研 究 速 報
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Anisotropic Deformation and Strength Properties of Wet-Tamped Sand in Plane Strain Compression at Low Pressures (Part II)
——Deformation Characteristics at Extremely Small Strain Level——
低拘束圧下での突き固めた不飽和砂の変形強度特性の異方性 (II)
——微小ひずみレベルでの変形特性の異方性——

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1. INTRODUCTION

The response analyses of soil structures subjected to monotonic and cyclic loadings demand a proper evaluation of the soil stiffness. However, unlike the anisotropy of strength, that of the stiffness at small strain levels is almost unknown. In the present study, the stiffness of wet-tamped loose Onahama sand was investigated for a wide strain range from 10^{-6} to 10^{-2}. From the test results, a degree of anisotropy of the stiffness was found.

2. SMALL STRAIN MEASUREMENT

A pair of four-gauge type "local deformation transducer" (LDT) shown in Fig. 1 was used to measure local axial deformation of plane strain specimen. The overall resolution of the LDT is $\pm 0.6\mu$m or ± 0.06 μm depending on the different degrees of amplification of the strain amplifier, which equaled axial strains of 7×10^{-6} and 7×10^{-7}, respectively. A more detailed description of this instrument is given elsewhere[1-4].

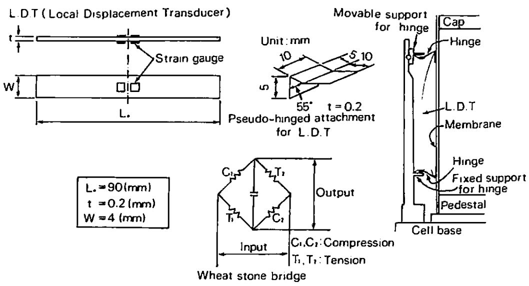

Fig. 1 Local deformtion transducer (LDT) used in this study

3. TEST RESULTS

3.1 Stress-Strain Relations at Small Strains

Figs. 2 and 3 show the typical relationships between the deviator stress q and the axial strain ε_1 for different angles δ at local axial strains less than 5×10^{-5} (0.005%) at $\sigma_3=0.2$ and 0.4kgf/cm², respectively (see also Figs.4 (b) and (c) of Dong et al.[5]). It may be seen that the initial relations are virtually linear at axial strains less than about 1×10^{-5}, irrespective of the different angles δ. In this study, the slope in this region is defined as the initial Young's modulus, E_{max}. Fig. 3 (b) shows the result of a test in which a small cycle of unloading and reloading with a double amplitude axial strain of about 0.003% was applied. It may be seen that the behavior during the cyclic loading is rather elastic and further, the peak-to-peak stiffness E'_{max} for the cycle is very similar to the initial stiffness E_{max} defined for the very beginning of virgin loading. This means that E_{max} as shown in Figs. 2 and 3 can be considered as the elastic moduli as obtained from dynamic tests.

Despite some degree of scatter in water content and void ratio among the specimens shown in Figs. 2 and 3, it may be seen that E_{max} is clearly a function of angle δ. Fig. 4 shows the stress-strain relations at axial strains less than 10^{-3} (0.1%) for those shown in Fig. 2. It may be seen that the stress-strain curves for axial strains greater than 0.01~0.02% are also a function of δ as E_{max}. As has already been shown in the previous papers[5),6)], for both wet-tamped Onahama sand and air-pluviated silver Leighton Buzzard

