent research of Tatsuoka et al., (2015, 2018), the degree of saturation (S_r) is suggested as a key indicator. Since the compaction work at the site is usually performed under unsaturated conditions, the compaction effect, strength, and deformation characteristics of compacted soil are considered to be greatly influenced by "suction". The study also mentioned that the changes in the degree of saturation strongly influence the microstructure of the soil, which reflects the suction at the time of compaction. This shows the requirement of understanding the most important relationship between soil suction and the degree of saturation in unsaturated soil mechanics.

The ability to measure the suction in unsaturated soils has paved the way to understand and develop unsaturated soil mechanics. In the past, several methods have been developed to measure suction both in the field and in the laboratory (Fredlund & Rahardjo, 1993). Matric suction has been considered an important variable in defining the state of stress in unsaturated soil. Consequently, significant efforts have been made to control and measure matric suction precisely.

In general, the relationship between soil suction and volumetric water content is widely used in unsaturated soil mechanics, and it is called the soil water characteristics curve (SWCC) or soil water retention curve (SWRC). The volumetric water content is often replaced by gravimetric water content or degree of saturation.

The SWCC is one of the most important physical properties of unsaturated soil, since there is a relationship between the SWCC and the shear strength of unsaturated soil, (Fredlund & Rahardjo 1993). The suction dependency on the mechanical behaviour of unsaturated soils has been discussed by many researchers (Cui and Delage 1996; Fredlund and Vanapalli 1978). Therefore, to encourage geotechnical engineers to implement unsaturated soil mechanics theory in practice, several methods for the prediction of SWCC have been developed.

Some of them are axis translation techniques (Hilf 1956) and hanging column techniques (Vanapalli et al. 2008). The axis translation technique does not have the ability to measure air pressure under atmospheric conditions. Whereas the hanging column technique imposes the suction in terms of negative pressure for supplying/draining from the saturated sample to the unsaturated state. In addition, the hanging column technique mainly uses the ceramic disk in the apparatus, which enables the soil specimen to achieve its equilibrium stage after a long time. None of these techniques measure the suction values directly at the compacted state, representing the unsaturated field conditions.

The direct measurement of suction is possible using the tensiometer representing the same conditions as the field (Murray and Sivakumar 2010). However, tensiometers are expensive.

To the author's knowledge, the question of the precise measurement of suction under the conditions of the compaction at the site is still open. Very limited research is done on the measurement of the suction immediately after the compaction.

Hence, to address the above shortcomings, the current study obtained SWCC using the membrane filter technique to save time and developed a methodology to evaluate the suction directly after compacting at a specific density and degree of saturation using a membrane filter in triaxial apparatus. The suction obtained from the two methods is compared by changing the soil type and compaction level. Such a trial for measuring suction in two different methods using the membrane filter technique is new.

The SWCC in the current study is obtained using the membrane filter technique in the pressure plate apparatus to save time and to ensure an efficient comparison between the two methods. Nishimura (2013) and Wang et al. (2017) indicated that the equilibrium time required for the SWCC measurements using the membrane filter is much shorter than using the ceramic disk. In addition, the SWCC obtained through the membrane filter technique proved to be more efficient and reliable.

The methodology developed in the current study could replicate the measurement of suction under field unsaturated conditions, just like at the earthwork site conditions. The suction values measured using this methodology are compared with the SWCC to understand the disparity. This comparison would help to understand how suction changes with the compaction in the field, which could be different from the drying curve of SWCC. Further, it could help to predict the mechanical behaviour of soils in an accurate way.

2. Materials and methodologies

2.1. Materials

The current study employed two materials: Inagi sand and Katori sand. Inagi sand used in this study is the type of natural deposit sand that has been extensively studied due to the large-scale construction plan of Tama New Town in the 1960s in Tokyo (Wang et al. 2017). Katori sand is also the natural deposit of sand that is collected in larger quantities for a wide range of testing. Essentially, the two testing materials used in the current study are actual banking materials that were collected from the earthwork construction site in Japan.

