A GRAPHICAL METHOD FOR MEMBRANE PENETRATION IN TRIAXIAL TESTS ON GRANULAR SOILS

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ABSTRACT

In granular soils, membrane penetration is significant which will affect the measurement of the specimen volume change since it is measured from the specimen water that came out of the specimen when the specimen is compressed. The volume of the expelled water represents both the specimen shrinkage and the membrane penetration. Correction has to be made to eliminate the effect of membrane penetration. A graphical method to determine the membrane penetration is described and the results are compared with the actual membrane penetration determined from the consolidation of dummy specimens. There are four test materials involved which are sands of uniform grain size of 0.3, 0.6, 1.18 and 2.0 mm. Four test series dealt with consolidated drained triaxial tests on saturated specimens. The effective stresses applied are 50, 100, 200, 300 and 400 kPa. The fifth test series was the tests on dummy specimens made from thin layer of test materials enclosing a solid concrete cylindrical core. The specimen water expelled from the consolidation of the dummy specimens is purely due to membrane penetration. In this study, it is observed that membrane penetration increases with effective confining pressure and as well as the grain sizes. The result shows that half of the cases complied with the proposed method. It indicates the potential to be a good and simple alternative for the determination of membrane penetration. However further investigation is required.

Keywords: *Consolidation Curve, Granular Soils, Membrane Penetration, Triaxial Test*

1.0 INTRODUCTION

In triaxial tests on granular soils, membrane penetration is the deflection of the enclosing rubber membrane into the interstices over the side of the cylindrical specimen whenever the cell pressure is elevated to begin the consolidation stage. It is a normal procedure for triaxial test on saturated specimen that the change in the specimen's volume is monitored base on the specimen water that being expelled out or drawn in. The occurrence of membrane penetration during the consolidation stage will affect the determination of the specimen volume at the end of the stage and thus in turn will affect the stress-strain interpretation during the shearing stage. Therefore a good and reliable method is required in order to produce a high quality data when granular soil is tested. The simplicity of the method is of utmost priority where the need of extra test can be avoided.

Membrane compliance plays a significant role in increasing the cyclic loading resistance of a granular soil as determined by undrained, cyclic triaxial compression tests. The effects of this phenomenon are particularly significant in tests on gravels or gravelly soils due to the large particle sizes of such materials. The application of consolidation pressures prior to testing causes the rubber confining membrane to penetrate into the specimen peripheral voids. During undrained cyclic loading, the effective confining pressure is reduced as excess pore pressures buildup in the sample, and thus the membrane rebounds from the penetrated voids due to the reduction in effective confining pressure. However, because the specimen is undrained, a water content redistribution occurs as pore water migrates from within the specimen to the zones where rebound of the penetrating membrane has occurred, resulting in densification of the specimen and a reduction in the induced excess pore water pressures. The overall effect of membrane compliance is to make the specimen appear stronger, and thus lead to an overestimation of the cyclic loading resistance of the in-situ material [1].

Undrained loading tests are widely used to assess the susceptibility of soils to liquefaction. Variation, with changes in effective confining stress, of the penetration of the membrane confining a soil sample into the voids between the particles (membrane compliance) invalidates the assumed testing conditions of constant volume without drainage. This can have a serious detrimental impact on the accuracy and validity of such tests, particularly for medium to coarse sands as well as gravels, and no completely reliable procedures currently exist either for mitigation of membrane compliance effects during testing or for post-test correction of the results of conventional undrained tests [2].

However, the effect of membrane penetration is difficult to eliminate. Volume change due to membrane penetration in the triaxial test was first discovered by Newland and Allely [3]. Since that, a number of experimental methods [4;5], and theoretical investigations [6;7;8] have been developed to address this problem. Miura and Kawamura [9] have summarised all related studies into four broad categories. Category I is to establish a method for direct evaluation of the amount of membrane penetration. Meanwhile the studies in Category II aim to eliminate or reduce the membrane penetration during the undrained loading.

In Category III, the theoretical and analytical investigations of the effects of membrane penetration and membrane compliance are studied meanwhile the change in the undrained shear behaviour due to membrane compliance including the bedding error problem in the triaxial specimen is evaluated in Category IV.

Historically, gravelly soils have typically been assumed to be “safe” from liquefaction failures. However, recent improvements in understanding of the effects of membrane compliance on triaxial test results, along with documentation of a number of field cases in which gravels have liquefied, has led to the realisation that such soils can liquefy. As a result, the importance tp develop a method to correctly assess the dynamic strength of these coarser soils has become apparent. Previous attempts at mitigating membrane compliance effects during testing, or making post-test corrections to conventional undrained test results, have not been fully successful in providing verifiably correct test results [10].

Empirical formula are commonly applied to quantify the amount of membrane penetration in triaxial test, however the disadvantage of this method is that they involved a few variables and material properties. The behaviour of membrane penetration is very complex where it is governed by membrane stiffness and thickness, grain size and shape and the magnitude of the effective confining pressure [11]. The accuracy of the material properties applied can significantly affect the result. The amount of membrane penetration increases with increasing effective lateral stress. Example of an empirical equation by [8] is as follows.

$$V_m = \frac{d_g}{2d_{spec}} V_0 \sqrt[3]{\frac{\sigma'_3 d_g}{E_m t_m}} \tag{1}$$

Where V_m is the volume of membrane penetration, d_g is the grain mean diameter, d_{spec} is the specimen diameter, V_o is the specimen volume, σ'_3 is the effective lateral pressure, E_m is the membrane Young Modulus and t_m is the membrane thickness.

