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Anisotropic Deformation and Strength Properties of Wet-Tamped Sand in Plane Strain Compression at Low Pressures (Part V)
——Modelling of Stress-Strain Relation——
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（V）
——応力ひずみ関係の定式化——

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INTRODUCTION

In the previous paper (Dong and Tatsuoka, 1991 b), it is shown that the original hyperbolic equation (OHE) and its modified versions using constant coefficients of correction (c_1 and c_2) for the peak strength τ_{max} and the maximum shear modulus G_{max} fail to model any entire stress-strain curve from very small to large strain levels of wet-tamped Onahama sand subjected to plane strain compression (PSC). To eliminate this long standing problem of the hyperbolic representation of stress-strain relation, Tatsuoka and Shibuya (1991a and b) proposed a new form of hyperbolic equation. This uses coefficients c_1 and c_2 which are a function of shear strain, expecting that it can model most stress-strain relations of soils and rocks for a wide range from extremely small strain levels to the peak stress condition. In this and last paper, the formulation of the anisotropic stress-strain relations of wet-tamped Onahama sand (Dong et al., 1990a and b, 1991a and b) by using the new hyperbolic equation will be presented. Further, the effect of inherent anisotropy on the paramenters involved in the new model is discussed.

FORMULATION OF STRESS-STRAIN RELATION

The new form of hyperbolic equation is expressed as;

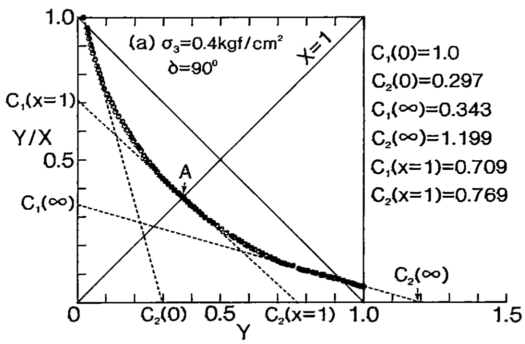
$$Y=Y_e+\frac{X-Y_e}{1/c_1(X)+(X-Y_e)/c_2(X)} \quad (1)$$

where Y and X are the normalized stress τ/τ_{max} and strain γ/γ_r ($\gamma_r=\tau_{max}/G_{max}$). Y_e and X_e are the values of Y and X at the elastic limit ($Y_e=X_e$). c_1 and c_2 are a function of X for $Y\geqq Y_e$. When $X_e=Y_e=0$ is assumed for simplicity, Eq. (1) becomes;

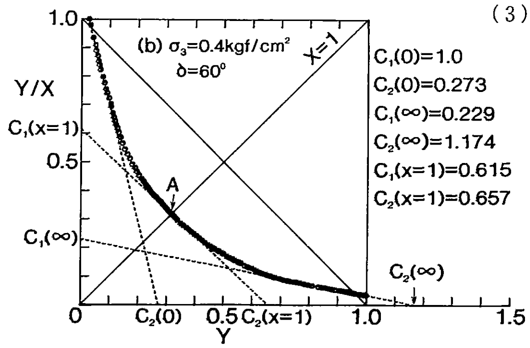
$$Y=\frac{X}{1/c_1(X)+X/c_2(X)} \quad (2)$$

Further, they proposed the following functions for $c_1(X)$ and $c_2(X)$;

$$c_1(X)=\frac{1+c_1(\infty)}{2}+\frac{1-c_1(\infty)}{2}\cdot\cos\left\{\frac{\pi}{(\alpha/X)^m+1}\right\} \quad (3)$$



(a) $\sigma_3=0.4$kgf/cm² and $\delta=90°$



(b) $\sigma_3=0.4$kgf/cm² and $\delta=60°$

Fig. 1 Determination of the parameters for the newly proposed model

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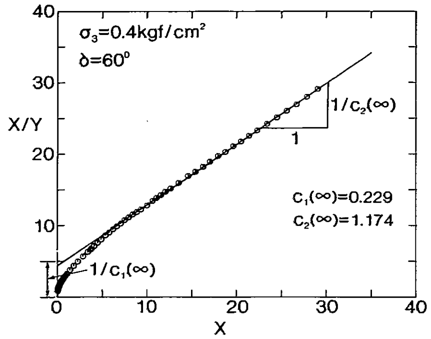


