Implementation of Image Processing Technique for Measuring Membrane Penetration in Triaxial Testing on Gravelly Soils

Mise En Oeuvre D'une Technique De Traitement D'image Pour Mesurer La Pénétration De La Membrane Dans Des Essais Triaxiaux Sur Des Sols Gravillonnaires

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ABSTRACT: The volume change that occurs due to membrane penetration into peripheral voids of gravelly specimens during hydrostatic compression test in a conventional triaxial apparatus is studied by performing a set of hydrostatic compression tests on gravelly specimens with different initial relative densities. During the isotropic loading on the specimens, the total volume changes of the specimens were determined by measuring the amount of water seeping out of the specimens at different loading steps. Image processing technique was implemented simultaneously to determine the skeletal volume changes of the specimens. In this regard specimens were compressed to isotopic pressures from 10 to 500 kPa following a step-loading mode. Images of the specimens were captured continuously at different confining pressures. The volumetric membrane penetration was then calculated for each specimen at each confining pressure. The normalized membrane penetration and the ratio of volumetric skeletal strains to axial strains were determined and compared for the tested specimens. The results indicate that an increase in relative density of the specimen leads to an increase in the ratio of volumetric skeletal strains to axial strains and a decrease in the normalized membrane penetration.

RÉSUMÉ : Le changement de volume qui se produit en raison de la pénétration de la membrane dans les vides périphériques des échantillons de gravier pendant l'essai de compression hydrostatique dans un appareil triaxial conventionnel est étudié en effectuant un ensemble de tests de compression hydrostatique sur des échantillons de gravillons avec différentes densités relatives initiales. Pendant la charge isotrope sur les échantillons, les changements de volume total des échantillons ont été déterminés en mesurant la quantité d'eau qui s'écoule des éprouvettes à différentes étapes de chargement. La technique de traitement de l'image a été mise en œuvre simultanément pour déterminer les changements de volume squelettique des échantillons. A cet égard, les spécimens ont été comprimés à des pressions isotopiques de 10 à 500 kPa suivant un mode de chargement par étapes. Les images des échantillons ont été capturées en continu à différentes pressions de confinement. La pénétration de la membrane volumétrique a ensuite été calculée pour chaque échantillon à chaque pression de confinement. La pénétration de la membrane normalisée et le rapport des déformations volumiques du squelette aux déformations axiales ont été déterminés et comparés pour les échantillons testés. Les résultats indiquent qu'une augmentation de la densité relative de l'échantillon conduit à une augmentation du rapport des souches volumétriques du squelette aux souches axiales et à une diminution de la pénétration de la membrane normalisée.

KEYWORDS: Gravelly soil, Membrane Compliance, Image Processing, Liquefaction Resistance, Isotropic Consolidation.

1 INTRODUCTION

The intrusion of membrane into the peripheral voids of a granular specimen is known as membrane penetraion. This phenomenon significantly affects the results of undrained triaxial or hollow cylender tests performed on coarse grain specimens especially gravelly specimens (Evans and Seed 1987, Nicholson et al. 1993, Haeri and Shakeri 2010). As the grain size increases, the importance of considering such an effect becomes greater.

The volume change due to membrane penetration depends on the soil grain size and gradation, confining pressure, density, soil fabric, method of specimen preparation, and membrane thickness and properties. Mean grain size and confining pressure have the strongest effects on the membrane compliance, and other factors appear to have marginal effects (Evans and Seed 1987, Nicholson et al. 1993). This phenomenon was first recognized by Newland and Alley 1957. By assuming that axial strain (ε_a) is equal to radial strain (isotropic behaviour) of the specimens during hydrostatic compression or rebound in triaxial testing, volume change due to membrane penetration could be determined according to Equation (1) as suggested by Newland and Alley (1957).