In addition, Kramer *et. al.* commented that in the analytical methods by Molenkamp and Luger [7] and Baldi and Nova [8], the assumed deformed shapes of the membrane poorly represent the actual shape assumed by a membrane stretched across an array of spheres and subjected to an unbalanced transverse pressure. Other limitations are both models violate the displacement boundary condition and the stress boundary conditions. Recently, studies have been directed towards correcting, eliminating or properly reducing the membrane penetration during the undrained loading e.g. Miura and Kawamura [9] who introduce Toyoura standard sand to be placed around the triaxial specimens as a membrane penetration reducing layer. The average diameters are 0.64, 1.25 and 3.0 mm for test materials and 0.18 mm for Toyoura sand. The study indicates that the formation effect of using Toyoura sand layer depends strongly on the particle size of the test specimen.

The application of empirical equations can be cumbersome where the soil and the membrane properties need to be predetermined. The main aim of the study is to develop an alternative and relatively simpler method for determining the membrane penetration to ease the interpretation of data acquired from conducting triaxial test on granular specimens. A graphical method was developed to predict the volume of membrane penetration from the consolidation curve. The consolidation curve for granular specimen represents the change in volume due to specimen shrinkage plus the membrane penetration relative to time. When the membrane penetration is determined the actual volume of the specimen compression due to the consolidation pressure can be obtained and a more effective interpretation of soil stress-strain response can be achieved.

2.0 GRAPHICAL ESTIMATION METHOD FOR MEMBRANE PENETRATION

A graphical method is proposed to determine the volume of membrane penetration from the graph of isotropic consolidation curve. The method is aimed to provide a simple and convenience alternative compared to the existing empirical equations. The method is intended to save the hassle of finding the soil grain size and the membrane properties as required by the empirical formulae.

The procedure applied in the graphical method is as follows.

1. Draw the best straight lines through the initial and the tail parts of the isotropic consolidation curve. Call their intersection as point “a”.
2. Draw from point “a” a bisector line between the best straight lines in (1) which will cut through the consolidation curve at point “b”. Let the distance a-b be “L”.
3. Move a further distance of “L” from point “b” away from point “a” along the bisector line and mark the point as “c”.
4. Draw a perpendicular line through point “c” until it intersects the consolidation curve at point “d”. Point “d” represents the volume of membrane penetration.

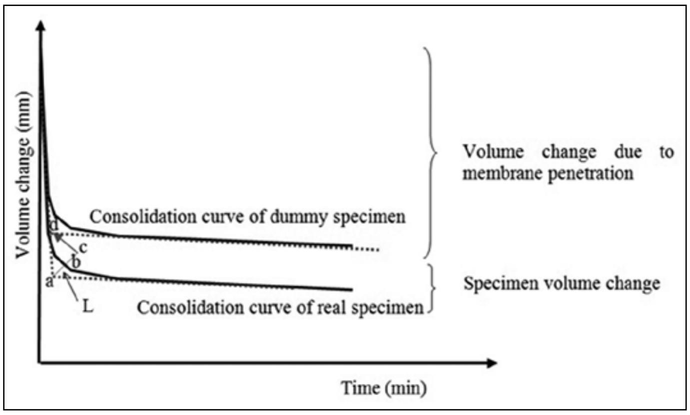

Figure 1: Schematic diagram to estimate membrane penetration isotropic consolidation curve

This procedure is applied to estimate the membrane penetration and the result is compared with the actual volume of membrane penetration obtained from consolidation tests on dummy specimens.

3.0 TEST MATERIALS

Figure 2 shows quartz sand of uniform grain sizes which are; 0.3, 0.6, 1.18 and 2.0 mm diameter. The application of these different grain sizes is to determine the behaviour of membrane penetration relative to grain sizes under various effective lateral pressures. The actual volume of membrane penetration for a specific grain size was determined by conducting isotropic consolidation tests on dummy specimens which was formed by having a thin layer of the test material of about 2.5 mm thickness enclosing a solid rigid cylindrical core of 45 mm diameter and 100 mm high.

The core was made up of steel tube of diameter 45 mm and 100 mm height. The tube was filled up with the compacted test material. Moreover the thin layer of the test material on the outside of the core was pre-consolidated before conducting the membrane penetration test in order to ascertain that the thin layer of soil does not undergo shrinkage during the test. This is to ensure that the expulsion of the specimen water is purely due to membrane penetration. Consolidated drained triaxial test were conducted on saturated specimens of 50 mm diameter and 100 mm high. Shear strength behaviour of the 0.6mm diameter grain size specimen will be determined.

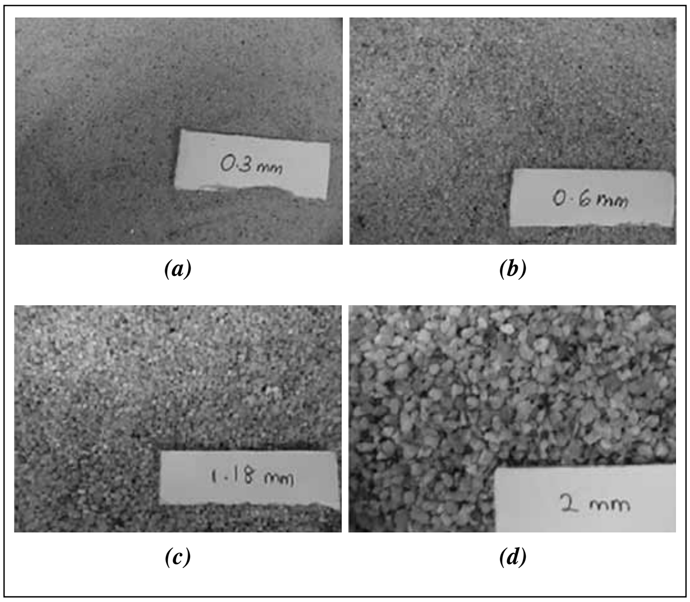

Figure 2: The four sizes of quartz sand as the test materials of diameter (a) 0.3 mm (b) 0.6 mm (c) 1.18 mm and (d) 2.0 mm

