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COMPARISON OF DIRECT AND INDIRECT MEASURED SOIL-WATER CHARACTERISTIC CURVES FOR A SILTY SAND

T. Abeykoon[1], R.S. Udukumburage[2], *C. Gallage[3] and T. Uchimura[4]

[1]Faculty of Engineering, University of Moratuwa, Sri Lanka; [2,3]Science and Engineering Faculty, Queensland University of Technology, Australia; [4] Department of Civil Engineering, University of Tokyo, Japan

*Corresponding Author, Received: 19 May 2017, Revised: 30 May 2017, Accepted: 20 June 2017

ABSTRACT: It is time consuming and needs sophisticated testing apparatus to determine unsaturated soil properties such as hydraulic conductivity and shear strength. Therefore, engineers hesitate to use unsaturated soil properties in economical geotechnical problem solving. To promote the use of unsaturated soil properties in geotechnical engineering designs, numbers of methods have been developed to estimate/predict unsaturated soil properties. The Soil-water characteristic curve (SWCC) defines the relationship between the soil suction and water content. During past few decades, different measuring and estimation/prediction methods have been developed by researchers to ascertain SWCC of soils. Among them, direct and indirect methods are widely used to measure the SWCC of soil. Indirect methods such as axis-translation technique are commonly used in the laboratory to determine SWCC. It is important to understand how well the indirectly measured SWCC is related to actual soil-water retention properties of soil during drying and wetting process. Bridging that research gap, in this study, Soil water characteristic curve (SWCC) of sandy soil was measured using both indirect (Axis translation method using Tempe Pressure Cell) and direct methods. The direct measured SWCCs were obtained by subjecting the instrumented soil column and model embankment to wetting and drying cycles. When comparing SWCCs measured by direct and indirect methods, it was found that the indirect method provides a very close agreement with the outcomes of direct methods. This ensures that the SWCCs measured in the laboratory by using indirect methods can be used in Geotechnical Engineering practice.

Keywords: Soil water characteristic curve, Unsaturated soil, Tempe pressure cell, Matric suction, Instrumented soil column, Instrumented model embankment

1. INTRODUCTION

The measurement of soil parameters for unsaturated soil condition has always been a time consuming and exorbitant approach and as a result, geotechnical engineers finding it difficult to incorporate prevalent knowledge of unsaturated soil mechanics into routine geotechnical designs and problem solving. In addition, laboratory experimentation of this nature requires rigorous process and technical expertise that might be impractical for quick decision making tasks. To encourage the utilization of unsaturated soil properties in geotechnical designs, numerous methods have been proposed and developed within the past few decades [1,2].

The soil water characteristic curve (SWCC) defines the constitutive relationship between the soil-water potential and water content of unsaturated soils which can be utilized to bridge the gap between the saturated and unsaturated soil parameters. The complex unsaturated soil behavior can be investigated through this conceptual framework and vast amount of research has been carried out in this regard [3,4]. Key elements of these research were to comprehend the unsaturated soil behavior according to the change in soil water content (i.e. gravimetric, volumetric water content or degree of saturation).

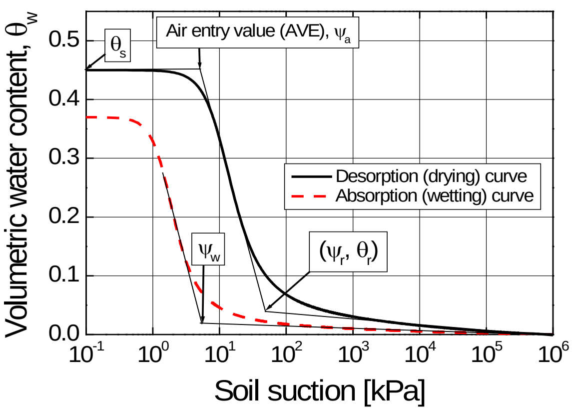


Fig. 1 General SWCC for a soil [5]

Furthermore, soil- water characteristic curve is central to the behavior of an unsaturated soil and can be related to other properties describing the behavior of soil, such as unsaturated coefficient of permeability and the shear strength [6-8]. Therefore, in geotechnical engineering practice, unsaturated soil mechanics theories in routine practice and numerical models, based on the SWCC and saturated soil properties, have been developed to predict unsaturated permeability function and unsaturated shear strength properties.

