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Performance of high-capacity tensiometer in constant water content oedometer test

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Abstract

Background: Matric suction is one of the stress-state variables which governs the behaviour of unsaturated soils. In order to evaluate the effect of matric suction on the behaviour of unsaturated soil under constant water content condition, rapid measurement of change in matric suction during the test is required. High-capacity tensiometer can be used to rapidly measure the change in matric suction of unsaturated soil.

Methods: In this paper, an oedometer apparatus was modified to incorporate a high-capacity tensiometer to investigate the compression behaviour of unsaturated soil under constant water content condition. The design of the oedometer apparatus was described. Two soils which are kaolin FP grade (commercial kaolin which has a fine grain size) and residual soil from Bukit Timah Granite were used to evaluate the performance of the high-capacity tensiometer.

Results: The results showed that kaolin paste is helpful in improving the contact condition between the soil specimen and high-capacity tensiometer. The equilibrium time of the high-capacity tensiometer was about 10 min. Evaporation effect reported by other researchers was not observed with the high-capacity tensiometer.

Conclusion: The change in matric suction due to loading and unloading was accurately captured by the high-capacity tensiometer.

Keywords: Unsaturated soil, High-capacity tensiometer, Pore-water pressure measurement, Constant water content, Oedometer test

Background

The properties of unsaturated soils such as shear strength, volume change and permeability are different from those of saturated soils due to the presence of matric suction s which is the pore-water pressure (u_w) referenced to the pore-air pressure (u_a). Thus, matric suction measurement is important in investigating the behaviour of unsaturated soil. However matric suction measurement faces challenges such as limited range of matric suction which can be measured, and stability of matric suction reading during measurement.

In order to investigate the behaviour of unsaturated soils, constant matric suction condition is commonly implemented either using the axis-translation technique [8, 11, 14, 21, 22] or by controlling the relative humidity of the soil [5, 11]. The reasons for using

constant matric suction instead of constant water content condition are due to the long equilibrium time t_{eq} needed to measure matric suction and the difficulties in interpreting the test results for constant water content condition [2]. However, the use of axis-translation technique has its critique. The axis-translation technique hinders cavitation in the unsaturated soil specimen which is unnatural as the air pressure in the field condition is not artificially elevated [4] and can only be justified if the water is rigid [13]. The effect of cavitation on the unsaturated soil specimen is unclear but some experimental tests using osmotic suction gave different results compared to tests using the axis-translation technique [17, 25, 26].

High-capacity tensiometer (HCT) [6, 7, 19, 20, 24] measures negative pore-water pressure of soil beyond the pressure commonly associated with cavitation and at the same time allows rapid measurements of the pore-water pressure. The principle of HCT is to use a very small water reservoir between the transducer sensing diaphragm and the high air-entry (HAE) disk so that it is difficult for cavitation to take place. By pressurizing the water in the water reservoir at a high pressure, all the remaining air is dissolved. Thus, when the specimen is placed in contact with the high-air entry disk, water in the HCT starts to equilibrate with the water in the soil specimen and the water inside the water reservoir can sustain a high negative pore-water pressure. However, the use of HCT has not been standardized as there are several issues that remain to be solved such as: How small the water reservoir of the HCT should be? What is the best method to saturate the HCT? And, how to ensure good contact between the soil specimen and the HCT?

With regards to the size of the water reservoir of the HCT, at first it is believed that the water reservoir should be extremely small (i.e. 200 μm gap or about 3 mm^3 water volume) to inhibit the formation of air bubbles [19]. However, further investigation by Mendes and Buzzi [15] indicated that it is possible to increase the size of the water reservoir up to approximately 1100 mm^3 .

