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An Experimental Method for Determining Membrane Penetration

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TECHNICAL NOTE

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ABSTRACT: A new and simple experimental method is proposed for the determination of membrane penetration due to changes of the effective confining pressure in triaxial and hollow cylinder tests. The proposed method has advantages over existing methods in that it requires neither special devices nor questionable assumptions. It only requires a series of drained isotropic compression tests in a conventional triaxial device with plastic liners. The results from the proposed method are compared to those from several existing experimental and analytical methods.

KEYWORDS: membranes, plastics, membrane compliance, triaxial tests, volume change, plastic liner

In triaxial tests, the volume change is accurately determined by measuring the amount of water expelled from or drawn into a fully saturated specimen. The specimen is usually encased by a flexible thin rubber membrane. When confining pressure is applied to a specimen via the rubber membrane, the membrane deforms and penetrates into the pores among soil particles on the perimeter surface. When the effective confining pressure varies during the test, the volume change measurement will be erroneous if membrane penetration is not accounted for. The major factors influencing membrane penetration are effective confining pressure and grain size and shape as well as the specific characteristics of the given rubber membrane. Although there are several experimental methods for predicting the amount of membrane penetration, most of them are based on questionable assumptions.

Review of Previous Methods

Previous investigations which have attempted to evaluate membrane penetration under varying confining pressures are summarized as follows:

1. An experimental approach based on the assumption that a specimen behaves isotropically during an isotropic compression test so that the volumetric strain, ε_v, equals three times the axial strain, ε_z (Newland and Allely 1959; Roscoe et al. 1963; and Lin and Selig 1987).
2. An experimental approach using rigid dummy rods with varying diameters placed coaxially in the center of the triaxial specimen based on the assumption that the true volume change (ε_v excluding membrane penetration) is proportional to the volume of the specimen (El-Sohby 1964; Raju and Sadasivan 1974).
3. An experimental approach employing varying size and shape of specimens to utilize the assumption that true volumetric strains from them will be the same for a given degree of compaction and specimen preparation (Frydman et al. 1973; Vaid and Negussey 1984).
4. Analytical solutions based on the assumption that the perimeter of the specimen is suitably represented as some regular array of uniform spheres equal in size to the representative particle size (Molenkamp and Luger 1981; Baldi and Nova 1984; and Kramer and Sivaneswaran 1989).

Although the first experimental method is convenient and easy to perform, considerable error may be introduced in the evaluation of the membrane penetration. Granular soils are frequently deposited in approximately horizontal layers, where individual particles seek a stable position with respect to the gravitational force and neighboring particles. This results in a structurally preferred particle orientation. Thus, the assumption that a specimen behaves isotropically during an isotropic compression test may be highly questionable. It is a generally known fact that the direction of deposition (specimen preparation) shows stiffer response in comparison to the direction perpendicular to it under an isotropic compression test (Haruyama 1981; Ochiai and Lade 1983).

In the second experimental method, isotropic compression tests are conducted with different-size dummy rods placed coaxially inside the specimen. When the diameter of the dummy rods increases, the soil volume decreases, whereas the surface area exposed for the membrane penetration remains unchanged. The magnitude of membrane penetration is obtained by extrapolation of the curve of volume change versus specimen volume to zero specimen volume. However, this method may include some errors caused by the possible effects of differences in the spatial arrangement (packing) of particles associated with the different

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size of dummy rods. Also, it requires manufacturing several sizes of the dummy rods and special specimen caps (El-Sohby 1964; Raju and Sadasivan 1974).

The third experimental method requires specimens of various shapes (hollow cylinders and solid cylinders) or multiple triaxial specimens of different diameters. Assuming that hollow cylinder specimens and solid cylinder triaxial specimens prepared by similar procedures have similar particle packing and density, their true volumetric strains resulting from a particular isotropic pressure increment are expected to be the same. However, recent experimental results by Ishibashi and Choi (1991) raise a question about this assumption. They showed that the specimen preparation mold forced soil particles to arrange themselves in a special fashion such that the specimen produces a localized fabric in the vertical direction around the mold boundary. The influence of the mold on the particle arrangement was found to be reduced in the radial direction from the perimeter surface. These results imply that small-sized or thin-walled hollow cylinder specimens may be more influenced than a large-sized specimen by the localized fabric. Therefore, the assumption used in this experimental method, that the particle packings among different sizes of specimens are similar, may be erroneous.

In the fourth analytical method, some simplifying assumptions are necessary. It is assumed that soil specimens are represented by uniform spheres regularly packed around the perimeter surface and that the representative particle size can be suitably chosen. For a well-graded soil, the analytical models require calibration to determine a representative particle size that best fits experimental results. Different assumptions in the shape of membrane deformation under a confining pressure were made by different researchers (Molenkamp and Luger 1981; Baldi and Nova 1984; and Kramer and Sivaneswaran 1989).

