Evaluation of Mechanical Parameters in Terms of Void Ratio for Tottori Dune Sand

by

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Results of triaxial drained compression tests on the Tottori Dune sand are presented. The hysteretic nature of membrane penetration and non-linear behavior in e-log σ_m relations are shown. Angles of shearing resistance at failure and at maximum contraction due to dilatancy, and normalized shear modulus are also treated. The effects of initial void ratio on the behavior and parameters are discussed.

Key words : Sand, Triaxial test, Compression index, Membrane penetration, Angle of shearing resistance

1. Introduction

Numerical simulation techniques are useful for understanding those phenomena that are encountered in soil grounds and for investigating mechanisms of the phenomena. For realizing numerical analyses such as finite element anlyses, constitutive equations for the soil in the ground of interest have to be developed. In facts many attempts to develop the constitutive models for soils have been made and some successes have been obtained for various types of idealized soils. Thus, the practical importance and usefulness of numerical methods has become more and more. The problem how to correctly determine parameters used in the constitutive models has become one of main subjects in the field of geotechnical engineering.

The Authors have investigated stress-strain behavior of sands using the Tottori Dune sand as a sample and examined the applicability of an elasto-plastic constitutive model to the soil[1],[2]. The experiments of which the results will be shown in this paper were performed as a part of such a broader investigation. One of subjects of this article is to discuss the effects of void ratio on some mechanical parameters used commonly in many constitutive models.

In formulating a constitutive model for a soil, it is essentially required to evaluate the volume change due to dilatancy, v_D. Dilatancy is defined as the volume change caused by the change in deviatoric component of stresses. There are two alternatives for evaluating dilatancy.

First, v_D can directly be evaluated through tests in which deviatoric components vary but hydrostatic component is held constant. This type of test is called σ_m constant test. When these tests are carried out in triaxial testing apparatus, cell pressure will vary.

The other is an indirect method. For instance, in triaxial tests, the effective stress path is followed along which the cell pressure is held constant, while deviatoric and hydrostatic components being changed. In this methos, also a series of isotropic compression tests have to be carried out because the volume change due to the change in hydrostatic component, denoted by Δv_C, have to be eliminated from the measured total volume change Δv; we make the assumption that $\Delta v_D = \Delta v - \Delta v_C C$.

In both σ_m constant tests and isotropic compression tests, cell pressure is not held constant but varied. For granular soils, the membrane, which encloses a triaxial specimen, penetrates into the specimen, being subjected to the change in cell pressure. Measured volume change of the specimen have to be corrected for the membrane penetration. The correction methods for the membrane penetration have so far benn investigated[3],[4],[5].

Membranes usually used for the soil testing can be considered elastic, however some studies show that the phenomenon of membrane penetration will be somewhat hysteretic and the magnitude of the penetration depends on the loading history such as loading, unloading and reloading. The "in-elastic" behavior of the membrane penetration will be discussed in this paper.

Volume change behavior of soils in isotropic compression tests can, for almost all kinds of fine soils, be assessed by using the linear relationship between void ratio e and the log of mean effective stress σ_m. As will be shown later, the linearity can not always be observed for granular soils. The extent to which e-logσ_m relations are non-linear will be evaluated by considering the compression index to be a function of cell pressure and loading conditions.

Furthermore, mechanical parameters such as normalized shear modulus, angles of shear resistance at failure and at maximum contraction due to dilatancy will be treated; the effects of initial void ratio on these parameters will be discussed.

2. Sample

The sample used in this study is a coarse sand taken at a location in the Tottori Dune area. The sample was cleaned by removing impurities contained in it and then dried. The grain size distribution is shown in Fig.1. Specific gravity Gs is 2.70; maximum and minimum void ratios are 0.888 and 0.579, respectively.

