Distinct element modelling of stress-path dependent behaviour of interfaces

Modèle par éléments distincts du comportement d'interfaces dépendant du chemin de contrainte

E.Evgin & B.Li – *Department of Civil Engineering, University of Ottawa, Canada*
K.Fakharian – *Department of Civil Engineering, Amirkabir University of Technology, Tehran, Iran*

ABSTRACT: Experimental data are presented for the stress path dependent behaviour of interfaces with anisotropic surface roughness characteristics. The results show that the load resistance of the interface can vary up to twenty five percent depending on the stress path followed in an experiment. In biaxial tests, directions of load increment and displacement increment were not concordant. A three dimensional discrete element analysis also showed similar results.

RÉSUMÉ: Des données expérimentales son présentées au sujet du comportement dépendant du chemin de contrainte d'interfaces présentant une rugosité de caractère anisotropique. Les résultats démontrent que la résistance à la charge de l'interface peut connaître des variations allant jusqu'à vingt-cinq pour-cent selon le chemin de contrainte suivi durant l'essai. Lors d'essais biaxiaux, la direction de l'accroissement de la charge et celle de l'accroissement du déplacement n'étaient pas concordants. Une analyse tridimensionnelle par éléments discrets a donné des résultats similaires.

1. INTRODUCTION

The characteristics of interfaces play an important role on the load-displacement response of piles, pipelines, offshore gravity platforms, and earth retaining structures. Experimental studies show that the behaviour of interfaces is influenced by the surface roughness of construction materials. Other influencial factors are soil type, stress-strain-strength characteristics of soil, moisture content, particle shape, grain size distribution, density of soil, stress path, and boundary conditions (Desai, 1981; Uesugi and Kishida, 1986; Boulon, 1989). The effect of stress paths on the behaviour of a sand-steel interface was investigated by Evgin and Fakharian (1996). An elasto-plastic hierarchical model (Navayogarajah et al., 1992) was used by Fakharian and Evgin (2000) to simulate the stress-path dependent behaviour of interfaces.

Anisotropy in soils has been the subject of many experimental and theoretical studies (Mroz et al., 1978; Prevost, 1978; Dafalias, 1975). In rock mechanics, the importance of anisotropic behaviour of rock joints has been well recognized (Huang and Doong, 1990). Anisotropy at soil-structure interfaces, however, has not attracted much attention. In this paper, some experimental data are presented to show the significance of anisotropy on the behaviour of soil-structure interfaces. A biaxial apparatus was used in the experimental work. These tests were performed on interfaces between sand and a steel plate.

In the numerical analysis part of this paper, the path dependent interface behaviour was simulated using the distinct element method, DEM. This numerical technique is well suited for the solution of applied mechanics problems in discontinuous materials (Cundall and Starck, 1979; Rothenburg and Bathurst, 1992). The method has been shown to be very useful in: (1) the failure analysis of brittle materials such as rock, ice, ceramics, (2) the simulation of the mechanical behaviour of granular materials, (3) the modelling of the mechanical behaviour of fractured and jointed rock masses, (4) modelling the mechanical behaviour of ice rubble, (5) the development of macroscopic constitutive relations from microscopic distinct element modelling, etc. The method is potentially useful for large deformation and failure problems. In particular, discontinuous deformations can be handled with ease. In relation to interface studies, DEM produced simulatations for the behaviour of a dense sand-rough steel plate interface subjected to constant normal stress conditions (Evgin and Fu, 1997). Circular particles and units of two circular particles bonded together were used in a two-dimensional DEM analysis. Evgin (2000) simulated the liquefaction phenomenon in interfaces using a two-dimensional distinct element code. Calculated results were in agreement with the measured values. In the present paper, an attempt was made to simulate the behaviour of an interface between dense sand and a steel plate by using a three-dimensional distinct element model.

