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Anisotropic Deformation and Strength Properties of Wet-Tamped Sand in Plane Strain Compression at Low Pressures (Part I)
——Strength Anisotropy——
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(1)
——強度の異方性——

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1. INTRODUCTION

The failure mechanism of fill-type dams during earthquakes has been investigated by means of a series of shaking table tests on dam models[1] in the laboratory (Fig. 1). For the analysis of the results of the model tests, the strength and deformation characteristics of the model sand (i.e., wet-tamped Onahama sand) are needed. On the other hand, a series of experimental studies[2)~4)] have shown that for dry or saturated sand specimens prepared by using the method of pluviation through air or under water, the inherently anisotropic fabric has a significant influence on the deformation and strength properties and plays an important role in bearing capacity and slope stability problems. However, such a study as above has not yet been carried out for wet-tamped sand. Furthermore, the anisotropy in the stress-strain relations in the very small strain region is scarcely understood owing to poor measurements in the small strains.

A series of plane strain compression tests of wet-tamped Onahama sand was carried out to study the stress-strain and failure characteristics and its anisotropy for a wide strain range from 10^{-6} to that at the peak at low stress levels as in the dam models. Two improved methods of measuring small local axial strain and lateral deformation of specimen, LDT[5] and LDMS[6),7)], were used to obtain accurate stress-strain relations. In this paper, the strength characteristics are described.

2. OUTLINE OF THE EXPERIMENT

2.1 Testing material and Preparation of Specimens

The physical properties of Onahama sand are shown in Fig. 2. The dimensions of the rectangular specimen were 105mm high, 40mm wide in the σ_3 direction and 81mm long. With the bedding plane in parallel to the σ_2-direction, the angles δ of the σ_1-direction relative to the bedding plane employed were 0°, 15°, 30°, 45°, 60° and 90°. Since it was found very difficult to prepare a wet-tamped specimen at an arbitrary angle δ other than 0° and 90°, the following new technique was developed (Fig. 3): (a) First,

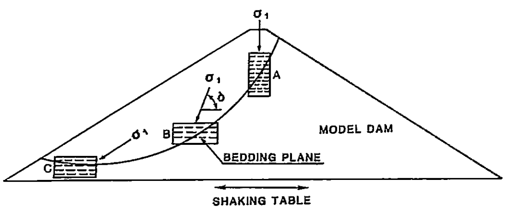

Fig. 1 Stress conditions in an earthfill or rockfill dam model at a moment during shaking

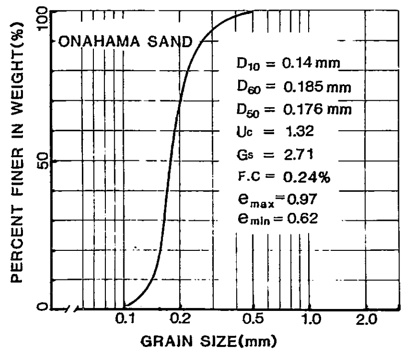

Fig. 2 Physical properties of Onahama sand

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the wet sand with a water content w of 2～4% was placed into a mold of duralumin set at a prescribed angle δ. The mold was larger than the final obtained specimen. An compacted thickness of each layer was 10mm except the last layer. By using a plunger which was 0.226kgf in weight having a base of 3.95cm×3.95cm, each layer was lightly compacted by tamping about 10～20 times with a travel length of 28.5cm. The compacted thickness was carefully controlled in order to obtain a homogeneous specimen. This procedure was repeated until the whole specimen was completed. Subsequently, the compacted specimen was put into a freezer at −20°C for 5 hours to avoid any disturbance that might occur during the subsequent specimen trimming process. (b) The mold together with the specimen was taken out from the freezer and was set gently at the angle δ. Then, the uppermost parts of the two pre-divided side platens B were removed from their remaining parts. Then, superfluous sand was scraped out and the surface was flattened by using a thin steel blade with utmost caution not to disturb the specimen. Then, a covering side plate was fixed to the mold covering the flattened surface of specimen. (c) Subsequently, the similar procedures were repeated. (d) Finally, a

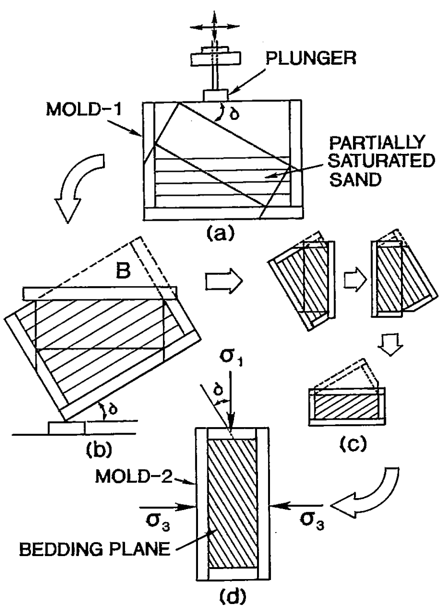


Fig. 3 Procedure to prepare wet-tamped specimens having angles δ other than 90° and 0°

specimen at the angle δ was obtained. The specimen together with the mold was again put into a freezer at −20°C in order to avoid any disturbance during the subsequent set-up of the specimen in the triaxial cell.

2.2 Palne Strain Comprssion Tests

The frozen specimen was set on the pedestal of the triaxial cell and was enclosed with a 0.2mm-thick latex membrane, the ends of which were then sealed onto the cap and pedestal. The specimen was thawed at a partial vacuum of 0.05kgf/cm^2 under the isotropic stress condition. Subsequently, the specimen dimensions were measured by which the initial void ratio $e_{0.05}$ was defined. In total, forty six PSC tests were performed at an axial strain rate of 0.05%/min. The water content was varied in a range between 2% and 4%. The minimum principal stress σ_3 was applied by a partial vacuum and was kept constant during shearing. Corrections of σ_1 and σ_3 against membrane forces were performed by using the method C-2-M[4], and more detailed descriptions of the apparatus and the testing methods are given elsewhere[4),6),7)].

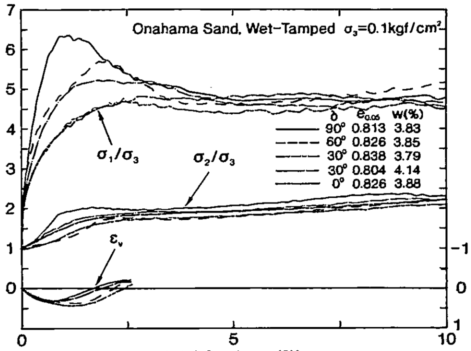
3. TEST RESULTS

3.1 Stress-Strain Relations

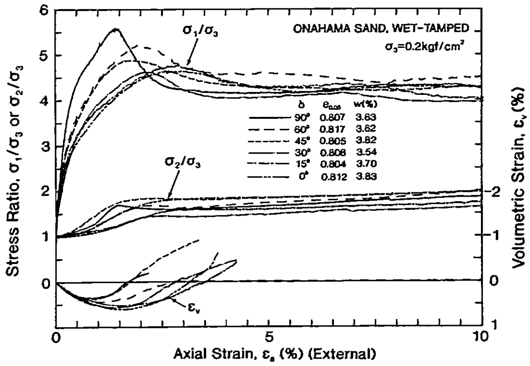
Figs. 4(a) and (b) show the typical relationships among the stress ration σ_1/σ_3 and σ_2/σ_3, the axial and volumetric strains ε_1 and ε_v for different angles δ under three different confining pressures. The value of ε_v was obtained from the measured values of ε_1 and ε_3 before the termination of the measurement of ε_3 at a certain value of ε_1 beyond the peak after which the change of ε_v was assumed zero. As may be seen from these figures, the deformation and strength characteristics of wet-tamped Onahama sand were considerably anisotropic. It may further be seen that at the residual conditions with ε_1=6～10%, the strengths were almost independent of δ. It is also noteworthy that despite that the specimens were loose, they exhibited a large degree of post-peak strain-softening at δ=90°, while this tendency decreased as δ decreased.

3.2 Empirical Equations for Strength

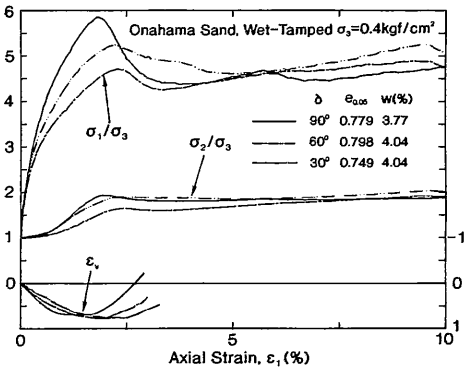
The stress ratio at failure, $R_{max}=(\sigma_1/\sigma_3)_{max}$, was examined for the tests performed. This is a function of several factors;



(a) σ_3=0.1kgf/cm²



(b) 0.2kgf/cm²



(c) 0.4kgf/cm²

Fig. 4 Typical strerss-strain relationships of wet-tamped Onahama sand for different δ

$$R_{max}=F(e_{0.05},\ w,\ \sigma_3,\ \delta) \qquad (1)$$

First, the function F was obtained for $\delta=90°$. From the Mohr-Coulomb failure criterion, we obtain the following the equation:

$$R_{max}(\delta=90°)=\frac{1+\sin\phi}{1-\sin\phi}+c\frac{2\cos\phi}{(1-\sin\phi)\sigma_3} \qquad (2)$$

Since it was inevitable to have some degree of scatter in the water content w and void ratio $e_{0.05}$ among the specimens, the function F in Eq. (1) was obtained by using the following assumptions:

