A simple apparatus for the measurement of membrane penetration

by

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Abstract

This paper presents an experimental investigation of membrane penetration. A new simple apparatus was developed with which one-dimensional compression tests on sand specimens can be performed. The horizontal upper surface of a specimen is covered with a membrane. The height of specimen can be controlled by spacer disc plates of different thicknesses.

The results of the tests, carried out to determine the amount of membrane penetration, on two kinds of sand samples are presented. It is shown that, although the apparatus used in this investigation is very simple, results obtained with it are comparable and consistent with those obtained with more combersome apparatus used in previous work on the membrane penetration.

Key words : Membrane penetration, Sand, Correction, K_0 compression

1. Introduction

The results of triaxial tests, especially, on coarse grained soils with varying cell pressure involves the effect of the membrane penetration. How to evaluate the effect is a problem of imprtance.

The perimeter surface area of a specimen, whether in the conventional triaxial test or in other types of tests such as hollow or solid cylinder torsional shear tests, is covered with a thin membrane. The membrane is preferred to be as thin as possible in order that its flexural stiffness is low and that the confining pressure distributes uniformly. The thin and flexible membrane penetrates the perimeter voids of the specimen under the net pressure difference between the cell pressure and the porewater pressure as shown schematically in **Fig.1.** If this net pressure changes during a test, whether under the undrained conditions or drained conditions, the amount by which the membrane penetrates the voids will change. Consequently, the volume changes measured under drained conditions or the porewater pressure measured under undrained conditions may be inaccurate; therefore the results have to be corrected for the membrane penetration.

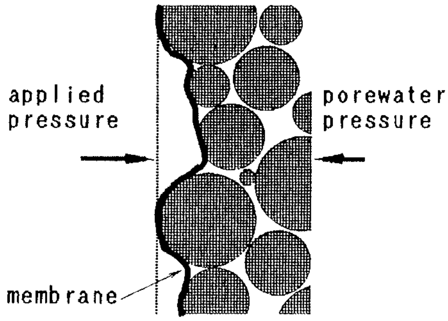


Fig.1: Schematic representation of the membrane penetration.

A number of methods, experimental and analytical, have been proposed to correct the results of triaxial tests for the membrane penetration or to minimize its effects.

The experimental methods can be classified into three groups:

(a) Only one specimen of an initial density is tested to determine the amount of membrane penetration occurring for any specimens of that density (Newland & Allely, 1959; and Bohac & Feda, 1992));

(b) Several specimens of various volumes are tested to extrapolate the membrane penetration as the volume change of a specimen that has no volume (Roscoe et al.,1963; Raju & Sadasivan, 1974; Frydman et al.,1973; Vaid & Negussy, 1984), or the contact area of the membrane with the specimen is varied to extrapolate the correct volume change as the volume change of a specimen that has no contact area with the membrane (Choi & Ishibashi, 1993); and

(c) The membrane penetration effect is actively minimized by performing the tests in which the membrane penetration does not occur (Kiekbusch & Schuppener, 1977; Raju & Venkataramana, 1980; Lade & Hernandez, 1977; Tokimatsu & Nakamura, 1986; Seed & Anwar, 1986).

Analyses of the membrane penetration have been made by Molenkamp & Luger (1981), Baldi & Nova (1984) and Kramer et al.(1990). Analytical methods are based on assumptions, e.g. about the geometry of fabrics of sand particles and the mechanics of the membrane. The assumptions are usually too simplified. The results have to be verified experimentally with one of the experimental methods. Thus, the experimental methods are considered preferred.

Kramer et al. (1990) used a shallow rectangular mold called 'membrane penetration frame' to verify their analytical method. In the frame a uniform array of steel spheres is covered by a membrane. The amount of membrane penetration is directly measured because the array of steel spheres is considered rigid.

This study is concerned with the experimental investigation of membrane penetration. A simple apparatus was newly developed. Membrane penetration tests were carried out on two samples by using the developed apparatus. The tests were performed with the purposes to examine if there is some difficulty in the testing procedure and if the results to be obtained from the tests will be reasonable.