Currently, there are well-established direct and indirect methods to measure SWCC for a particular soil. Direct methods include pressure plate, Buchner funnel, tensiometers, and pressure membranes. These methods measure the pore-water pressure in the soil or impose a known air pressure to soil and allow the water content to come to equilibrium with the imposed air pressure. Among these methods, conventional pressure plate is the most common method. Indirect methods include filter paper and heat dissipation sensors. These methods use measurements or indicators of water content or a physical property that is sensitive to changes in water content. The direct methods are recognized for higher accuracy of the outcome, however, blatant problems of the direct method are the costly and time-consuming nature of the approach which encourages users to follow simple indirect methods to determine soil specific water retention curve (Fig. 1).

The suction values are mostly deemed as matric suction (U_a-U_w) and seldom use of total suction can be seen in literature. Mostly, the soil moisture content is represented as volumetric water content (θ), yet gravimetric water content (ω) is also being used in unsaturated soil mechanics to determine

SWCC. The absorption and desorption curves (Fig. 1) refer to the wetting and drying process, respectively, in which the difference in water content at saturation between drying and wetting is the residual air content. In Fig.1 the SWCC during wetting process is not the same as drying process, which is referred to as hysteresis, i.e., the soil's ability under the similar suction to have two different water contents when the soil is being wetted or dried. For a specified suction value, the soil being wetted has less water content than the soil being dried [9] & [10].

In this study, SWCC of sand has been determined using both direct and indirect laboratory methods in order to investigate the degree of agreement between SWCCs derived from each method. A Tempe pressure cell was used to conduct the indirect approach by repeating three drying-wetting cycles whereas direct methods were approached through instrumented soil column and model tank.

2. TEST MATERIAL

Edosaki sand from Ibaraki prefecture in Japan was used as the test material throughout the investigation. Wet sieving and hydrometer analysis were performed on selected representative samples conforming to the JGS (Japanese Geotechnical Society) standard test methods. The fine material (percentage finer than 0.075 mm) of Edosaki, amounts to 16.4% and the grain size distribution for the aforementioned soil is shown in Fig. 2 below. Apart from grain size distribution, the other basic soil properties such as specific gravity, minimum & maximum void ratios, compaction and Atterberg limits were conducted in accordance with JGS standard test methods and the results are given in Table 1. According to Unified Soil Classification System (USCS), the test material was classified as 'silty sand'.

Table 1 Property table of Edosaki soil [3]

Properties	Edosaki sand
Specific gravity, G_s	2.75
Mean grain size, D_{50} (mm)	0.22
Coefficient of uniformity, $C_u=D_{60}/D_{10}$	17.10
Coefficient of gradation, $C_c=(D_{30})^2/(D_{10}*D_{60})$	3.97
Sand content (%)	83.60
Fines content (%)	16.40
Plastic index	NP
Maximum void ratio, e_{max}	1.59
Minimum void ratio, e_{min}	1.01
Max. dry density, $\rho_{d(max)}$ (g/cm^3)	1.72
Optimum water content (gravimetric), W_{opt}(%)	16.02

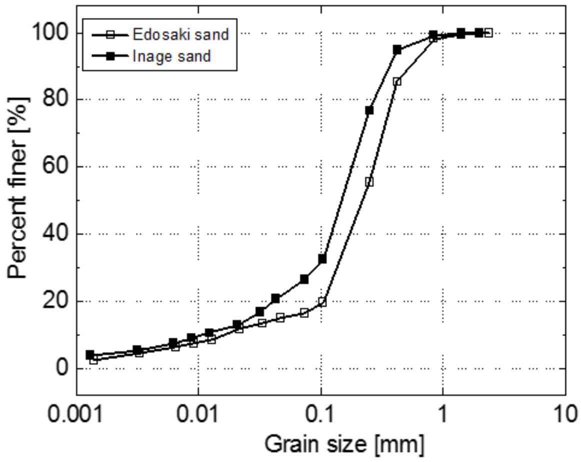


Fig. 2 Grain size distribution of Edosaki sand [3]

3. TEST APPARATUS

3.1 Apparatus Used for Indirect Measurement of SWCC

A Tempe pressure cell (Fig. 3) was used to obtain water retention curve for Edosaki sand using indirect measurements. This apparatus comprised of a brass cylinder (Φ = 50 mm and h= 60 mm), a base plate, a high air-entry porous ceramic disk (300 kPa) and a top cap. A representative soil specimen is placed on the ceramic disk which is embedded on top of the base plate and the water flow through the specimen is controlled by a tube connected to the base plate. A tube connected to the top plate enables to regulate the air pressure at an appropriate level during the experiment.

