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Membrane Penetration Effects on Shear Strength and Volume Change of Soil During Triaxial Test

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Abstract. In a triaxial test of soil, a specimen in the cell is enclosed by a rubber membrane to separate soil particles from the surrounding water that represents the confining pressure. Upon increasing the confining pressure, this membrane penetrates the voids between the particles of the specimen and cause errors in triaxial test results, these errors lead to changes in shear strength and volume change measurements. Therefore, the results need to be corrected for membrane penetration. This paper emphasizes the importance of correcting triaxial test results for membrane penetration by presenting the influence of membrane penetration on shear strength and volume change measurements. It was concluded that the rubber membrane can produce apparent increase in volume change and shear strength either due to membrane penetration (when the test is at drained condition) or due to membrane compliance (when the test is at undrained condition).

INTRODUCTION

Membrane penetration is a term used to describe the penetration of the rubber membrane surrounding the specimen into the voids of soil particles in triaxial testing during consolidation stage [1-5], maximum penetration occurs at the moment of elevating cell pressure during consolidation stage [5-7], Figure 1 shows the difference in membrane penetration throughout the consolidation stage. Even though the membrane used for the triaxial test is the thinnest possible to avoid lateral deformation resistance, deviation in results can occur and therefore careful correction must be made [8-10]. During performing undrained tests on loose sand, volume change under undrained condition did not keep constant due to membrane penetration effect, that was the observation when the membrane penetration was first addressed by Newland et al. [7]. Since that time many methods and techniques have been developed to estimate and reduce membrane penetration effect, these methods can be categorized in three categories; theoretical methods [11-13], experimental methods [3, 14-20] and graphical method [5]. However, these methods are either followed complicated, lengthy and not a practical procedure or not applicable because they lacked experiment validation, applied for limited particle sizes and at limited confining pressures and some of them were applied for only undisturbed samples. Therefore, a complete and comprehensive method to define membrane penetration behavior does not yet exist among the current methods.

However, recent studies have shown advancement in determining volume change due to membrane penetration, Haeri et al [21] have implemented image processing technique during triaxial test to determine volume change due to membrane penetration. Enyue et al [22] have introduced an analytical solution to determine volume change due to membrane penetration. The presented solution was validated using dummy specimens of iron rods at different diameters, the obtained results were found matching the prediction from the analytical solution. Lade [23] has mentioned that, the water injection into the specimen to balance the volume change due to membrane penetration is considered a valuable method that can be used for drained and undrained condition, the water injection can be automatically and continuously controlled by a computer.

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Yan and Li [24] have eliminated membrane penetration effect by painting the outer surface of a Latex rubber membrane, then the membrane was allowed to be dried and hardened. Flora et al [25] stated that, it is reasonable to neglect the membrane penetration effect on liquefiable soil after conducting undrained cyclic triaxial test.

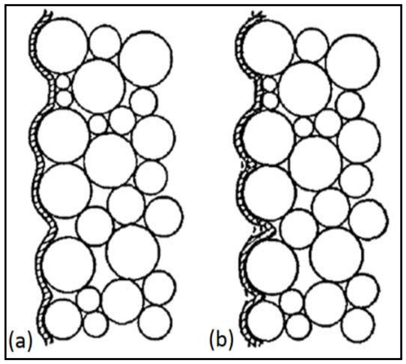

FIGURE 1. (a) Membrane penetration at the end of consolidation (b) Membrane penetration at cell pressure increment [11]

MEMBRANE PENETRATION EFFECTS IN DRAINED AND UNDRAINED TRIAXIAL TEST

A triaxial load test can be in two conditions, either drained or undrained loading condition depending on the flow of pore water and the loading rate. In drained condition, the loading is applied very slowly at a given strain rate with pore water valve opened, the volume change of a specimen can be measured using different devices based on the water that comes in or out the specimen. While at undrained condition, loading is applied rapidly with pore water valve closed, the resulted stress behavior is obtained by measuring the pore water pressure throughout the test [11, 16, 26-28]. Therefore, accurate stress-strain curve and shear strength behavior are fully depending on the measurement of volume change and pore water pressure.

In undrained condition, membrane either penetrate in or rebound out of the peripheral voids between soil particles, the increases in pore water pressure cause the membrane to rebound out of soil particles, therefore the confining pressure is influenced by membrane penetration, the magnitude of penetration is controlling the amount of deviated results. Also, membrane compliance occurs at undrained loading condition. During applying axial loading on the specimen after membrane penetration has occurred, any changes in pore water pressure is accompanied by changes in specimen density and water content. Loss specimen will undergo decreases in water content and density as specimen contracting. While in dense specimen, water content and void ratio will increase as specimen expanding. All these changes are because of compliant nature of the rubber membrane during undrained condition [1, 3, 12, 29, 30].

