DEFORMATION PROPERTIES OF SAND IN MODEL PRESSUREMETER AND TORSIONMETER TESTS

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ABSTRACT

Two series of tests using miniature pressuremeter and torsionmeter were carried out on sand specimens in a triaxial chamber in which stress boundary conditions were fully controlled. The deformation moduli estimated based on the elasticity theory were compared with those obtained from triaxial tests subjected to various types of stress path starting from its isotropic consolidation state.

The results showed that the deformation moduli corresponding to the Young's modulus $E$, Poisson's ratio $\nu$ and shear modulus $G$ depend on stress path and stress level of the specimens. The deformation moduli estimated from the pressuremeter tests and torsionmeter tests were in the range of those estimated from triaxial tests under various conditions of stress paths.

On the sandy deposits, the deformation moduli estimated from the pressuremeter and the torsionmeter tests could not be widely used for engineering practices simply because the pressuremeter and the torsionmeter can provide only limited stress conditions.

Key words: in-situ test, triaxial compression test, laboratory test, sand, elasticity, pressuremeter test (IGC: D6/C8)

INTRODUCTION

The pressuremeter test was developed by Menard in France as a method of estimating the in-situ strength-deformation characteristics of soils. Presently, this is used in many countries, especially in Europe. Further development on the pressuremeter test especially the self-boring pressuremeter test devices were achieved by Baguelin, Jezequel, Le Mee and Le Mehaute (1972) and by Wroth and Hughes (1973) respectively. The analytical methods to obtain the undrained stress-strain relations from the results of pressuremeter test in undrained condition were developed by Baguelin et al (1972), Ladanyi (1972) and Palmer (1972).

The applicability of pressuremeter test for cohesionless soil, i.e. sandy deposit, has not been discussed comprehensively. A research group in England proposed a model to interpret the results of the pressuremeter tests

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for sandy deposits and has been trying to apply their model to engineering practices (Wroth and Windle, 1975; Hughes, Wroth and Windle, 1977; Jewel, Fahay and Wroth, 1980).

Since it is difficult to avoid the disturbance of the inner wall of cavity in the field, model pressuremeter tests in laboratory condition were carried out by use of large triaxial cell (Jewel, Fahay and Wroth, 1980; Kagawa and Ishii, 1983, 1984; Futaki and Satoh 1983, 1984). The basic mechanical characteristics of the pressuremeter tests have been investigated by these studies.

The vane test which is a kind of the torsionmeter test is widely used to estimate the in-situ undrained strength of cohesive soils. The analytical solution making it possible to obtain the stress–strain curve of soil directly from the results of an undrained vane test was developed by Baguelin, Frank and Jezequel (1976) and Ohta (1979).

There are criticisms of the careless use of in-situ tests, e.g. the report of Ladd, Foott, Ishihara, Schlosser and Poulos (1977) on pressuremeter test. So, to make soil parameters estimated from in-situ tests clearer is an interesting theme for raising the validity of in-situ test.

The purpose of this investigation is the collection of the fundamental data needed in using the pressuremeter (expansion of cylindrical probe) and the torsionmeter (twist of cylindrical probe) for sandy deposits in engineering practice. The miniature pressuremeter test and torsionmeter test were carried out for sandy soil specimens in triaxial chamber in which stress boundary conditions were fully controlled. The deformation moduli estimated based on the elasticity theory were compared with those obtained from triaxial tests subjected to various types of stress path starting from isotropic consolidation state.

Since the specimen generally does not behave as an ideal elastic body, the elastic moduli in this investigation should be considered as "apparent" or "equivalent" elastic moduli.

**DEPENDENCY OF DEFORMATION MODULI OF SAND ON STRESS PATH AND STRESS LEVEL**

At the start of this investigation sand specimens used in triaxial tests were subjected to ten different stress paths all starting from the isotropic consolidation state.

Toyoura sand was used in this investigation and its physical properties are shown in Fig. 1. The Standard Method of JSSMFE (JSF-Standard : T 26-81 T) was employed in specifying \( e_{\text{max}} \), \( e_{\text{min}} \).

![Figure 1. Physical properties of Toyoura Sand](image)

The specimens were prepared by plunging the rod (6 mm in diameter) into the sand twenty times for each of four layers. The plunging method produces more isotropic specimen than the tapping method (Oda, 1972). The void ratios of the specimens ranged from 0.684 to 0.748 while the target was 0.7. Although these scatters are likely to influence the test results, any correction was not adopted.

The specimens of 35.8 mm in diameter and about 70 mm in height were covered by rubber membrane of 0.2 mm thickness. The top and bottom ends of the specimen were lubricated by using two rubber membranes of 0.2 mm thickness with a teflon disk of 0.1 mm thickness with silicone oil in between (see
Fig. 2. Decreasing method of end friction

Fig. 3. Stress paths in experiments

\[
\begin{align*}
\Delta \varepsilon_a &= \frac{1}{E} (\Delta \sigma_a - 2 \nu \Delta \sigma_r) \\
\Delta \varepsilon_r &= \frac{1}{E} (\Delta \sigma_r - \nu (\Delta \sigma_a + \Delta \sigma_r))
\end{align*}
\]

where \( E, \nu \) are Young's modulus and Poisson's ratio, \( \varepsilon_a, \varepsilon_r \) are axial and horizontal strain.

For general stress paths

\[
\begin{align*}
E &= \frac{2 \Delta \sigma_a^2 - \Delta \sigma_a \Delta \sigma_r - \Delta \sigma_r^2}{2 \Delta \varepsilon_a \Delta \sigma_a - \Delta \varepsilon_a \Delta \sigma_r} \\
\nu &= \frac{\Delta \varepsilon_r \Delta \sigma_a - \Delta \varepsilon_a \Delta \sigma_r}{2 \Delta \varepsilon_r \Delta \sigma_r - \Delta \varepsilon_a \Delta \sigma_a - \Delta \varepsilon_a \Delta \sigma_r}
\end{align*}
\]  

(1)

(2)

For constant confining pressure condition, \( \Delta \sigma_r = 0 \)

\[
\begin{align*}
E &= \frac{\Delta \sigma_a}{\Delta \varepsilon_a} \\
\nu &= -\frac{\Delta \varepsilon_r}{\Delta \varepsilon_a}
\end{align*}
\]  

(3)

(4)

For infinitesimal strain, the change of volumetric strain \( \Delta \varepsilon_v \) is expressed as,

\[
\Delta \varepsilon_v = \Delta \varepsilon_a + 2 \Delta \varepsilon_r
\]  

(5)

Substituting Eq. (5) into Eq. (4)

\[
\nu = -\frac{1}{2} \frac{1}{\Delta \varepsilon_a} (\Delta \varepsilon_a - \Delta \varepsilon_r) = -\frac{1}{2} \left( \frac{\Delta \varepsilon_a}{\Delta \varepsilon_a} - 1 \right)
\]  

(6)

From Eq. (6), \( \nu \) can be obtained as a function of axial strain and volumetric strain.

In this paper, initial tangential elastic moduli were mainly considered.

Typical example of how to decide \( E, \nu \) from stress-strain curve or volumetric strain-axial
Fig. 4. Decision of deformation moduli

strain curve are shown in Fig. 4, if $\Delta \sigma_r = 0$. In a repeated loading process, deformation moduli $E, \nu$ were similarly obtained from the gradient, $\Delta \sigma_r / \Delta e_r$ or $\Delta e_r / \Delta \sigma_r$.

The Young's moduli and Poisson's ratios thus obtained are shown in Figs. 5 and 6 where the numbers in circles indicate the stress paths shown in Fig. 3. Fig. 5 indicates that the Young's moduli in compression side are much larger than those in extension side.

of the stress space, while the Poisson's ratios are similar regardless of stress paths as shown in Fig. 6. The deformation moduli estimated from the triaxial drained compression and extension tests under the confining pressure being kept constant during shear are shown.

Fig. 5. Stress path dependency of $E$-values

TOYOURA SAND $e_c = 0.684 - 0.748$

Poisson's Ratio

TOYOURA SAND $e_c = 0.684 - 0.748$

Elastic Modulus

Fig. 6. Stress path dependency of $\nu$-values

Fig. 7. Dependency of $E$-values on stress level
in Fig. 7 against the consolidation pressure. In this paper $\sigma_e'$ is the effective consolidation pressure and $\epsilon_e$ is the void ratio after the isotropic consolidation.

Fig. 7 indicates that the $E$-values determined from the triaxial compression tests are about 3 times greater than those from the triaxial extension tests for the same consolidation pressure, and they increase linearly with the increase in the consolidation pressure. The $\nu$-values estimated from the triaxial compression tests are smaller than 0.5, while those from the triaxial extension tests are over 0.5. Although the $\nu$-values show a little scattering, it can be seen that they do not depend on the magnitude of the effective consolidation pressure.

The results indicate that the initial deformation moduli of Toyoura Sand estimated based on the elasticity theory are highly dependent on the stress paths and stress levels applied to the specimen.

**EXPERIMENTS WITH PRESSUREMETER AND TORSIONMETER**

*Miniature Pressuremeter*

Fig. 8 shows the schematical diagram of the miniature pressuremeter which expands its diameter by inflating the rubber membrane (0.5 mm thick). The dimensions of expansive probe are 15 mm in diameter and 37.8 mm in height. The volume change of the probe due to the membrane penetration, $V_m, p$ was not corrected because the $V_m, p$ calculated by use of the Molencamp and Luger method (1981) against the stress range of “pseudo-elastic” phase (as will be mentioned later) was at most 5% of the measured total volume change of the expansive probe in each case. The relations between the deformation moduli obtained from the pressuremeter and those from the other methods were not affected seriously by the correction of $V_m, p$.

The specimen which is 101.4 mm in diameter and about 80 mm in height contains the miniature pressuremeter at the center and is covered by rubber membrane of 1.2 mm thickness. Minimum readings of the pressure gauge and the burette are 1 kN/m² and 0.01 cc. The double tube is employed to reduce the expansion of tube connecting the expansion probe of the pressuremeter and the pressure control burette.

*Miniature Torsionmeter*

Fig. 9 (a) and (b) show the miniature torsionmeter being contained in the specimen placed on the pedestal of triaxial chamber. This triaxial apparatus was a modification of triaxial vane testing apparatus developed by Kenny and Landva (1965). Torsionmeter basically consists of a metal cylinder with vanes outside the cylinder. The test was carried by rotating the torsionmeter with the rate of $6.28 \times 10^{-3}$ rad/sec measuring the torque needed in increasing the angle of rotation. Six different types of cylinder with vanes shown in Fig. 10 were used. The size of the specimens and the covering membrane are the same as those in the pressuremeter tests.

*Preparation of Sand Specimens and Test Procedure*

The procedures of preparing specimens for pressuremeter and torsionmeter tests are identical.

The expansive probe of pressuremeter or
The cylinder with vanes of torsionmeter is set on the pedestal in the triaxial chamber. Then the expansive probe of pressuremeter is connected to the pressure control burette, the cylinder with vanes to the torquemeter.

The sand former with a rubber membrane is set on the pedestal and de-aired water is poured into the sand former. Before pouring sand into the sand former, a high vacumm was applied to the top of the triaxial cell to de-air the water in the triaxial chamber, especially in the pressuremeter (see Fig. 11).

Air-dried sand was poured into the sand former and was plunged with a metal rod (6 mm in diameter) for each of four layers to achieve the void ratio required (0.7).

Before dismantling the sand former, a low vacuum (about 20 cm of water column) was applied to the base of the specimen to help the specimen to stand by itself.

Isotropic consolidation pressure (49, 98, 147 and 196 kN/m²) was applied to the specimen and 15 minutes were taken in most cases for consolidation.

The water volume expelled from or drawn into the specimen and injected into the expansive probe were measured in the pressuremeter tests after the application of an additional increment of water pressure (9.8 or 19.6 kN/m²) on the inner surface of the expansive probe. The relation between the torque and the angle of rotation was obtained from the torsionmeter tests.
All the tests were carried out under drained condition.

The Results of the Pressuremeter Tests

Typical results of the pressuremeter tests are shown in Fig. 12: the ordinate is the inner pressure, the left abscissa is the circumferential strain at the boundary between the probe and the specimen and the right abscissa is the circumferential strain at the outer boundary of the specimen. Consolidation pressure was chosen in a range from 49 kN/m² to 196 kN/m². Typical "pressure-expansion curve" (see Fig. 13) consists of the three parts, i.e. the initial curve (O→A) before the pressure applied to the inner surface of the pressuremeter reaches the consolidation pressure, the following linear part (A→B) and the third part (B→C) up to the end of the loading. Since AB gives an impression of an elastic range for the soil, it is called the 'pseudo-elastic' phase of the test. In this investigation the second linear part is the object of the study.

The result of the pressuremeter repeated loading test is shown in Fig. 14. The virgin loading, unloading and reloading contain linear part respectively as shown in Fig. 14 and there is an evident difference between the tangential gradients of the virgin loading, unloading and reloading curves. This implies that linear part in the virgin loading does not represent only the elastic behaviour of the sand, while in the unloading and reloading processes the sand behaves more elastically.

The Results of the Torsionmeter Tests

The shear stress distribution on the side of the vane is assumed to be uniform, and those on the top and bottom edges of the vane are assumed also to be uniform (see Fig. 15). The cylinder with vanes was lubricated at the edges and torque mobilized on the edges of rotating cylinder was expected not to influence the test results. Considering that isotropic consolidation is adopted and fabric anisotropy is reduced by the procedure of pre-
Fig. 15. Assumed distribution of shear stress on side and edge of vane.

Comparing the specimen, it may be adequate to assume that $\tau_V = \tau_H = \tau$ where $\tau_V$ and $\tau_H$ are the shear resistances mobilized on the vertical and horizontal shear planes respectively. The relation between the torque $T$ and the shear stress $\tau$ may be given as follows:

$$\tau = \frac{T}{2 \pi X_1^2 H + 4/3 \pi (X_1^2 - X_2^2)} \quad (7)$$

Fig. 16 shows the effect of numbers of vane on the $\tau - \theta$ relations where $\theta$ denotes the angle of rotation of the vanes. Fig. 17 shows the effect of vane height ($X_1 - X_2$) (see Fig. 15) on the $\tau - \theta$ relations. These two figures show that the relations between the shear stress calculated by means of Eq. (7) and the angle of rotation are affected to some extent by these two factors, but not very seriously. Typical relations between $\tau$ and $\theta$ are shown in Fig. 18. The cylinder with vanes in this figure is the type B-2 (see Fig. 14).

Mobilized shear stress increases with the increase in consolidation pressure and each result shows the softening tendency after the shear resistance reaches the peak. The angles of rotation at the peak shear resistance are approximately identical in all the cases. It is already known (Hata, Ohta, Fukagawa and Shikata, 1982) that $\tau - \theta$ relation is not strongly influenced by the rate of the rotation of vane for sandy specimens.
ANALYSIS OF TEST RESULTS BASED ON THE ELASTICITY THEORY

Miniature Pressuremeter

An elastic hollow cylinder of inner radius \( r_i \) and outer radius \( r_o \) is considered (Fig. 19). The material is assumed to be isotropic, homogeneous and linearly elastic. When the pressure \( \sigma_i \) in the cavity is increased by \( \Delta \sigma_i \) and the pressure on the outer surface is kept constant, the soil moves outwards in the plane strain and axi-symmetrical condition.

![Fig. 19. Expansion of elastic hollow cylinder](image)

The increments of radial, circumferential and vertical pressures \( \Delta \sigma_r, \Delta \sigma_\theta, \Delta \sigma_z \) are principal, therefore the shearing occurs without being accompanied by the rotation of the principal stresses.

The equilibrium equation is

\[
\frac{d\sigma_r}{dr} + \frac{\sigma_i - \sigma_o}{r} = 0 \tag{8}
\]

The radial and circumferential strains \( \varepsilon_r, \varepsilon_\theta \) are respectively given by:

\[
\varepsilon_r = -\frac{du}{dr}, \quad \varepsilon_\theta = \frac{u}{r} \tag{9}
\]

where \( r \) = the distance from the center of cavity, \( u \) = the radial displacement and \( \varepsilon_r, \varepsilon_\theta \) are positive for compression. The stress-strain relations in the plane strain condition are

\[
\begin{align*}
\sigma_r &= \frac{E}{(1+\nu)(1-2\nu)} [(1-\nu)\varepsilon_r + \nu\varepsilon_\theta] \\
\sigma_\theta &= \frac{E}{(1+\nu)(1-2\nu)} [\nu\varepsilon_r + (1-\nu)\varepsilon_\theta] 
\end{align*} \tag{10}
\]

where \( E \) = Young’s modulus, \( \nu \) = Poisson’s ratio.

Substituting Eqs. (9) and (10) into Eq. (8), a differential equation is obtained:

\[
\frac{d^2u}{dr^2} + \frac{1}{r} \frac{du}{dr} - \frac{u}{r^2} = 0 \tag{11}
\]

Solving Eq. (11) with the boundary conditions, i.e. \( \sigma_r \), \( \sigma_\theta \), \( \sigma_o \), the displacement of an arbitrary element around the pressuremeter is given as:

\[
\begin{align*}
\Delta u &= \frac{1}{E} \left[ (1+\nu)(1-2\nu) \frac{\sigma_i r_i^2 - \sigma_o r_o^2}{r^2} - \frac{(1+\nu)}{r} \frac{r_o^2 r_i^2 (\sigma_i - \sigma_o)}{r^2} \right] \\
&= \frac{1}{E} \left[ (1+\nu) \frac{2(1-\nu)}{r_o^2 - r_i^2} - \frac{(1+\nu)}{r} \frac{r_o^2 r_i^2 (\sigma_i - \sigma_o)}{r^2} \right]
\end{align*}
\]

Therefore the circumferential strain at the inner surface is given by:

\[
\frac{\Delta \varepsilon_\theta}{r_i} = \frac{(1+\nu)}{E} \left[ (1-2\nu) \frac{r_i^2 + r_o^2}{r_o^2 - r_i^2} \right] \sigma_i - \frac{(1+\nu)}{E} \left[ 2(1-\nu) \frac{r_o^2}{r_o^2 - r_i^2} \right] \sigma_o
\]

As the stress applied on the outer surface, \( \sigma_o \) is kept unchanged, the relation between the strain increment and the inner pressure increment at the inner surface is consequently expressed as:

\[
\Delta \left( \frac{u_i}{r_i} \right) = \frac{(1+\nu)}{E} \left[ (1-2\nu) \frac{r_i^2 + r_o^2}{r_o^2 - r_i^2} \right] \Delta \sigma_i \tag{12}
\]

where \( \Delta (u_i/r_i) \), \( \Delta (u_o/r_o) \) are the increments from the reference isotropic consolidation state.

Similarly the circumferential strain of the outer surface, \( u_o/r_o \), is given by:

\[
\frac{u_o}{r_o} = \frac{2(1-\nu^2)}{E} \frac{r_i^2}{r_o^2 - r_i^2} \sigma_i - \frac{(1+\nu)}{E} \left[ (1-2\nu) \frac{r_o^2 - r_i^2}{r_o^2 - r_i^2} \right] \sigma_o
\]

Therefore the relation between the strain increment and the inner pressure increment at the outer surface is expressed as:

\[
\Delta \left( \frac{u_o}{r_o} \right) = \frac{2(1-\nu^2)}{E} \frac{r_i^2}{r_o^2 - r_i^2} \Delta \sigma_i \tag{13}
\]

When the initial tangential gradients obtained from the Eqs. (12) and (13) are represented by \( K_1, K_2 \) respectively, the deformation moduli \( \nu \) and \( E \) are expressed as:

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\[
\nu = \frac{(1 - 2K_1/K_2) r_i^2 + r_o^2}{2(1 - K_1/K_2) r_i^2} \\
E = \frac{r_i^2}{K_2} \left[ 1 - \left( \frac{(1 - 2K_1/K_2) r_i^2 + r_o^2}{4(1 - K_1/K_2) r_i^2} \right)^2 \right] \\
\Delta(u_i/r_i), \Delta(u_o/r_o) \text{ are obtained from the experimental results through the following equation:} \\
\Delta \left( \frac{u_i}{r_i} \right) = \sqrt{\frac{\Delta V_P}{\pi h r_i^3}} + 1 - 1, \\
\Delta \left( \frac{u_o}{r_o} \right) = \sqrt{\frac{\Delta V_P - \Delta V_S}{\pi h r_o^3}} + 1 - 1
\]

where \( \Delta V_P \) is the volume change of the expansive probe of the pressuremeter, \( \Delta V_S \) is the volume change of the specimen and \( h \) is the height of the expansive probe.

**Miniature Torsionmeter**

It is considered that shearing stress is applied along the inner surface of an elastic hollow cylinder with the outer surface being fixed as shown in Fig. 20. It is assumed that the material is isotropic, homogeneous and linearly elastic. As the circumferential displacement of an arbitrary element around the torsionmeter, \( \nu \), depends only on shear stress \( \tau_{r\theta} \) the equilibrium equation is:

\[
\frac{d\tau_{r\theta}}{dr} + 2 \cdot \frac{\tau_{r\theta}}{r} = 0
\]  

(14)

The shear strain \( \gamma_{r\theta} \) is expressed as follows:

\[
\gamma_{r\theta} = -\frac{d\nu}{dr} \cdot \frac{1}{r}
\]  

(15)

The stress-strain relation is given by:

\[
\tau_{r\theta} = G \gamma_{r\theta}
\]  

(16)

By solving Eq. (14) we obtain:

\[
\tau_{r\theta} = \frac{c}{r^4}
\]  

(17)

where \( c \) is an integral constant.

The shear stress \( \tau_{r\theta} \) applied along the inner surface \((r=r_i)\) causes the torque \( T (=2\pi r_i^2 \cdot c/r_i^4 = 2\pi c) \) with respect to the central axis of the cylinder. Therefore considering Eq. (17) and \( c = T/2\pi \), the following equation is given:

\[
\tau_{r\theta} = \frac{T}{2\pi r^2}
\]  

(18)

Substituting Eqs. (16) and (18) into Eq. (15) and considering the boundary condition, i.e., the circumferential displacement, \( \nu = 0 \) at the outer surface, \( r = r_o \), the angle of rotation, \( \theta \), is given by:

\[
\theta = \frac{T}{4\pi G} \left( \frac{1}{r_i^3} - \frac{1}{r_o^3} \right)
\]

**CORRELATION AMONG DEFORMATION MODULI**

**Pressuremeter Test**

The dependency of the deformation moduli of a sand on the stress path and stress level was found to be appreciable through a series of the triaxial tests, as mentioned in the beginning of this paper. Since the changes in three principal stresses experienced by soil elements around the pressuremeter probe are not equal to each other, the stress conditions around the pressuremeter are different from those of the conventional triaxial tests. However the deformation moduli estimated from the pressuremeter and torsionmeter tests were of the order of the deformation moduli estimated from the triaxial tests under various conditions of stress paths. These results would be useful in interpreting the pressuremeter and the torsionmeter test results.

The deformation moduli, \( E \) and \( \nu \), determined from pressuremeter tests are plotted in Fig. 21 against the consolidation pressure. Fig. 21 shows the results obtained from the virgin loading, unloading and reloading processes respectively.
Fig. 21. Deformation moduli estimated from pressuremeter tests

It may be seen from Fig. 21 that (1) the $E$-values obtained from the unloading and reloading processes are about 3 times greater than those from the virgin loading process against the same consolidation pressure, (2) Poisson’s ratio ranges from 0.6 to 0.8 in the virgin loading process and does not depend on the magnitude of the consolidation pressure, and (3) the $\nu$-values estimated from the unloading and reloading processes tends to scatter compared with those from the virgin loading process.

Comparing Fig. 21 with Fig. 7, the $E$-values obtained from the triaxial extention tests are almost the same as those from the virgin loading process in the pressuremeter tests, and those from the triaxial compression tests are nearly equal to those from the unloading and reloading processes in the pressuremeter tests against the same consolidation pressure.

However if a material shows complicated stress path dependency, such as that for example in the case of anisotropic material etc, the interpretation of the pressuremeter test results becomes more difficult, because the deformation moduli changes not only with the current stress level but also with the stress path, and moreover the pressuremeter test results give only one (virgin process) or two (virgin and repeated process) deformation moduli for a case with a particular set of stress path and stress level.

Repeated loading in triaxial tests were conducted to estimate the $E$-values to be compared with those obtained from the repeated loading in the pressuremeter tests. A typical results of the repeated loading in triaxial compression and extention test are shown in Fig. 22. The deformation moduli obtained from the repeated triaxial loading tests were shown in Fig. 23. It can be seen in Fig. 23 and Fig. 21 that the $E$-values obtained from the unloading and reloading processes in the pressuremeter tests nearly equal to those from the repeated triaxial extention and compression loading tests for the same consolidation pressure. This means that the sand spec-
imens behave more elastically in the repeated loading process.

As to the Poisson's ratio, a dependency on stress path and stress level is not so appreciable and the scatters were generally large. Since the Poisson's ratio is considered as functions of strain or stress level, the difference of Poisson's ratio between initial loading process and repeated loading process may be affected by these strain or stress level. Further investigation is needed to define the basic characteristics of the $\nu$-values of sand.

**Torsionmeter Tests**

Shear modulus $G$ is obtained from the results of the torsionmeter tests, while $G$ can also be calculated from Young's modulus $E$ and Poisson's ratio $\nu$ obtained either from the pressuremeter tests or the triaxial tests by use of the following equation:

$$G = \frac{E}{2(1+\nu)}$$

The $G$-values estimated from the triaxial tests under various conditions of stress paths show the distinctive stress path dependency similar to that of the $E$-values estimated from the triaxial tests. However, if a material shows complicated stress path dependency, the interpretation of the torsionmeter test results becomes difficult as in the case of the pressuremeter.

Fig. 24 shows the shear modulus $G$ obtained from the torsionmeter, the triaxial tests and the pressuremeter tests respectively against the consolidation pressure. It becomes apparent that the $G$ values estimated from the torsionmeter tests are similar to those by the triaxial extension tests under the confining pressure being kept constant and those by the virgin loading process of the pressuremeter tests for the same consolidation pressure.
CONCLUSIONS

The following conclusions are deduced from the investigations:

1. It becomes clear through the triaxial tests under various conditions of stress paths that the deformation moduli, especially Young's modulus $E$, of a sand depends largely on stress path and stress level.

2. The Young’s moduli $E$ estimated from the virgin loading process of the pressuremeter tests are similar to those of the virgin loading process in the triaxial extension tests for the same consolidation pressure.

3. The Young’s moduli $E$ estimated from the repeated loading process of the pressuremeter tests are nearly equal to those of the repeated loading process of the triaxial compression and extension tests. This means that the sand specimens behave more elastically in the repeated loading process.

4. The dependency of the Poisson’s ratio on the stress path and stress level is more complicated than that of the Young’s modulus $E$.

5. The shear modulus $G$ shows the similar dependency on the stress path and stress level as the Young’s moduli $E$ does.

6. The shear moduli $G$ obtained from the torsionmeter tests are similar to those from the triaxial extension tests and the virgin loading process of the pressuremeter tests for the same consolidation pressure.

7. The pressuremeter test gives one or two deformation moduli corresponding to a particular set of stress path and stress level, therefore the interpretation of the results of pressuremeter tests becomes more difficult if a material shows complicated dependency on stress path and stress condition.

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