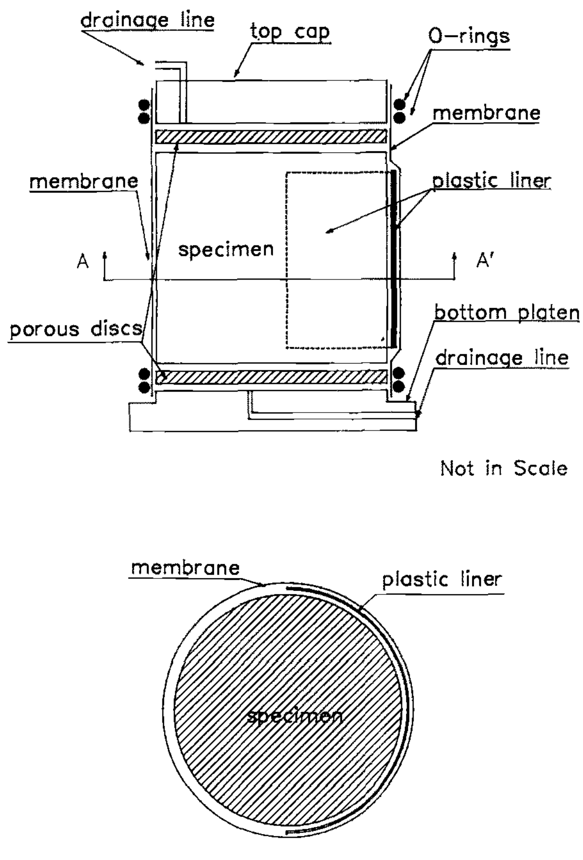

FIG. 1—*Sketch of specimen with a plastic liner.*

A New Experimental Method

A new and simple experimental method for correcting the membrane penetration effect on the volume change measurement has been developed. This method does not require any special device or varying size of specimens. A conventional triaxial device with thin plastic liners will suffice for the proposed method.

The total volume change of a granular specimen under an isotropic compression test is mainly composed of two sources: deformation of the specimen itself and the membrane penetration into the voids of the grains on the perimeter surface of the specimen. The proposed experimental method utilizes the method in which the initial volumes of the specimens can be kept constant, whereas the areas of the membrane in contact with perimeter particles can be changed for each specimen by using varying size of plastic liners inserted between the membrane and soil particles on the perimeter surface (Fig. 1). A series of isotropic compression tests were carried out on several conventional triaxial specimens prepared by the same method (tamping) with different sizes of the plastic liner. The specimens were fully saturated with the aid of carbon dioxide (CO_2) circulation. The true volumetric strains from those specimens as a function of isotropic pressure should be the same, while the measured volume changes are different due to the differences in the area of membrane in contact with soil particles. From a series of isotropic compression tests, the contribution to the total measured volume change from the membrane penetration may be separated.

The total volume change from an isotropic compression test may be expressed in the following form

$$\Delta V_t = \Delta V_s + \Delta V_m + \Delta V_l \quad (1)$$

where

ΔV_t = measured total volume change,
ΔV_s = true volume change from the soil skeleton,
ΔV_m = volume change from the membrane penetration, and
ΔV_l = volume change from linear compliance.

The terms in Eq 1 are all divided by volume of the specimen (V_{sp}), and the last term on the right side is transposed to the left side to get

$$\Delta V_t/V_{sp} - \Delta V_l/V_{sp} = \Delta V_s/V_{sp} + \Delta V_m/V_{sp} \quad (2)$$

where

$$\Delta V_l = \beta \cdot A_l$$

$$\Delta V_s/V_{sp} = \varepsilon_v$$

$$\Delta V_m = \alpha \cdot A_m$$

and

β = unit linear penetration factor (cm³/cm²),
A_l = area of the plastic liner,

α = unit membrane penetration factor (cm³/cm²), and
A_m = area of the membrane in contact with particles.

Equation 2 becomes

$$\Delta V_t/V_{sp} - \beta \cdot A_l/V_{sp} = \varepsilon_v + \alpha \cdot A_m/V_{sp} \quad (3)$$

The plastic liner used in this study is much harder than the rubber membrane so that the contribution from the liner to the total volume change is almost negligible. However, the factor β can be calculated with at most minor error by some analytical solution such as Kramer and Sivaneswaran's solution (1989) based on the Young's modulus of the plastic liner and the representative particle size of the specimen. Equation 3 represents a linear equation with a slope of α and intercept of ε_v. The terms on the left side are all known values for a given isotropic pressure increment. Then the values of α are obtained from a series of isotropic compression tests.