2. EXPERIMENTAL RESULTS

Evgin and Fakharian (1996) conducted experiments to study the two- and three-dimensional behaviour of an interface between dense sand and a rough steel surface under constant normal stress and constant stiffness conditions. Sand blasting was used to achieve a uniform roughness in all directions on the surface of the steel plate. The influence of various stress paths on the stress-displacement relations and shear strength characteristics of the interface were investigated. The experimental results showed that the coefficient of friction corresponding to the resultant peak and residual shear strengths were independent of stress paths. On the other hand, stress paths significantly influenced the shear stress versus tangential displacement curves and the volume change response of the interface. The direction of the tangential displacement increments did not coincide with the direction of the shear stress increments except for one-directional interface tests.

In the experimental part of this study, a biaxial interface apparatus (Evgin and Moore, 1999) was used. Experiments were conducted on an interface between medium dense sand and a steel plate with anisotropic surface roughness characteristics. The anisotropy on surface roughness was achieved by attaching metal strips on the interface plate as shown in Figs. 1a and 1b. The interface lies in the x-y plane and the metal strips are parallel to the y-axis. In order to avoid any contact with the vertical walls of the soil container, the metal strips were made 40 mm long, which allowed 10 mm wide space in both x and y-directions between the strips and the walls. The dimensions of the contact surface were 60 mm x 60 mm.

Crushed-quartz sand was used in these experiments. The characteristics of this sand can be found in Evgin and Fakharian (1996). In all the tests discussed here the normal stress was 100 kPa. The interface was sheared in five different stress path tests.

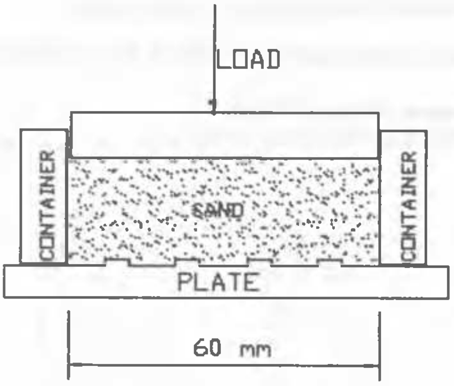

Figure 1a. A cross-section of the soil container

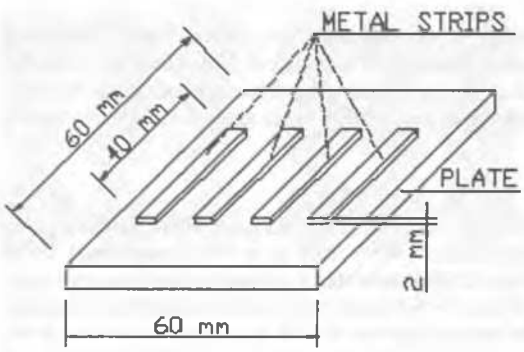

Figure 1b. Interface plate with metal strips

Test 1: This a displacement controlled test. The sample was sheared in the x-direction. There was no loading in the y-direction.

Test 2: First, a 100 N load was applied in the y-direction. Subsequently, the sample was subjected to x-direction displacements. During this part of the test, the load in the y-direction was maintained at 100 N. However, the sample was free to move in the y-direction.

Test 3: This test was similar to Test 2 except that the y-direction load was 200 N and it was maintained at that level.

Test 4: This test was also similar to Test 2 and Test 3, however, the y-direction load was increased to 255 N before shearing the sample in the x-direction.

Test 5: This is a displacement controlled test. The sample was sheared in the y-direction. There was no loading in the x-direction.

Figure 2 illustrates the directions of the applied loads (stress paths) in each test. The behaviour of the interface in each test is shown in the following figures. In Test 1 and Test 5, the shearing of the samples was in one direction. The tangential force-displacement relation for these tests are shown in Fig. 3. The shear resistance developed in Test 1 is about 25% larger than the resistance of the interface sheared in Test 5. Figure 4 shows the failure envelope ploted in the plane of interface using the results of all five tests. Anisotropic surface roughness of the steel plate caused the failure envelope to take approximately an elliptical shape.