$$\Delta V_m = \Delta V_T - \Delta V_S \quad (1)$$

where ΔV_m , ΔV_T and ΔV_S are volume changes caused by membrane penetration, total volume changes and soil skeletal volume changes, respectively. ΔV_T can be measured by a volume change transducer during drained tests on saturated soils, and ΔV_S is determined by multiplying soil skeletal volumetric strain ($\Delta\varepsilon_{v,S} = 3\Delta\varepsilon_a$) by the total volume of the specimen (ΔV_T). However, the assumption of the isotropic deformation under isotropic loading for measuring ΔV_S is a challenging issue as isotropic loading of granular soils can lead to anisotropic deformation (El-shoby and Andrawes 1972, Vaid and Negussey 1984). Therefore, a more accurate method is needed to measure the volume changes of the specimens and volume changes caused by membrane penetration. Another procedure was proposed by Vaid and Negussey (1984) to evaluate the membrane penetration based on the assumption that the deformation of the specimen is isotropic during the unloading steps of an isotropic consolidation test. However, the assumption that soils are isotropic during the unloading may not be accurate enough. Seed et al. (1989), for example, showed that specimen strains are not completely isotropic in unloading stages, and the assumption that the volumetric strain is equal to three times the axial strain in isotropic unloading may also lead to considerable errors.

One of the most accurate methods to determine the skeletal volume changes and the amount of membrane penetration is measuring the axial and radial strain directly. For this purpose, strain guage and girth belts can be used to measure the specimen radial strain accurately. However, measurement of the radial strain at only one point is not representative of the radial strain of the specimen on average. Therefore, three belts are needed at least to measure the radial strain of a specimen to an acceptable level. In addition to the mechanical and electrical difficulties in installing girth belt for measuring the radial strain, it is not easy to apply this technique for small specimens with the diameter equal to or smaller than 100 mm. Another method which has been developed recently to measure the axial and radial strain directly is image processing technique. This technique has been widely used to track a variety of experimental events and can be used to measure the strains in triaxial tests with sufficient accuracy (Macari et al. 1997). This method is used in this research to determine the skeletal volume change of specimens and the volume changes caused by membrane penetration according to equation (1).

2 TESTED MATERIAL

The soil used in this study was obtained from the outskirts of the Kan river, west of Tehran. The soil comprising of 60% gravel (>4.76 mm) and 40% sand is classified as GW according to the Unified Soil Classification System (USCS). The coefficients of uniformity and curvature are C_u=16.7 and C_c=2.2, respectively. The mean grain size (D_{50}) is 5.5 mm and the maximum grain size of the test material is 12.5 mm.

3 SPECIMEN PREPARATION

Specimens were prepared by compacting four layers of the tested material (mixed with 5% water content) with a specific density using wet tamping method in a split mold following the under-compaction procedure of Ladd (1978). The surface of each compacted layer was scarified to make a better interlocking between the layers. After the specimens were prepared, they were kept with their mold in a freezer for 18 hours, after which the specimens were taken out from the mold and the dimensions and weight of the reconstituted frozen specimens were measured. The frozen specimens were then placed in the triaxial apparatus for starting the main tests. The dimensions of the specimens were used to determine the initial void ratio and density of each specimen.

The first step for starting the tests was the saturation of the specimen by flushing CO_2 gas into the specimen for at least 20 minutes. The de-aired water was then flushed through the specimens gravitationally for more than four hours to melt all the frozen parts of the specimens. During this process, an effective confining pressure of 10 kPa was maintained on the specimens. Saturation of the specimens was continued to obtain a B-value of greater than 0.95 by applying the required back pressure. After the saturation, the specimens were isotropically consolidated, during which the volume change and the axial strain were recorded at different pressure.

4 MEASUREMENT OF MEMBRANE PENETRATION

Sixteen specimens with different densities were isotropically compressed to determine the amount of membrane penetration at different pressures ranging from 1 to 500 kPa. For this purpose, the volume change caused by membrane penetration was evaluated by implementing both the automatic volume change device and the digital image processing technique during the isotopic consolidation tests. The amount of the water seeping out of the specimens during isotropic loading was measured by the automatic volume change device, yielding the total volume change (ΔV_T) of the specimen. The image processing technique determines the true skeletal volume change (ΔV_S) of the specimen. Some grid lines were marked on the membrane before testing to facilitate highlighting the points. Images of the specimen in triaxial cell were captured every minute automatically with a precise digital camera with a resolution of 12 Mega pixels (2736H: 3648V). The results of isotropic consolidation tests are summarized in Table 1, which are described in the next paragraphs.