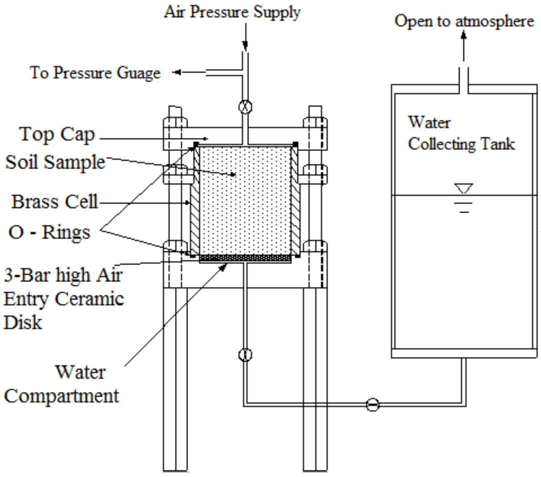


Fig. 3 Schematic diagram of Tempe pressure cell [5]

3.2 Apparatus Used for Direct Measurement of SWCC

A soil column and soil box tests instrumented with pressure transducers and water content measuring sensors (Theta probes) was conducted on Edosaki sand aiming to measure drying and wetting soil-water characteristic curves directly.

3.2.1 Pore-water pressure transducers

Fig. 4 depicts the strain gauge type pressure transducers with the capacity of 100 kPa. Moreover, transducers were modified by attaching ceramic cups in order to measure both positive and negative pore-water pressures (-90 kPa to +100 kPa). The ceramic cup consists of an AEV of 100 kPa and a saturated water permeability of 7.56 × 10-7 cm/sec.

3.2.2 Moisture content sensors

ADR (Amplitude Domain Reflectometry) probes were used to measure the volumetric water content of the Edosaki sand and the previous research has established that ADR probes have a lower

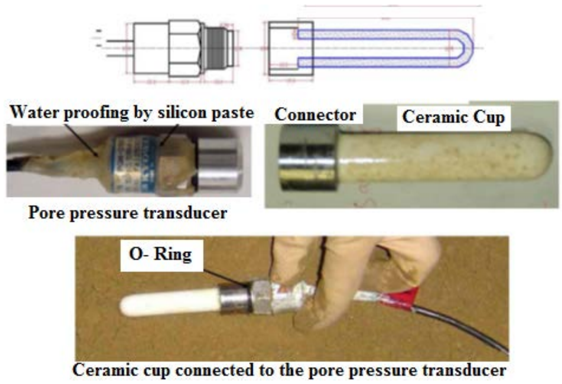


Fig. 4 Modified pressure transducer

sensitivity to salinity and temperature effects [7] & [8]. ADR probes utilized in this study have a very short response time (1-5 seconds) up to an accuracy of ± 1% with soil specific calibrations.

4. METHODOLOGY

4.1 Indirect Measurement of SWCC

Prior to commencing the study, the high AEV ceramic disk was saturated and subsequently it was verified by the procedure illustrated by Gallage et al. (2010). In order to persist the saturation of the system, a water tank was connected after saturation of the ceramic disk. A soil specimen (dry density = 1.35 g/cm^3, gravimetric water content = 10%) was placed in the brass cylinder such that a target density was achieved and then specimen was saturated as depicted in Fig 5. The weight of the assembly was constantly monitored to identify the point of saturation at which the adjacently measured weight becomes constant. From periodic observations, it was noted that the time taken for saturation was 2 to 3 days.