The apparatus developed and used in the present study, described later, was found to be similar to the apparatus used by Kramer et al.(1990); the K0 conditions are realized in both apparatus. In the present study, however, the apparatus was designed to test sand samples, while in Kramer et al.(1990), to test regularly packed almost rigid arrays of steel spheres.

In this paper, the apparatus used is described in detail; the results of the tests are shown and compared with the results obtained in the previous work. As a conclusion, the effectiveness of the apparatus will be shown.

2. Experimental Methods: Review

It is in Newland and Allely (1959) that the correction for the membrane penetration was proposed in the first. They assumed that soils deform isotropically when subjected to isotropic stresses, i.e. the axial strain, ε_a, is assumed to be equal to the radial strain, ε_r. Under this assumption, the amount of membrane penetration, ε_{vMP}, is given as

$$\varepsilon_{vMP} = \varepsilon_v - 3\varepsilon_a, \tag{1}$$

where ε_v is the volumetric strain to be determined from the volume change measured in a usual way, e.g. by a burette.

The assumption above is questionable. Bohac and Feda(1992) showed a diagram for the membrane penetration correction, having been determined from K_0 triaxial tests. Under the K_0 conditions, in which no radial strain occurs, the membrane penetration is given simply as

$$\varepsilon_{vMP} = \varepsilon_v - \varepsilon_a. \tag{2}$$

Suppose that, when the net pressure applying to the membrane changes, the volume change of ΔV is measured. The measured volume change is the sum of the true volume change, ΔV_S, and the amount of membrane penetration ΔV_{MP}, i.e.,

$$\Delta V = \Delta V_S + \Delta V_{MP}, \tag{3}$$

where ΔV and ΔV_S are defined so as to be positive when volume contraction occurs. This equation indicates that, if no true volume change occurs, the measured volume change gives the amount of membrane penetration. The condition of no true volume change would be implemented by extrapolating the measured volume change for a volumeless specimen. For the extrapolation, specimens of different volumes have to be tested. This idea was employed by Roscoe et al.(1963), Raju & Sadasivan (1974), Frydman et al. (1973) and Vaid & Negussy (1984).

An alternative idea is based on the following equation:

$$\Delta V_{MP} = \Delta v_{MP} \cdot A_M, \tag{4}$$

where A_M is the area on which the membrane contacts with the specimen, and Δv_{MP} is the amount of membrane penetration per unit contact area. If A_M is null, the measured volume change gives the true volume change. The condition of no contact area will be realized in two ways: one is to use an inclusion, between the specimen and the membrane, of which size varies; the other is not to use flexible membrane. The former way was adopted by Choi & Ishibashi (1992); the latter way by Kiekbusch & Schuppener (1977), Raju & Venkataramana (1980), Lade & Hernandez (1977).

Roscoe et al.(1963) performed drained triaxial isotropic compression tests on sand specimens of 38.1mm diameter, each with a cylindrical brass rod 75mm high placed coaxially within it. The rod diameter varied from 6.4 to 35mm. The volume changes measured by burettes were plotted against the rod diameter and the membrane penetration was determined as the extrapolated volume change for the specimens' diameter 38.1mm.

One discrepancy in this method is that, when the top platen rests on the dummy rod, the vertical stress on the soil around the dummy rod will not be the same as the radial stress. The vertical pressure on the soil will be less than the applied isotropic cell pressure. Therefore the specimens are not subjected to isotropic stresses. To overcome this inconsistency, Raju and Sadasivan (1974) modified the mechanism of the top platen.

Takada(1982) asserted that such a modification as one Raju and Sadasivan (1974) made is not required. If the membrane penetration correction is applied not only to the results of drained isotropic compression tests but also to the results of tests under different stress conditions, the true isotropic stress conditions are not necessarily required, as Takada (1982) asserted. Otherwise, however, the isotropic stress conditions are preferred because different stress conditions will cause the different fabrics of particles and therefore different amount of the membrane penetration.

Frydman et al. (1973) and Vaid and Negussy (1984) employed varying size and shape of specimens but did not use the dummy rods.

It is assumed in these methods mentioned above that the membrane penetration is neither affected by the rod diameter nor by the size or shape of the specimen. This assumption, however, may be questionable because the particle packings among different sizes of specimens may not be similar (Choi and Ishibashi, 1992).