4.0 SHEAR STRENGTH AND MEMBRANE PENETRATION TESTS

There are two types of specimens involved in this study, which are (1) real specimens and (2) dummy specimens having a rigid cylindrical core. A consistent standard preparation procedure was adopted for each type of the real specimen in order to ensure all the tests began with respective identical density. Consolidated drained triaxial tests were conducted on the real specimens. The actual volume of membrane penetrations during specimen isotropic consolidations were determined from the membrane penetration tests on the dummy specimens.

4.1 Preparation of real specimens and consolidation drained triaxial tests

The real specimens of initial diameter 50 mm and height 100 mm were used in the consolidated drained triaxial tests. They were compacted during preparation to achieve a dense specimen condition. The mould was placed directly on the pedestal with the membrane gripped to its base using O-ring while the top is folded over the mould. The membrane was extracted to the mould inner wall using vacuum. The sand was poured and compacted in 5 layers with 10 blows for each layer using a wooden rod of diameter 45mm. The same dry weight of sand was used in the preparation of each specimen type in order to achieve the same initial dry density. The dry weight of soil for grain size of 0.3, 0.6, 1.18 and 2.0 mm are 286.63, 297.32, 309.85 and 300.42 g respectively. Once a specimen has been completely filled, the top cap is placed over and the membrane is folded over the top cap and gripped by O-ring. Then vacuum pump was connected to the back pressure line which is connected to the top cap. At this point the mould can be split and removed. The vacuum was released once the cell pressure of 15 kPa has been applied. This is to avoid the specimen from collapsing. This is followed by filling the specimen with water from the bottom and allowed the air to escape through the top back pressure line until there is over flow. This was followed with saturation stage where water is pushed into the specimen until minimum Skempton's B value [13] of 0.97 is achieved for all test series. This was followed by the consolidation stage and finally the shearing stage.

4.2 Preparation of dummy specimens and membrane penetration tests

The dummy specimens were prepared by placing the cylindrical steel tube and filled it up with the compacted material. The inner core tube was located eccentrically in the mould and subsequently the sand was poured and compacted around the core. The top cap was placed over the dummy specimens and followed by filling with water and saturate it in the same manner as the real specimens. Then the specimens were pre-consolidated right to the final effective lateral pressure intended in the consolidation process for one hour before lowering the cell pressure to 10 kPa greater than the applied back pressure. There are two types of membrane penetration tests conducted on dummy specimens which are; (1) Isotropic consolidation test and (2) Incremental isotropic effective pressure versus membrane penetration test. The first test series is to determine the consolidation curve purely due to membrane penetration. The second test series is to determine the behaviour of membrane penetration relative to small increments of isotropic effective pressure. There is no shearing for the dummy specimens.

5.0 RESULTS OF THE CONSOLIDATION TESTS ON REAL SPECIMENS

The isotropic consolidation curves for the four types of the test materials of grain sizes of 0.3, 0.6, 1.18 and 2.0 mm are shown in Figures 4, 5, 6 and 7 respectively. Each test material was consolidated at effective stress of 50, 100, 200, 300 and 400 kPa.

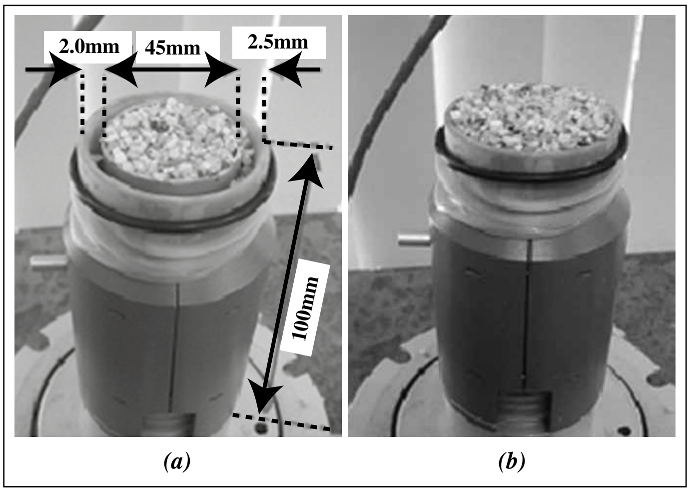

Figure 3: Dummy specimen with rigid cylindrical core
(a) Sand particles were placed over and around the rigid core
(b) Fully prepared dummy specimen for particle size of 2.0 mm

The graphs give the total volume change which comprises the specimen volume change and the volume of membrane penetration. Apparently for each particle size the graphs show that there is increase in the total volume change as the consolidation pressure increases. Besides, there is also a general increase in the total volume change as the particle size increases. However, the actual behaviour of membrane penetration and specimen compression relative to pressure and particle size can only be determined when the actual membrane penetration is recognised from the results of consolidation test on dummy specimens.

6.0 RESULTS OF THE CONSOLIDATION TESTS ON DUMMY SPECIMENS

Consolidation tests were conducted on dummy specimens to determine the actual membrane penetration since any amount of water expelled from the specimens is purely due to membrane penetration. The dummy specimen cannot undergo compression since it is made from cylindrical solid concrete core and the thin outer layer of soil has been pre-compressed at the beginning of the test. The graphs of total volume compression as in Figures 4, 5, 6 and 7 are superimposed with the graphs of consolidation tests on dummy specimens, at effective confining pressure of 50 kPa as shown in Figures 8, 9, 10 and 11 for particle sizes of 0.3, 0.6, 1.18 and 2.0 mm respectively.