The tangential displacements of the interface plate in Tests 2, 3 and 4 are plotted in Fig. 5. These three displacement curves clearly show that the direction of displacement increments do not coincide with the direction of force increments. For example, the x and y components of the displacement increments near the

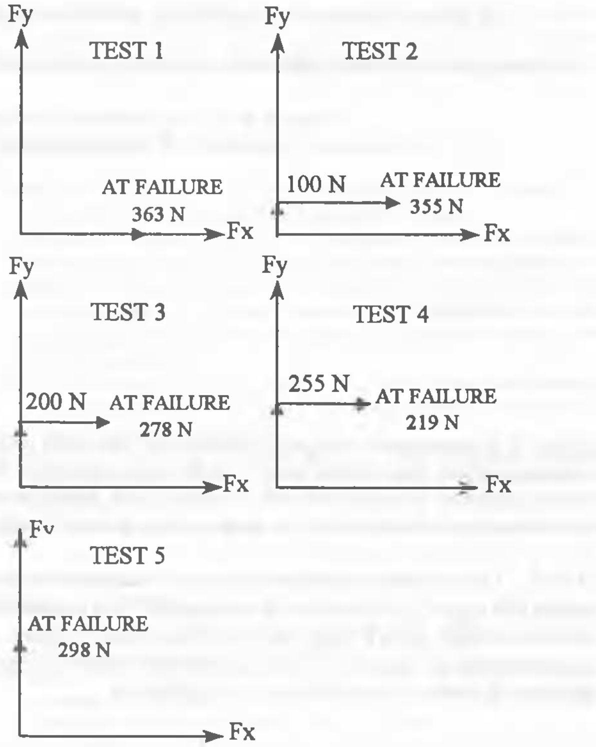

Figure 2. Directions of applied loads in five stress path tests

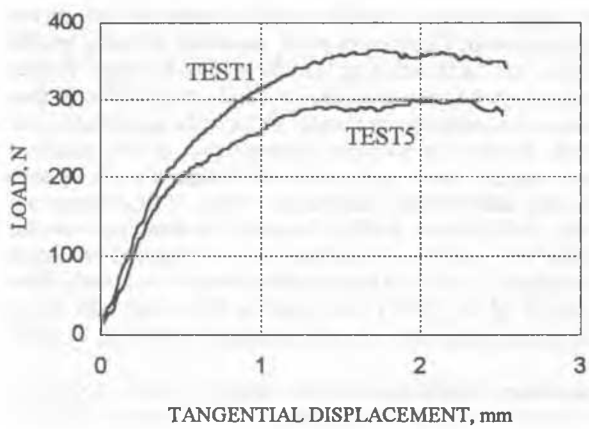

Figure 3. Tangential force versus tangential displacement in Test 1 and Test 5

failure state in Test 4 are about the same, although only the x-force is increasing and there is no change in the y-direction force. The direction of the resultant displacement increment is somewhat closer to the direction of the total resultant force acting on the interface.

3. DISTINCT ELEMENT ANALYSIS

In this study, a three-dimensional distinct element code, PFC^{3D} was used (Itasca, 1999). Simulations were performed for an interface with anisotropic surface roughness properties.

Anisotropy in surface roughness was achieved by changing the surface geometry from a smooth plane surface to a smooth surface with "speed bumps" as shown in Fig. 6. The speed bumps correspond to the metal strips used in the experimental part of this study. There was a minimum of 0.1 m space between the vertical walls of the soil container and the nearest speed bump. The coefficient of friction for all smooth surfaces was 0.2. The overall dimensions of the interface plane were 1m by 1m and the total height of the soil sample was 0.435m. The height of the speed bumps was 0.035 m. These dimensions were chosen for a preliminary design of a large size interface apparatus. The