Wet sieving analyses were performed on Inagi sand and Katori sand as these materials contain fines (Particles finer than 0.075mm) contents of 4.75%, and 18.8 %, respectively. The physical properties of the soils are shown in Table 1. The maximum dry density ($\rho_{d,max}$) and optimum water content (w_{opt}) are obtained from the standard proctor test for 1.0 E_c conforming JGS 0711-2009 method. The particle size distribution curves for the soils are shown in Fig. 1. In this study, it is shown that the optimum degree of saturation ($S_{r,opt}$) is defined as the degree of saturation S_r when $\rho_{d,max}$ is obtained for a given compaction energy level (CEL). The optimum degree of saturation for Inagi sand and Katori sand is 86.5 % and 83.1 %, respectively.

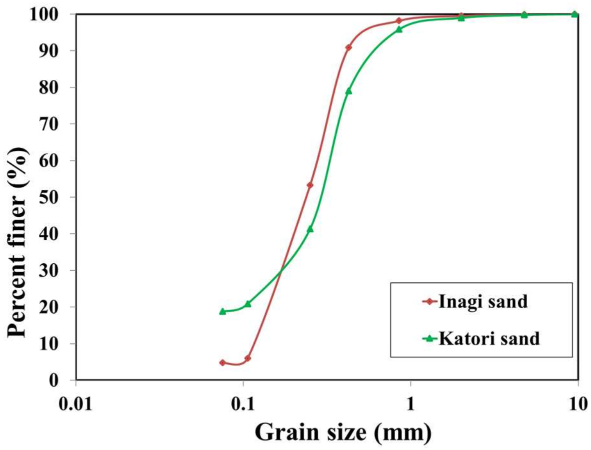


Figure 1. Particle size distribution of Inagi sand and Katori sand.

Table 1. Physical properties of the soils used

Material	Inagi sand	Katori sand
Fines Content (F_c %)	4.75	18.8
Specific Gravity, G_s	2.65	2.754
$\rho_{d,max}$ (g/cm^3)	1.69	1.67
D_{10} (mm)	0.12	0.075
D_{30} (mm)	0.18	0.17
D_{60} (mm)	0.28	0.33
U_c	0.96	1.14
U_c'	2.38	4.48
W_{opt} (%)	18.5	19.6
$S_{r,opt}$ (%)	86.5	83.1

2.2. Experimental Setup

2.2.1. Suction measurement using Pressure plate apparatus

A traditional pressure plate apparatus, in which a membrane filter (SUPOR 450) was installed and employed to obtain the soil water characteristic curve (SWCC) in the suction range of 0.1-20 kPa. The membrane filter technique is an efficient and reliable procedure compared to ceramic disk despite their great difference in thickness and air entry value for obtaining SWCC (Nishimura 2013; Wang et al. 2017). The membrane filter used in the study is M450, with a thickness of 140 μm and an air-entry value to be around 250 kPa. The hydraulic conductivity of the membrane filter is 1 × 10^{-5} cm/s (Wang et al. 2017). The description of the membrane filter can be found (Nishimura 2013; Wang et al. 2017).

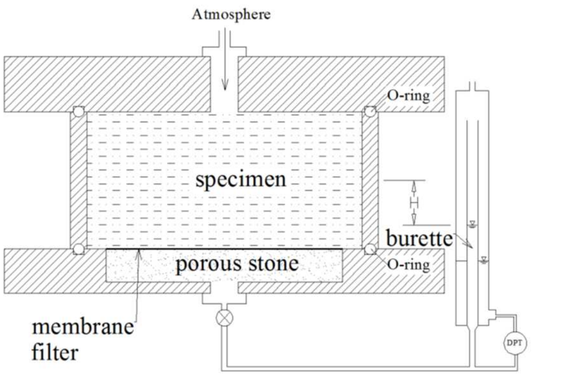


Figure 2. Pressure plate apparatus equipped with membrane filter.

Fig. 2 shows the full layout of the pressure plate apparatus along with the membrane filter. The evaporation effect was not considered severely because the test period of the membrane filter was much shorter, and the evaporation effect should be minor. The thickness of the membrane filter is 0.14 mm (for each test, a new membrane filter was saturated and then used). A differential pressure transducer (DPT) was used with the apparatus to record the volume of water flowing in/out during a test.

The suction was applied by the hanging column method solely (the maximum elevation difference is about 2 m) for the suction range of 0.1-20 kPa, in which the tested specimen is placed at a higher position than the water surface elevation in the burette connected to the apparatus. By doing so, a negative pore water pressure was applied to the specimens. The time taken for each suction step to achieve the equilibrium stage is around 12 hours, as the membrane filter technique provides easy water movement. Thus, the time to complete each test is very fast, about 12 to 15 days.