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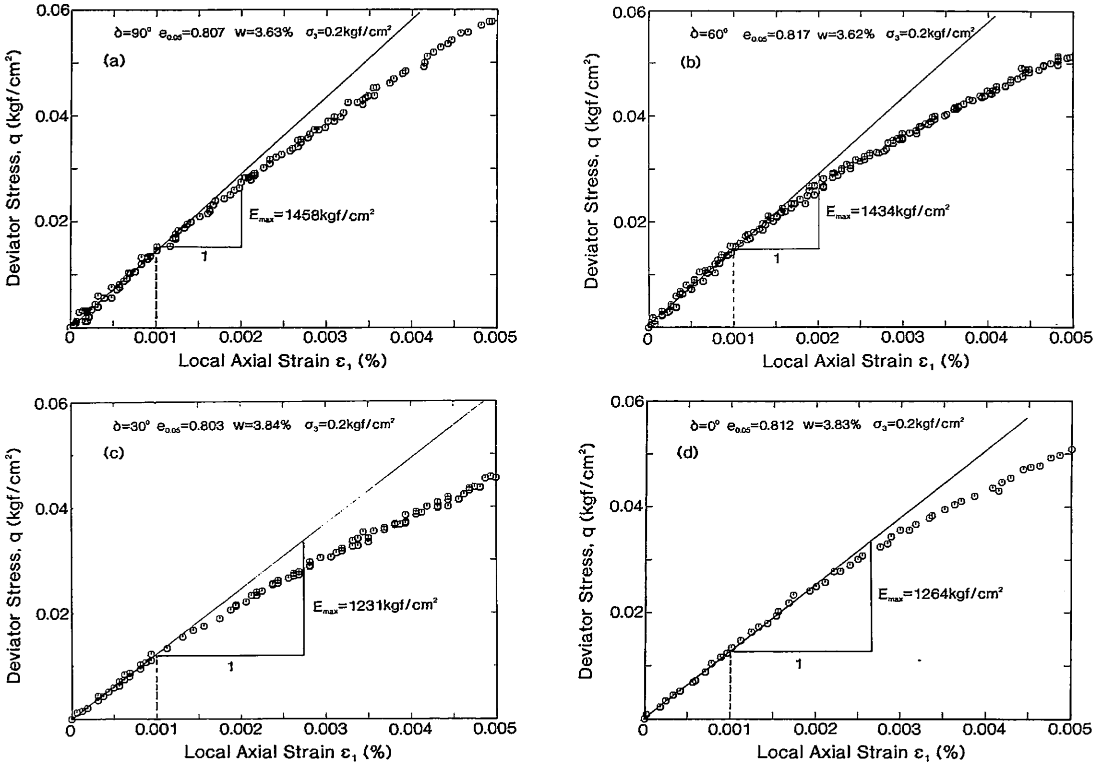


Fig. 2 Typical relationships between q and ε_1 for different δ at local axial strains less than 5×10^{-5} at $\sigma_3=0.2$kgf/cm²

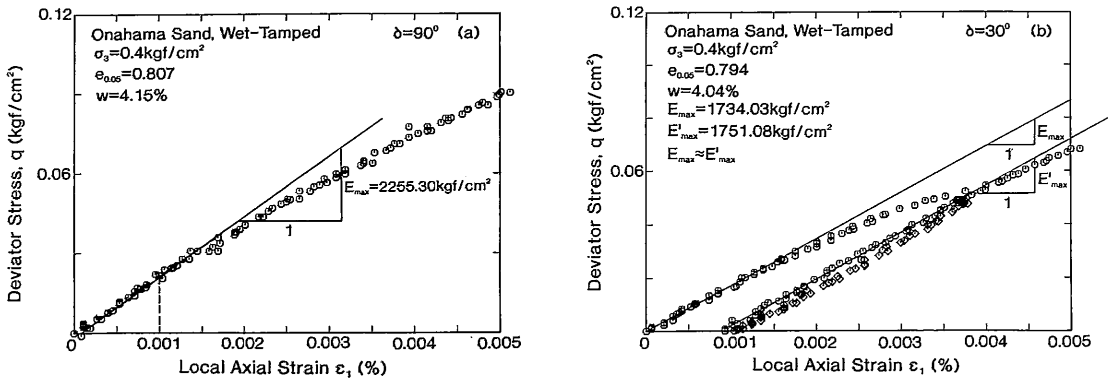


Fig. 3 Typical relationships between q and ε_1 for different δ at local axial strains less than 5×10^{-5} at $\sigma_3=0.4$kgf/cm²

sand, the peak strength from similar PSC tests was considerably anisotropic. However, the initial stiffness E_{max} of air-pluviated silver Leighton Buzzard sand was found rather isotropic for $\delta=0\sim90$ degrees[6]. It seems therefore that the degree of the anisotropy of the initial stiffness depends on the method of specimen preparation or the type of sand or both.