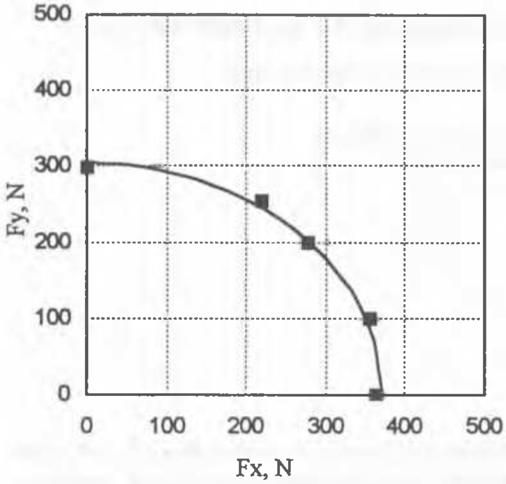

Figure 4. Failure envelope (measured)

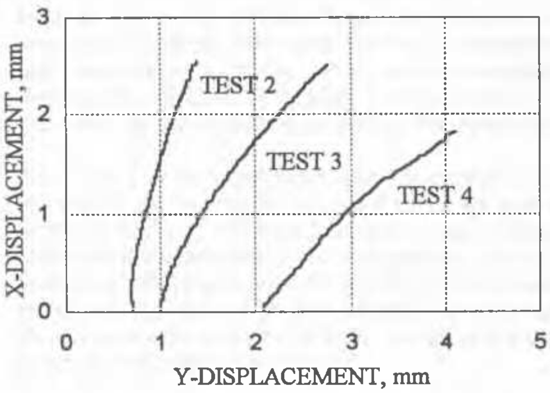

Figure 5. Tangential displacement components in x and y-directions in Tests 2, 3, and 4

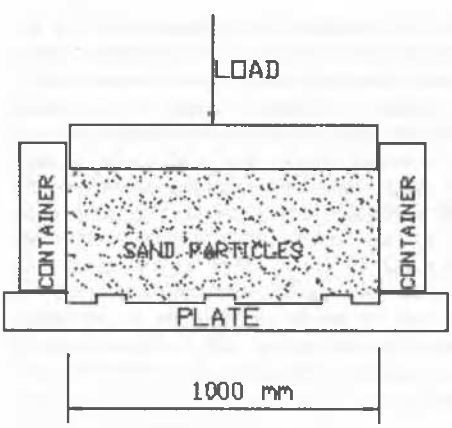

Figure 6. Particle container in DEM analysis

calculations were used to determine the magnitude of the maximum tangential force, the amount of tangential displacement required for the mobilization of the maximum shear resistance of the interface, stress distribution, strain distribution, and some other quatities useful for mathematical modelling purposes. Each analysis had two stages. Spherical soil particles were created in the first stage and the vertical load was applied. The shearing of the sample took place in the second stage.

A total of 5820 particles were used in the simulations. The diameter of the particles ranged between 22 mm to 32 mm. The coefficient of friction between the particles was 1.0. Other parameters required in the calculations are given in Table 1.

Figure 7 shows the tangential force versus tangential displacement curve for the interface subjected to loading in the x-direction (ANALYSIS 1) and in the y-direction (ANALYSIS 2) (see Fig. 2 for the orientation of speed bumps with respect to x-direction and y-direction).

Table 1. Parameters used in DEM analysis

Normal stiffness of walls	1×10^{9} N/m
Shear stiffness of walls	1×10^{9} N/m
Normal stiffness of particles	0.7×10^{7} N/m
Shear stiffness of particles	1×10^{7} N/m
Coef. of friction of walls	0.2
Coef. of friction of balls	0.2