All the specimens tested were made by static compression using a tamping rammer. Attention was paid to ensuring good contact between the specimen and the pedestal of the apparatus. The specimens were saturated by supplying water from the supply tank to the bottom of the specimen and collected from the top. This test measures the suction continuously by draining water from a saturated specimen and/or supplying water to unsaturated soil, which differs from the actual soil compaction process at the site.

2.2.2. Suction measurement using membrane filter method in triaxial apparatus

A special apparatus called linkage double cell triaxial apparatus is used (shown in Fig. 2.) to measure the soil suction for each compacted state. The suction was evaluated directly after compacting at a certain density and degree of saturation with the help of pore air pressure and pore water pressure transducers by using the membrane filter method in the triaxial apparatus. The measurement is done in an unsaturated condition while keeping the pore air pressure open to atmospheric conditions. Thus, the suction measured by this method is closer to the actual suction at sites of earthwork.

The soil specimens were prepared using moist tamping by the undercompaction technique (Rs, 1979). This method was chosen as it closely follows the compaction procedure carried out at the site of layer-by-layer roller compaction. The cylindrical specimens with a diameter of 50mm and height of 100mm were prepared in 5 equal layers of 20mm each in a split specimen mould (shown in Fig. 3). A small hand rammer of weight 594gm was used for compaction. Such a method prevents the over-compaction of lower layers when the upper layers are compacted by the rammer blows, and hence is a better specimen preparation method than the conventional moist tamping method.

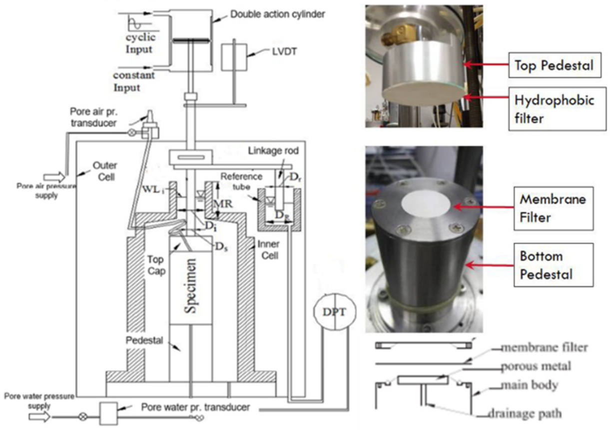


Figure 3. Linkage double-cell triaxial apparatus with the ability to control and measure suction (modified from Wang et al. 2017).

The prepared sample is carefully placed onto the bottom pedestal of the triaxial apparatus and then sealed with the top pedestal. Then the pore air pressure and pore water pressure measurements were recorded to calculate the suction. A hydrophobic filter was attached to the top cap, which prevented water flow and measured air pressure with the help of a pore air pressure transducer. At the bottom pedestal, a membrane filter (same as the one used for SWCC) was attached, which prevented airflow and measured water pressure using a pore water pressure transducer. The membrane filter is saturated before installing on the porous stone of the bottom pedestal (shown in Fig. 2.). This membrane filter technique was previously used in the simple shear and Triaxial apparatus for monotonic or cyclic loading tests (Nishimura 2013; Ishikawa et al. 2014; Wang et al. 2016).

The pore air pressure transducer is open to the atmospheric pressure considering the pore air pressure as 0 kPa. However, the pore water pressure is measured for the soil specimens after compaction, varying the D_c and S_r in each soil type. So, the soil matric suction can be evaluated by the negative value of the measured pore water pressure. It can be written as

$$s = u_a - u_w \quad (1)$$

where, u_a = pore air pressure = P_{atm} = 0 kPa and u_w = pore water pressure (kPa)
hence Eqn. 2.1 can be rewritten as:

$$s = -u_w \quad (2)$$

To ensure reliability, the measured suction value from the triaxial apparatus is compared with the standard method of obtaining suction from the soil water characteristic curve (SWCC). The current study compares the suction measured from the triaxial apparatus to the SWCC, which is discussed later in the paper.

3. Experimental results

The two laboratory suction measurement techniques were evaluated in this study: 1. Pressure plate apparatus (SWCC) using membrane filter technique 2. Membrane filter method using triaxial apparatus.