In drained condition, total volumetric strain is caused by soil volume change and the volume change due to membrane penetration, therefore actual volumetric strain can be obtained after determining the volume change due to membrane penetration and minus it from the total measured volumetric strain, this is very important step in formulation of constitutive model of granular soil. The more accurate of membrane penetration correction, the more reliable results [7, 31, 32].

MEMBRANE PENETRATION EFFECTS ON GEOTECHNICAL PROPERTIES

Several geotechnical researchers had studied and investigated the effects of membrane penetration phenomenon in triaxial tests [5, 12, 13, 33-36]. The effects of membrane penetration are caused by the membrane mechanical properties, grain size and type of soil which eventually influenced the shear strength, volume change, pore water pressure and the measured deviatoric stress either by negligible or significant effects [37].

According to what has been mentioned before, the total measured volume change is consisting of volume change due to membrane penetration and volume change due to soil strain, Newland et al. [7] have expressed this statement in a mathematical expression as shown in Eq. (1)

$$\Delta V_T = \Delta V_{soil} + \Delta V_m \tag{1}$$

Where:
ΔV_T = total volume change,
ΔV_m= volume change caused by membrane penetration,
ΔV_{soil} = volume change caused by soil deformation.
Seed and Anwar [16] have improved the equation that developed by Newland et al. [7] as shown in Eq. (2)

$$\Delta V_T = (\mathcal{E}_v \times V_0) + (\mathcal{E}_m \times A_s) \tag{2}$$

Where
A_s= soil surface area covered by the membrane,
$\mathcal{E}_v$ = total volumetric strains,
V_0 = sample volume prior to change in stress and
$\mathcal{E}_m$ = membrane penetration per unit membrane surface area.

Due to its importance and necessity, volume change due to membrane penetration have been experimentally investigated by applying different techniques [1, 3, 7, 14, 15, 34, 38-41]. However, these experimental investigations were successful to a certain extent.

Aniza et al. [42] have investigated the membrane penetration effect in granitic soil by using a dummy and real specimens. Results showed the clear increase in total measured volume change due to membrane penetration effect. Figure 2 illustrating the volume change with respect to effective stress with and without effect of membrane penetration.

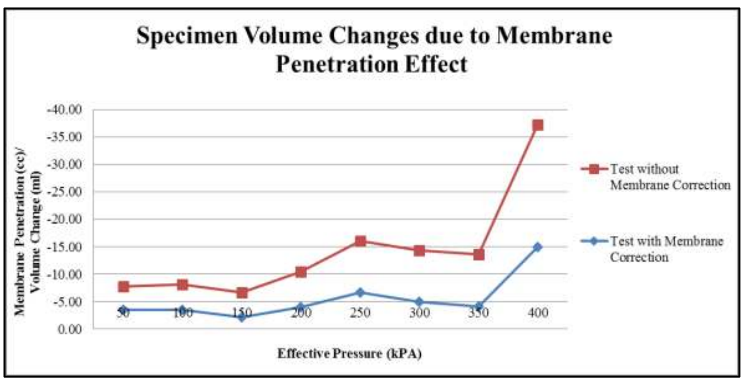

FIGURE 2. Volume change due to membrane penetration effect [42]

Henkel et al. [8] stated that membrane stiffness E_m may be a reason to cause increases in deviator stress. Thickness of the membrane and type of membrane material controls the value of E_m, therefore determining thickness of membrane is essential prior to any correction procedure. Eq. (3) presents deviator stress increases due to membrane resistance according to Henkel et al. [8].

$$\delta(\sigma_d)_m = \frac{4E_m t_m \varepsilon}{D_c} \tag{3}$$

$$D_c = \sqrt{4\pi A_c} \tag{4}$$

Where $\delta(\sigma_d)_m$ is the additional deviator stress due to membrane resistance, t_m is membrane's thickness, D_c represents the post consolidation sample's diameter, A_c is the average post consolidation sample's cross-sectional area and ε is axial strain.

Previous literature showed different studies to determine E_m [8, 43]. However, most of the theoretical methods that utilized E_m in the proposed equations have assumed the value of E_m is constant [12, 13].

Additional to the aforementioned effects of membrane penetration on deviator stress and volume change which eventually effect shear strength, Molenkamp et al., Haeri et al. and Kramer et al. [13, 26, 32] all proved that membrane penetration causes apparent increases in shear strength. Aniza et al. [42] also presented the effect of membrane penetration on shear strength, results showed that higher shear strength exhibited when the effect of membrane penetration was not deducted as shown in Fig. 3.

