Mechanical properties of sand with strain history by ocean wave loading
Propriétés mécaniques de l'histoire des déformations d'un sable par le chargement des ondes océaniques

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SYNOPSIS The effect of strain history due to shear stress variation over long term by ocean wave loads on the mechanical properties of sand is examined by using specimens with and without shear strain history prepared artificially. Three kinds of tests were carried out by triaxial testing apparatus, i.e., undrained monotonic compression and extension test, dynamic deformation tests on shear modulus and undrained cyclic triaxial tests on liquefaction. The results show that the effect of shear strain history is represented by the decrease of degradation rate of effective stress during both monotonic and cyclic loading, and the increase of shear modulus and liquefaction strength. Further, the relation between shear modulus and liquefaction strength is discussed from the viewpoint of establishing a brief evaluation method of mechanical properties in the seabed ground.

INTRODUCTION

Soil grounds generally have a strain history due to earthquake motion, ocean waves and vibration by pile driving, traffic load and so on. Investigations on the influence of such strain history to strength-deformation properties, in particular liquefaction strength, were conducted by Finn et al. (1970) and Seed et al. (1975). While these researches are related to the asseismic history wherein the duration of shaking is comparatively short, it is important to examine the effect of strain history over long term by ocean wave-induced stress, when the problems of stability of seabed ground is discussed. Though it is well known that the strength of soils with strain history increases in comparison with that of soils without such a history, it may be difficult to confirm those for natural seabed deposits because of the difficulty of undisturbed sampling, in particular for sandy ground. This paper describes some mechanical properties of sand specimens with and without shear strain history, which are made artificially in the laboratory, from monotonic and cyclic undrained triaxial tests, and the relation between liquefaction strength and shear modulus at very small strain to establish brief evaluation methods of in-situ strength and deformation properties.

TESTING METHOD

With the cyclic triaxial testing machine used in the experiments, it is possible to measure with high accuracy stress and displacement of specimens from very small strain to large strain near failure, because a high sensitivity load cell and non-contact type displacement sensor are installed in the triaxial cell. The material used was Toyoura sand. Its physical properties are average particle size D_{50}=0.15mm, specific gravity G_s=2.65, maximum and minimum void ratio e_{max}=0.933, e_{min}=0.629, and the coefficient of uniformity U_c=1.39. Specimens 5cm in diameter and 10cm in height were made by air pluviation method and fully saturated by de-aerated water. After consolidation at the prescribed effective confining pressure σ_c'(=50~200kPa), three kinds of specimen were prepared; namely, a specimen with no shear strain history (PA), and specimens given shear strain history by drained cyclic loading with the number of cycles 10^4 (SH10^4) and 10^5(SH10^5) at the amplitude of shear strain of $\gamma=5\sim7\times10^{-4}$. Tests conducted were undrained triaxial compression and extension tests at the strain rate of 0.26%/min. and undrained cyclic triaxial tests at the frequency of 0.5Hz.

The magnitude of the amplitude of shear strain history was determined as follows. The stress ratio τ/σ_c' by the wave force at a depth z measured from the surface of the seabed is given by the following equation (Seed et al. (1978)).

$$\frac{\tau}{\sigma_c'} = \frac{\pi \cdot \rho_w \cdot H}{\rho' \cdot \cosh(\frac{2\pi h}{L}) \cdot L} e^{-2\pi\frac{z}{L}} \qquad (1)$$

where τ, σ_c', ρ_w, ρ', H, L and h are the maximum shear stress, effective confining pressure, density of water, density of soil, the height of wave, the wave length and the depth of water, respectively. Now, when we assume H (=Hmax × 1/3:Hmax is the maximum height during 100-yr storm in the North Sea) and L as 10.6m and 120m, respectively, based on the data by Wiegel (1964) and Lee et al. (1975) in the case of h=20m and shear wave velocity Vs in the seabed ground is assumed 100m/s to 130m/s, corresponding to that of loose deposited sand layer, the shear strain calculated from the shear modulus and τ in eq.(1) is given as 4 to 7×10^{-4} at depth of z=0m to 20m.