The Tempe pressure cell was connected to a system as depicted in Fig 3. It should be noted that water level of the water tank was constantly maintained at half sample height and vented to atmosphere and thereby conserve zero pressure (Ua = Uw = 0 kPa) in the specimen. Once the sample weight was constant, the measured weight was recorded for the corresponding zero suction value (Ua - Uw = 0). Following this, air pressure (Ua) was increased to another value (i.e., 0.5, 1.0, 2.0, 3.0, 5.0, 7.0, 10.0, 20.0, 50.0, 100.0 and 200.0 kPa) through the air supply inlet, resulting specimen water to drain out (i.e. analogous to drying process) to the water tank through base plate until the specimen moisture equilibrates (i.e. constant weight of the assembly). During the weighing process, inlet and outlet tubes were remained closed. Then the weight of the specimen was recorded for the corresponding matric suction value (Ua = Uw = 5 kPa) and the procedure was repeated for all the suction values.

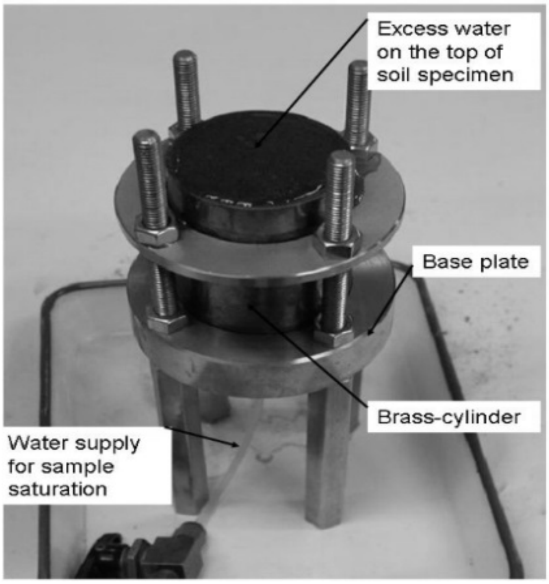


Fig. 5 Saturation of the specimen [5]

The wetting process was carried out through reverse approach by dropping the air pressure at the inlet of the top plate from 200 kPa to 0 kPa. After Ua dropped down to 0 kPa, the specimen was taken out and oven dried to measure the corresponding gravimetric water content of the sample. This water content together with previous change in weight of the assembly was used to back-calculate the water contents corresponding to the other suction values. The suctions were then plotted against their corresponding water contents to obtain the SWCCs. The Fredlund- Xing equation (Eq. (1)) was used to determine the best-fit curves (Fig. 6) for the obtained experimental data during drying and wetting cycles [11].

$$\theta(\psi, a, n, m) = C(\psi)\frac{\theta_s}{\left\{\ln\left[e + (\psi/a)^n\right]\right\}^m} \quad (1)$$

Where,

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

θ = Volumetric water content

ψ = Suction (kPa)

ψ_r = Sunction corresponding to residual water content $\theta_r (kPa)$

θ_s = Saturated water content

a, m, n = Fitting parameters (a has the unit of pressure kPa)

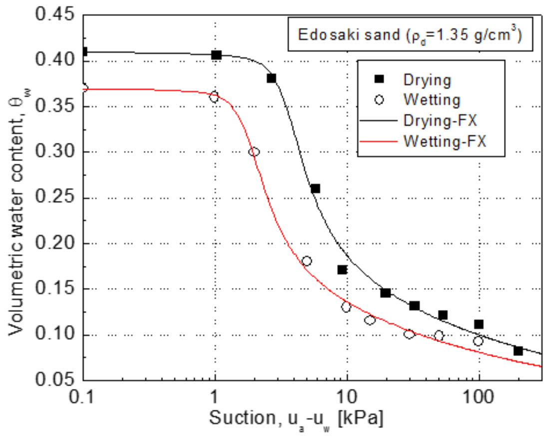


Fig. 6 Drying and wetting SWCC for Edosaki sand

4.2 Direct Measurement of SWCC

4.2.1 Column test with direct measurements of water content and suction

The column was subjected to three cycles of wetting and drying during which soil water contents and pore-water pressures were continuously recorded at four different depths in the column. This section describes the experimental setup including sensors used to measure pore-water pressure and water content and the preparation of the soil column.

(a) Pore-water pressure transducers

Initially, ceramic cups were saturated by immersed in the water and followed by applying vacuum condition for 24 hours period prior to embed in soil. Fig 4 shows the ceramic cup and pressure transducer assembly. The pressure transducers were re-calibrated for the laboratory working pressure range of -60 kPa to +60 kPa to compare the calibration factors with the manufacturer defined curves. Fig 7 depicts the manufacturer defined calibration chart for the pressure transducers.