Saturating the HCT can be challenging especially when the air-entry value of the ceramic disk is very high (i.e. around 1500 kPa). The most common method used to saturate the HCT is by applying a high water pressure and sometimes followed with applying a vacuum (e.g., [7]). The water pressure used should be high enough such that the water can penetrate the high-air entry disk into the water reservoir and dissolve the air in the water reservoir. Acikel and Mancuso [1] proposed to circulate CO_2 through the HCT. Unfortunately, Acikel and Mancuso [1] only showed measurement of matric suction of less than 700 kPa, which is less than the maximum matric suction of 1500 kPa that can be measured by using high water pressure to saturate the HCT [7, 15, 19, 23]. Thus, it is not certain whether the proposed procedures of using CO_2 can be used to achieve higher matric suction measurement.

Oliveira and Marinho [18] showed that the contact condition between HCT and the soil specimen can be improved by using a soil paste (i.e. kaolin or residual soil) with water content between its plastic and liquid limits. Several advantages in using the soil paste are:

1. It helps to maintain hydraulic conductivity between the water in the specimen and the water in the HCT,

2. It reduces the evaporation of water in the HCT prior to placing the specimen in contact with the HCT, and
3. It improves the contact condition between the HCT and the soil specimen especially when the surface of the soil specimen is rough.

The versatility of the HCT is in its small size which allows it to be installed into any device using minimum modification. Thus, HCT can be installed in oedometer and tri-axial apparatuses to measure the matric suction. Under constant water content condition, the pore-air pressure of the soil specimen u_a is at atmospheric condition. Thus, it is possible for the soil specimen to dry due to evaporation during the test [9]. Such a situation is not desirable as it becomes difficult to interpret the relationship between the measured matric suction and the water content of the specimen. Latex or aluminium membrane covering the exposed surfaces of the soil specimen is commonly used to reduce the evaporation of the water in the soil specimen during the test [9, 16, 20, 23].

In this paper, an oedometer apparatus was modified to incorporate a HCT with efforts to minimize the problems of the HCT described above. Kaolin FP grade (commercial kaolin which has a fine grain size) and residual soil from Bukit Timah Granite were used to evaluate the performance of the HCT.

Test set-up

Jotisankasa et al. [9] and Tarantino and De Col [23] have also performed constant water content oedometer tests with HCT. However, the modified oedometer described in this paper is different from the modified oedometers of Jotisankasa et al. [9] and Tarantino and De Col [23] which are shown in Fig. 1. The design of the HCT used in this study follows the design of He et al. [7]. The schematic drawing and picture of the HCT are given in Fig. 2. The high-air entry (HAE) disk, 10 mm in diameter, was placed at the top of the tensiometer shroud while the pore-water pressure transducer was placed at the bottom of the tensiometer shroud. The tensiometer shroud has a 0.1 mm gap between the high-air entry disk and the pressure transducer thus effectively giving a water reservoir of less

Fig. 2 HCT which is used in this study. **a** Schematic drawing of HCT. **b** Picture of HCT. **c** Evaporation tests

than $19 \mu\text{m}^3$. An O-ring was placed between the tensiometer shroud and the pore-water pressure transducer to prevent water leakage.

Evaporation test was performed by repeatedly drying and wetting the HCT and then letting the HCT dry until it cavitates. The drying was conducted by exposing the HCT to the atmosphere while the wetting was conducted by placing a drop of water on the top of the HAE disk of the HCT. The result of the evaporation test is shown in Fig. 2c. The evaporation test indicates that the HCT is responsive and can measure negative pore-water pressure of up to 1300 kPa before it cavitates.

In order to incorporate the HCT into the oedometer apparatus, a modified base plate was designed. The schematic drawing of the modified base plate is given in Fig. 3a. The modified base plate replaces the base plate of the conventional oedometer apparatus and allows the HCT to be attached. The modified oedometer apparatus is shown in Fig. 3b. The purpose of attaching the HCT at the bottom of the oedometer is to minimise the effect of evaporation on the HCT which is apparent in the test results of Jotisankasa et al. [9] and also to improve the contact condition between the HCT and the soil specimen as the soil specimen is loaded. Both Jotisankasa et al. [9] and Tarantino and De Col [23] used two tensiometers installed in the top load cap of their modified oedometer apparatuses.