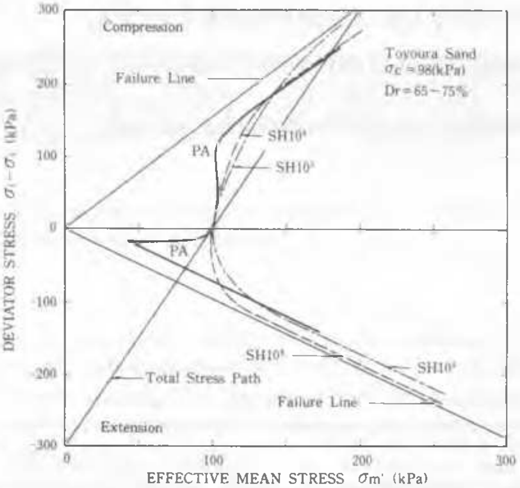


Fig. 1 Effective stress paths for undrained monotonic loadings

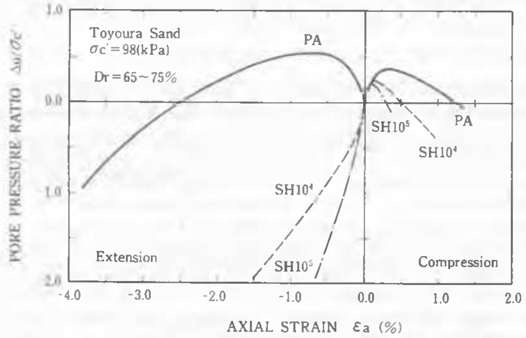
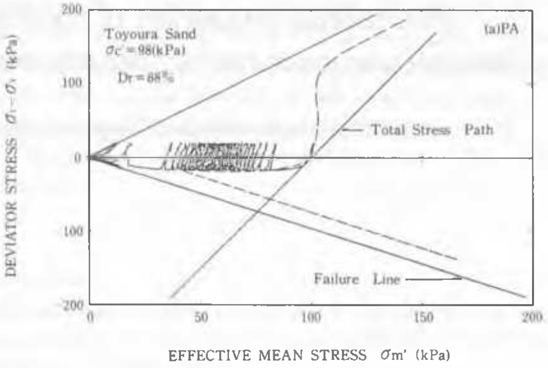
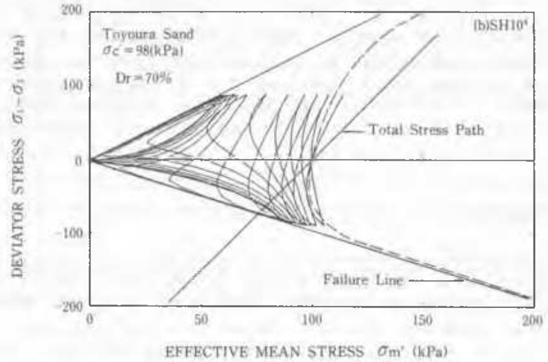


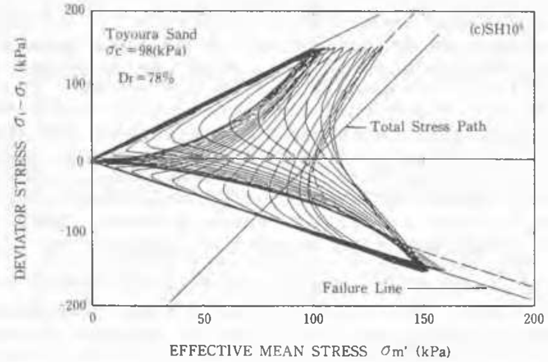
Fig. 2 Relation between pore pressure ratio and axial strain for undrained monotonic loadings



(a) Specimen without strain history (PA)



(b) Specimen with strain history (SH10^4)



(c) Specimen with strain history (SH10^5)

Fig. 3 Effective stress paths for undrained cyclic loadings

TEST RESULTS

Excess pore water pressure under monotonic and cyclic loadings

Fig. 1 shows the effective stress paths obtained by triaxial compression and extension tests at σ_c'=100kPa for three kinds of specimen. It is clearly shown in the figure that the extent of variation of effective mean stress σ_m' during shear is remarkably affected by the existence of shear strain history; in particular notable for extension stress. Fig. 2 which shows the relation between $\Delta u/\sigma_c'$ and axial strain ε_a is prepared to confirm these tendencies on the build-up of excess pore water pressure Δu. It can be seen from this figure that both the peak value of $\Delta u/\sigma_c'$ and the axial strain at the maximum positive excess pore water pressure decrease with the increase of the number of cycles for compression. In the case of extension, the tendency to generate Δu is noticeably influenced by the shear strain history. The excess pore water pressure of 50% of the initial effective mean stress is generated in samples without shear strain history followed by negative Δu beyond 2.5% of the axial strain. Conversely, the excess pore water pressure always demonstrates a negative value for specimens with shear strain history. Fig. 3 (a), (b) and (c) show the effective stress paths during undrained cyclic shear tests with results of undrained monotonic shear tests shown by broken line, for specimen of PA, SH10^4 and SH10^5, respectively. It is pointed out from these figures that in the case of PA specimen, as effective mean stress drastically decreases in consequence of the generation of excess pore water pressure at