On the other hand, Stokoe et al[7]. has shown that the initial shear modulus of air-pluviated sand measured by a seismic method in a large cubic specimen was found not isotropic. Namely, the shear modulus G_{VH} obtained by applying dynamic shear stresses $\Delta\tau_{max}$ in the vertical direction on vertical planes and in the horizontal direction on horizontal planes was about 20% smaller than G_{HH} obtained by applying $\Delta\tau_{max}$ in the orthogonal horizontal directions on vertical planes. The shear modulus at $\delta=45$ degrees obtained in the present study corresponds to the smaller one, G_{VH}. A further study will be needed to obtain a general framework for this point.

3.2 Empirical Equations of Initial Stiffness

Before clarifying the effect of δ on E_{max}, the dependency of E_{max} on void ratio $e_{00.5}$, confining pressure σ_3 and water content w was first examined. Based on the previous study[8], it was assumed that the effect of $e_{0.05}$ and σ_3 on E_{max} at $\delta=90°$ can be evaluated using the followig equation;

$$E_{max}(\delta=90°)=A\left\{\frac{(2.17-e_{0.05})^2}{1+e_{0.05}}\cdot\sigma_3{}^m+a_1w+a_2w^2\right\} \quad (1)$$

where E_{max} and σ_3 are in kgf/cm², w is in percent.

The term for the effect of w in Eq. 1 is in the same form with that for the cohesion intercept c (see Eq. 4 of Dong et al.[5]). The coefficients A, m, a_1 and a_2 were determined by using the nonlinear least square method as used for determining the empirical equations for the strength[5] by using twenty three sets of measured data. These values thus determined are $A=3462.71$, $m=0.69$, $a_1=4.33\times10^{-3}$ (kgf/cm²) and $a_2=5.30\times10^{-3}$ (kgf/cm²).

Then, the effect of δ on E_{max} was assumed to be expressed by the following uncoupled equation:

$$E_{max}(\delta)=E_{max}(\delta=90°)\times g(\delta) \quad (2)$$

For each data at $\delta\neq90°$, the value of g (δ) was obtained by dividing the measure value of E_{max} (δ) by the value of E_{max} ($\delta=90°$) obtained by substituting the measured values of $e_{0.05}$, σ_3 and w into Eq. (1). Fig. 5 shows the relationship between g (δ) and δ. The averaged curve was obtained by the least square method under the following conditions:

(a) Two different cubic relations are fitted, separated at $\delta=30°$.

(b) The slope at $\delta=0°$ and 90° is zero.

These conditions are similar to those used for the function f(δ) which defines the strength anisotropy (see Fig. 5 of Dong et al.[5]). The averaged relation thus obtained is;

$$g(\delta)=1.0-7.51\times10^{-5}(\delta-90°)^2-3.93\times10^{-7}(\delta-90°)^3 \quad (30°\leqq\delta\leqq90°) \quad (3)$$

$$g(\delta)=0.875+6.36\times10^{-5}\delta^2-4.33\times10^{-6}\delta^3 \quad (0°\leqq\delta\leqq30°)$$

The function g(δ) greatly depends on δ, despite some degree of scatter in the data points. g(δ) has a minimum point at $\delta\fallingdotseq30°$

Figs. 6(a) and (b) show the correlation between the measured values of E_{max} and the ones obtained by using Eqs. (1) and (2) for $\delta=90°$ and $\delta=0°\sim90°$ respectively. It may be seen that Eqs. (1) and (2) fit the measured data very well.