(a) ϕ in Eq. (2) is independent of w, but is a function of $e_{0.05}$;

$$\frac{1+\sin\phi}{1-\sin\phi}=a_1+a_2e_{0.05} \qquad (3)$$

(b) The cohesion c is independent of $e_{0.05}$, but is a function of w, with c=0 at w=0, as;

$$c=a_3w+a_4w^2 \ \ (c:\ kgf/cm^2,\ w:\ \%) \qquad (4)$$

Substituting Eqs. (3) and (4) into Eq. (2), we obtain the following equation:

$$R_{max}(\delta=90°)=a_1+a_2e_{0.05}$$
$$+2(a_1+a_2e_{0.05})^{0.5}(a_3w+a_4w^2)/\sigma_3 \qquad (5)$$

The coefficients $a_1 \sim a_4$ in Eq. (5) were determined by means of a nonlinear least square method (a program named SALS in the library of the computer center, University of Tokyo) for twenty three data points at $\delta=90°$. The values of $a_1 \sim a_4$ obtained were; $a_1=15.73$, $a_2=-13.29$, $a_3=1.28\times10^{-2}$kgf/cm² and $a_4=-1.86\times10^{-3}$kgf/cm². For the change in w, the value of c has the peak at w=3.72%. This tendency is general for this type of specimen.

Next, it was further assumed that the effect of δ on R_{max} can be separated by the following uncoupled equation;

$$R_{max}(\delta)=R_{max}(\delta=90°)\times f(\delta) \qquad (6)$$

The value of $f(\delta)$ in Eq. (6) for each data at δ other than 90° was obtained by dividing the measured value of $R_{max}(\delta)$ by that obtained by substituting the measured values of $e_{0.05}$, w and σ_3 into Eq. 5, assuming that $f(\delta)$ is independent of $e_{0.05}$, w and σ_3. Fig. 5 shows the relationship between the value of $f(\delta)$ and the angle δ for the data points at $\delta\neq90°$. The averaged curve, which was obtained by the least square method under the following conditions:

(a) Quadratic and cubic relations are fitted for two regions of δ separated at $\delta=30°$

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

The function $f(\delta)$ obtained is;

$$f(\delta)=1.0-6.40\times10^{-6}(\delta-90°)^2+7.23\times10^{-7}(\delta-90°)^3 \quad (30°\leq\delta\leq90°) \qquad (7)$$

$$f(\delta)=0.819+5.43\times10^{-3}\delta-1.80\times10^{-4}\delta^2 \quad (0°\leq\delta\leq30°) \qquad (8)$$

Apparently, the function $f(\delta)$ is a distinct function

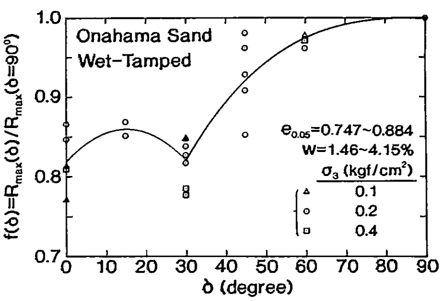
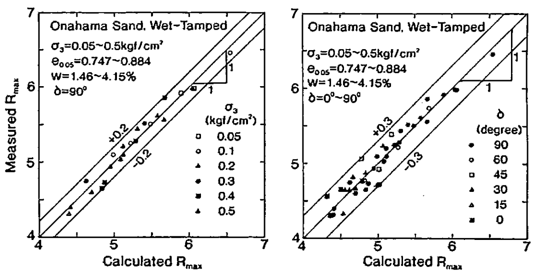


Fig. 5 Relationship between the $f(\delta) = R_{max}(\delta)/R_{max}(\delta=90°)$ and the bedding angle δ



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

Fig. 6 Correlation between measured and calculated values of R_{max};

of δ, despite some degree of scatter in the data points. It can also be seen that $f(\delta)$ has two minimum points at $\delta \fallingdotseq 30°$ and $\delta \fallingdotseq 0°$. It was found that the general tendency of the function $f(\delta)$ is similar to those for air-pluviated Toyoura sand and water-pluviated Shirasu. This result suggests that the strength anisotropy is rather independent of the three different specimen preparation methods.

Fig. 6 (a) and (b) show the correlation between the measured values of R_{max} and those calculated by using Eqs. (5) and (6) for $\delta=90°$ and $\delta=0°\sim90°$, respectively. It may be seen that Eqs. (5) and (6) fitted the measured data very well.

4. CONCLUSIONS

A series of PSC tests on wet-tamped loose specimens of Onahama sand was performed. Based on the experimental results, the following conclusions can be drawn.

(a) The degree of strength anisotropy was significant in specimens of Onahama sand, which would play an important role in the behaviour of the model tests using this type of sand.

(b) The tendency of strength anisotropy was similar in a broad sense with those for air-pluviated Toyoura sand and water-pluviated Shirasu specimens, despite the different specimen preparation methods employed.

(c) The post-peak strain softening was observed in the loose wet-tamped sand, particularly at $\delta=90°$, which may lead to progressive failure in model tests using this type of sand.

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