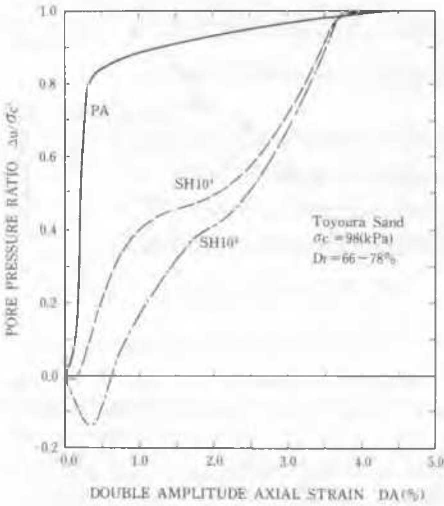


Fig. 4 Relation between pore pressure ratio and double amplitude of axial strain for undrained cyclic loadings

extension, liquefaction produces under smaller amplitude of shear stress in comparison with the case of SH10^4 and SH10^5 specimens, although the relative density Dr of each specimen is almost constant. Fig. 4 gives the relations between pore pressure ratio $\Delta u/\sigma_c'$, where Δu means the accumulated excess pore water pressure at $\sigma_1-\sigma_3=0$, and double amplitude of axial strain DA based on the test results by undrained cyclic loading. While $\Delta u/\sigma_c'$ is about 0.9 when DA nearly equals 1%, and after that DA drastically increases in the PA specimen, the rate of increase of $\Delta u/\sigma_c'$ to the increase of DA is smaller in the SH10^4 and SH10^5 specimens than that of the PA specimen. Namely, specimens with shear strain history demonstrate gradual increase of DA because of cyclic mobility even if $\Delta u/\sigma_c'$ certainly increases to 1.0 under larger amplitude of shear stress.

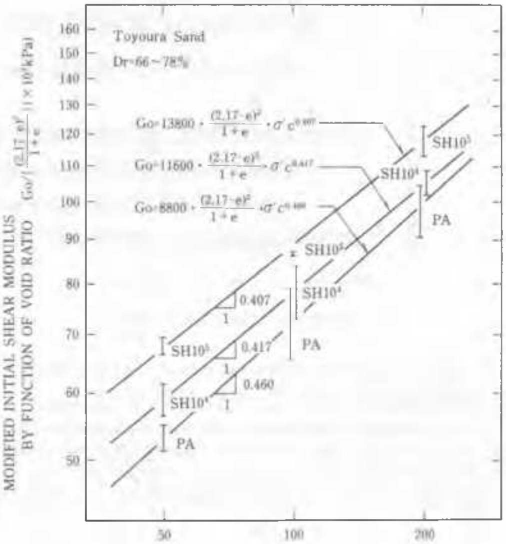


Fig. 5 Relation between shear modulus at very small strain and effective confining pressure

Shear modulus at very small strain

Fig. 5 demonstrates the relations between shear modulus G_0 at very small strain level, normalized by a function of void ratio e proposed by Richart et al. (1970), and effective confining pressure σ_c'. It can be seen that the relations of G_0 versus σ_c' for specimens with the same shear strain history are approximately represented by straight lines on log-log scaled diagram, and these relations are formulated by the equation presented by Richart et al. (1970), that is, by $G_0=A\cdot F(e)\cdot\sigma_c'^{\,n}$ where A and n are material constants. Also, it is pointed out that constant A certainly increases and n slightly decreases with the increase of the number of cycles of the pre-shear strain

