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# RESIDUAL STRAIN-STRESS RELATIONSHIP FOR PREDICTION OF PERMANENT EARTHQUAKE DEFORMATION OF EMBANKMENT DAMS

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## INTRODUCTION

A number of approaches have been proposed over the past two decades for the estimation of earthquake-induced permanent deformation of embankments and earth dams ( Lee, 1974; Seed, 1979; Kuwano and Ishihara,1988 ). However, these methods have not adequately considered the deformed configuration of dams affected by seismic loading. Because of this, Ishihara et al (1990) proposed a new residual strain-stress relationship which combines the cyclic and confining stresses in a more appropiate manner for a more realistic estimation of permanent deformation. Application of this relationship to different materials is presented in this paper.

## RESIDUAL STRAIN-STRESS RELATIONSHIP

Ishihara et al(1990) have proposed the following relationship (Fig. 1):

$$\bar{\tau}=\bar{\tau}_c+\bar{\tau}_d=\frac{\gamma_c+\gamma_{res}}{a+b(\gamma_c+\gamma_{res})}(\bar{\sigma}_o')^n$$

where $P_a$ = atmospheric pressure; $\bar{\tau}_c = \tau_c/P_a$ = static component of shear stress; $\bar{\tau}_d = \tau_d/P_a$ = peak value of the dynamic component of the shear stress ; $\gamma_c$ = shearing strain caused by $\tau_c$ ; $\gamma_{res}$ = residual shearing strain caused by $\bar{\tau}$ ; $\bar{\sigma}_o' = \sigma_o'/P_a$ =confining stress ; a= inverse of the initial tangent to the hyperbolic curve; b=inverse of the limiting stress ratio at failure; n= slope of lines through average data points corresponding to equal residual strains.

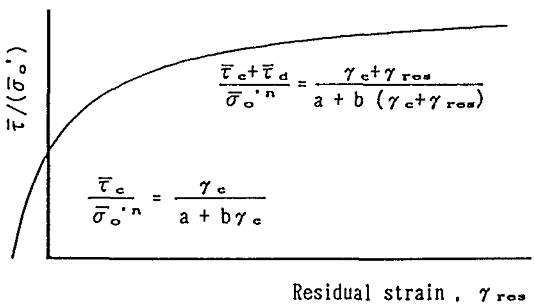


Fig.1 Residual strain-stress relationship

The parameters a,b, and n are calculated from experiments using the torsional shear test apparatus which reproduces the in-situ seismic stresses closer and in a better manner than triaxial devices.

## MATERIALS AND TESTING PROCEDURES

Table I shows the characteristics of the materials used in this study. Rock II, Filter, Transition, Transition2 and Core were taken from a dam site,and KU-1 and KU-2 were taken from borrow pits near Kushiro city, Hokkaido.

**Table I**

| MATERIAL | $D_{50}$ (mm) | $\gamma_d$ (KN/m³) | w (%) |
|---|---|---|---|
| KU-1 | 2.77 | 17.80<br>18.62 | 2.0<br>1.0 |
| ROCK II | 2.42 | 17.96<br>18.37<br>18.82 | 4.0<br>5.0<br>6.0 |
| KU-2 | 1.86 | 17.61 | 2.5 |
| FILTER | 1.50 | 18.33<br>19.22 | 10.0<br>5.0 |
| TRANSITION | 1.05 | 18.38 | 10.0 |
| TRANSITION2 | 0.65 | 18.15 | 10.0 |
| CORE | 0.40 | 15.31 | 12.5 |

Hollow cylindrical specimens with 150 mm inner diameter, 250 mm outer diameter and 142 mm height were employed in all tests. Multiple series of torsional shear tests were conducted by subjecting samples first to different states of static initial stress and then to dynamic torsional shear stress with an irregular time history. The static state of stress in the triaxial mode is expressed as $(\sigma_{ac} - \sigma_{rc})/2\sigma_o'$, where $\sigma_{ac}$ and $\sigma_{rc}$ are the axial and radial stresses respectively,applied initially to the samples. The static state of stress in the torsional mode is expressed as $\tau_c/\sigma_o'$ where $\tau_c$ is the initially applied torsional shear stress. Table II shows the different values of these ratios used in this study as well as the values of the mean confining stress.