Choi and Ishibashi(1992) proposed to use specimens of the same size and shape but not to use dummy rods. They placed a plastic liner, less flexible than the membrane, between the specimen and the membrane; the size of the liner and therefore the area covered by the liner was varied. This method is simple but the effects of the liner on the deformation of the specimen have not been examined.

Kiekbusch & Schuppener (1977) and Raju & Venkataramana (1980) coated the surface of a deformed membrane by liquid rubber, which becomes stiff when dried. Lade & Hernandez (1977) and Raju & Venkataramana (1980) used a method in which a thin rigid inclusion covering whole the perimeter surface of the specimen is placed between the soil specimen and the membrane. In these methods, the flexibility of the membrane is lost and it is difficult to evaluate the axial load resistance of the membrane.

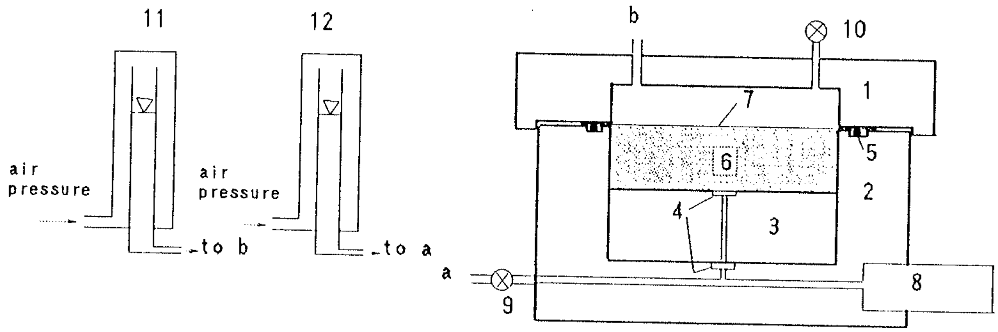
Raju & Venkataramana (1980), Tokimatsu & Nakamura (1986) and Seed & Anwar (1986) employed the methods in which the volume change due to membrane penetration was compensated for by injecting an equivalent volume of water into the soil. These methods are promising, but one of the previously mentioned methods for measuring the membrane penetration has to be used.

Kramer et al. (1990) used a shallow rectangular mold called 'membrane penetration frame' to verify their analytical method. In the frame a uniform array of steel spheres were made as a specimen; the horizontal surface of the specimen was covered with a membrane. The membrane was allowed to penetrate into the specimen by applying vacuum in the specimen. In this apparatus the specimen is compressed under the K_0 conditions. We should note that the regularly packed array of steel spheres deforms so little that the volume of the water expelled from the specimen gives directly the amount of membrane penetration.

3. Experiments

3.1 Apparatus

Fig.2 shows schematically the apparatus that has been developed and used in this study. The main part of the apparatus is a cylindrical cell composed of the upper and lower molds made of brass. The inner diameter of the molds is 60mm. A specimen is prepared in the lower mold so that a prescribed density is obtained. The specimen is covered with a membrane. The upper mold is fastened to the lower mold to sandwich the membrane. Of course, the material of the specimen and that of the membrane must be the same as those to be used in actual mechanical tests, in



1 upper mold; 2 lower mold; 3 spacer disc; 4 porous stones; 5 O-ring; 6 specimen; 7 membrane; 8 porewater pressure transducer; 9 drainage valve; 10 air-release valve; 11,12 air-/water-pressure transformation instruments (volume change measurement instruments)

Fig.2: Schematic representation of the apparatus developed and used in this study.

which the membrane penetration has to be accounted for.

The cell pressure and the back pressure can be applied through two air-/water-pressure transformation instruments, which are used also for measuring the volume change of the specimen. One is connected to the inside of the upper mold to supply the cell pressure and the other to the specimen to supply the back pressure. Each of the instruments is composed of an inner burette and an outer transparent tube. These two instruments should indicate the same volume change if no air is contained in the connections, in the cell and/or in the specimen, because the molds are rigid. However, if air is contained there, these two instruments will give different indications. The volume change measured with the instrument connected to the specimen was used for the evaluation of the membrane penetration.