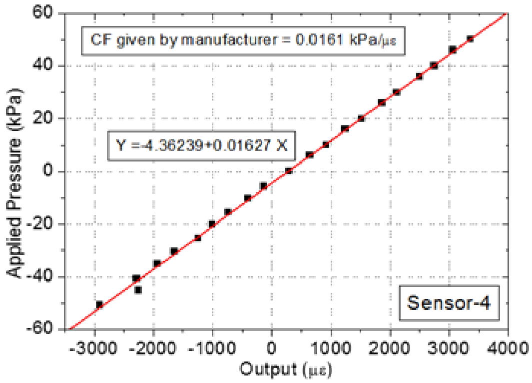


Fig. 7 Calibration chart for the pressure transducers

(b) Moisture content sensors

In order to soil specifically calibrate ADR probes, oven-dried soil was mixed with distilled water and packed into a plastic cylinder of 80 mm in inner diameter and 100 mm in height as uniformly as possible by manual compaction into five equal layers up to the full volume of the cylinder. The sample was then weighted by using an electronic balance to obtain the wet weight of the sample. ADR probe was vertically inserted to the soil and output was connected to the data logger in order to read output voltage. The output of the ADR probe was observed in the computer screen and the value was noted once it was stable. The soil sample was oven-dried to obtain the gravimetric water content, m and bulk dry density of soil, ρ_d. The corresponding volumetric water content, θ, can be obtained as follows, assuming the density of water to be 1 g/cm^3.

$$\theta = m^* \rho_d \quad (2)$$

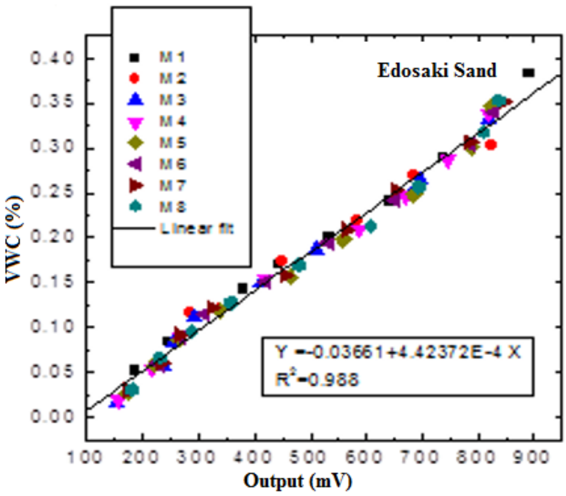


Fig. 8 Calibration chart for ADR moisture sensors

Same procedure was carried out for different for different water contents to obtain a calibration chart specific to Edosaki sand (Fig. 8).

(c) Column test and its measurements

As shown in Fig. 9, a cylindrical column which has an inner diameter of 200 mm and a height of 600 mm was filled by compacting wet Edosaki sand (initial water content = 14 %) to achieve dry density of 1.35 g/cm3. During the sand column preparation, four ADR probes (M) and four modified pressure transducers (P) were installed to measure volumetric water content and suction of soil, respectively. P4 and M4, P3 and M3, P2 and M2, and P1 and M1 were installed in the soil at the depth of 60, 180, 300, and 420 mm from the top soil surface, respectively. A gravel layer was placed at the bottom of the column to facilitate draining of water. The soil column was wetted by pouring water in to the top of the column and the drying was then allowed naturally in the room environment. During the period of about 66 days, the column was subjected three cycles of wetting-drying to investigate the sensor responses as shown in Fig. 10 & 11.

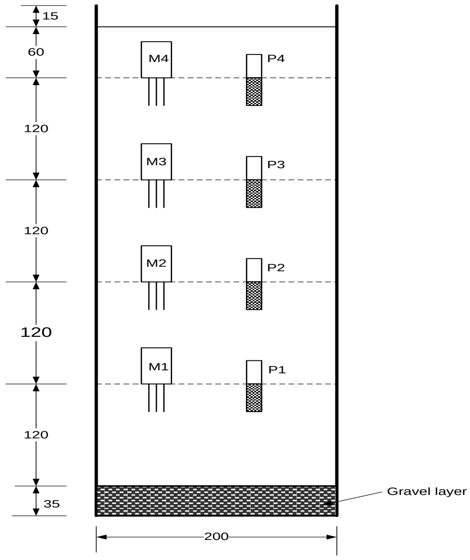


Fig. 6 Schematic diagram of the soil column and the sensor arrangements

4.2.2 Model tank test with direct measurements of water content and suction

The tank used in the model tests is shown in Fig. 12. This tank has a length of 220 cm, width of 80 cm, and height of 100 cm. The walls of the tank are made of steel plates except for the front side which is made of acryl g lass for easy observation of the deformation process.