3.1. Measurement of suction using Pressure plate apparatus

For the SWCC test, suction ranging from 0.1 kPa to 20 kPa was applied using the membrane filter technique (Ishikawa et al. 2014). A series of tests were conducted on Inagi sand and Katori sand at two different initial densities each to obtain SWCC. The effect of density on the water retention ability was studied. The test conditions of the soil specimens for SWCC are listed in Table 2. The experimental results of SWCC were best fitted using the predicted model suggested by van Genuchten (1980).

Initially, Mualem, 1976 proposed a model for predicting the permeability of unsaturated porous media from the knowledge of SWCC. This proposed model includes a dimensionless water content, Θ:

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (3)$$

where θ stands for volumetric water content and subscripts 's' and 'r' indicate the saturated and residual volumetric water content, respectively. To solve the model proposed by Mualem (1976), van Genuchten (1980) proposed an equation to correlate Θ with pressure head h:

$$\Theta = \frac{1}{[1+|\propto h|^n]^{1-1/n}}, \text{ for } h < 0 \quad (4)$$

$$\Theta = 1, \text{ for } h \geq 0$$

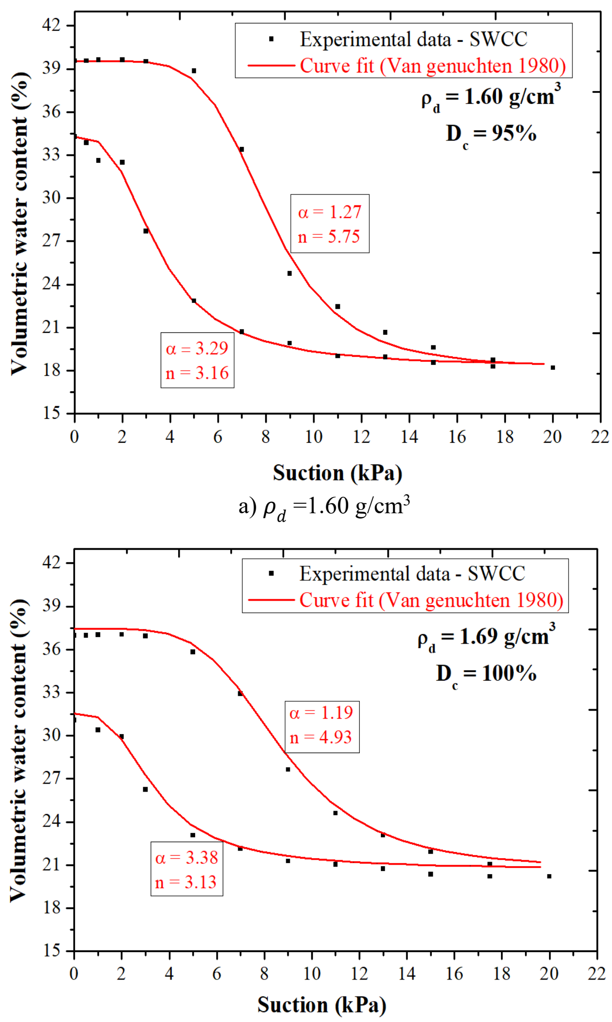
where α and n are model parameters, and α is a unit of (m^{-1}) when the unit of h is (m); h is pressure head (m). It is assumed that the suction (kPa) $s = \gamma_w * h$, γ_w is the unit weight of water in this study.

The fitting parameters in Eq. 4 describe the shape of the SWCC curve. To best fit the experimental data, these parameters can be obtained by the least square optimization method using experimental data and nonlinear curve fitting algorithms, as explained by van Genuchten (1980). The model parameters α and n were determined from the drying process of the SWCC curve.

The air entry values are determined by the fitting curve of the drying SWCC. The van Genuchten (1980) fitting parameters (α and n) for the SWCC curve and the air entry values are mentioned in Table 2 for each testing case. The experimental data of SWCC, along with the best fit curve for all the tested Inagi sand, and Katori sand cases, are shown in Fig. 4. and Fig. 5.

Table 2. Physical properties of the soils used

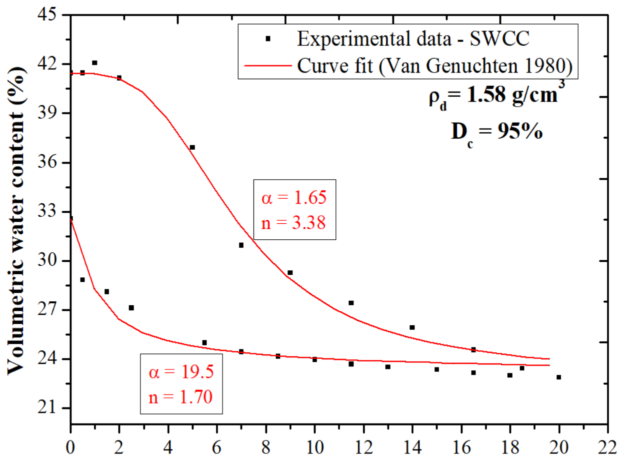
Material	**Void ratio**	**Dry density**	**Compaction**	**van Genuchten (1980)**		**Air entry value**
	e	$\rho_{d,max}$ **(g/cm³)**	D_c **(%)**	**α**	**n**	**AEV**
Inagi	0.649	1.60	95	1.27	5.75	4.4
Inagi	0.566	1.69	100	1.19	4.93	4.8
Katori	0.735	1.58	95	1.65	3.38	2.9
Katori	0.649	1.67	100	1.26	4.53	4.2



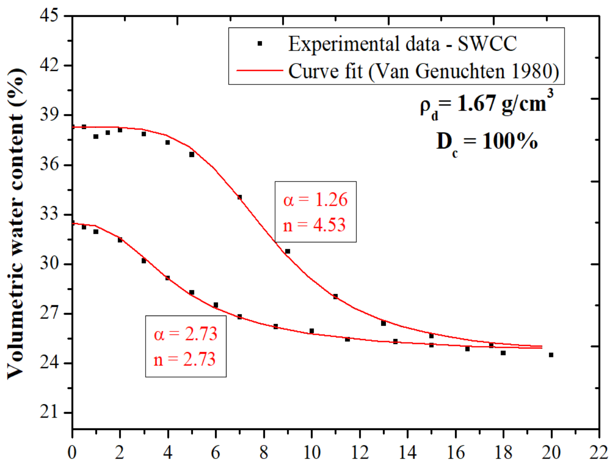
a) ρ_d =1.60 g/cm³

b) ρ_d = 1.69 g/cm³

Figure 4. SWCC curve for Inagi sand at a) ρ_d =1.60 g/cm³ and b) ρ_d = 1.69 g/cm³.



a) ρ_d =1.58 g/cm^3



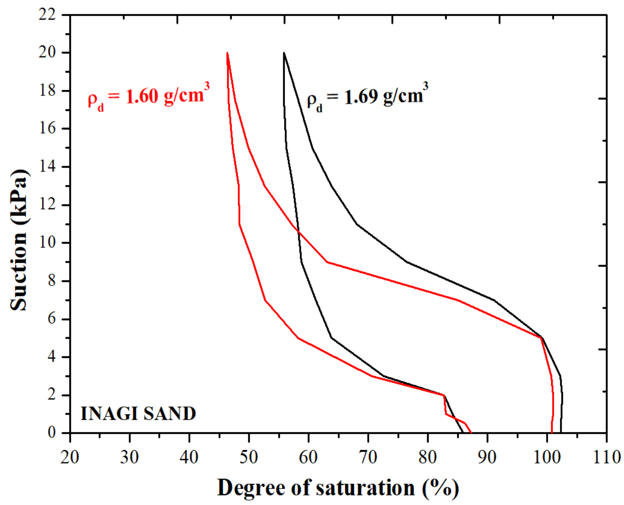
b) ρ_d = 1.67 g/cm^3

Figure 5. SWCC curve for Katori sand at a) ρ_d = 1.58 g/cm^3 and b) ρ_d = 1.67 g/cm^3.