7.0 BEHAVIOUR OF MEMBRANE PENETRATION RELATIVE TO ISOTROPIC EFFECTIVE PRESSURE

The membrane deflects deeper into the interstices as the pressure increases. This is as indicated by the behaviour of the membrane penetration curves with respect to the effective confining pressure of 50 kPa plotted in Figures 8, 9, 10 and 11. The actual amount of the membrane penetration is presented in Table 1 and the behaviour of the membrane penetration for the different particle sizes (0.3 – 2.0 mm) considered relative to the effective

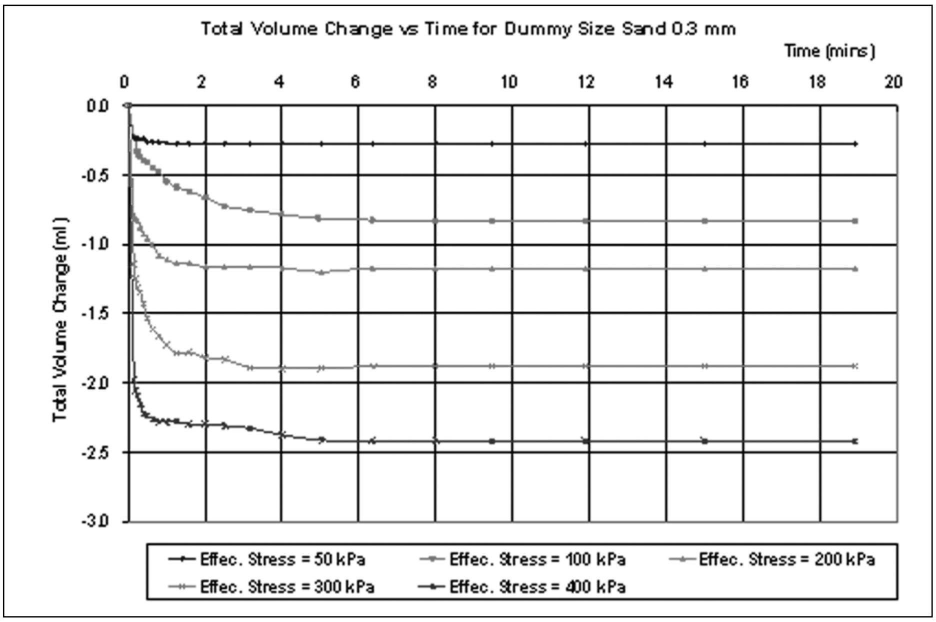

Figure 4: Total volume change during isotropic compression for grain sizes (0.3 mm)

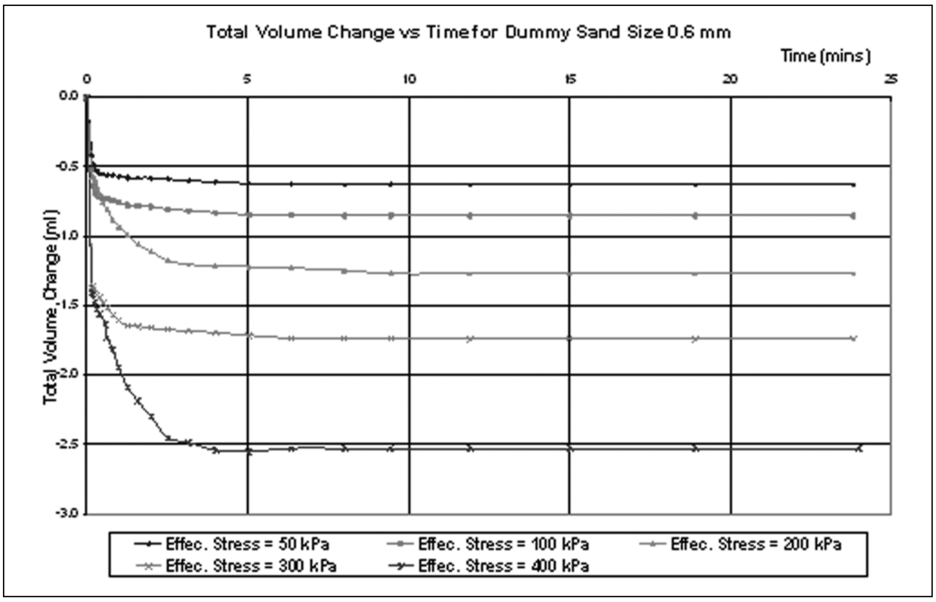

Figure 5: Total volume change during isotropic compression for grain size (0.6 mm)