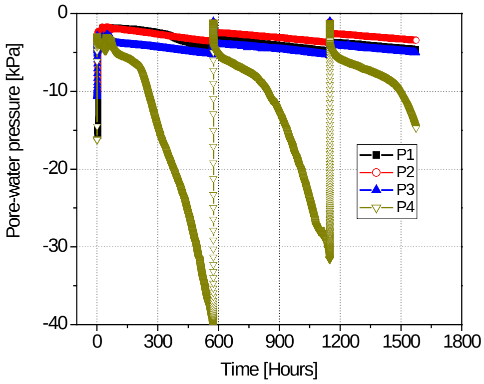


Fig. 10 Responses of pore pressure transducers embedded on soil column

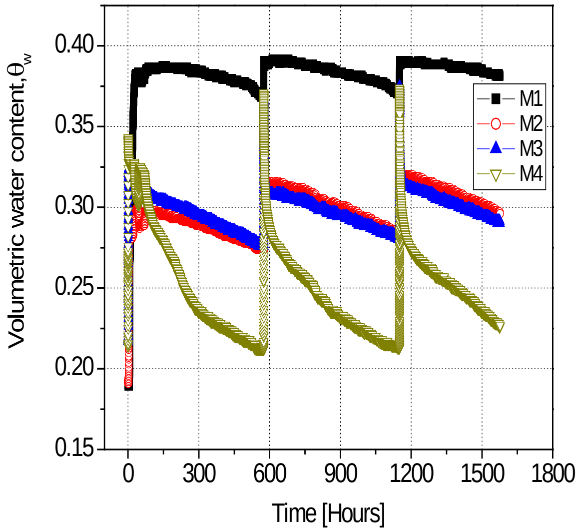


Fig. 11 Responses of the water content sensors embedded on soil column

The box is divided in to three sections, i.e., the central portion which is 197 cm long and used for construction the slope and the left and right chambers each 11.5 cm wide for collection and discharging water, respectively. These

three sections are divided by perforated walls with metal meshes attached to them to allow easy movement of water without washing out the soil grains. For these model tests, the inner wall of the left chamber is made impermeable by attaching a thin acryl sheet.

Edosaki sand was oven dried for 48 hours under a constant temperature of 110^{0}C and the soil lumps were crushed manually once the temperature of dried material was reduced to room

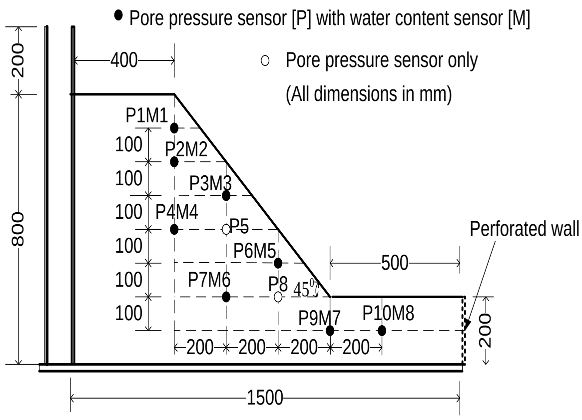


Fig. 12 Schematic diagram of model tank

temperature. Subsequently, water content (natural) was measured and excess amount of water was added to achieve the pre-determined initial water content (i.e. 16%). Once the soil became moisture

uniformed, the model embankment was prepared by wet compaction. Pre-determined soil density was maintained throughout the process by keeping 50 mm soil layers for compaction. The same procedure was repeated until the full height of the soil model was obtained. Further, pressure transducers and moisture sensors were embedded at specific locations as the soil placement progressed.