The drainage out of and into the specimen is controlled by the drainage valve. The undrained conditions can be achieved by closing the drainage valve and therefore the B-value of the specimen can be measured to check the degree of saturation. The measurement of porewater pressure, including the back pressure, is made with a porewater pressure transducer.

The initial height of a specimen, H_0, can be specified by placing one (or more) spacer disc plate(s) in the lower mold before preparing the specimen. Spacer plates of different thicknesses were prepared so that H_0 can be varied in five ways: 40, 20, 9, 4 and 2mm. The initial height of 40mm means that no spacer plate is placed in the lower mold.

3.2 Membrane and sand samples

3.2.1 membrane

Latex membranes of 0.2mm thickness were used. The material and the thickness is the same as those which have been used in triaxial tests on Tottori Sand at Tottori University.

3.2.2 sand samples

Two kinds of sand samples were tested: a sand sample taken at the Toyoura beach, Yamaguchi Prefecture, and one taken at the Tottori dune, Tottori Prefecture. The former is called Toyoura Sand; the latter Tottori Sand. Toyoura Sand is a fine grained sand that has been most widely used in Japan as a standard sand sample. Tottori Sand is a coarse grained sand that has been used, in Tottori University, in many types of model tests and mechanical tests. The

Table 1: Physical properties of the samples used.

	Tottori Sand	Toyoura Sand
ρ_s (g/cm^3)	2.70	2.64
emax	0.888	0.977
emin	0.579	0.655

Note: Tatsuoka et al.(1993) was referred to for the data for Toyoura Sand.

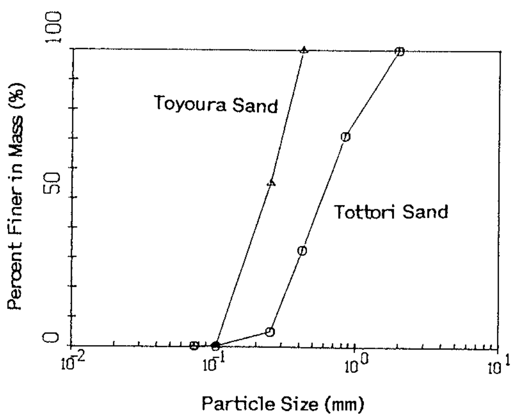


Fig.3: The particle size distributions for the samples used.

grain size distribution curves of these samples are shown in **Fig.3**. Some indices for the physical properties of these samples are given in **Table 1**.

3.3 Preparation of specimens

The samples, having been washed to remove contaminants and dried, were used. Any sample was de-aired in the boiled water and cooled just before being tested. Specimens were made by pouring the sample by a spoon into the lower mold filled with de-aired water. The surface of specimen was leveled off with a knife-edge so carefully that it coincides to the top of the mold's perimeter.

In a series of membrane penetration measurement tests, specimens having the same density and different initial heights have to be prepared. By preliminary investigations, it was found not easy to prepare specimens of the same density, especially low density or high void ratio, by the method described above; the operation of the leveling by a knife edge may disturb the specimen and the density may be different between specimens. The effects of the difference in the density on the determination of the membrane penetration will be discussed in the discussion section.

The prepared specimen was covered with a membrane. It was tried that no air bubble would be let come into the specimen; invisible air bubbles possibly exist and they lead to the decrease in the degree of saturation. It is believed, however, that a back pressure of adequate intensity can improve the degree of saturation of the specimen.

3.4 Procedures for measuring membrane penetration

The deviation of the water pressure applied to the inside of the upper mold from the pore pressure is the effective vertical pressure, p', that applies to the specimen.

A back pressure of 1.0kgf/cm^2 (96kPa) was applied at first. The effective stress was incrementally applied; firstly it was increased from 0.2 (19.6) to 3.0kgf/cm^2 (294kPa) and then decreased to 0.2kgf/cm^2 (19.6kPa). This cycle of the loading and unloading was repeated three times.

The test, described above, has to be performed on at least three, and preferably more, specimens of different initial heights among 40, 20, 9, 4 or 2mm and of the same initial density. If the density of a specimen of an initial height is deviated extremely from other specimens' densities, an another specimen of the initial height should be remade and retested.