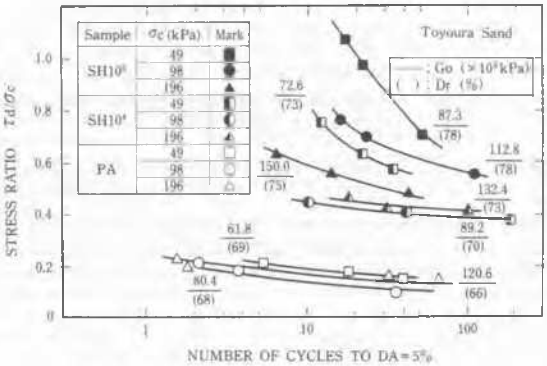


Fig. 6 Relation between stress ratio and number of cycles

Relations between liquefaction strength and maximum shear modulus

Fig. 6 shows the relations between cyclic shear stress ratio and the number of cycles required to cause 5% double amplitude shear strain for three kinds of samples. It can be seen that cyclic shear stress ratio increases remarkably when a pre-shear strain history is given to a sample, although its relative density is held more or less constant. Moreover, the cyclic shear stress ratio τ_d/σ_c' depends on the confining pressure σ_c' in the SH10^4 and SH10^5 specimens, while τ_d/σ_c' of PA specimen is almost independent of σ_c' in the range of 50 to 200 kPa. The relations between σ_c' and τ_d/σ_c' at $N_\ell=20$ cycles are shown in Fig. 7. It is shown in this figure that τ/σ_c' increases more due to shear strain history when σ_c' is low than when σ_c' is high. Comparing qualitatively the influence of shear strain history on liquefaction strength, the ratio of τ_d/σ_c' at $N_\ell=20$ of SH10^5 specimen to that of PA specimen is about three to four for σ_c'=200kPa and about seven for 50kPa. Such dependency of liquefaction strength on the confining pressure has been pointed out for undisturbed dense sand by Yoshimi et al. (1984).

The correlation between shear modulus G_0 at very small strain level and liquefaction strength was experimentaly investigated by Tokimatsu et al.

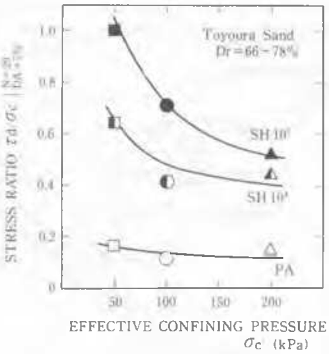


Fig. 7 Relation between stress ratio and effective confining pressure

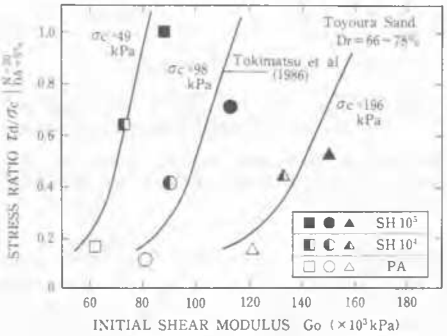


Fig. 8 Relation between stress ratio and shear modulus at very small strain

(1986). Fig. 8 shows the relations between τ_d/σ_c' at $N_\ell=20$ and G_0 at $\gamma=10^{-5}$ measured prior to the liquefaction test for three kinds of sample. It is pointed our from this figure that 1) cyclic shear stress ratio of samples having the same shear strain history decreases with the increase of confining pressure in spite of the increase of G_0, and 2) while the relations between τ_d/σ_c' at $N_\ell=20$ and G_0 are not unique for the confining pressure ranging from 50 to 200kPa, comparatively good correlations seems to exist when σ_c' is held constant, as shown by the solid line in the figure. Also, it is known that the rate of the increase of τ_d/σ_c' at $N_\ell=20$ to the increase of G_0 becomes smaller with the increase of σ_c'. Fig. 9 shows the relation between τ_d/σ_c' at $N_\ell=20$ and G_0 normalized by the square root of σ_c' based on the relations shown in Fig. 5. It can be clearly seen that liquefaction strength is approximately evaluated by the normalized shear modules $G_0/\sqrt{\sigma_c'}$ regardless of the degree of pre-shear strain history and the amount of confining pressure.

CONCLUSIONS

(1) Influence of the shear strain history on the magnitude of excess pore water pressure is significant. This is particularly true during extension.

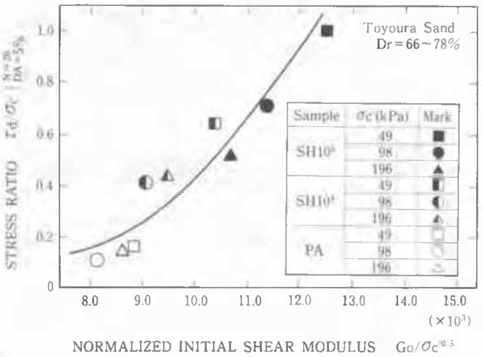


Fig. 9 Relation between stress ratio and normalized initial shear modulus

(2) Maximum shear modulus G_0 is definitely increased by the shear strain history, and the relation among G_0, void ratio e and effective confining pressure σ_c' is expressed by $G_0=A \cdot F(e)\ \sigma_c'^{n}$ as proposed by Richart et al. (1970), where A is the material constant depending on the extent of shear strain history.

(3) Liquefaction strength is remarkably increased by giving shear strain history, and the relation between cyclic shear stress ratio τ_d/σ_c' at $N_\ell=20$ and G_0 normalized by $\sqrt{\sigma_c'}$ is uniquely given.

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