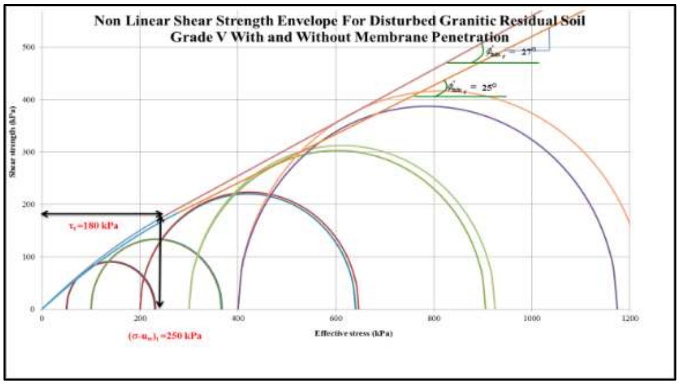

FIGURE 3. Shear strength envelope with and without membrane penetration correction [42]

FACTORS AFFECTING MEMBRANE PENETRATION

An assessment of past experimental studies on membrane penetration demonstrates that, in spite of the fact that a general theory has not been formed yet, there is general concurrence on the factors which have a significant effect on the amount of membrane penetration [18]. Soil particles size is controlling the amount of membrane penetration, large particle sizes will offer greater membrane penetration volume as shown in Fig. 4a. Shape of soil particle also control the amount of membrane penetration; angular particle shape produces greater membrane penetration comparing to rounded particles. According to previous experiments, it was found that membrane penetration increased by increasing confining pressure, Figure 4b shows the influence of confining pressure on membrane penetration. Relative density of a soil has little effect on the amount of penetration, this was figured out when two samples at different densities offered almost same amount of penetration. According to the previous theoretical proposed equation to estimate the amount of membrane penetration, the thickness of membrane is inversely proportional to membrane penetration volume. Researchers have carried out experiments using different types of material for the membrane such as Neoprene and Latex, results show that different material of membrane exhibited different amount of penetration [1, 3, 5, 10, 12, 18, 30, 34, 38].

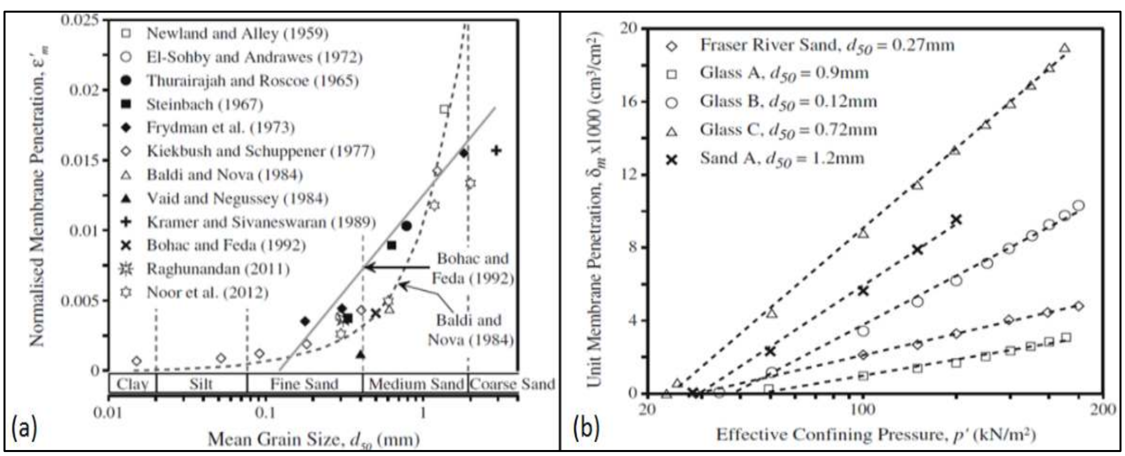

FIGURE 4. (a) Influence of grains size on the membrane penetration, (b) Influence of confining pressure on the membrane penetration [3, 44]

MEMBRANE COMPLIANCE

Membrane compliance is a phenomenon that occurs in undrained triaxial test, it can be defined as the membrane movements towards and outwards the specimen during elevating confining stress and increasing pore water pressure respectively [45]. During consolidation stage, confining pressure is increases which push the membrane to penetrate the peripheral voids as shown in Fig 5a. Since the test is at undrained condition, so the pore water pushes the membrane outwards, a decrease in confining stress results in movement of pore water to the peripheral voids, thus, the penetrated membrane will be rebounded from the peripheral voids (Fig. 5b). This will lead to redistribution of water content of the specimen during undrained loading (Fig 5c). The skeletal structure will contract as a result of migration of pore water from interior to peripheral voids in order to balance the water volume as shown in Fig 5d. Therefore, at the end of undrained loading, density of specimen will be higher than the initial density. Thus, properties of soil that measured after finishing the test may not represent actual site condition because of specimen contraction due to membrane compliance [1, 17, 46, 47].