However, as will be shown later, the densities of specimens of H_0=4 and 2mm could not be made identical to the densities of higher specimens; therefore the data obtained for specimens of H_0=4 and 2mm were not used for the determination of membrane penetration.

4. Results

4.1 Initial Void Ratio

For Tottori Sand, specimens of five initial heights, 40, 20, 9, 4 and 2mm, were prepared in the way described in the section 3.3. The method could not yield a constant initial void ratio as shown in **Fig.4**. The initial void ratio for specimens of H_0=4 and 2mm became larger than e_0 for specimens of H_0=9, 20 and 40mm. This implies that the heights of 4 and 2mm are too small compared with the particle size. Therefore, for Toyoura Sand, only specimens of H_0=9, 20 and 40mm were prepared and tested. The dependence of the initial void ratio on the initial height will be further discussed in the discussion section.

4.2 Membrane Penetration

4.2.1 Tottori Sand

Fig.5 shows the results of the test on a 40mm high specimen of Tottori Sand. The volume change measured by the burette, ΔV, is plotted against the logarithm of applied effective pressure, p'. The measured volume change ΔV corresponding to a pressure p' is the volume of the water eapelled out of the specimen when the effective pressure varied from 0.2kgf/cm^2 (19.6kPa), in the first loading, to the pressure p' in any loading or unloading stage.

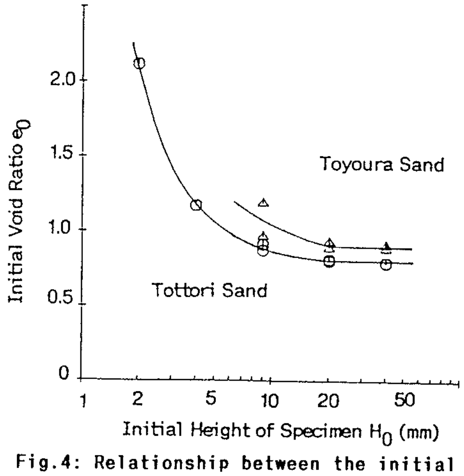


Fig.4: Relationship between the initial void ratio and the initial height of specimen.

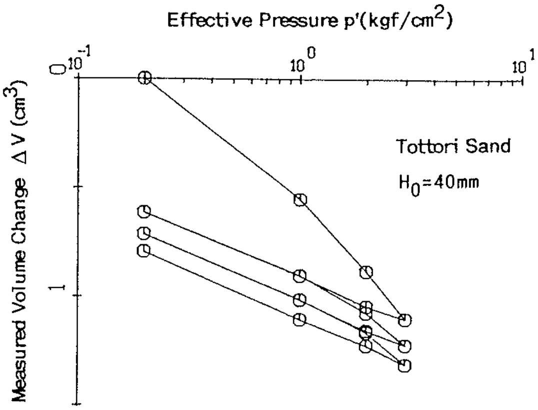


Fig.5: The measured volume change for Tottori Sand.

In **Figs.6(a) to (f)**, ΔV is plotted against H_0 with a parameter of p'. Each figure corresponds to a loading or unloading stage. We can see in every figure that ΔV varies linearly with H_0 for any p'. The straight lines drawn in the figures were determined by the method of least-squares. An extrapolated value of ΔV for H_0=0 from the straight line for an effective pressure p' gives the amount of membrane penetration when the effective pressure varied from 0.2kgf/cm^2 (19.6kPa) in the first loading stage to the value p' in the loading/unloading stage concerned.

The amount of membrane penetration thus determined is shown in **Fig.7**, where the membrane