Subsequent to the successful setting-up of the model tank, the soil was subjected to wetting for 19 hours by applying an artificial rain of 40 mm/hr which was followed by 24 hours natural drying period. Afterwards, a rainfall of 80 mm/hour was applied for 2.2 hours duration as the second wetting cycle and then again allowed to dry it for

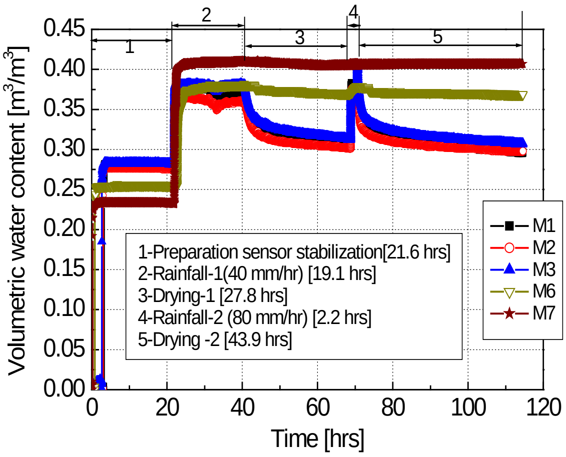


Fig. 13 ADR sensor responses with time

48 hours. Figure 13 & 14 depict, the temporal distribution of the pore water pressure transducer and water content sensor responses, respectively.

present a similarity apart from slight difference that may arise due to incongruity of approach.

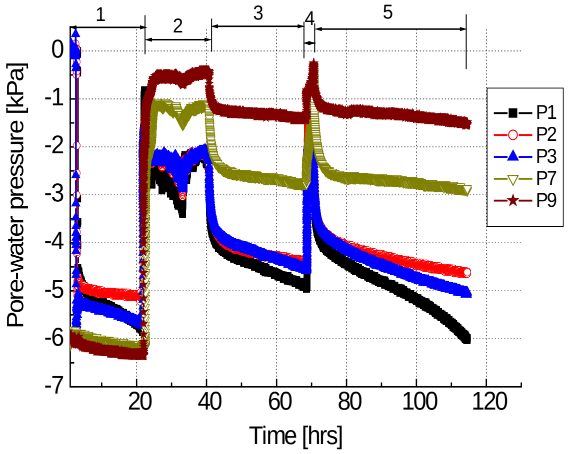


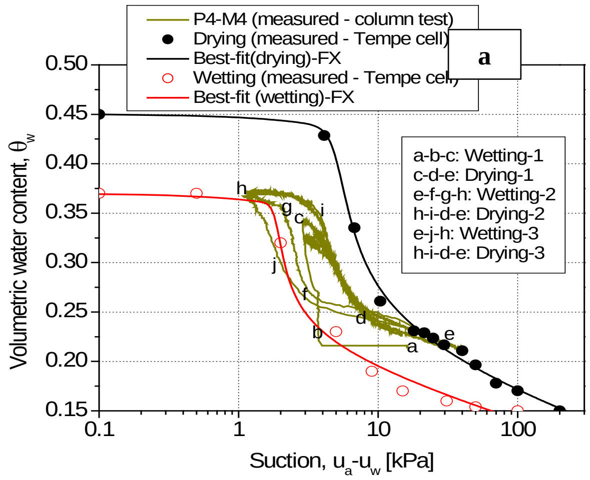
Fig.14 Pressure transducer responses with time

5. RESULTS AND DISCUSSIONS

Using the Tempe pressure cell and the associated test procedure explained in this paper, both drying and wetting SWCCs for the test material (Edosaki soils) were measured in the laboratory. Fig. 6 depicts the measured SWCCs for the Edosaki soil specimen at the initial dry density of 1.35 g/cm^3, in which the suctions were then plotted against their corresponding water contents to obtain the SWCCs and the Fredlund- Xing equation was used to determine the best-fit curves (Fig. 6) for the obtained experimental data during drying and wetting cycles.

Column test and model tank tests were employed as the direct measurements of water content and suction. To obtain SWCCs from the results of the column test, the measured volumetric water content was plotted against measured suction at each level. As blatantly depicted in Fig. 15, water retention curves obtained from soil column test subsequent to a series of wetting and dying cycles present a close agreement with indirectly measured (tempe pressure cell) SWCC, irrespective of slight over estimation of drying curve in the indirect method.