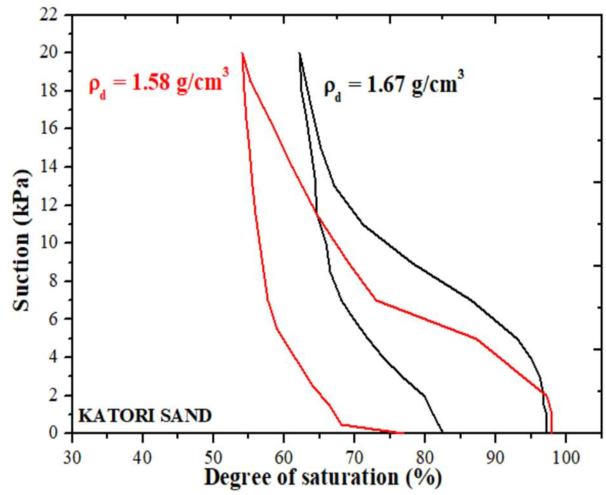
3.1.1. Effect of initial density on SWCC

Fig. 6 (a) and (b). shows the relationship between suction and degree of saturation (S_r) with the different initial density conditions for the Inagi sand and Katori sand, respectively. Under the same suction, the volumetric water content and S_r increases with an increase in specimen density for either drying or wetting curves. The SWCC shifts right with the increase in initial density showing that the suction increases significantly with the increase in density under the same degree of saturation.

With the increase in the density at the same degree of saturation, the suction value increases as the size and number of pores decrease. As a result, the radius of the meniscus decreases, and the corresponding suction increases. Therefore, the suction required for air to enter into the soil matrix increases. Similarly, for the same volumetric water content, the higher the density is, the greater the suction value. Thus, the air entry values (AEV) increase with the increase in initial density, as shown in Table 2. Kawai et al. 2000 also observed a similar trend of increase in air entry values with the increase in density for the clayey soils.



(a) Inagi sand



(b) Katori sand

Figure 6. Comparison of SWCC curve at different initial densities. a) Inagi sand b) Katori sand

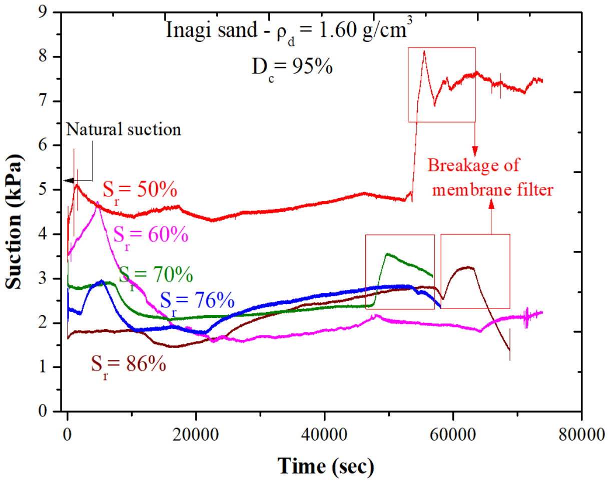
The van Genuchten (1980) parameters like α and n change with the increase in the initial density. The α value decreases with the density, whereas the AEV value increases with the density. It indicates that the α value is inversely proportionate to the air entry value. The variation in the n value denotes the change in the slope of the SWCC.

3.2. Measurement of suction using triaxial apparatus

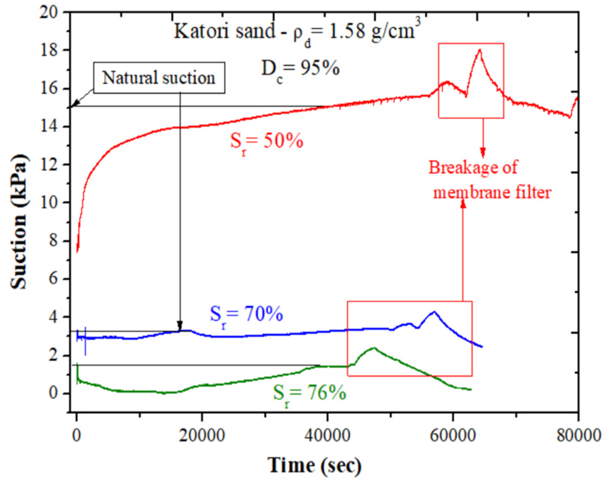
To replicate the natural conditions at the earthwork, the suction is measured immediately after the compaction in an unsaturated state. The suction was evaluated directly at a certain density and degree of saturation. The suction measured from the triaxial apparatus is termed to be "natural suction" in the current study. The pore air pressure and pore water pressure are measured immediately after the compaction using the pore air pressure transducer and pore water pressure transducer in the triaxial apparatus, respectively.