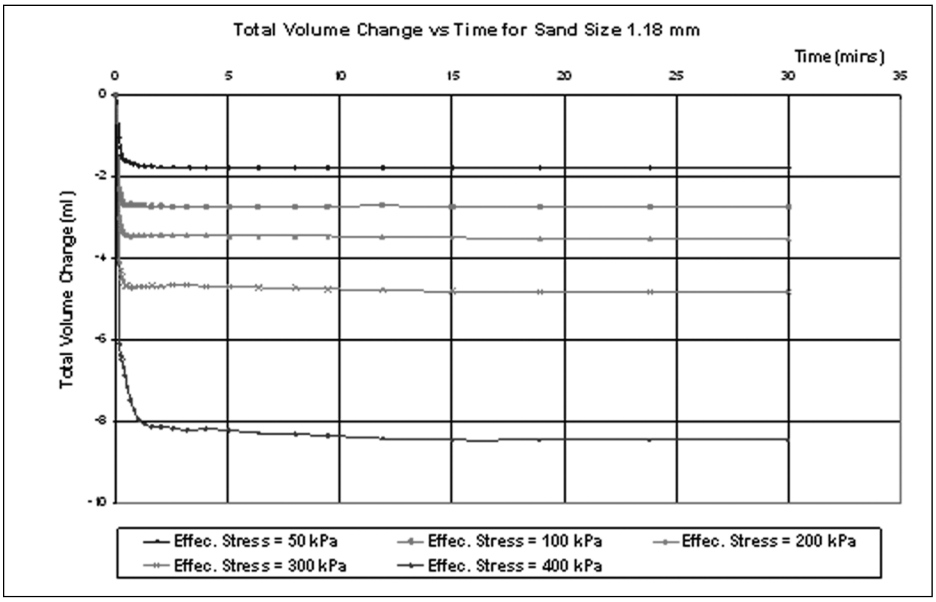

Figure 6: Total volume change during isotropic compression for grain size (1.18 mm)

confining pressure (50 – 400 kPa) is shown in Figure 12. Apparently as the particle size increases (0.3 – 2.0 mm) there is a greater membrane penetration for all effective confining pressures (50 – 400 kPa). However there is not much different in the membrane penetration for particle sizes 0.3 and 0.6 mm. This is may be due to the relatively small interstices between the soil grains.

Figures 8, 9, 10 and 11 show that the compression of the specimens only took place when the membrane penetration has been fully mobilised. This is when the points representing the end of membrane penetration are located before the curve portion of the consolidation graphs for the real specimens. It is anticipated that the curve segment is where the specimen compression is taking place. In other words the occurrence of specimen compression is indicated when the consolidation graph start to curve out from the initial linear portion towards the horizontal asymptote. This is a very important attribute of the membrane penetration behaviour.

The occurrence of the specimen compression when the membrane has been fully stretched irrespective of the effective confining pressure is giving a clear indication that the membrane is of less stiffness compared to the sand specimens. That is why the membrane penetration give way first to the applied effective confining pressure before the specimen compression is mobilised. However there is a difficulty to exactly locate the point of membrane penetration prior to the curve segment. That is the reason for this graphical method, which is to provide a simple way of identifying the point.

The dotted lines in Figures 8, 9, 10 and 11 show the graphical construction for the estimation of membrane penetration for the particle sizes of 0.3, 0.6, 1.18 and 2.0 mm respectively. The graphical predictions of the membrane penetration are compared with the actual indicated by the 100% consolidation curve from dummy specimens. The actual membrane penetration is considered to comply with the proposed graphical procedure when the estimation is close.

Table 2 (page 29) provides the evaluation on the effectiveness of the proposed graphical method. The number of cases that comply and did not comply with the proposed graphical method is equal. Material with smaller grain size

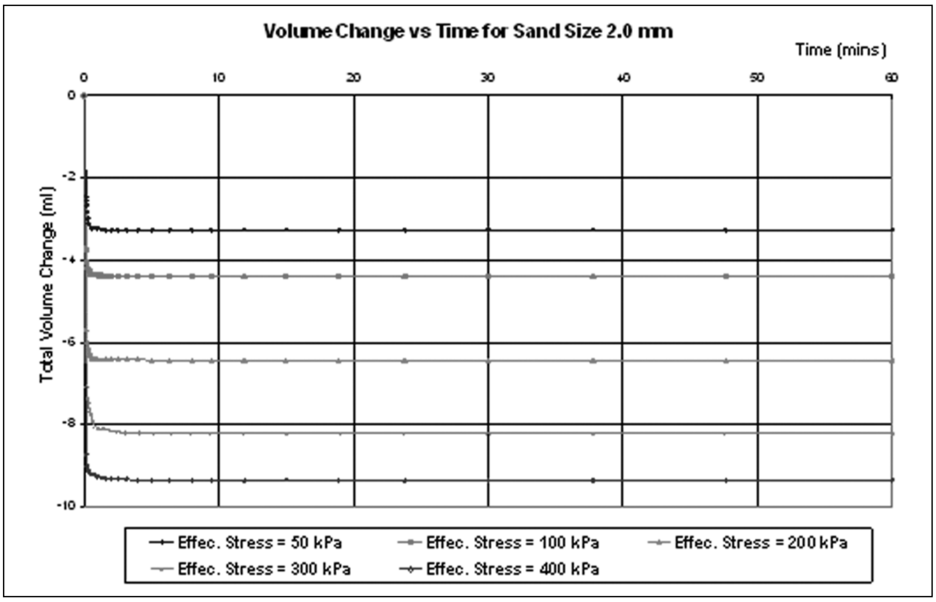

Figure 7: Total volume change during isotropic compression for grain sizes (2.0 mm)