3. Experimental procedures

All the tests of which results will be discussed in this paper are triaxial

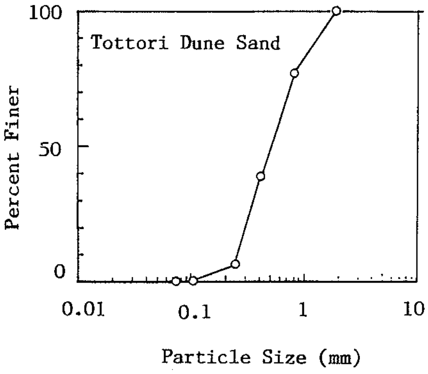

Fig.1: Particle size distribution of the sample.

compression tests.

3.1 Preparation of test specimens

Sand particles having been boiled in the distilled water were poured with a spoon into a mold filled with water. A prescribed density was realized by tapping the mold. Relative densities D_R of 30, 40 and 80% were prescribed. For loose specimens of D_R=30%, the tapping was not done.

The mold containing the sample was frozen in a refrigerator. The frozen specimen of 5cm in diameter and 12cm in height was removed from the mold and placed in a triaxial cell to be defrosted. Cell pressure of 20 kPa was applied during the defrosting.

3.2 Tests for correcting membrane penetration

For the correction of the membrane penetration, the method proposed by Roscoe et al.[3] was adopted: i.e., isotropic compression tests were carried out on specimens containing a central brass rod. Three brass rods of different diameters of 8, 15 and 30mm were used. The outer diameter of specimens is the same as that of triaxial specimens. The tests were carried out on samples of D_R=30,40 and 80%.

3.3 Isotropic compression tests

In isotropic compression tests, confining stress was varied from 20 to 500 kPa. A cycle of loading, unloading and reloading was applied. The tests were carried out on samples of the three relative densities.

3.4 Drained triaxial compression tests

After the isotropic consolidation up to a prescribed cell pressure, strain-controlled drained triaxial compression was made holding the cell pressure constant. The rate of axial strain was 0.6%/min. Two tests were carried out for a particular value of cell pressure. Values of cell pressure were 100, 200 and 300kPa.

4. Results and Discussion

4.1 Correction for membrane penetration

The results of an isotropic compression test on the specimen having a

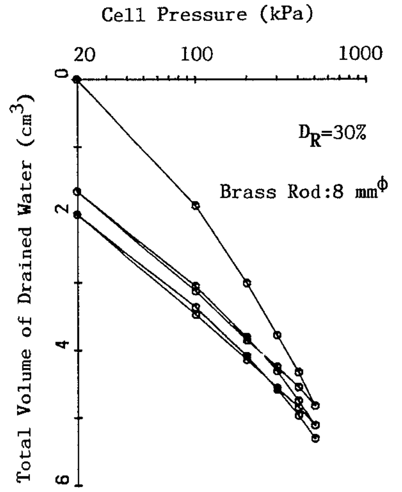

Fig.2: Results of the membrane penetration test on a loose sample; the brass rod of 8mm in diameter.

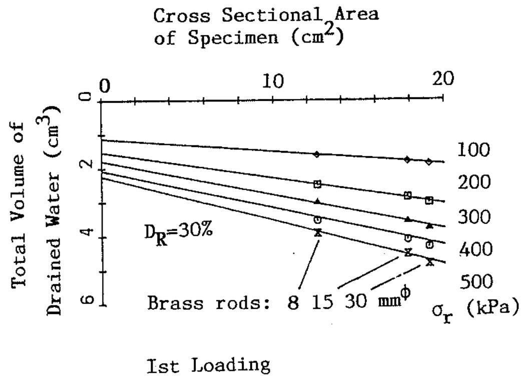

Fig.3: The way for determinig the membrane penetration; for the first loading on the loose sample.