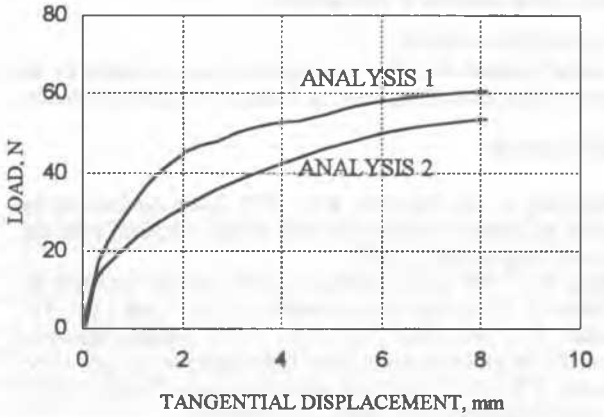

Figure 7. Tangential load versus tangential displacement curves calculated by PFC[3D]

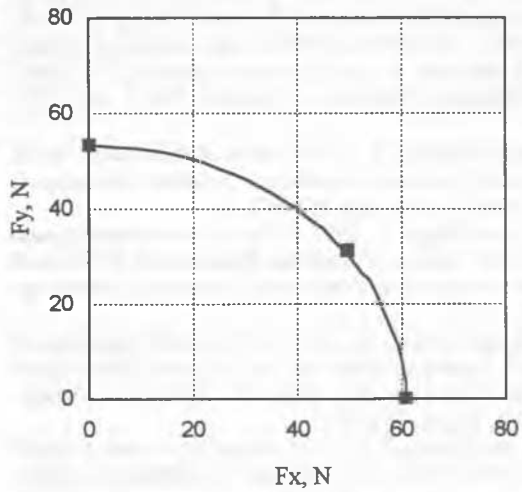

Figure 8. Failure envelope (calculated)

A comparison indicates that the maximum tangential force that can be resisted by the interface is about 14% larger for the x-direction loading than the y-direction loading. The tangential displacement required for the maximum tangential force to develop was comparable in both the x- and y-directions.

The calculated failure envelope is shown in Fig. 8. The third point in this figure was obtained from a DEM analysis in which the sample was sheared in a displacement controlled analysis. The interface plate was moved an equal amount in both the x- and y-directions in each increment. The failure envelope has an elliptical shape similar to experimental failure envelope. However, a direct comparison is not possible because of many reasons including the size effects.

4. CONCLUSIONS

Anisotropic surface roughness caused the load carrying capacity of an interface to vary with loading direction. The difference between the maximum and minimum values of tangential force was about 25% in the experiments and 14 % in the DEM analysis. In general, the direction of the applied force increment and the direction of the displacement increment experienced by the interface do not coincide with the exception of one directional shearing. When the sample is subjected to load increments in both x and y-directions, the resultant of displacement increments was approximately parallel to the resultant tangential force acting on the interface at that moment.

ACKNOWLEDGMENT
Financial support for this investigation was provided by the Natural Sciences and Engineering Research Council of Canada.

REFERENCES

Rothenburg, L. and Bathurst, R.J., 1992. Micromechanical features of granular assemblies with planar elliptical particles. Geotechnique, 42(1), 79-95.

Boulon, M., 1989. Basic features of soil-structure interface behaviour. Computers and Geotechnics, Vol. 7, pp. 115-131.

Cundall, P.A. and Strack, O.D.L., 1979. A discrete numerical model for granular assemblies. Geotechnique, 29, pp. 47-65.

Dafalias, Y.F., 1975. On Cyclic and Anisotropic Plasticity. Ph.D. thesis, University of California at Berkeley.

Desai, C.S., 1981. Behavior of interfaces between structural and geologic media. State-of-the Art Paper, Proceedings, Int. Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, MO, pp. 619-638.

Evgin, E., 2000. An experimental study and numerical simulation of liquefaction at a soil-structure interface. 53rd Canadian Geotechnical Conference, Montreal, Vol. 2, pp. 1075-1082.

Evgin, E. and Fakharian, K., 1996. Effect of stress paths on the behaviour of sand-steel interfaces. Canadian Geotechnical Journal, