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 III)
## ——Shear Deformation Characteristics——
## 低拘束圧下での突き固めた不飽和砂の変形・強度の異方性 (III)
## ——せん断変形特性——

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### 1. INTRODUCTION

In the framework of a long-term research project on the deformation and strength characteristics of soils and rocks for a wide range of strain from $10^{-6}$ to $10^{0}$, a series of plane strain compression (PSC) tests on loose wet-tamped Onahama sand with local measurements of extremely small axial and lateral strains was performed by Dong et al[1),2)]. Since the value f $\sigma_2$ varies with the increase in $\sigma_1$ in PSC tests performed at a constant confining pressure, $\sigma_3$, the values of Young's modulus E can not be readily obtained from the relationship between the deviator stress $q=\sigma_1-\sigma_3$ and the axial strain $\varepsilon_1$. For such PSC tests, when the material properties are isotropic with a Poisson's ratio $\nu$, the value of $E_{PSC}=q/\varepsilon_1$, as reported by Dong et al[2)]. is linked to E as $E_{PSC}=E/(1-\nu^2)$. However, at small strain levels, since $\nu$ is around 0.13 to 0.27 as will be reported in this paper, the value $E_{PSC}$ is very close to E. On the other hand, the shear modulus G in PSC is obtained directly from the relationship between the shear stress $\tau=(\sigma_1-\sigma_3)/2$ and the shear strain $\gamma=\varepsilon_1-\varepsilon_3$. Poisson's ratio $\nu$, however, can not be obtained directly as G, but, for isotropic material, $\nu$ is linked to the ratio of principal strains $\nu_{PSC}=-\varepsilon_3/\varepsilon_1$ as $\nu=\nu_{PSC}/(1+\nu_{PSC})$.

Herein reported are the shear deformation properties of loose Onahama sand, particularly anisotropy of shear modulus and Poisson's ratio. The experimental methods and the physical properties of sand tested have been reported elsewhere[1),2)]. The method to measure very small lateral strains was described by Shibuya et al[3)].

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### 2. RESULTS AND DISCUSSIONS

Fig. 1 shows the relationships between the shear stress $\tau=(\sigma_1-\sigma_3)/2$ and the shear strain $\gamma=\varepsilon_1-\varepsilon_3$ for similar values of density and water content at $\sigma_3=0.2$ and $0.4\ \mathrm{kgf/cm^2}$, but for different angles $\delta$ (the angle of the direction of the major principal stress relative to the bedding plane). A clear tendency of

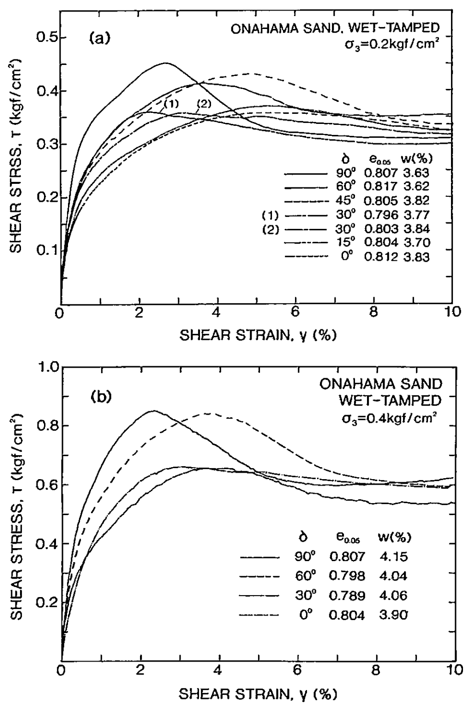


Fig. 1 Relationships between the shear stress $\tau=(\sigma_1-\sigma_3)/2$ and the shear strain $\gamma=\varepsilon_1-\varepsilon_3$ for the maximum shear strain of 10 %: (a) $\sigma_3=0.2$ and (b) $0.4\ \mathrm{kgf/cm^2}$.

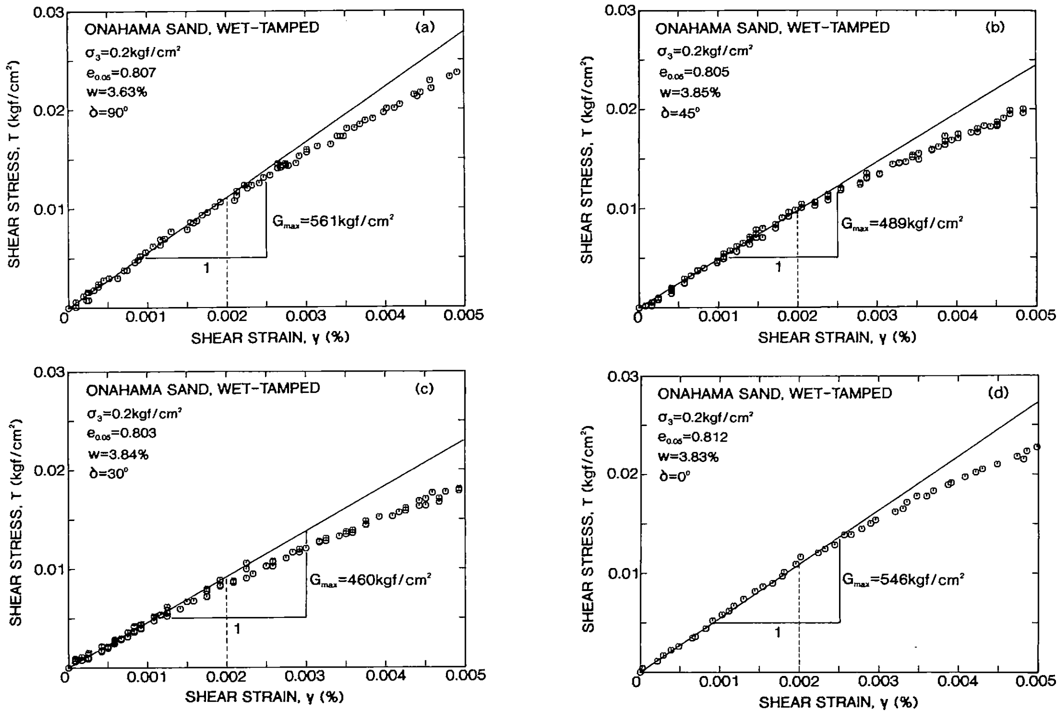


Fig. 2 Relationships between the shear stress $\tau=(\sigma_1-\sigma_3)/2$ and the shear strain $\gamma=\varepsilon_1-\varepsilon_3$ for the maximum shear strain of 0.005 %: for different angles $\delta$ at $\sigma_3=0.2$ kgf/cm².

anisotropy can be seen. Figs. 2(a) through (d) and Figs. 3(a) through (d) show some typical relations at extremely small shear strain levels less than 0.005 %. It can be seen that in each case, the initial part for a range of shear strains less than about 0.002 % is linear (also elastic as shown in Fig. 3b of Dong et al[2]). It may also be seen that the value of the initial shear modulus $G_{max}$ defined for the initial linear part is a function of the angle $\delta$. This suggests that both the deformation properties from very small to large strain levels and the peak strength are anisotropic, but only the residual strength is rather isotropic.

The value of $G_{max}$ for each test was divided by its corresponding value at $\delta=90$ degrees for the same density, water content and $\sigma_3$, which was estimated by using the following equation:

$$G_{max}(\delta=90^0)=A_G\ \{\frac{(2.17-e_{0.05})^2}{1+e_{0.05}}\cdot\sigma_3{}^m+a_1w+a_2w^2\} \quad (1)$$

Eq. (1) has the same form as that for $(E_{PSC})_{max}$ (i.e., Eq. (1) of Dong et al[2].). The values of the coefficients were obtained by means of a nonlinear least mean square method, which are $A_G=1292.86$, $m=0.69$, $a_1=4.33\times10^{-3}$ (kgf/cm²) and $a_2=5.30\times10^{-3}$ (kgf/cm²).

Fig. 4 shows the ratio $G_{max}(\delta)/G_{max}(\delta=90^0)$ plotted against the angle $\delta$. A clear tendency of anisotropy can be seen as in the case of the strength and the initial Young's modulus $(E_{PSC})_{max}$ (Fig. 5 of Dong et al[1),2)], respectively). Fig. 5 is another figure showing the strength anisotropy for this sand in terms of the ratio of $\phi_0(\delta)/\phi_0(\delta=90^0)$, where $\phi_0=\arcsin\{(\sigma_1-\sigma_3)/(\sigma_1+\sigma_3)\}_{max}$.

It may be noted, however, that the tendency of the anisotropy for $G_{max}$ is different from those for the strength and $(E_{PSC})_{max}$ in that $G_{max}$ has a more remarkable minimum value at $\delta$ around 30 degrees with $G_{max}$ at $\delta=0$ being very similar to that at $\delta=90$ degrees. This is because $G_{max}$ is defined as $(E_{PSC})_{max}/2(1+\nu_{PSC})$ and the Poisson's ratio $\nu_{PSC}=-\varepsilon_3/\varepsilon_1$ at small strain levels is relatively large and small at $\delta=30$ degrees and 0, respectively, as shown in Fig. 6. The values of $\nu_{PSC}$ shown in Fig. 6 were directly

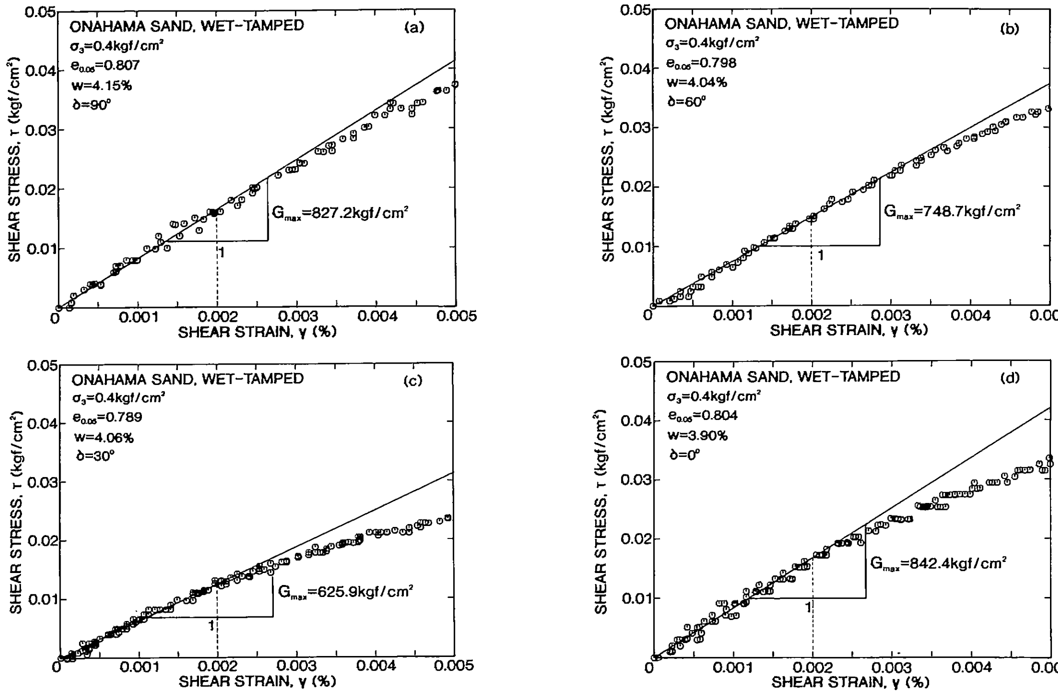


Fig. 3 Relationships between the shear stress $\tau=(\sigma_1-\sigma_3)$ / 2 and the shear strain $\gamma=\varepsilon_1-\varepsilon_3$ for the maximum shear strain of 0.005 %: for differet angles $\delta$ at $\sigma_3=0.4$ kgf/cm².

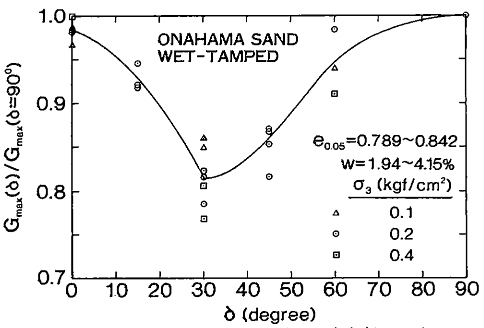


Fig. 4 Relationship between $G_{max}$ $(\delta)/G_{max}$ $(\delta=90°)$ and $\delta$

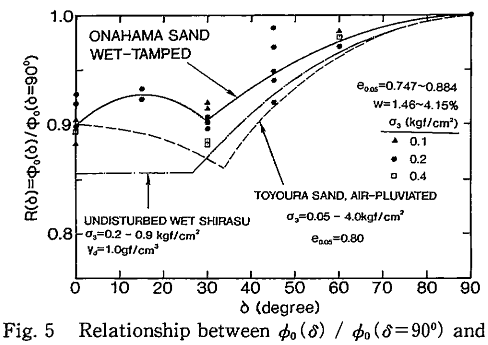


Fig. 5 Relationship between $\phi_0(\delta)$ / $\phi_0(\delta=90°)$ and $\delta$ : $\phi_0=\arcsin\{(\sigma_1-\sigma_3)$ / $(\sigma_1+\sigma_3)_{max}$ (The data for Toyoura sand and Shirasu from Tatsuoka et al., (1986) and (1990), respectively)