A piece of dry filter paper was placed at the top of the specimen to separate the soil specimen from the dry porous stone. The purpose of using dry filter paper is to

let the pore-air be in a drained condition when the soil specimen is loaded in a constant water content condition. On the other hand, once the soil specimen reaches the fully saturated condition, it allows the excess pore-water pressure to drain during compression.

Soil specimens and testing procedures

Two soils were used. The first soil is kaolin FP grade while the second soil is a residual soil from Bukit Timah Granite [10] which was sieved through sieve #8 (2.36 mm) in order to satisfy the maximum grain size requirement for oedometer test in [3] /D2435M (2011). The soil was first mixed with water to approximately 1.5 times its liquid limit into a slurry. The slurry was then consolidated in a consolidation tank at a consolidation pressure of 150 kPa. The soil sample was then divided into smaller samples to prepare the soil specimens for the oedometer tests. Figure 4 shows the grain size distributions and Table 1 shows the basic soil properties of the soils. The kaolin and residual soil are classified as ML and SM, respectively, according to the unified soil classification system.

In order to minimise sample disturbance, the soil specimen was first cookie cut with a 6.3 cm internal diameter ring that has a sharpened edge. The soil specimen was then air dried until it reached the desired water content. Once the soil specimen reached the desired water content, the soil specimen was then cookie cut with a 5 cm internal diameter oedometer ring. For the kaolin specimen, the specimen was directly placed on the

Table 1 Basic soil properties of the kaolin and the residual soil

Basic soil properties	Kaolin	Residual soil
G_s	2.66	2.65
PL (%)	32	34
LL (%)	60	56
PI (%)	28	22
SL (%)	21	24

HCT. However, the residual soil specimen has a rough surface and kaolin paste was used to improve the contact condition between the residual soil specimen and the HCT.

Once the soil specimen was placed on the HCT, the pore-water pressure of the soil specimen was monitored until it reached equilibrium. The soil specimen was then loaded incrementally under constant water content condition in order to observe the change in pore-water pressure. The load increment ratio used was unity. The duration for each loading step was determined based on the pore-water pressure reading and was deemed completed when the HCT reached equilibrium. Long loading duration may cause evaporation effects on the soil specimen. If the HCT reads positive excess pore-water pressure, the loading duration follows the conventional saturated oedometer test (approximately 1 day/loading step following [3] /D2435M (2011) method A).

The kaolin specimens were named using “KwXsY” where K stands for kaolin, w stands for the gravimetric water content, X is the water content of the specimen, s stands for matric suction, and Y is the matric suction of the specimen. The naming of the residual soil specimens from Bukit Timah Granite were named using similar convention that is “BTwXsY” where BT stands for Bukit Timah Granite.

Equilibrium time of kaolin and residual soil specimens

Lourenço et al. [12] observed three variations of the HCT response during the initial pore-water pressure measurement before it reaches equilibrium which are equilibrium types A, B and C. Equilibrium type A is the normal equilibrium which is desired where

the negative pore-water pressure reaches the negative pore-water pressure of the soil specimen slowly. Equilibrium type B is when a higher initial negative pore-water pressure was registered before rebounding to the equilibrium negative pore-water pressure. Lourenço et al. [12] suggested that this phenomenon is due to the water inside the soil specimen not in equilibrium condition prior the suction measurement. Equilibrium type C is when the negative pore-water pressure never reaches equilibrium. Lourenço et al. [12] suggested that equilibrium type C is due to the continuous loss of water from the specimen. Such an effect can be attributed to evaporation.

Six kaolin specimens (Kw60s40, Kw47s252, Kw37s399, Kw48s287, Kw42s347, Kw30s468) were used to evaluate the equilibrium time taken by the HCT to equilibrate with the soil specimens and the results are shown in Fig. 5. For the kaolin specimens, no kaolin paste was used as an interface. Figure 5 shows that the equilibrium time can be up to 10 min. In most of the cases, the equilibrium time follows equilibrium type A except for Specimen Kw47s252 which follows equilibrium type B.