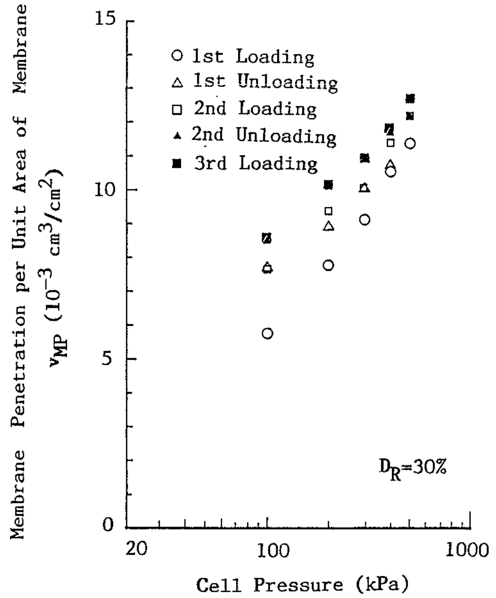

Fig.4: Relationships beween the membrane penetration per unit area of membrane and cell pressure; the loose sample.

central rod of 8mm in diameter is shown as an example in Fig.2. The total volume of water expelled from the specimen is plotted against cell pressure. Similar results were obtained for specimens having central rods of other diameters, 15 and 30mm.

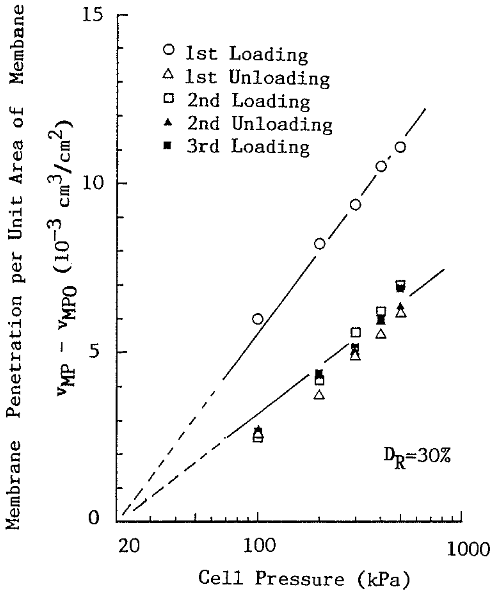

Fig.5: Relationships between membrane penetration per unit area of membrane and cell pressure for the loose sample. The membrane penetration is determined for each loading condition.

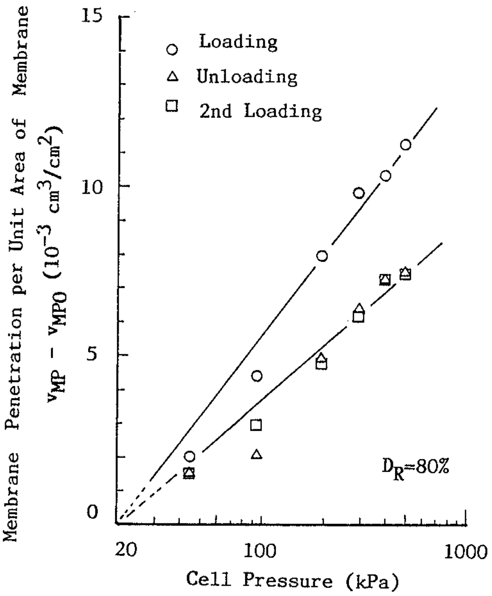

Fig.6: Relationships between membrane penetration per unit area of membrane and cell pressure for the dense sample. The membrane penetration is determined for each loading condition.

Such results as those shown in Fig.2 can yield the relationships between the total volume of drained water and the cross sectional area occupied by soil grains. An example is presented in Fig.3, in which the relationships in the first loading are shown.

In the figure cell pressure is taken as a varying parameter. A straight line corresponding to a particular value of cell pressure was obtained. By extrapolating the straight lines to vertical axis, the magnitude of the membrane penetration can be evaluated as the ordinates of intersections; the ordinates correspond to the state in which soil grains are not contained in specimens.

The magnitude of the membrane penetration determined by the way mentioned above is plotted against cell pressure in Fig.4 for the case of D_R=30%. There is some scatter depending on the testing condition such as loading, unloading and reloading.