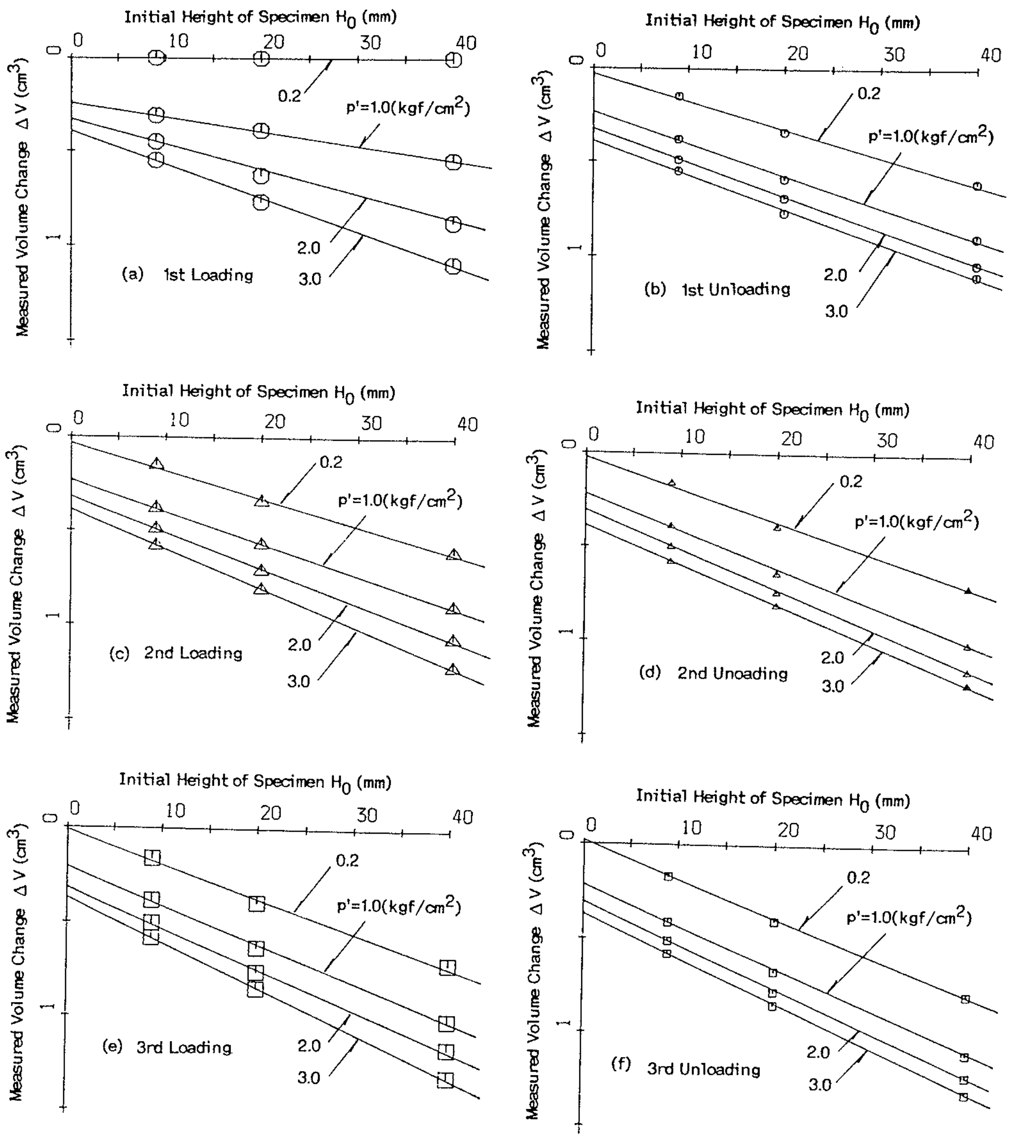


Fig.6: The relationship between the measured volume change and the initial height of specimen for each loading/unloading stage.

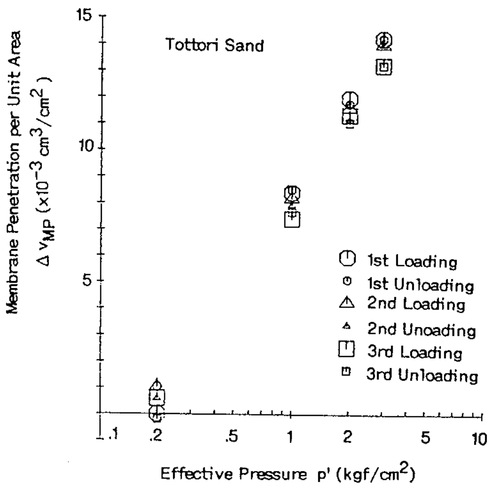


Fig.7: The membrane penetration per unit area of membrane vs. the effective pressure.