Equilibrium Type B appears to be due to poor contact condition between the HCT and the soil specimen. When the contact condition between the HCT and the soil specimen

Fig. 5 Equilibrium of the HCT for the kaolin specimens. **a** Type A equilibrium. **b** Type B equilibrium

is poor, some air is trapped in the contact and causes the air pressure to rise beyond atmospheric air pressure and cause the HCT to give a higher suction than the suction of the soil specimen. However, with time the air pressure reduces and the water in the soil specimen equilibrates with the water inside the HCT water reservoir, and the HCT will read the matric suction of the specimen. The concern of this type of equilibrium is that there is a possibility of the HCT cavitating prior to the pore-water pressure rebound to the equilibrium pore-water pressure reading.

For the residual soil specimens from Bukit Timah Granite, a kaolin paste was used as an interface between the HCT and the soil specimen. Kaolin paste serves to cover the high air entry disk to prevent evaporation which allows more time to set up the specimen. It also improves the contact condition between the residual soil specimen and the HCT. Two residual soil specimens (BTw20s902 and BTw26s332) were used to evaluate the equilibrium time taken by the HCT to equilibrate with the soil specimen and the results are shown in Fig. 6. The results showed that the residual soil specimens gave a relatively consistent equilibrium time (roughly 8 min). However, small fluctuations in the pore-water pressure were observed prior to reaching equilibrium. This is likely due to the re-distribution of pore-water pressure inside the kaolin paste and the residual soil specimen.

Response of the HCT in constant water content oedometer test

The results from the constant water content test on the kaolin specimens are shown in Fig. 8. In general, the application of net normal stress caused the pore-water pressure to increase due to an increase in degree of saturation and is referred to as mechanical wetting (Fig. 8b). Such observation is consistent with the observations of Jotisankasa et al. [9] and Tarantino and De Col [23] provided that no evaporation occurred during the test. It appears that the evaporation issue which was apparent in Jotisankasa et al. [9] experiments shown in Fig. 7 was not apparent in Fig. 8b as the pore-water pressure always increases when the soil specimen was loaded. Therefore, placing the tensiometer at the base of the oedometer apparatus appears to be effective in avoiding the effects of evaporation on the HCT reading.

The pore-water pressure response during the constant water content oedometer test for kaolin specimen can be differentiated into three states. The three states are the unsaturated state (Fig. 9a), the transition state (transition between unsaturated state to the saturated state as illustrated in Fig. 9b) and the saturated state (Fig. 9c). The states in Fig. 9 are indicated in Fig. 8. In the transition state, the response of the soil specimen following positive excess pore-water pressure generation behaves just like in a saturated test. As the top of the specimen was covered with dry filter-paper and dry porous stone, it is possible for the water to escape and therefore allows the positive excess pore-water pressure to dissipate after it reached a peak pore-water pressure (Fig. 8b, c).

There is a difference between the duration required for the specimen to reach the end of primary compression (t_{end}) and the duration required for the pore-water pressure to reach equilibrium (t_{eq}) for the saturated and unsaturated states. In Fig. 9, the difference between t_{end} and t_{eq} is indicated as Δt . It is important to ensure that the load is applied until both t_{eq} and t_{end} have been reached. Based on the reported tests results, it appears that t_{eq} of up to 20 min is sufficient for each load increment for the unsaturated state. For transition and saturated states, it is recommended to use 24 h loading duration, same as conventional oedometer tests, to ensure that the positive excess pore-water pressure has fully dissipated.