Table 1. Result of isotropic consolidation test.

Test No.	Dr (%)	ε_s / ε_a	Correction Ratio	Error (%)	S (cm^3	S' (%)
1	0	2.11	1.000	2.76	0.04	0.705
2	0	2.18	0.999	3.13	0.03	0.682
3	0				0.03	0.672
4	0	2.16	0.999	4.41	0.03	0.690
5	0	2.23	1.001	2.26	0.03	0.668
Ave.	**0**	**2.17**			**0.03**	**0.683**
6	30	2.30	1.000	1.38	0.02	0.420
7	30	2.49	1.001	1.69	0.02	0.501
8	30	2.57	1.001	2.35	0.02	0.472
9	30	2.31	1.000	1.61	0.02	0.418
10	30	2.52	1.000	1.82	0.03	0.532
11	30	2.35	1.001	4.63	0.02	0.486
Ave.	**30**	**2.42**			**0.02**	**0.471**
12	50	2.73	1.001	5.62	0.01	0.294
13	50	2.85	1.000	0.52	0.01	0.312
14	50	3.11	1.001	2.41	0.01	0.346
15	50	2.71	1.001	0.09	0.01	0.252
16	50	3.05	1.001	2.56	0.02	0.447
Ave.	**50**	**2.89**		**2.48**	**0.01**	**0.330**

Macari et al. (1997) used the two dimensional procedure developed by Parker (1987) to correct apparent magnification of the specimen size due to the multiple refraction of light rays passing through the triaxial cell fluid and the plexiglass. The same methodology was also taken in the present study to minimize the errors associated with the perspective and magnification effects. The variation of the true specimen radius with that calculated based on the procedure proposed by Macari et al. (1997) follows a linear trend. Therefore, the strains in the two dimensional images taken from the specimens can be equal to the strains in the actual specimens. As shown in Figure 1, an image from a specimen in the first stage of consolidation (σ'_3 = 10 kPa) was compared with an image of the specimen in the last stage of consolidation (σ'_3 = 500 kPa) to measure the sckeletal strain of the specimen by measuring the axial and the radial strains.

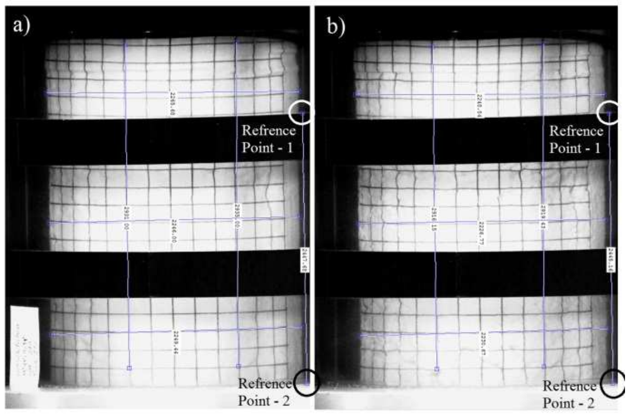

Figure 1. Using digital image processing for measuring the axial and radial strains in test no. 16, image of the specimen in effective consolidation stress of (a) 10 kPa and (b) 500 kPa.

In order to calibrate the image processing technique, two reference points in the longitudinal direction of the triaxial cell, with no strain during the isotropic loading, were selected on each image, and the distance between them was measured (Figure 1). The ratio of these distances in the two images is named the correction ratio, which is used for calibrating the images. Due to the fixed position of the camera during the test, the correction ratios were close to one, as reported in Table 1. In order to check the accuracy of this method, the axial strains measured with the image processing technique were compared with the measurements of the LVDT. The errors associated with the image processing method (with an average of less than 2.5% and a maximum of less than 6%) is summarized in Table 1. It is also assumed that radial strains are the same in all directions, implying the axisymmetric conditions in isotropic loading, which is consistent with the results of Macari et al. (1997).

After calibrating the images, the radial and axial strains were measured. For this purpose, three pairs of points in the radial direction and two pairs of points in the axial direction were marked on both of the images before and after consolidation (Figure 1). The three pairs of points in the radial direction were selected in the top and bottom quarter and the middle of the height of the specimen. By assuming a zero strain at the top and bottom of the specimen, the true skeletal strain and the ratio between the axial and the true skeletal strain were calculated.