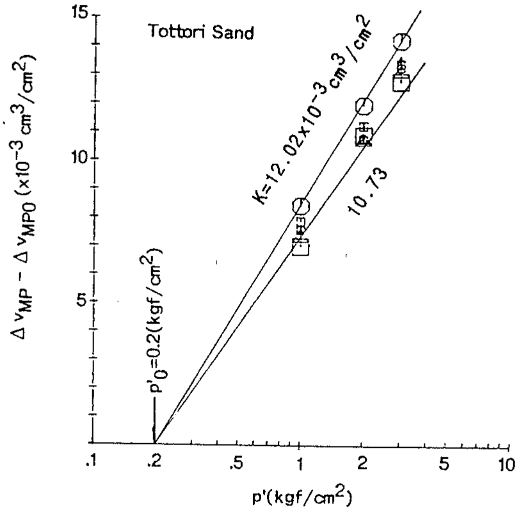


Fig.8: The relationship between the change in the membrane penetration, $\Delta v_{MP} - \Delta v_{MP0}$, and the effective pressure.

penetration per unit area of the membrane, Δv_{MP} is plotted against p'. From this figure, we can express the unit membrane penetration as a function of p' by the following equation:

$$\Delta v_{MP} - \Delta v_{MP0} = K \log\left(\frac{p'}{p'_0}\right), \tag{5}$$

where Δv_{MP0} is the unit membrane penetration when $p'=p'_0$. In order to examine the difference in K between the loading/unloading stages, $\Delta v_{MP} - \Delta v_{MP0}$ is plotted against p' in **Fig.8**. We can see that K is nearly constant independently of the loading/unloading stages. At present, however, we can not conclude that the coefficient K is independent of loading/unloading stages or stress history to which specimens have been subjected because the fabric of soil particles may be different between those stages. The values of K were determined, by the method of least-squares, from Fig.8 and given in **Table 2**. In the table, the data for Toyoura Sand is also shown.

4.2.2 Toyoura Sand

The results obtained for Toyoura Sand are shown in **Figs.9**, **10** and **11**, which are corresponding to Figs.5, 7 and 8, respectively. The observation that the coefficient K is nearly constant for Tottori Sand seems not to be the case for Toyoura Sand. This is mainly caused by the more variation of the density between specimens for Toyoura Sand (see Fig.4).

5. Discussion

As was shown in Fig.4, e_0 for 2 and 4mm high specimens could not be made identical to e_0 for higher specimens. The reasons why such high initial void ratios were obtained for low specimens are considered as follows:

1. At the end of the procedure for preparing specimens, the filled mass of the sample was leveled off by a knife-edge. According to the observation, the surface tended to be slightly concave after the leveling off. The proportion of the volume of the concave space to the total volume of the specimen is much higher for lower specimens. This leads to the relatively higher

Table 2: Values of the coefficient K in Eq.(3)

		Tottori Sand	Toyoura Sand
1st	Loading	12.02	12.90
	Unloading	11.03	8.96
2nd	Loading	10.86	6.93
	Unloading	11.11	7.31
3rd	Loading	10.73	6.10
	Unloading	11.31	7.34
Average		11.177	8.257
Standard Deviation		0.4193	2.244

