CONSTITUTIVE MODEL FOR THREE –DIMENSIONAL BEHAVIOR OF ANISOTROPIC SOILS

By Erwin Lara Rizardo, CE

ABSTRACT

This study is based on the concept that the deformation strength characteristic of cohesionless soils is significantly influenced by the rotation of principal stress axes. Inherent anisotrophy on the mechanical properties of sand induced during deposition of sand particles in the specimen preparation process has notable effect on shear strength, shear deformation and dilatancy behavior. Shear strength and shear stiffness are both maximum at principle stress direction 2α equal to 0° and maximum at 2α equal to 150°. This tendency can be explained with the predominant sliding on horizontal potential mobilized plane where the interlocking between sand particles that is shear resistance is minimum. The constitutive model named as "Multi-Directional Sliding Model" is applied to the deformation-strength characteristics of sand with anisotropic mechanical properties in general three-dimensional stress condition. Its applicability and influence on inherent and induced anisotropy is examined. It has been found out that the model tends to overestimate the deformation compared with the measured deformation, however good qualitative result is observed between predicted and measured values. Furthermore, inherent anisotropy is predicted by the modification of shear resistance on potential sliding plane and hardening effect in the direction of preshearing and softening effect in the opposite direction are properly predicted with Masing's rule for the cyclic shear stress-strain relationship on the potential sliding plane which is combined into the model.

INTRODUCTION

Background and Rationale

Recent investigations reveal that the rotation of principal stress axes that is commonly encountered in the *in-situ* ground exerts a remarkable influence on the deformation strength characteristic of cohesionless soils. Miura, K., Miura S. and Toki, S. (1986) pointed out the importance of the effects of the rotation of principal stress direction on the deformation behavior of sand. Lade and Duncan, Tatsuoka and Miura, and Toki predicted no plastic deformation under the principal stress rotation with three principal values kept constant. Furthermore, Prevost (1979) proposed the plasticity model adequate for simulating the deformation behavior of soils undergoing principal stress rotation. Matsuoka and Nakai have developed the models suitable for three-dimensional stress-strain behavior of anisotropic sands by formulating the shear–normal stress ratio versus shear strain relationships on "Compounded Mobilized Plane" and Spacial Mobilized Plane" respectively.

Some studies on the prediction of the response of cohesionless soils to rotational change in stress state are attempted. Miura, K., Miura S. and Toki, S. have drawn out the following deformation features of anisotropic sand under the rotation of principal stress axes namely, principal stress rotation with the magnitude of three principal stresses unchanged resulted larger deformation and volume change than that due to the shear without the rotation, and the coaxiality between principal directions of stress and strain increments.

The model which is referred to as "Multi-Directional Sliding Model" is developed for the deformation behavior of anisotropic sand under the general stress condition. In the proposed model it is assumed that granular materials such as sand have innumerable potential sliding planes oriented densely and their deformation mechanism is governed by the sliding deformation on planes. The sliding deformation on a given plane is specified by the quadratic hyperbolic relation between shear strain and stress obliquity with the help of Masing's rule and the linear relationship between strain increment ratio and stress ratio. The three-dimensional anisotropic stress-strain relationships are derived by extending the postulates of "Compounded Mobilized Plane Theory" by Matsuoka which states that the three dimensional deformation is represented as linear summation of strain increments produced in the imaginary two-dimensional stress-strain systems.

Objectives of the Study

This study aimed to verify the background for the modeling of soil stress-strain behavior in general three-dimensional stress condition, the theory of "Multi-Directional Sliding Model" with a verification of its application with some series of element tests available for the stress condition with principal stress axes and inherent and induced anisotropic deformation-failure behavior of sand in general stress condition with the rotation of principal stress axes. The study further aimed to evaluate and verify the model for sand with inherent and induced anisotropy.

METHODOLOGY

Using a hollow cylindrical torsional shear apparatus that can subject a hollow cylindrical specimen of 30mm inner radius R_i, 50mm outer radius R_o, 200 mm height H, to axial load F, torque T, inner cell pressure p_i and outer cell pressure p_o under independent control, a series of drained shear tests with the rotation of the principal stress axis were conducted on sand with inherent anisotropy. Specifically, Toyoura standard sand, washed, oven dried and consisting of subangular quartz particles with specific gravity, mean diameter and uniformity coefficient of 2.65, 0.18mm and 1.50, respectively, was used in this study.

In order to examine the anisotropic fabric effects on mechanical properties of sand, a series of tests referred to as Shear Test with Fixed Principal Stress Axes or simply known as F test was performed. In all F tests, the axes of principal stress increment coincided completely with those of principal stress and therefore the difference among all tests existed only in the relative direction of the major principal stress axis to the depositing axis of sand particles. Consequently, the effects of the initial anisotropic fabric on the mechanical response of sand can be evaluated.