Further evaluation of the performance of the HCT is given by the oedometer tests on the residual soil specimens from Bukit Timah Granite (Fig. 10). Specimen BTw26s332 was loaded up to net normal stress of 3260 kPa and then inundated prior to being unloaded. Specimen BTw20s902 was loaded up to net normal stress of 3260 kPa and then unloaded to net normal stress of 51 kPa, reloaded to 3260 kPa and then inundated. No collapse was observed for both of the soil specimens and both of the soil specimens reached the fully saturated condition with positive excess pore-water pressure prior to inundation. However, for soil specimen BTw20s902, unloading prior to inundation caused the soil specimen to have negative pore-water pressure due to dilation of the soil with hysteresis in the pore-water pressure during loading and unloading. After inundation, both of the soil specimens registered residual positive pore-water pressure of about 50 kPa.

A similar pore-water pressure response was observed for both the residual soil specimens as shown in Fig. 11. The pore-water pressure response in unsaturated state (Fig. 11a) appears to have a small secondary wetting where the pore-water pressure slowly increases. The secondary wetting seems to be due to the secondary compression. As the secondary compression occurs, the degree of saturation increases slowly due to the reduction in void ratio and thus increases the pore-water pressure (mechanical wetting). Similar to the kaolin specimens, t_{eq} seems to only require approximately 200 s to reach the end of primary wetting when the soil specimen is in unsaturated state. Thus, the same loading duration which is 20 min can be used for the unsaturated state.

Several recommendations are given for conducting constant water content oedometer test with pore-water pressure measurement based on the experimental observations:

Fig. 10 Results for constant water content oedometer tests of residual soil specimens. **a** Change in void ratio due to loading at constant water content condition. **b** Change in pore-water pressure due to loading at constant water content condition

1. Placing the high-capacity tensiometer at the bottom of the specimen avoids effects of evaporation and improves the contact condition between the HCT and the soil specimen.
2. Using kaolin paste as an interface between HCT and soil specimen reduces the effect of evaporation on the HCT prior to the placement of the specimen and also improves the contact condition of the specimen.
3. There is a difference between duration for the specimen to reach the end of primary compression (t_{end}) and for the pore-water pressure to reach equilibrium. Based on the test results, it appears that 20 min is sufficient for each load increment when the soil is in the unsaturated state.
4. Once the soil specimen reaches the saturated state, use 24 h duration between load increments as used in the conventional oedometer test.

Fig. 11 Pore-water pressure responses of residual soil specimens. **a** Pore-water pressure response of BTw20s902 at 815 kPa net normal stress (unsaturated state). **b** Pore-water pressure response of BTw20s902 at 3260 kPa net normal stress (transition state). **c** Pore-water pressure response of BTw26s332 at 3260 kPa net normal stress (saturated state)

Conclusion

In this paper, the performance of a high-capacity tensiometer (HCT) in a modified oedometer apparatus developed to conduct constant water content test on unsaturated soils was evaluated. A modified base plate was constructed in order to incorporate the HCT into the oedometer apparatus to measure the pore-water pressure of the unsaturated soil specimen. The modified base plate was made such that the HCT is at the bottom of the specimen to reduce evaporation effect on the HCT and also to ensure a good contact condition between the HCT and the soil specimen.

Two consolidated specimens which are kaolin FP grade and residual soil from Bukit Timah Granite were used to evaluate the performance of the HCT. A kaolin paste was used as an interface between the residual soil specimen and HCT while no soil paste was used as an interface between the kaolin specimen and HCT. The kaolin paste allows more time to set up the specimen and improves the contact condition between the residual soil specimen and the HCT.

The equilibrium time which is needed by the HCT to read the initial matric suction of the soil specimen is about 10 min. Once the soil specimen is loaded, there is a difference between the durations to reach end of primary compression and for the pore-water pressure to reach equilibrium. Based on the test results, 20 min appear to be sufficient for each load increment for the soils tested when the soil is in the unsaturated state. However, once the pore-water pressure becomes positive (transition and saturated states), it is recommended to follow the test duration of a conventional saturated oedometer test (approximately 24 h) for each load increment.

Authors' contributions

MW carried out the tests, conducted the analyses and drafted the paper. ECL provided directions for the conduct of the tests, guided the analysis and the drafting of the paper. Both authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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