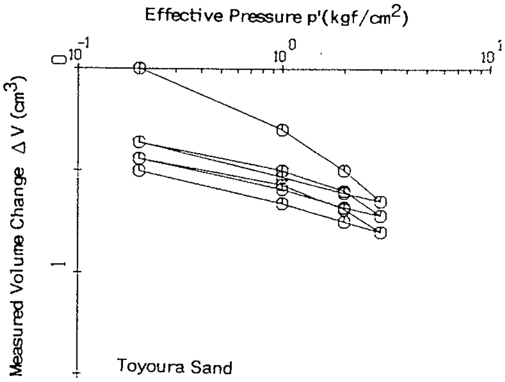


Fig.9: The measured volume change for Toyoura Sand

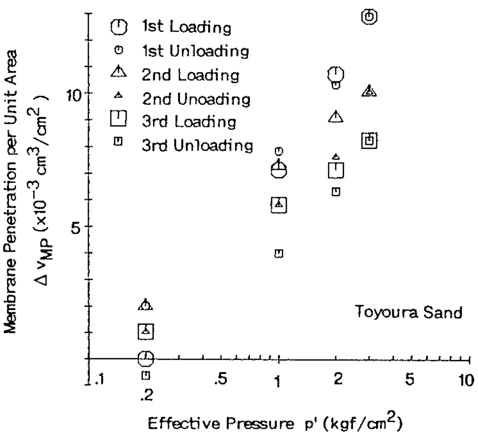


Fig.10: The membrane penetration per unit area of membrane vs. the effective pressure.(Toyoura Sand)

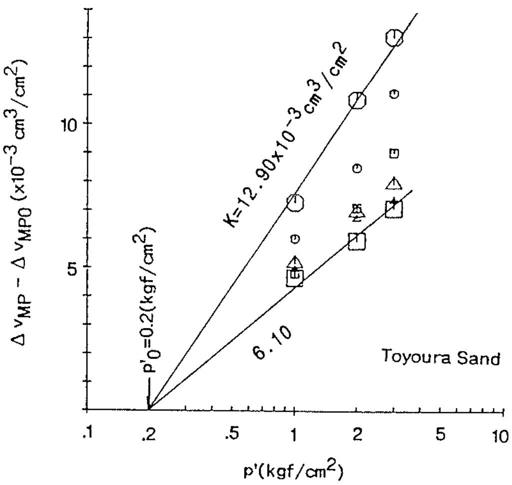


Fig.11: The relationship between the change in the membrane penetration, $\Delta v_{MP} - \Delta v_{MP0}$, and the effective pressure.

initial void ratios for lower specimens.
2. The effect of the gravity causes the densification of specimens; higher specimens are more susceptible to this effect.
3. Sand particles fall down with the acceleration of gravity and collide with the filled mass even in the water. The collision disturbs and densifies the filled mass. This effect depends on the repetition number of pouring. The more number is required for higher specimens.

We can compare the values of the coefficient K in Eq.(3) between Tottori Sand and Toyoura Sand. For Tottori Sand, which is a coarse grained sand, larger values of K were obtained than Toyoura Sand, which is a fine grained sand, in any loading/unloading stage except in the first loading stage. This phenomenon can be intuitively understood.

In **Fig.12**, the coefficient K is plotted against the mean particle diameter, in which the results obtained by Frydman et al.(1973) are also shown for comparison. The membrane used by them is 0.3mm thick while the membrane in the present study is 0.2mm thick; taking this into account, we can conclude that the results obtained in the present study are consistent with results from the previous work. In other words, although a very simple apparatus was used in this study, the membrane penetration can be reasonably determined.

6. Conclusions

In this paper, the results of the tests carried out with a simple apparatus, developed for determining the membrane penetration, were presented. Following conclusions were obtained:

1. The apparatus developed enables us to perform the tests on specimens of various heights, but, if the height of specimen is too low, such as 4 or 2mm, the density can not be made identical to the densities of higher specimens.
2. The amount of membrane penetration determined on two samples, Tottori Sand and Toyoura Sand, is comparable and consistent with the results obtained in previous work.

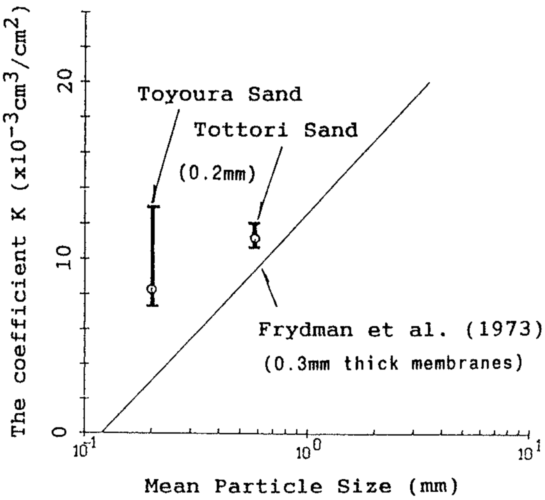


Fig.12: The relationship between the coefficient K in Eq.(3) and the mean particle diameter of the samples.

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