The general tendency of g(δ) was found very similar to f(δ). It means that the other parameters being the same, the ratio E_{max}/q_{max} is rather independent of $e_{0.05}$ and δ. This point may be seen from Fig. 7. Namely for a constant σ_3,this ratio is rather independent of $e_{0.05}$ and δ and w, but it is a distinct function of σ_3. From the structures of f(δ) and g(δ) determined, the ratio E_{max}/q_{max} is a complicated function of σ_3. As seen from Fig. 7, for the first approximation, the ratio E_{max}/q_{max} is of the order of 1200 to

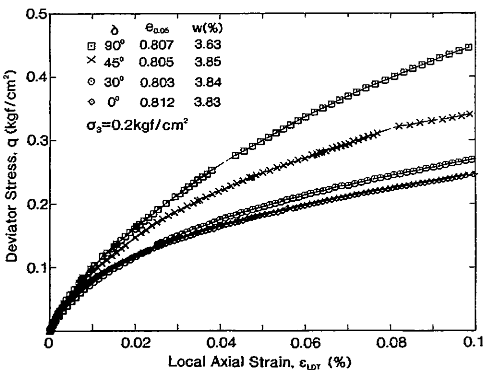


Fig. 4 Relationships between q and ε_1 for different δ at local axial strains less than 0.1% at $\sigma_3=$ 0.2kgf/cm² (see Fig. 2)

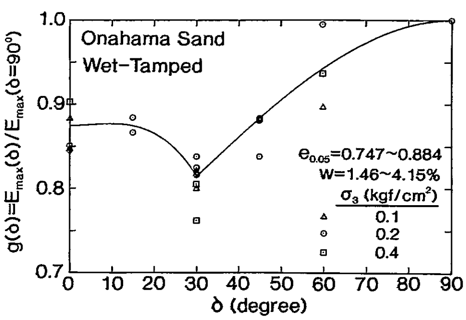
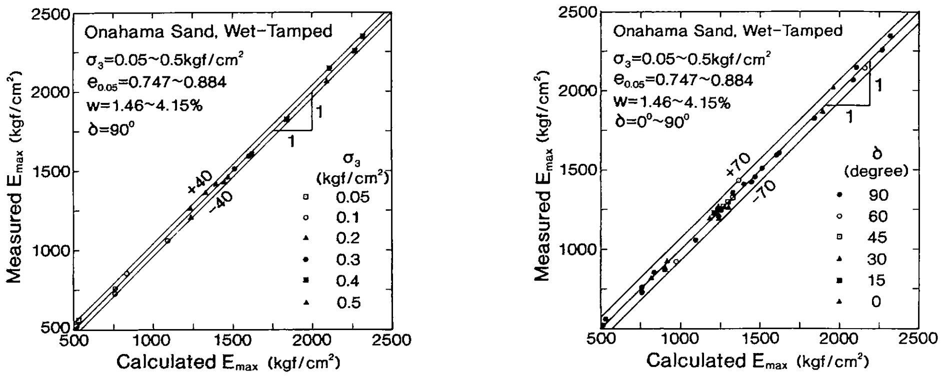


Fig. 5 Relationship between g (δ) and δ



(a) at $\delta=90°$ for different σ_3, and (b) for different δ

Fig. 6 Correlation between the measured and calculated values of E_{max}:

2000、 or for a better approximation, E_{max} is proportional to $q_{max}{}^{0.65}$

4. CONCLUSIONS

Based on the experimental results, the following conclusions can be drawn.

(a) For wet-tamped loose Onahama sand, the initial stiffness E_{max} defined for a range of axial strain less than 10^{-5} was anisotropic.

(b) The anisotropy of E_{max} and the peak principal stress ratio R_{max} was similar. The ratio E_{max}/q_{max} was rather independent of the void ratio and water content and was slightly a function of σ_3.

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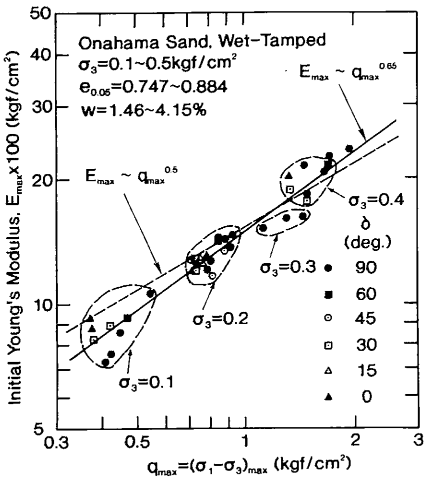

Fig. 7 Relationship between E_{max} and q_{max}

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