The scatter has often been neglected by previous studies, for example Roscoe et al.[3] and Frydman et al.[4], although the scatter was observed. The neglect might be allowed for routine or practical purposes but not allowed for the purpose of evaluating the volume change behavior not only

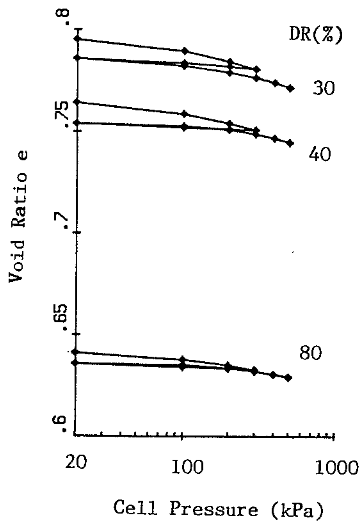

Fig.7: Relationships between void ratio and cell pressure in isotropic compression tests.

in the first loading but also in other conditions.

In this study, we account for the loading history dependence of the membrane penetration by evaluating the magnitude of penetration in each of loading conditions. For each condition, the deviation of the membrane penetration at any cell pressure from that at cell pressure of 20kPa was determined. It was plotted against the log of cell pressure. The results are shown in Fig.5 for D_R=30% and in Fig.6 for D_R=80%.

Two linear relationships can be seen: one for the first loading the other for other conditions. The linear relationships can be expressed, denoting total membrane penetration by v_{MP} and cell pressure by σ_c, as

$$v_{MP} - v_{MP}0 = K \log(\sigma_c/\sigma_{c0}) \quad \text{--------------------(1)}$$

where v_{MP0} is the membrane penetration when σ_c is σ_{c0}(=20kPa). Of course, the coefficient K take different values in the first loading and in other conditions.

4.2 Nonlinear e-logσ_c behavior in isotropic compression

The results of isotropic compression tests are shown in Fig.7 in the form of e-logσ_c. For any relative density, remarkably non-linear re-

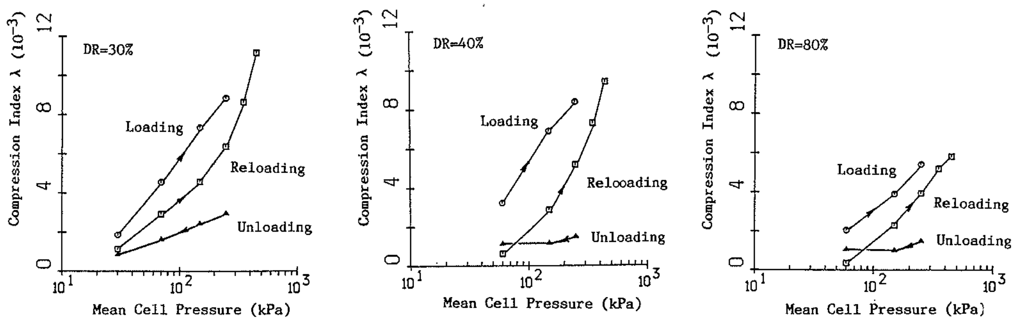

Fig.8: Relationships between compression index and cell pressure. (a):Relative density is 30%, (b): 40%; and (c): 80%.

lationships are seen.

It is usual to assess the isotropic compression behavior by two constants: compression index λ and swelling or recompression index κ. The simplified assumption of bi-linearity has been adopted in almost all previous studies because it is rather complicated to take into account the non-linearity.

We assess compressibility by defining the compression index λ as:

$$\lambda = - de / d\ln \sigma_c \qquad \text{--------------------(2)}$$

Hereafter we use the term "compression index" in the wide sense. When necessary, the compression index in the narrow sense will be used so as to distinguish from swelling index or recompression index. The differentiation in Eq.(2) have to be replaced by the finite difference in evaluating compressibility with experimental data that is ordinarily discrete. Eq.(2) is rewritten to

$$\lambda = - (e_1 - e_2) / \ln(\sigma_{c1}/\sigma_{c2}) \qquad \text{--------------------(3)}$$

where subscripts 1 and 2 denote any two adjacent states.