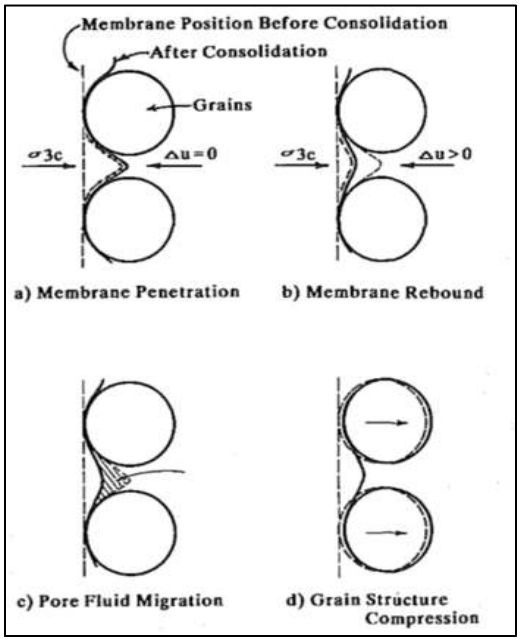

FIGURE 5. Membrane compliance effects [47]

When a specimen is subjected to axial loading after the membrane has penetrated, changing of pore pressure will cause redistribution of water content and consequently changing in density of specimen. Loose specimens will develop positive pore pressure; thus, void ratio and water content will decrease due to specimen contraction. Positive or negative pore pressures may develop in dense specimens [48-50]. The soil volume is actually changes during undrained testing due to redistribution and movement of pore water between internal and peripheral voids because of membrane compliance [46]. Results of undrained triaxial test are influenced by membrane compliance at different rates depending on factors such as effective confining pressure, grain size distribution, relative density, and membrane thickness [30]. Generally, the effect of membrane compliance during undrained loading can be summarized in Table 1.

TABLE 1. Influence of membrane compliance during undrained triaxial test [47]

Item	Compressive Soil	Expansive Soil
Porewater pressure	Increase	Decrease
Confining pressure	Decrease	Increase
Strength of soil	Decrease	Increase

According to Evans [1], the whole process of membrane compliance may be summarized as follows:

- After membrane penetration has occurred during consolidation stage of undrained test, it will rebound as pore pressure increases.
- This will result in water content redistribution as the water travels from the internal voids to peripheral voids with the specimen to fill the expanded volume of the peripheral voids.
- Consequently, skeleton soil structure becomes denser, i.e. the sample density at the end of the test is higher than initial density.

Since the membrane compliance significantly influences triaxial test results, numerous studies were conducted to minimize or eliminate this effect. The following table lists several attempts to minimize membrane compliance using different approaches and techniques, the limitation of these studies are also detailed in the table.

TABLE 2. Previous researches to minimize membrane compliance

Researchers	Minimizing methods	Limitations
Wong et al. and Martin et al. [49, 50]	Used sample diameter of 300 mm for testing sand specimen in triaxial test.	The use of this diameter for sand samples cannot decrease the effect of membrane compliance [51]
Chan [52] and Raju [53]	Coated side surface of the specimen with polyethylene sheets.	Utilizing this method may contribute to the reduction of membrane compliance but will increase lateral resistances of the sample [51]
Lade and Hernandez [39]	Utilized copper sheet for enclosing specimen	Utilizing this method may contribute to the reduction of membrane compliance but will increase lateral resistances of the sample [51]
Evans and Seed [48]	Used slurry and fine material for the elimination of coarse grains membrane compliance.	This technique causes deviations of shear strength measurements [43]
Haeri et al. [26]	Used sand to surround gravel specimen in triaxial test.	Caused increasing of sample density.

Summary

- The rubber membrane that encloses the specimen in triaxial test is penetrates peripheral voids of the specimen which influence the results of triaxial test.
- Different behavior of penetration has been observed when the specimen was subjected to drained and undrained loading condition.
- Shear strength, pore water pressure, deviator stress and volume change directly influenced by membrane penetration, therefore correction for these properties must be made to get accurate results.
- The amount of membrane penetration is not constant but it rather varies based on several factors such as particle sizes, particle shape, confining pressure, relative density, thickness of membrane and the material of membrane, therefore the amount of membrane penetration may increase or decrease according to these factors.
- Membrane compliance is a phenomenon that occurs in undrained loading condition which also causes errors in the obtained results and also cause changes in density of specimen, thus correction must also be made.

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