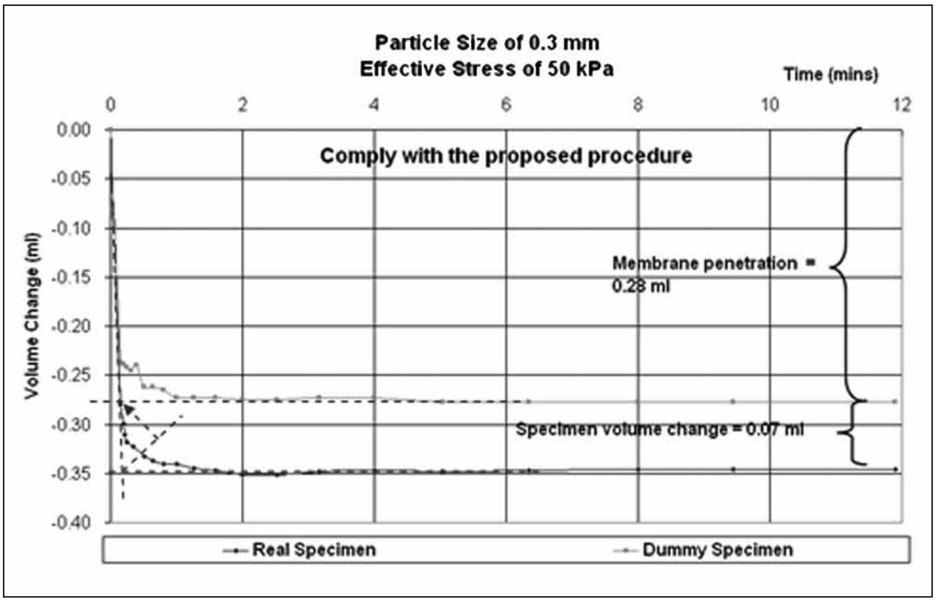

Figure 8: Graphs of isotropic consolidation on the dummy and real specimens of grain size 0.3 mm and effective stresses of 50 kPa

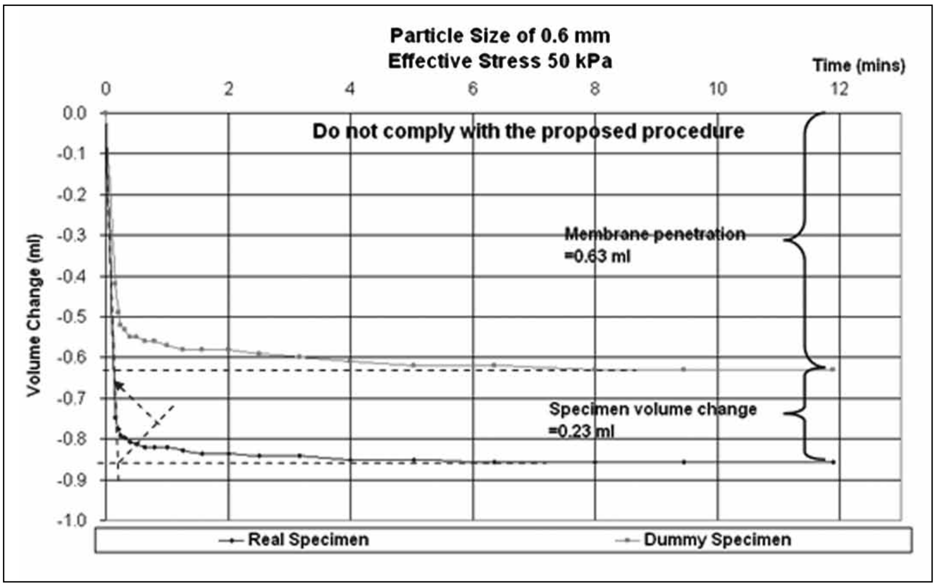

Figure 9: Graphs of isotropic consolidation on the dummy and real specimens of grain size 0.6 mm and effective stresses of 50 kPa

(0.3 mm) shows a higher compliance compare with a larger grain size (2.0 mm). It is also observed that there is less compliance for material consolidated at a higher effective confining pressure (e.g. 400 kPa). This suggests that the proposed method is promising and can be applied in the analysis of soil shear strength testing. However, further investigation should be conducted especially for material with larger grain sizes as well as the effect of different effective confining pressure.

8.0 SHEAR STRENGTH BEHAVIOUR OF TEST MATERIAL

The stress-strain and the volume change curve for sand of grain size 0.6 mm are shown in Figures 13 and 14 respectively. The stress-strain curves demonstrated a well defined peak except for the effective stress of 50 kPa. In Figure 14, less volume change is observed for test with higher effective confining pressure (400 kPa). This behavior is attributed to confining pressure and interlocking of particles, whereby interlocking increases as confining pressure increases. It also explains the slight dilation of specimen under lower effective confining pressure. The resulted shear strength behaviour is plotted in Figure 15. Apparently the shear strength envelope complied with the curved surface envelope [14] whereby it shows a non linear behavior at low stress.

9.0 CONCLUSIONS

The conclusions that can be drawn from this study are:-

1. The volume of membrane penetration contributes more than 60% of the total volume change. Therefore it is very significant to conduct membrane penetration correction when interpreting data from triaxial tests on granular soils.
2. Membrane penetration increases with effective confining pressure (50 – 400 kPa).
3. Membrane penetration increases as the soil particle become coarser (0.3 – 2.0 mm for all effective confining pressure).
4. The specimen compression is only triggered when the membrane penetration has been full mobilised. The occurrence of membrane penetration and specimen compression is a consecutive process i.e. they do not occur simultaneously.