In Figs.8(a), (b) and (c), the variation of the compression index with cell pressure is demonstrated. In the figure, λ is plotted vs. mean cell pressure $\bar{\sigma}_c = (\sigma_{c1}+\sigma_{c2})/2$. Compression index is a function of cell pressure and the functions are dependent on loading conditions. For any loading condition, λ increases with the increase of $\bar{\sigma}_c$.

The dependences of the compression index on cell pressure and loading conditions are influenced by relative density. The variation of the

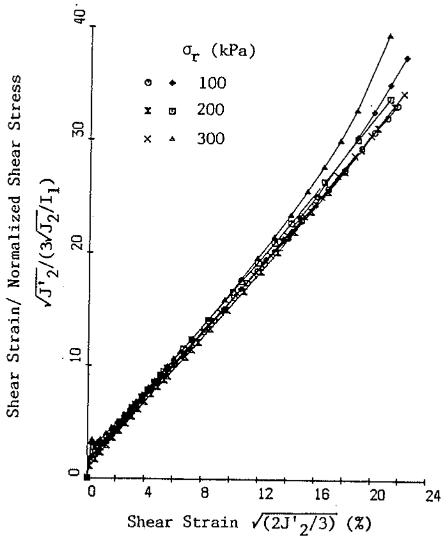

Fig.9: The ratio of shear strain to normalized shear stress vs. shear strain; for the loose sample.

compressibility with cell pressure is very large, for any relative density, in loading and reloading processes while it is slight in unloading.

In the formulation of stress-strain relationships for soils including sands, elasto-plasticity are frequently assumed in previous studies and successful results have been obtained. However, for the modeling of soil behavior, the dependence of the compressibility on confining stress or, in a wider sense, on mean effective stress, has been neglected for simplicity.

Taking into account the non-linearity of compression index as shown above will be important subject as more sophisticated simulation will be required in future.

4.3 Normalized shear modulus

In the elasto-plasticity assumption, we have to evaluate hardening or softening rules; the rules relate hardening or softening parameters to plastic variables that describes the plastic state. One of hardening parameters that have been adopted by many researchers is normalized shear stress, for example, $\sqrt{J_2}/I_1$ and one of plastic variables is plastic shear strain such as $\sqrt{J'_2}$, where I_1 is the first invariant of effective stresses and J_2 and J'_2 are the second invariants of deviatoric components of stress and strain tensors, respectively.

In Fig.9, the ratio of shear strain to normalized shear stress,

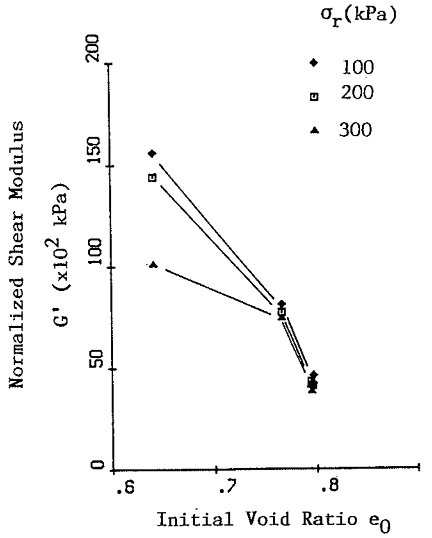

Fig10: Relationships between normalized shear modulus and initial void ratio.

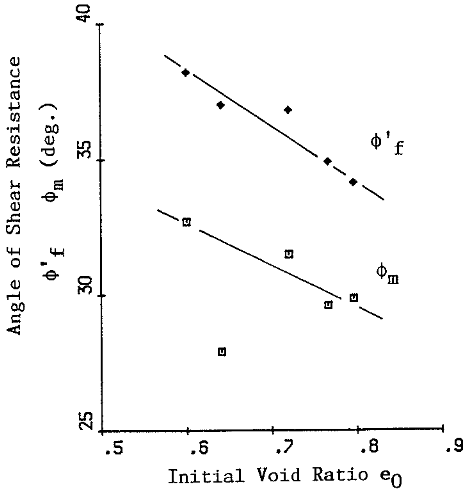

Fig.11: Angles of shear resistance vs. initial void ratio.