The measurement is recorded until the suction achieves an equilibrium state. Generally, it would be around 6-8 hours. Fig. 7 (a) and (b) shows the typical time history of the soil compacted at the same initial density with varying degree of saturation for Inagi sand and

Katori sand, respectively. The natural suction is the peak value or the stabilized value of the suction in the time history of the suction (marked in Fig. 7 (a) and (b)).



(a) Inagi sand



(b) Katori sand

Figure 7. Time history of suction measurement at 95% Degree of compaction. (a) Inagi sand (b) Katori sand.

The time history of suction clearly identifies the commencement of the measurement of the suction at t = 0 seconds. After a certain time in recorded measurement, the sudden jump in the measurement of suction value can be observed, and then either gradually approaches 0 kPa or tends to increase indefinitely. This is because of the problem in the membrane filter which is directly connected to the pore water measurement. During the measurement of pore water pressure, the water in the membrane filter was expected to come into contact with the pore water network in the specimen. At the same time, there is a possibility that in some areas, the contacts are lost due to the re-distribution of the pore water. The loss of contacts may cause the invasion of the pore air in the membrane filter. The loss of contacts may not easily happen for the small average particle size of soil particles. If the particle size of soil particles increases, the failure of membrane filter happens easily. It is the point where the membrane filter fails to do its purpose. There is a sudden jump of decrease or increase in the pore water measurement and then gradually approaching 0 kPa value or tending to increase indefinitely, which represents the failure of the membrane filter. The failure with the breakage of the membrane filter is clearly marked in Fig. 7 (a) and (b). Table. 3 and 4 show the measured natural suction values for Inagi sand and Katori sand in the compacted soil conditions, respectively.

Table 3. Measurement of suction from triaxial apparatus varying degree of compaction and degree of saturation – Inagi sand.

void ratio	dry density	Degree of compaction	Degree of saturation	Natural suction
e	ρ_d (g/cm³)	D_c (%)	S_r (%)	s (kPa)
0.649	1.60	95	40	18.3
0.649	1.60	95	50	5.21
0.649	1.60	95	60	4.74
0.649	1.60	95	70	2.99
0.649	1.60	95	76	2.98
0.649	1.60	95	86	1.85
0.566	1.69	100	60	4.75
0.566	1.69	100	70	3.4
0.566	1.69	100	76	3.2
0.566	1.69	100	86	2.1

Table 4. Measurement of suction from triaxial apparatus varying degree of compaction and degree of saturation – Katori sand.

void ratio	dry density	Degree of compaction	Degree of saturation	Natural suction
e	ρ_d (g/cm³)	D_c (%)	S_r (%)	s (kPa)
0.735	1.58	95	83	0.5
0.735	1.58	95	76	1.8
0.735	1.58	95	74	2.34
0.735	1.58	95	70	3.5
0.735	1.58	95	66	3.3
0.735	1.58	95	58	5.2
0.735	1.58	95	50	14.75
0.649	1.67	100	83	2.0
0.649	1.67	100	74.8	3.5
0.649	1.67	100	66.5	6.2
0.649	1.67	100	56	17.2

The natural suction values increased with the increase in initial density whereas decreased with the increase in degree of saturation. This trend can be clearly noticed in Fig. 7 (a) and (b), for both the cases of Inagi sand and Katori sand, respectively. The time required to attain the equilibrium condition is shorter for soil specimens compacted at high degrees of saturation when compared to soil specimens compacted at low degrees of saturation. This is due to the soil specimen's formation of a welldistributed microstructure and relatively homogeneous soil pores when compacted at high saturation levels. These homogeneous pores result in a stronger pore water distribution network and greater contact with membrane pores. Thus, it is easier to quantify in a short time. In addition, it can also be observed that the Katori sand with high fines content compacted at a low degree of saturation (S_r= 50%) has taken a longer time to achieve the equilibrium state (shown in 7(b)). The time taken to achieve the equilibrium state depends on the type of soil, degree of saturation used for the soil specimen, etc.