Fig. 2 X/Y～X fitting for the PSC test at $\sigma_3=0.4$kgf/cm² and $\delta=60°$

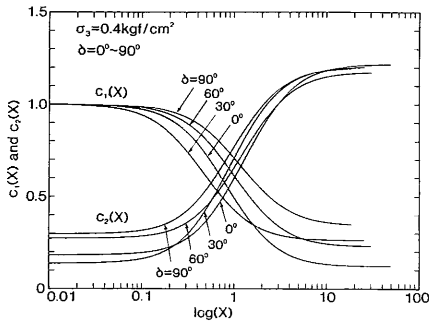


Fig. 3 Variation of the parameters $c_1(X)$ and $c_2(X)$ for PSC tests at $\sigma_3=0.4$kgf/cm² and $\delta=0°\sim90°$

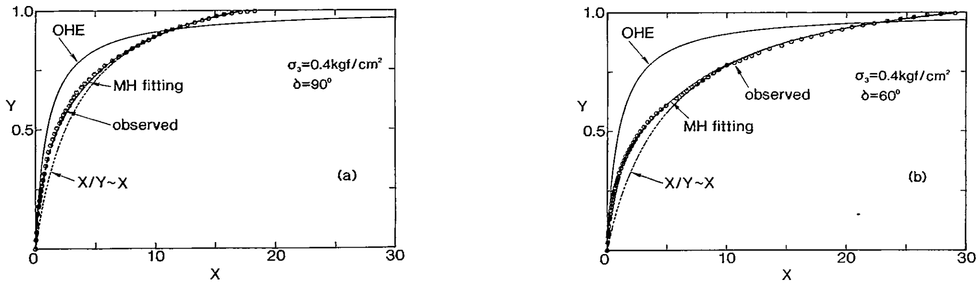


Fig. 4 Comparison of various hyperbolic equations with observed data for X=0～30
(a) $\sigma_3=0.4$kgf/cm² and $\delta=90°$, and (b) $\sigma_3=0.4$kgf/cm² and $\delta=60°$

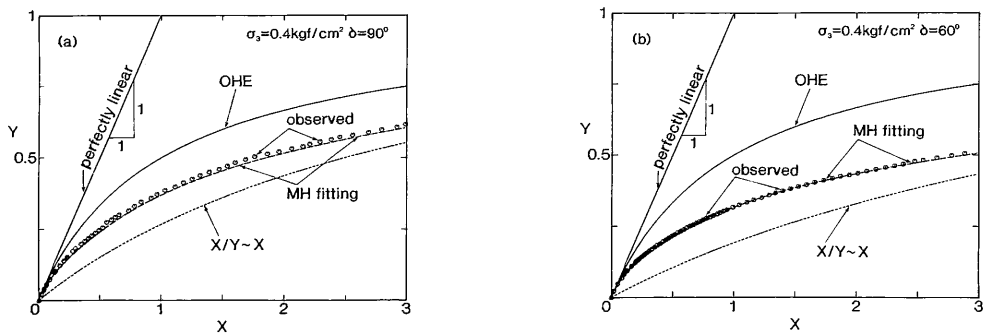
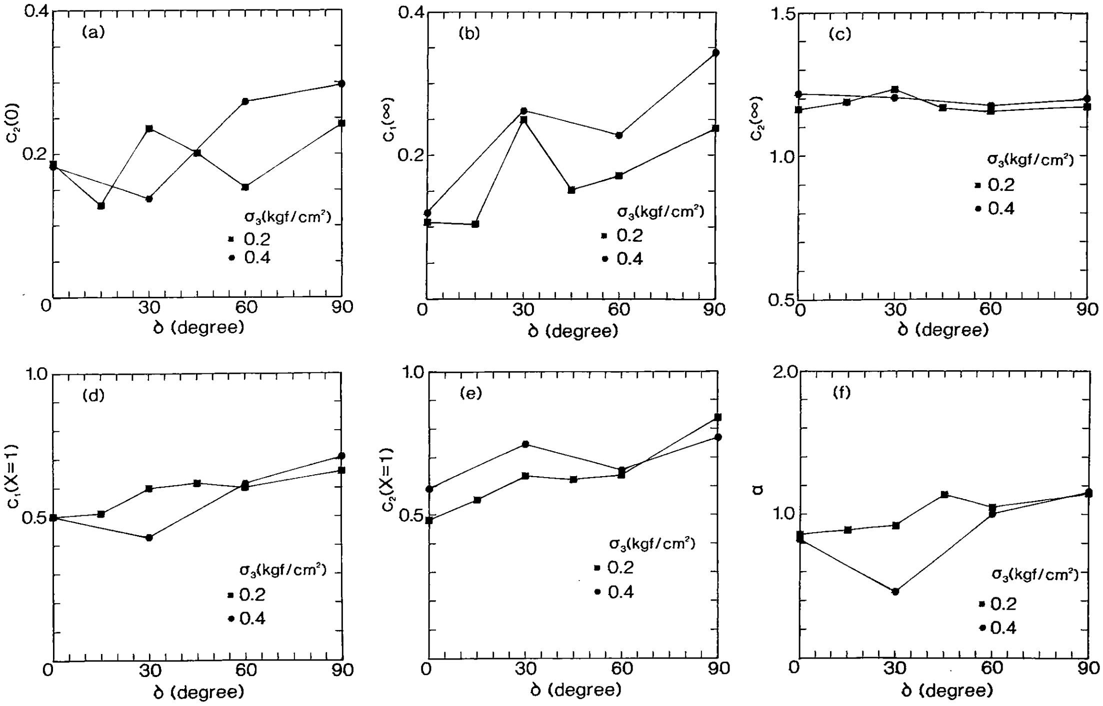


Fig. 5 Comparison of various hyperbolic equations with observed data for X=0～3
(a) $\sigma_3=0.4$kgf/cm² and $\delta=90°$, and (b) $\sigma_3=0.4$kgf/cm² and $\delta=60°$

$$c_2(X)=\frac{c_2(0)+c_2(\infty)}{2}+\frac{c_2(0)-c_2(\infty)}{2}\cdot\cos\left\{\frac{\pi}{(\beta/X)^n+1}\right\} \quad (4)$$

As the first approximation, m=n=1.0 is used in this study. The other parameters $c_2(0)$, $c_1(\infty)$, $c_2(\infty)$, α and β can be determined as follows. For the Y/X－Y plot of the data as shown in Figs. 1 (a) and (b), $c_2(0)$ is the intersect at the Y axis of the linear relation fitted to the initial part of the observed relation. $c_1(\infty)$ and $c_2(\infty)$ are the intercepts at the Y/X and the Y axes, respectively, of the linear relation fitted to the stress-strain relation observed at large strains. They can be obtained from the linear X/Y～X fitting as shown in Fig. 2, which corresponds to Fig. 1(b). In Fig. 1, at Point A, the diagonal for which X=1 intersects with the observed relation. Then, draw a straight line which is tangent



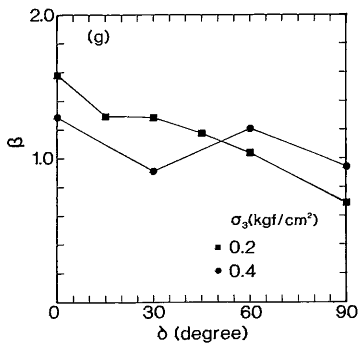


Fig. 6 Parameters as a function of δ;
(a) $c_2(0)$, (b) $c_1(\infty)$, (c) $c_2(\infty)$, (d) $c_1(X=1)$, (e) $c_2(X=1)$, (f) α and (g) β

to the observed relation at Point A. The intersects of the line with the Y/X axis and the Y axis are $c_1(X=1)$ and $c_2(X=1)$, respectively. The values of α and β are obtained by substituting these values of $c_1(X=1)$ and $c_2(X=1)$ together with $X=1$ into Eqs. (3) and (4). Fig. 3 shows the functions $c_1(X=1)$ and $c_2(X=1)$ for the data shown in Fig. 1 (b), together with those form a series of PSC tests at $\sigma_3=0.4$kgf/cm². In these tests, the angle δ of the σ_1-direction relative to the bedding plane was changed.

This modified hyperbolic relation is denoted as MH in Figs. 4 through 5. The other curves denoted as (X/Y~X) are the hyperbolic equation using the fixed values of $c_1(X)=c_1(\infty)$ and $c_2(X)=c_2(\infty)$ for each relation. It can be seen that this relation (MH) fits very accurately all these PSC test data for a wide range from extremely small to large strains. It was also found that this equation can model very well all the other stress-strain relations obtained for wet-tamped Onahama sand presented in Dong et al. (1990a, b, 1991a, b), irrespective of the angle δ and the confining pressure σ_3.