$\sqrt{J'_2}/(\sqrt{J_2}/I_1)$, is plotted against shear strain $\sqrt{J'_2}$. The results are for the case of D_R=30%. We can see a linear relationship being almost independent of the values of confining stress.

The linearity confirms the following hyperbolic type of equation:

$$\frac{\sqrt{J_2}}{I_1} = \frac{\sqrt{J'_2}}{(1/G')+(1/M)\sqrt{J'_2}} \tag{4}$$

where G' and M are constants. (1/G') is the ordinate of the intersect of the straight line and vertical axis in Fig.9. We call here G' the normalized shear modulus.

The dependence of G' on relative density of samples is shown in Fig.10. Initial void ratio e_0 is used instead of the relative density. When e_0 is low, G' may be lightly dependent on the magnitude of confining stress but, with higher values of e_0, G' is not dependent on confining stress.

4.4 Angle of shearing resistance at failure

Angle of shearing resistance ϕ' is one of the most important parameters for soils. In Fig.11, the effect of e_0 on ϕ' is examined. The phenomenon that

ϕ' decreases with increasing e_0 is not a new observation but some relationships between ϕ' and e_0 are obtained for various sands (for example, see Rowe[6]). The relation shown here is one for the Tottori Dune sand and it will be used for the evaluation of ϕ' for this sand.

4.5 Angle of shear resistance at maximum contraction due to dilatancy

Sands tend to contract or expand due to dilatancy when subjected to shear stress; in the low level of shear stress volume contraction occurs and in the relatively high level of shear stress volume expansion occurs. The state of stresses at which the dilatancy changes from contraction to expansion have to be defined by a parameter for the formulation of stress-strain relationship.

It is known, and it was also observed in this study, that the envelope of Mohr's circles of stress can be linear when the volume contraction is maximum. The slope of the envelope can give a parameter, the angle of shearing resistance at maximum contraction due to dilatancy, denoted by ϕ_m.

In Fig.11, ϕ_m is plotted against e_0. We see that ϕ_m tends to decrease with increasing void ratio and that the rate of variation is less than that for ϕ'. Thereby the difference between ϕ' and ϕ_m is decreasing with the increase in e_0. The minimum of relative density of specimens tested in this study was 30%; if more loose samples could have been prepared, the difference between ϕ' and ϕ_m would be less for higher initial void ratio. This is in accordance with the observation that samples with higher void ratio tend to continue to contract even near failure. The representative behavior of such loose samples will result in the liquefaction.

5. Conclusions

Triaxial drained compression tests were carried out on the Tottori Dune sand. The hysteretic nature of membrane penetration and non-linear behavior in e-log σ_m relations were shown. Angles of shearing resistance at failure and at maximum contraction due to dilatancy, and normalized shear modulus were also treated. The effects of initial void ratio on the behavior and parameters were discussed. Main conclusions are as follows:

1) The magnitude of membrane penetration can not be related uniquely to cell pressure but it is influenced by the loading conditions such as loading, unloading and reloading. The parameter K in Eq.(1) takes different values in the first loading and in other loading conditions.

2) Compression index defined as Eq.(2) or (3) varies with cell pressure. Cell pressure dependence is the largest for loose sample and the

least for dense sample.

3) The assumption of the hyperbolic type of equation for normalized shear stress and shear strain relations, Eq.(4), can be adopted in the examined range of confining stress for the sample. The normalized shear modulus decreases with the increase in initial void ratio.

4) Angles of shearing resistance at failue and at maximum contarction due to dilatancy vary with initial void ratio. Both angles decrease with increasing initial void ratio.

Acknowledgments

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