The E–W component of the horizontal ground acceleration ,obtained at Hachinohe harbour, during the Tokachi–Oki earthquake (1968) was used as the torsional loading. Ishihara et al (1990) have described in detail the test procedure.

**Table II**

| $\frac{\sigma_{ac}-\sigma_{rc}}{\sigma_{ac}+\sigma_{rc}}$ | $\tau_c/\sigma_o'$ | $\bar{\sigma}_o'$ |
|---|---|---|
| 0.00 | 0.2 | 1.0,1.5,2.0 |
| | 0.4 | 1.0,1.5,2.0 |
| 0.33 | 0.2 | 1.0,1.5,2.0 |
| | 0.4 | 1.0,1.5,2.0 |

## TEST RESULTS AND DISCUSSIONS

Fig. 2 shows typical curves of $\bar{\tau}/\bar{\sigma}_o'$ vs. $\gamma_{res}$ for one of the materials tested in this study. A total of 96 tests were performed on seven materials with different mean grain sizes and a summary of the test results is shown in Table III and Fig.3. It may be seen that as the grain size decreases, the exponent n and the b–value tend to decrease. The test data shown in Table III may be interpreted as representing the residual strain characteristics of the materials tested in this study.

**Table III**

| MATERIAL | $\gamma_d$ (KN/m3) | n | a | b | $\gamma_r$=a/b |
|---|---|---|---|---|---|
| KU–1 | 17.80<br>18.62 | 0.73 | 0.280<br>0.374 | 1.046<br>1.008 | 0.267<br>0.370 |
| ROCK II | 17.96<br>18.37<br>18.82 | 0.72 | 0.582<br>0.416<br>0.244 | 0.965<br>0.846<br>0.996 | 0.604<br>0.491<br>0.245 |
| KU–2 | 17.61 | 0.71 | 0.36 | 0.996 | 0.361 |
| FILTER | 18.33<br>19.22 | 0.63 | 0.394<br>0.335 | 0.903<br>0.879 | 0.436<br>0.381 |
| TRANS | 18.38 | - | - | 0.78 | - |
| TRAN2 | 18.15 | - | - | 0.81 | - |
| CORE | 15.31 | - | - | 0.73 | - |

## CONCLUSIONS AND RECOMMENDATIONS

The parameters, which define the hyperbolic function representing the residual strain–stress relationship, have been calculated for materials with different mean grain sizes. Also, correlations between some of these parameters and particle size have been found. The availability of the torsion shear apparatus is limited; for this reason, triaxial mode testing is recommended for the investigation of any correlation with the data obtained from tests performed in the torsional mode.

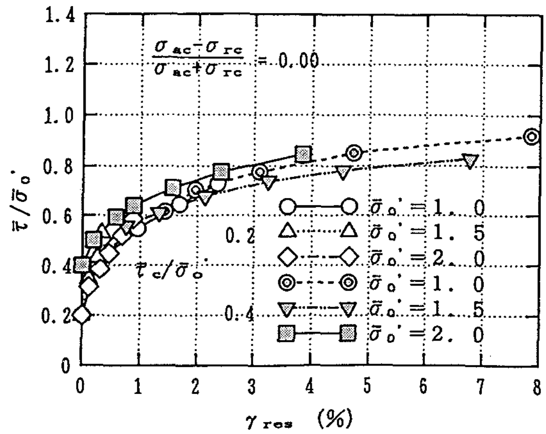


**Figure 2. Typical curves**

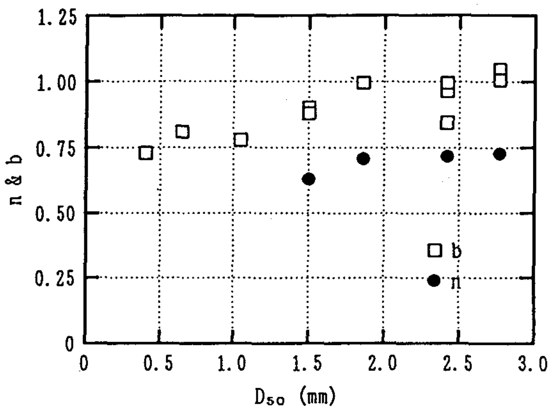


**Figure 3. Variations of b and n as functions of $D_{50}$**

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