On the other hand, the inherent anisotroy as represented by the angle δ affects the parameters $c_1(X)$ and $c_2(X)$ as shown in Fig. 3. Fig. 6 (a) through (g) show relationships between these parameters and δ. In these figures, the values of these parameters for the PSC tests at $\sigma_3=0.2$ and 0.4kgf/cm² are presented. The following general tendencies may be noticed:

(1) The parameter $c_2(\infty)$ is rather constant (around 1.2), irrespective of σ_3 and δ.
(2) As the angle δ decreases, the non-linearity of stress-strain relation increases, and correspondingly the parameters $c_1(0)$, $c_1(X=1)$, $c_2(X=1)$ and $c_1(\infty)$ decreases.

(3) The ratios $c_1(\infty)/c_1(X=1)$ and $c_2(0)/c_2(X=1)$ are rather constant, which are on average 0.4 and 0.3, respectively.
(4) The values of $c_1(\infty)$ and $c_2(0)$ are very similar. Also, the values of $c_1(X=1)$ and $c_2(X=1)$ are similar.
(5) The items (3) and (4) together mean that except $c_2(\infty)$, the other parameters are inter-related.

The value of Y at X=1, Y(X=1) means the value of τ/τ_{max} when γ is equal to γ_r ($\gamma_r=\tau_{max}/G_{max}$). As Y(X=1) increases, the linearity of stress-strain relation increases. Therefore, the parameter Y(X=1) can be called as "the linearity index". Fig. 7 shows the relationship between Y(X=1) and δ. It can be seen that Y(X=1) deceases as the angle δ decreases. Fig. 8 shows the relationships between Y(X=1) and the parameters $c_2(0)$, $c_1(X=1)$, $c_2(X=1)$ $c_1(\infty)$ and $c_2(\infty)$. It may be seen that all these parameters except $c_2(\infty)$ are proportional to Y(X=1). Therefore, using these correlations, the values of these parameters can be approximately estimated from Y(X=1). It is needed, however, to study further whether these correlations can be applied to more general cases.

SUMMARY

The new form of hyperbolic equation proposed by Tatsuoka and Shibuya (1991), which has the correction coefficients for initial stiffness and strength as a function of strain, can accurately simulate the stress-strain relations obtained from the PSC tests on wet-tamped Onahama sand. The angle δ, which is the parameter representing the inherent anisotropy, affects the parameters involved in this model. It was also found that these parameters are inter-related and controlled by the linearity index Y(X=1).

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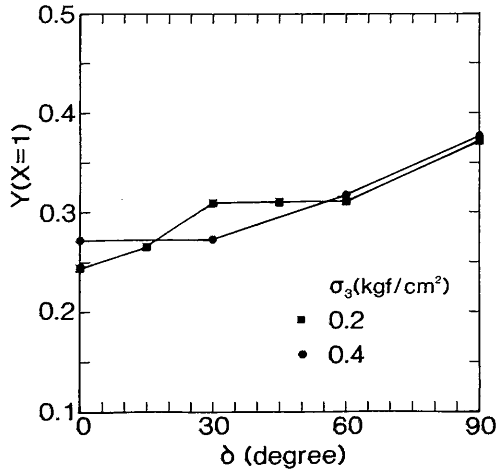

Fig. 7 Relationship between the linearity index Y(X=1) and the angle δ

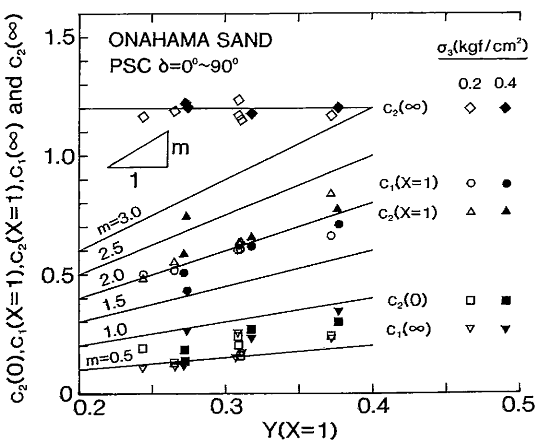

Fig. 8 Parameters $c_2(0)$, $c_1(X=1)$, $c_2(X=1)$, $c_1(\infty)$, and $c_2(\infty)$, as a function of Y(X=1)