Experimental Results

A series of drained isotropic compression tests were conducted on conventional triaxial specimens consisting of a mixture of spherical glass beads. The glass beads are composed of two diameters: 0.215 and 0.256 mm with a particle ratio of 1:1 and a mass ratio of 1 to 1.688. The membrane has a thickness of 0.03 cm and extension modulus of 1295 kPa. The plastic liners (polyethylene) are 0.97 mm thick and have a Young's modulus of 110 900 kPa. They are all in rectangular shapes with a height of 122.28 mm and varying widths (160.81, 193.55, and 219.30 mm). They were preshaped beforehand to fit the radius of the specimens closely by wrapping them around similar-size dummy rods for a day (Fig. 1). In this work, the size of the specimen was about 7.1 cm in diameter and 13.9 cm in height, which is the same size as that of the triaxial tests of interest.

Figure 2 shows an experimental result where the slopes of the linear best fit lines represent the unit membrane penetration (cm³/cm²). Ten data points for a A_m/V_{sp} represent an isotropic compression test from σ_c = 34.5 to 206.9 kPa with or without plastic liners. The data points on the far right are from the specimen without any plastic liner, so that membrane penetration occurs over the whole perimeter of the specimen. The total volume change measurements were obtained during loading after several cycles of loading and unloading to eliminate any plastic readjustment of soil structure. In this plot, the β value of the unit liner penetration was calculated by Kramer and Sivaneswaran's analytical solution (1989).

Figure 3 shows actual data points which are slopes of the best fit lines of Fig. 2. As can be seen, the first three data points are off the expected line. A smooth line was drawn to be used for unit membrane penetration.

Figure 4 shows several curves for unit membrane penetration calculations for isotropic compression pressures from 34.5 to 206.9 kPa. Curve (A) is based on Frydman et al.'s suggestion (1973), which is a linear equation on the semi-log plot. This method produced the highest estimation of membrane penetration for this comparison. Curves (C) and (D) are based on the analytical predictions. Kramer and Sivaneswaran's method predicts higher values of membrane penetration than the method proposed by Baldi and Nova. Curve (B) from the proposed experimental method falls in between them. A representative particle diameter 0.236 mm, which is an arithmetic average of two particle diameters (0.215 and 0.256 mm), was used for the determination of Curves (A), (C), and (D). It should be noted that