According to the measured data in Table 1, the specimen deformations are anisotropic since the ratio between the volumetric skeletal strains and the axial strains ($\varepsilon_s/\varepsilon_a$) is lower than 3. The ratio for specimens with the initial relative density of zero is 2.2 which grows by increasing the density of the soil. For the specimens with the initial relative density of 50%, the ratio is 2.9 implying a nearly isotropic deformation (Figure 2).

Deformation of a soil specimen under isotropic compression can be divided into two components: elastic deformation and deformation associated with the slippage of the soil grains due to isotropic pressure. The elastic deformation which is the main component of deformation in dense specimens is mostly isotropic, so the deformations of the dense specimens are nearly isotropic. For loose specimens, the deformation associated with slippage of soil grains is much larger than the elastic deformation of the specimen. The deformation associated with slippage of soil grains is not isotopic, so the deformations of loose specimens are anisotropic.

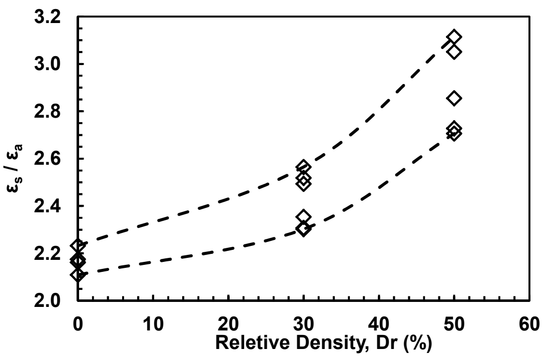

Figure 2. Variation of ratio between axial strain (ε_a) and true skeletal strain (ε_s) withrelative density of the specimens.

According to equation (1), the volume changes caused by membrane penetration can be calculated by the following equation from the results of isotropic compression tests:

$$\Delta V_m = \Delta V_T - \Delta V_S = \Delta V_T - \frac{\varepsilon_{s,f}}{\varepsilon_{a,f}} V_T \varepsilon_a \quad (2)$$

where, ΔV_T is the total volume change of the specimen, ε_a is the axial strain, and $\varepsilon_{s,f}$ and $\varepsilon_{a,f}$ are true skeletal and axial strains, respectively, in the final step of isotropic compression stage. Digital image processing was implemented to measure the skeletal strains at the end of the compression process and the specimen axial strain was measured continuously by an LVDT during the test. There is a linear correlation between the unit membrane compliance ($\Delta B_m = \Delta\varepsilon_m . V_T / A_m$) and the effective confining pressure (σ'_3) in a logarithmic scale (Ramana and Raju 1982; Baldi and Nova 1984; Nicholson et al. 1993; Ansal and Erken 1996; Haeri and Shakeri 2010). The slope of the graph of unit membrane compliance versus $\log\sigma'_3$ is called normalized membrane penetrations (S);

$$S = \frac{\Delta B_m}{\Delta \log \sigma'_3} \quad (3)$$

where, A_m is the total lateral surface area of the specimen. The slope of the lines in the plane of $\Delta\varepsilon_m$ versus $\log\sigma'_3$ is called S' which can be correlated with the normalized membrane penetration S according to the equation (4);

$$S = S' \frac{V_T}{A_m} \times \ln(10) \quad (4)$$

Results of isotropic compression tests from 10 kPa to 500 kPa on the specimens with initial relative density of zero are shown in Figure 3, as an example. For each test the value of S' was determined by curve fitting and normalized membrane penetrations (S) was calculated according to equations 3 and 4 (Table 1).

Although most of the previous studies on sands suggest that the influence of the density on membrane penetration and S value is relatively minor (Seed et al. 1989, Nicholson et al. 1993), the results of this study indicate that this may not be the case for gravels. As shown in Figure 4, the normalized membrane penetration or S values decrease with increasing density. According to Table 1, the average value of S for the specimens with the initial relative density of zero is 0.0393cm^3/m^2, this value decreases to 0.0271 cm^3/m^2 for the specimens with the initial relative density of 30%, and reaches to 0.0190 cm^3/m^2 for the specimens with the initial relative density of 50%. This is in agreement with the results of Ramana and Raju (1982), which indicate that there is a significant difference in the volume changes due to the membrane penetration measured for the specimens of uniform sand with different densities. The result of their study shows that the volume changes due to the membrane penetration of loose specimens are more than that of dense specimens.