In order to investigate the deformation characteristics of anisotropic sand under the principal stress rotation, another series of tests referred to as Test with Rotation of Principal Stress Axes otherwise known as R test was performed. Since each value of the three principal stresses can be determined from values of effective mean principal stress p', stress system parameter b and stress ratio $\sin \phi$, all of these were held constant throughout the principal stress rotation. It turned out that three principal stresses were kept constant despite the principal stress axes rotation. The deformation anisotropy of sand due only to the principal stress rotation can be assessed excluding the effects of the change in stress system and stress ratio.

A comparison between Stress-Strain Relationships under Irrotational Stress Condition and Stress-Strain Relationships under Rotational Stress Condition is presented to compare the Model as against experimental data.

RESULTS AND DISCUSSION

The stress paths adopted in both F Test and J Test are shown in Figures 1 and 2, respectively. Comparison between the F test results at different direction of principal stress axis shows a clear difference with the J test that adopts the influence of shear stress history.

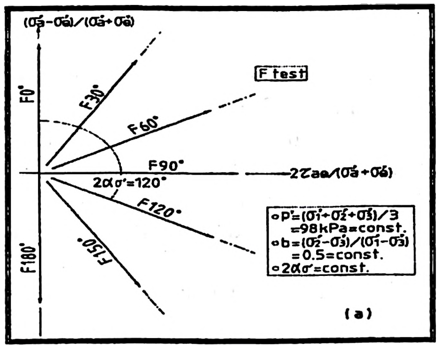

Figure 1. Stress Paths adopted in F-Test

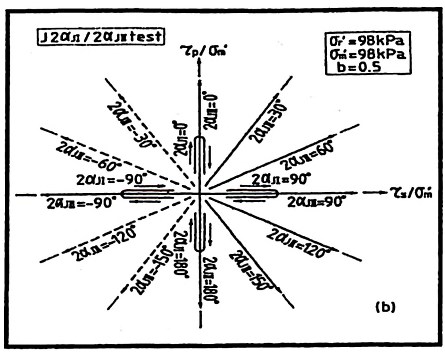

Figure 2. Stress Paths adopted in J-Test

In this study, strength properties, shear deformation, dilatancy and direction of the principal strain are considered based on experimental test results. Influence of inherent and induced anisotropy is clarified and the concept of "Multi Directional Sliding Model" was considered.

Shear Strength Properties. When the principal stress axis direction 2α is equal to $150°$, the minimum value for shear stress ratio is seen both in the measured and predicted curves as shown in Figure 3, however, the model tends to underestimate the shear strength slightly. Although the parameters for the constitutive model are determined from the failure-deformation behavior observed under axis symmetrical stress condition in triaxial shear test, the model can predict the shear strength characteristics of inherent anisotropic sand under general stress condition including the rotation of principal stress axis rotation.

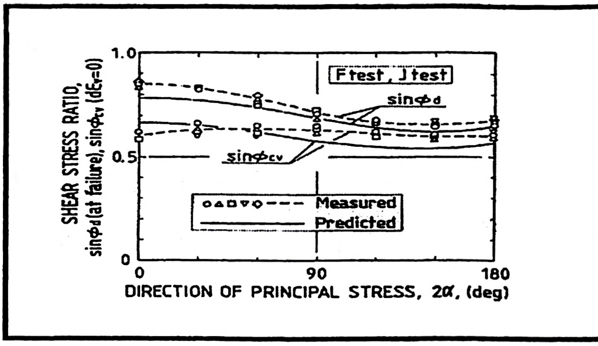

Figure 3. Measured and Predicted Plots on Shear Stress Ratios ($\sin\phi_d$ and $\sin\phi_{CV}$) against the Direction of Principal Stress (2α)

Shear Deformation and Dilatancy Behavoir. Modeling of shear deformation and dilatancy behavior of inherent anisotropic sand is examined based on the deformation behavior observed in F tests where sand specimen is sheared without preshearing. From the comparison with the measured deformation behavior, it can be said that there is a good conformity between measured and predicted deformation behavior. Modeling of induced anisotropy in shear deformation and dilatancy behavior of sand is examined based on the deformation behavior observed in J tests where sand specimen was sheared after preshearing in different principal stress direction or shear stress history. The measured and predicted behaviors show a quantitative difference, however, a good resemblance is seen between them qualitatively. The constitutive model tends to overestimate the deformation behavior, however, qualitative conformity between the measured and predicted values is observed. Hardening effect is determined in the direction of preshearing while softening effect is observed in the opposite direction in both measured and predicted behaviors.