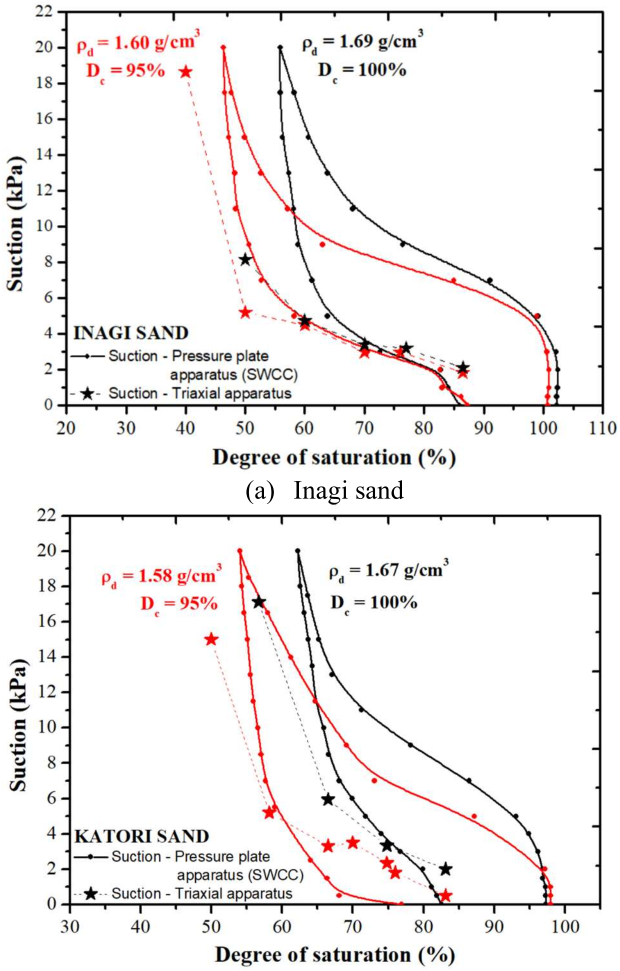
To ensure the reliability of these measured suction values, they are compared with the suction obtained from the soil water characteristic curve in the next chapter.

3.3. Comparison of measured suction from triaxial apparatus and SWCC

Fig. 8 (a) and (b). presents the comparison of the natural suction (measured suction values from triaxial apparatus) and the SWCC for Inagi sand and Katori sand, respectively. From both methods, the results exhibited an increase in the suction with the increase in the initial density, proving that an increasingly positive effect of suction contributed while increasing the density. Whereas the decreasing trend of suction is observed with the increase in the degree of saturation.

When the natural suction values are compared with the soil-water characteristic curve (SWCC), it is observed that the natural suction follows the trend of the wetting curve of the SWCC. This might be because of the increase in pore pressures at the same water content while undergoing the process of compaction if compaction is considered as the exhausted or undrained cyclic loading. Thus, leading to a decrease in the suction of the sample while measurement. That's why the specimen might have achieved the wetting curve state after compaction. Therefore, the natural suction moves towards the minimum hysteresis range in SWCC, which is the wetting curve. This kind of behaviour has also been observed by (Wang et al. 2017).

The comparison between the two methods in this study can be a very important implication for understanding the strength and deformation characteristics of unsaturated soils. Hereby, it is concluded that the measurement of suction (natural suction) from the triaxial apparatus is an efficient and reliable technique to replicate the field conditions (immediately after the compaction).



(a) Inagi sand

(b) Katori sand

Figure 8. Comparison of measured suction from triaxial apparatus and SWCC curve. (a) Inagi sand (b) Katori sand.

4. Conclusions

The current study outlines the influence of the initial density on suction for the soil with the two different techniques. A series of tests were conducted using pressure plate apparatus to obtain SWCC at different initial densities. The experimental data of SWCCs were best fitted using the van Genuchten (1980) equation. The obtained SWCC was compared to the measured natural suction values from the membrane filter method using triaxial apparatus. Accordingly, the following conclusions were drawn below:

1. The measurement of suction from the membrane filter method using triaxial apparatus (natural suction) is an efficient and reliable technique that replicates the field conditions.
2. With the increase in the initial density at the same degree of saturation, the suction value increases as the size and number of pores increase. Therefore, the air entry value increases with the increase in the initial dry density.
3. The natural suction is compared with the imposed suction from the soil-water characteristic curve (SWCC). It is observed that natural suction follows the trend of the wetting curve of the SWCC. This is because of the increase in pore pressure during the compaction

maintaining the same water content, which leads to a decrease in the suction of the sample. Therefore, the natural suction moves towards the minimum hysteresis range in SWCC, which is the wetting curve.

Conclusions derived from the current study state that the suction after the compaction in the field is more related to the imposed suction from the minimum hysteresis of SWCC.

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