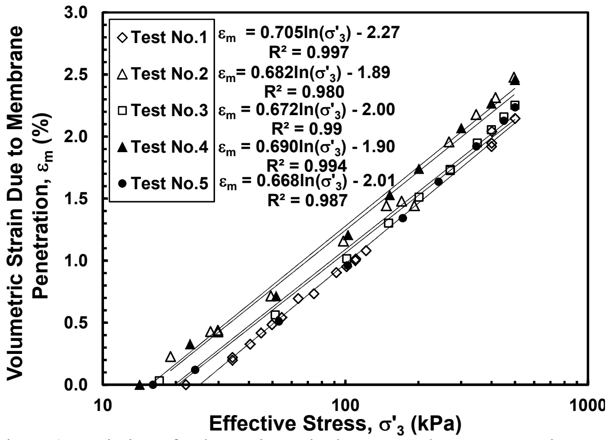

Figure 3. Variation of volumetric strain due to membrane penetration and effective stress during isotropic compression test for specimens with initial relative density of zero.

In Figure 5, S values of this study are compared with that of the previous studies. The present test result appears to fall into the reasonable range of the literature data. However, the observed scattering of data suggests possible influence of realative density on normalized membrane penetration.

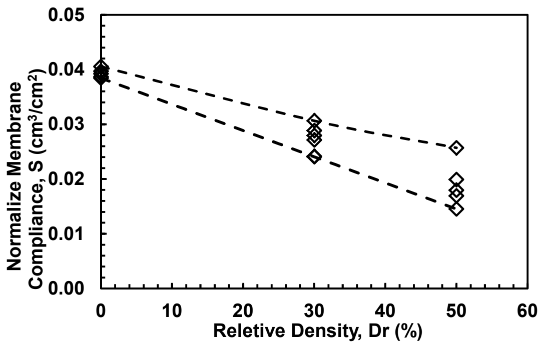

Figure 4. Variation of Normalize membrane compliance (S) with relative density of the specimens.

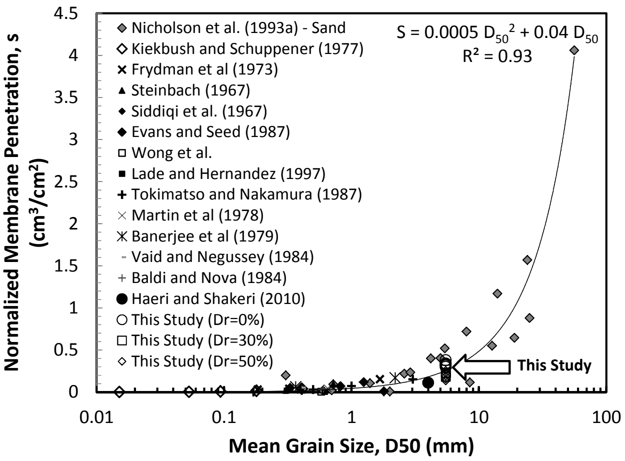

Figure 5. Comparison of measured normalized membrane penetration with previous studies

5 CONCLUSION

The volume change in isotropic consolidationtests was measured by a digital image processing technique, and the membrane penetration curve of the specimens with different densities (void ratio) was determined. Based on the results, the following conclusions can be drawn:

1- It was shown that image processing can be effectively used to evaluate the volume change due to membrane penetration.
2- Deformation of the specimens under hydrostatic loading is not isotropic, and the ratio of volumetric skeletal strain and axial strain ($\varepsilon_s/\varepsilon_a$) is lower than 3.
3- Deformation of soil specimens under hydrostatic loading was observed to be mostly isotropic in dense specimens and anisotopic in loose specimens.
4- The normalized membrane penetration or S value decreased with increasing density.

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