Shear Strain Path. The shear strain paths predicted by the constitutive model for loading process without preshearing as observed in F tests show qualitative conformity between the measured and calculated paths and signs that separate them from the principal stress axis is deviating in the direction of 2β equal to +/-90°. As shear resistance of sand element is considered weakest on a horizontal potential sliding plane parallel to the deposition plane, a model can explain well the inherent anisotropic deformation behavior. Furthermore, a comparison between the shear strain paths predicted by the constitutive model observed in J tests and the measured shear stress paths shows that the model can explain the influence of preshearing on strain paths. The measured and predicted shear strain paths both tend to deviate to opposite direction due to preshearing. The consistent effect of induced anisotropy by preshearing on shear stress path is also observed in this calculation and that the path deviates to the opposite direction.

CONCLUSIONS AND RECOMMENDATIONS

Based on the aforementioned results, the following conclusions were drawn:

1. Inherent anisotrophy on the mechanical properties of sand induced during deposition of sand particles in the specimen preparation process has notable effect on shear strength, shear deformation and dilatancy behavior. Shear strength and shear stiffness are both maximum at principle stress direction 2α equal to 0° and maximum at 2α equal to 150°. This tendency can be explained with the predominant sliding on horizontal potential mobilized plane where the interlocking between sand particles that is shear resistance is minimum.

2. Due to the inherent anisotropy, strain path tends to shift to the direction of principal strain direction, 2α equal to 90° or -90° that corresponds to simple shear deformation due to the dominant shear deformation on the horizontal potential sliding plane.

3. The induced anisotropy of sand has notable influence on shear behavior and dilatancy behavior observed in the reloading process after preshearing. However, its influence on shear strength is insignificant.

4. Shear strain and volumetric strain generated in the reloading process increases and decreases, respectively due to preshearing depending on the relative direction of principal stress. When principal stress direction is close to that of preshearing, hardening effect is observed and shear stress and volumetric strain are suppressed. On the other hand, the direction opposite to that of preshearing, a softening effect is distinguished.

5.The applicability of the constitutive model named as "Multi-Directional Sliding Model" on inherent and induced anisotropy is examined and it was found out that the model tends to overestimate the deformation compared with the measured deformation, however good qualitative result is observed between predicted and measured values. Furthermore, inherent anisotropy is predicted by the modification of shear resistance on potential sliding plane and hardening effect in the direction of preshearing and softening effect in the opposite direction are properly predicted with Masing's rule for the cyclic shear stress-strain relationship on the potential sliding plane which is combined into the model.

Based on the major findings and conclusions drawn from the results of the study, it is therefore recommended that the application of Multi-Directional Sliding Model to some boundary-value problems with Finite Element Method and the formulation of the program code of Multi-Directional Sliding Model (MDSM-E) to conventional triaxial shear test, triaxial shear test and pseudo plane strain analysis and stress-strain analysis on a potential sliding plane be considered for further study.

REFERENCES

Lade, P. V. & Duncan, J. M. (1975). Elasto-Plastic Strain-Stress Theory for Cohesionless Soil. *Proceedings of American Society of Civil Engineers, 101*, 1037- 1053.

Matsuoka, H. & Ishizaki, H. (1981). Deformation and Strength of Anisotropic Soil. *Proceedings of 10th ICSMFE, 1*, 699-702.

Miura, K. & Finn, W.D. (1987). A Multi –Dimensional Sliding Model o Soil Deformation. *Proceedings Of International Workshop on Constitutive Equations for Non-Cohesive Soils*, 465-480.

Miura, K., Miura, S. & Toki, S. (1986). Deformation behavior o Anisotropic Dense Sand under Principal Stress Axes Rotation. *Japanese Geotechnical Society Soils and Foundation, 26*(1), 36-52.

Miura, S. & Toki, S. (1984). Elastoplastic Stress-Strain Relationship or Loose Sands with Anisotropic Fabric Under Three-Dimensional Stress Conditions. *Soils and Foundations, 24*(2), 43-57.

Miura, K., Toki, S. & Miura, S. (1986). Deformation Prediction for Anisotropic Sand During the Rotation of Principal Stress Axes. *Japanese Geotechnical Society Soils and Foundation, 26*(3), 42-56.

Nakai, T. & Matsuoka, M. (1983). Shear Behaviors of Sand and Clay Under Three-Dimensional Stress Conditions. *Soils and Foundations, 23*(2), 26-42.

Towhata, I. & Ishihara, K. (1985). Modeling Soil Behavior Under Principal Stress Axes Rotation. *Proceedings of the 5th International Conference on Numerical Methods in Geomechanics,1*, 523-530.

Towhata, I. & Ishihara, K. (1985). Undrained Strength of Sand Undergoing Cyclic Rotation of Principal Stress Axes. *Soils and Foundations, 25*(2), 135-147.