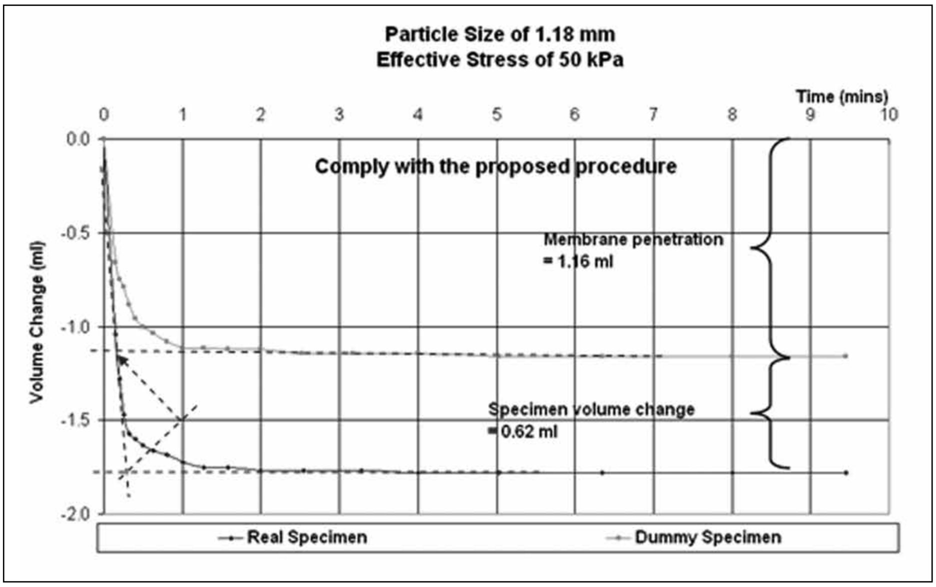

Figure 10: Graphs of isotropic consolidation on the dummy and real specimens of grain size 1.18 mm and effective stresses of 50 kPa

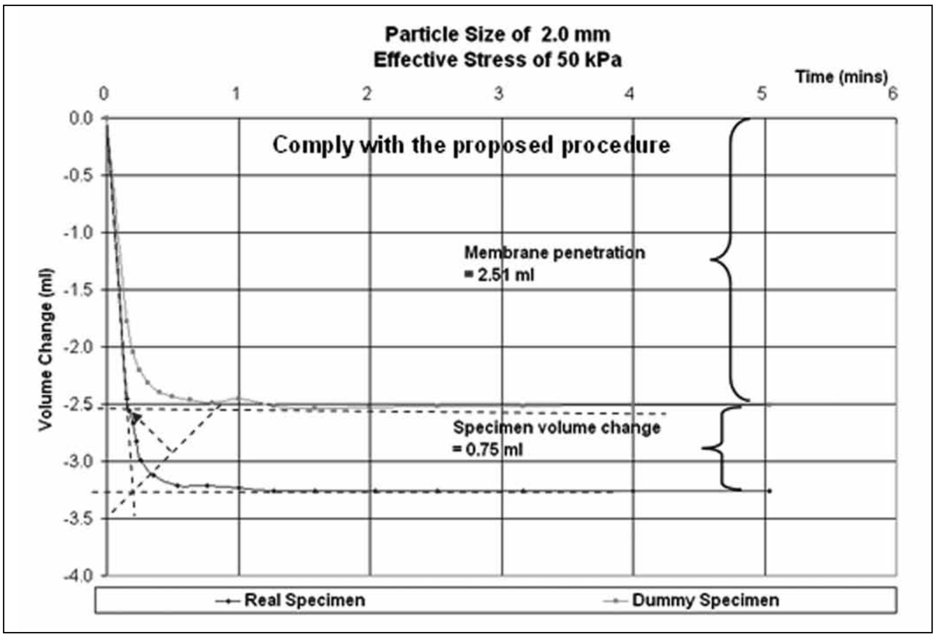

Figure 11: Graphs of isotropic consolidation on the dummy and real specimens of grain size 2.0 mm and effective stresses of 50 kPa

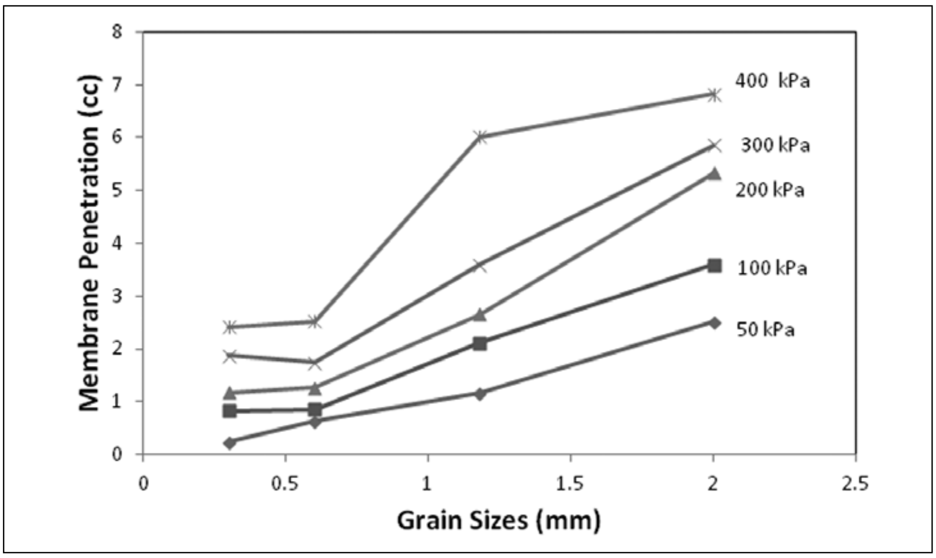

Figure 12: Comparison of membrane penetration relation to grain sizes (0.3, 0.6, 1.18 and 2.0 mm) under different effective confining stress (50 – 400 kPa)