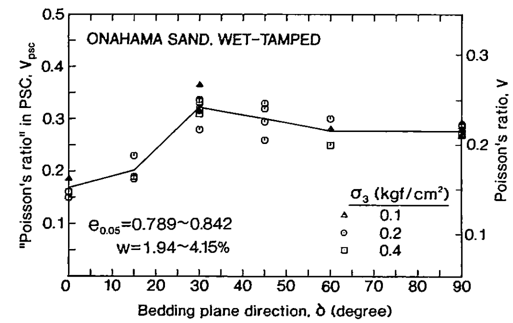


Fig. 6 Relationship between the Poisson ratio $\nu$ at small strain levels and the angle $\delta$

obtained from the linear relationships between $\varepsilon_1$ and $\varepsilon_3$ at very small strain levels as shown in Fig. 7 (thus may be somewhat different from $(E_{PSC})_{max}/2\cdot G_{max}-1)$. Note that the values of $\nu=\nu_{PSC}/(1+\nu_{PSC})$ are around 0.13 o 0.27, which are reasonable values as the elastic Poisson's ratios.

## 3. CONCLUSIONS

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

(a) The relationship between shear stress and

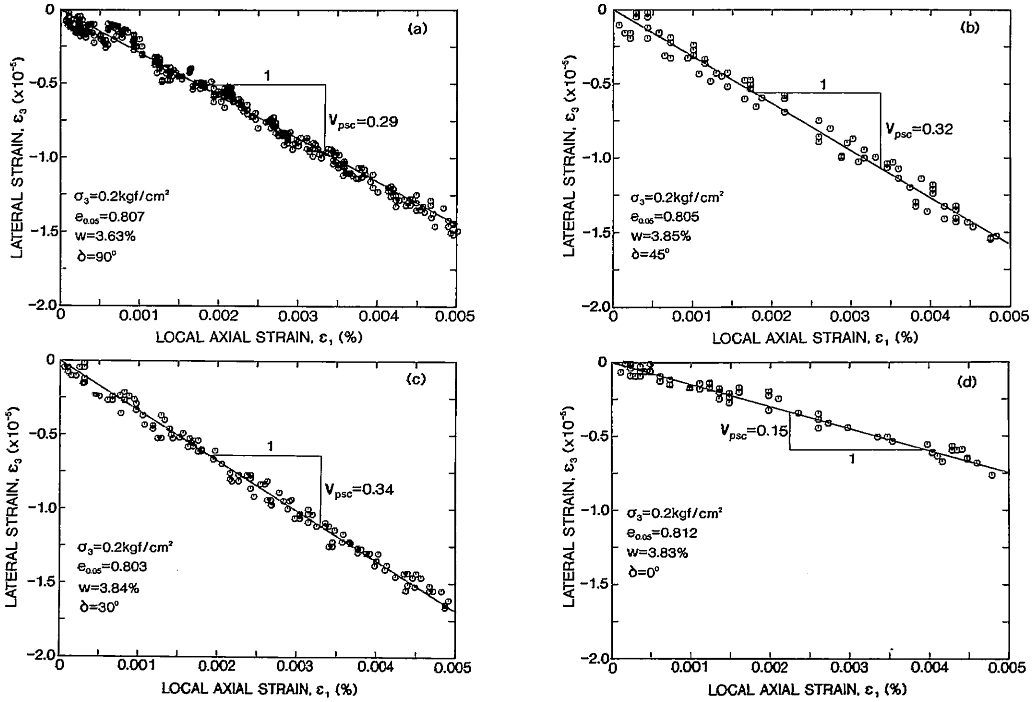


Fig. 7 Relationship between $\varepsilon_1$ and $\varepsilon_3$ for the maximum axial strains of 0.005 %: ( a ) $\delta=90$ degrees, ( b ) $\delta=$ 45 degrees, ( c ) $\delta=30$ degrees, and ( d ) $\delta=0$ degree ($\sigma_3=0.2$ kgf/cm$^2$)

shear strain was linear for a range of shear strain less than about 0.002%, for which the initial shear modulus $G_{max}$ could be defined confidently.

( b ) The value of $G_{max}$ was anisotropic. However, not as the peak strength and the initial Young's modulus $(E_{PSC})_{max}$, $G_{max}$ had a very clear minimum when the angle $\delta$ of the direction of the major principal stress relative to the bedding plane was about 30 degrees, with $G_{max}$ at $\delta=0$ being close to that at $\delta=90$ degrees. This was due to that the Poisson's ratio at very small strain levels was also anisotropic in a specific way.

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