The SWCCs measured in the laboratory using Tempe pressure cell and embankment model were then plotted on the same graph as shown in Fig. 16. It can be seen from these graphs that a great portion of directly measured SWCCs (main drying, main wetting, and scanning curves) lie within the indirectly measured drying and wetting SWCCs. Further, the hysteresis between the corresponding drying and wetting curves of the direct (model embankment) and indirect (tempe-cell) methods



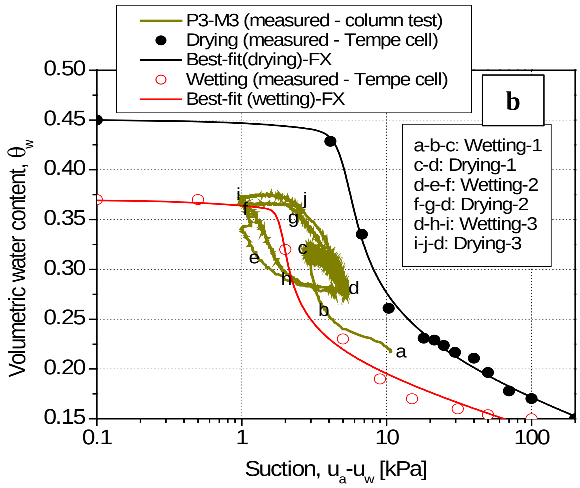
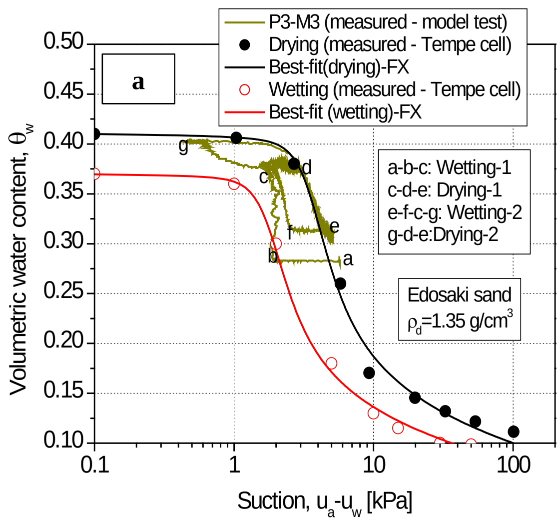


Fig. 15 SWCCs obtained from Tempe-cell and soil column test



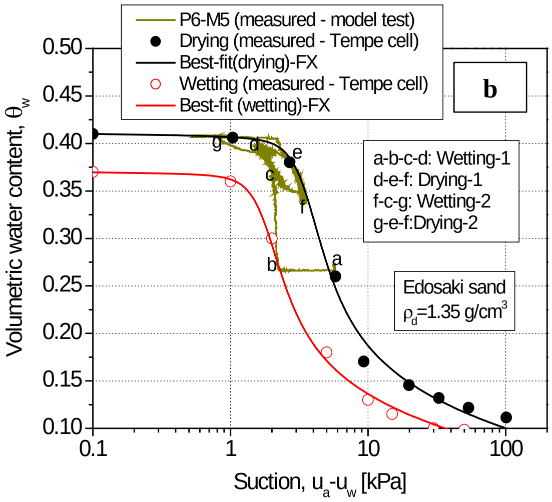


Fig. 16 SWCCs obtained from Tempe-cell and model embankment test

6. CONCLUSION

In this study, soil water characteristic curves (SWCC) for Edosaki sand was obtained using both direct and indirect methods. As for direct methods, instrumented soil column and model tank were subjected to wetting and drying cycles under controlled laboratory conditions and sensor responses were plotted at each sensor location to determine SWCC for sand. Keeping all the soil parameters and conditions constant, SWCC of Edosaki sand was experimentally obtained by Tempe pressure cell as simple indirect method. It is blatantly found that results of the indirect method provide a very close similarity to the outcomes of the costly, complex and time consuming direct methods (i.e. instrumented soil column and model tank). However, the slight variation of the SWCC in aforementioned methods may due to the experimental flaws and differential sensor outputs caused by insignificantly minor environmental impacts, yet can be disregarded when compared to the cons of direct methods. Taken together, these findings imply the practicality of the indirect methods to determine soil specific SWCC when compared to rigorous direct methods.

7. ACKNOWLEDGEMENTS

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