5. The shear strength envelope of 0.6 mm compacted sand specimens is curvi-linear. ■

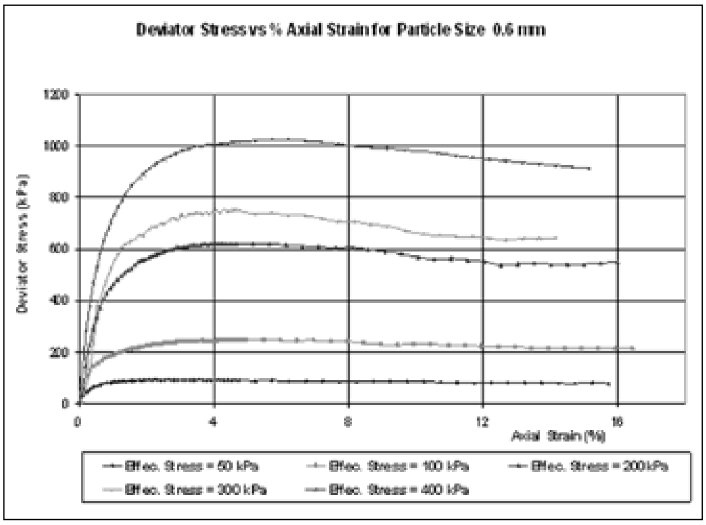

Figure 13: Stress-strain curve of specimen of grain size 0.6 mm

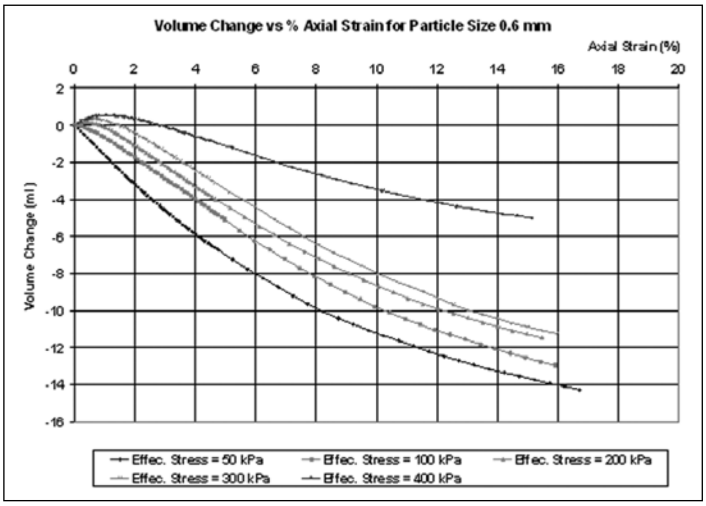

Figure 14: Volume change for specimen of particle size 0.6 mm

Table 1: Membrane penetration and specimen compression for the considered particle sizes at effective confining stress of 50, 100, 200, 300 and 400 kPa

Particle size (mm)	Effective Stress (kPa)	Membrane Penetration cc	Specimen Compression cc	% of Membrane Penetration
0.3	50	0.28	0.07	80.00
0.3	100	0.83	0.17	83.00
0.3	200	1.18	0.7	62.77
0.3	300	1.88	0.87	68.36
0.3	400	2.42	0.91	72.67
0.6	50	0.63	0.23	73.26
0.6	100	0.85	0.33	72.03
0.6	200	1.27	0.75	62.87
0.6	300	1.74	0.8	68.50
0.6	400	2.53	1.22	67.47
1.18	50	1.16	0.62	65.17
1.18	100	2.12	0.61	77.66
1.18	200	2.65	0.78	77.26
1.18	300	3.59	1.09	76.71
1.18	400	6.02	2.31	72.27
2.0	50	2.51	0.75	76.99
2.0	100	3.59	0.82	81.41
2.0	200	5.33	1.11	82.76
2.0	300	5.86	2.35	71.38
2.0	400	6.82	2.54	72.86

Table 2: Effectiveness of propose graphical method for the prediction of membrane penetration

Particle size (mm)	Numbers that comply with the proposed graphical methods	Numbers that do not comply with the proposed graphical methods
0.3	4	1
0.6	2	3
1.18	3	2
2.0	1	4
Total	**10**	**10**

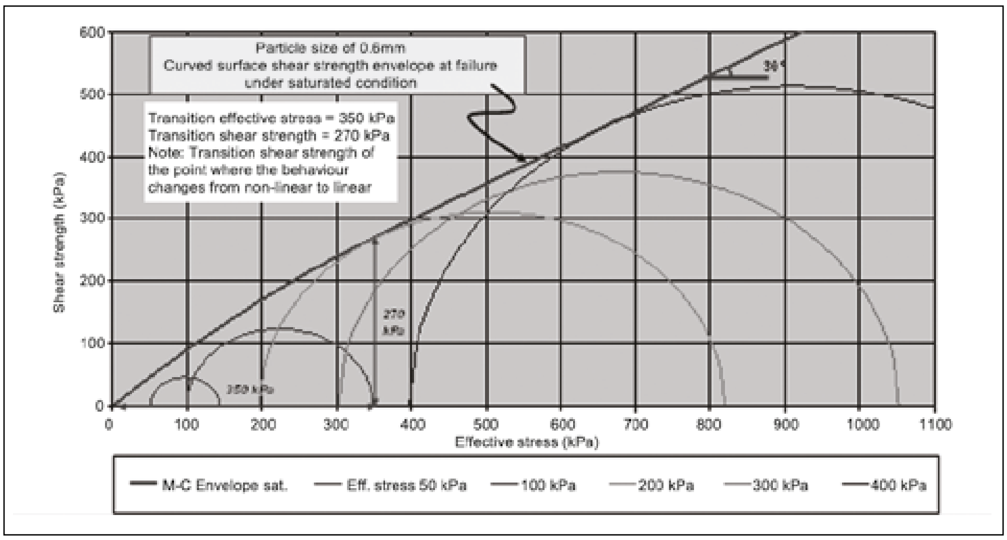

Figure 15: Curved surface shear strength envelope at saturation for particle size of 0.6 mm

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