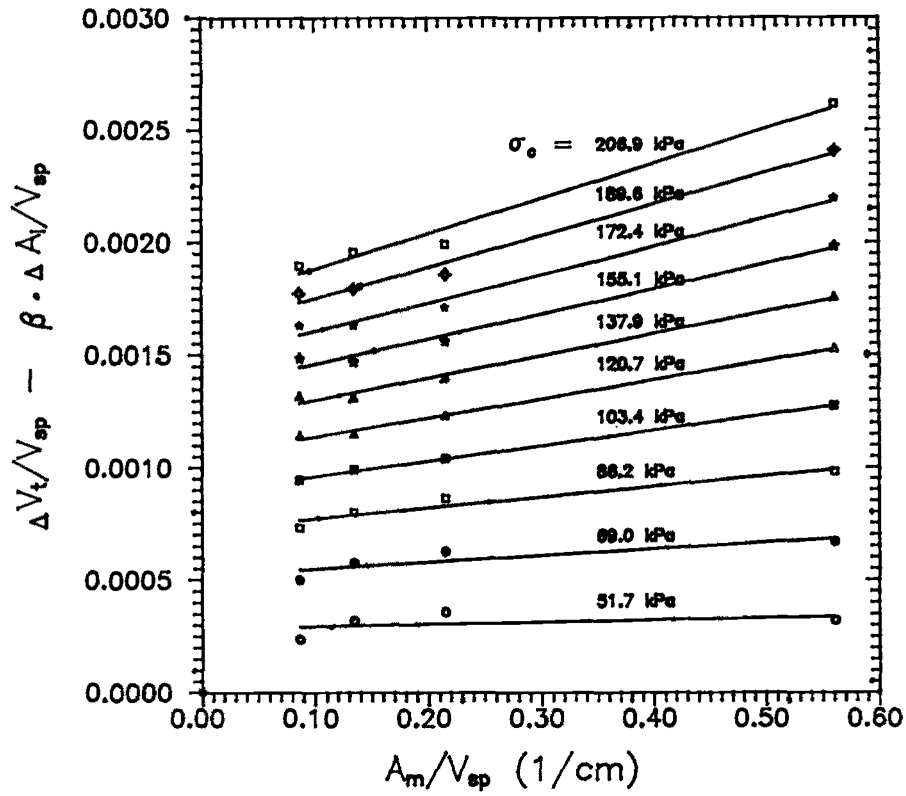

FIG. 2—*Experimental data for membrane penetration determination.*

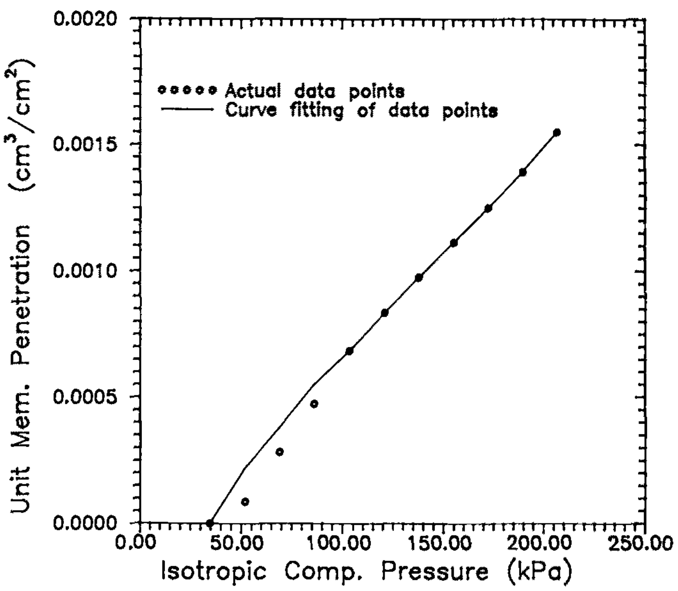

FIG. 3—*Experimental unit membrane penetration determination.*

the linear increase of Curve (B), especially near the end, contradicts authors' intuition. It could be due to nonuniform stress distribution in specimens generated by plastic liners. However, it is very difficult to evaluate this effect. It is believed that the severity of this problem will decrease as the flexibility of the plastic liner selected increases.

Conclusion

The proposed experimental method has advantages over existing experimental methods in that it does not need any special device or varying sizes of specimens for estimating the amount of the membrane penetration. It only requires a conventional triaxial device and several plastic liners of variable sizes. The size of the specimens for this method may be chosen to be the same as that of specimens of interest so that undesirable effects, if any, from different sizes may be eliminated.

The selection of the plastic liner is open to almost all kinds of plastic which are flexible enough to be wrapped around the specimen easily for pressure transmission to the specimen but rigid to resist against any substantial compliance under the expected confining pressure range.

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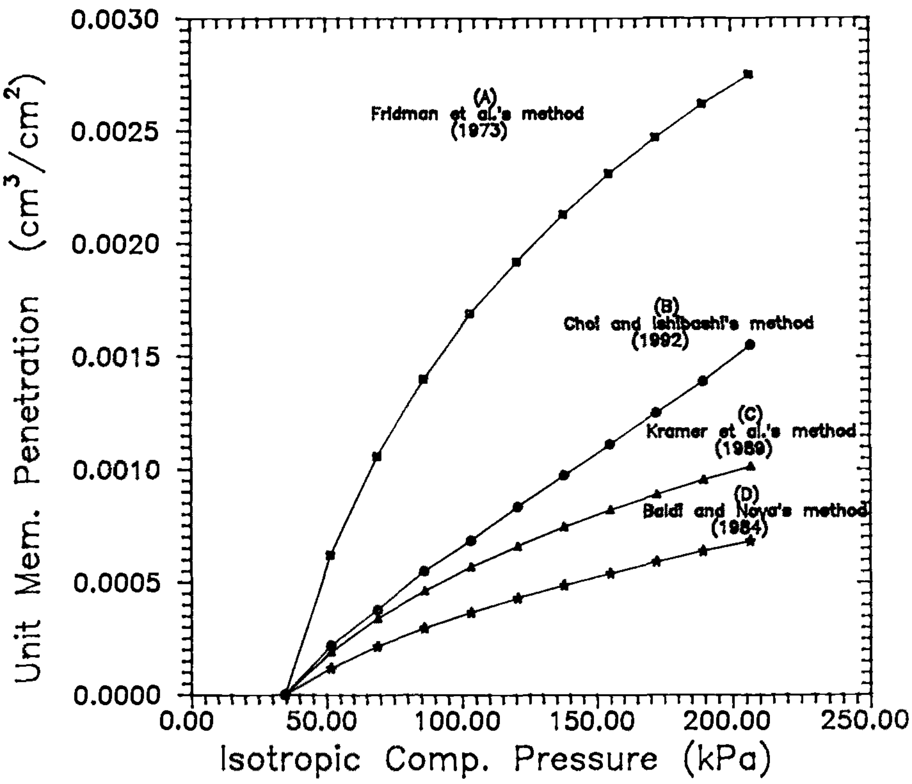

FIG. 4—*Experimental unit membrane penetration versus effective confining pressures in comparison with some other methods.*

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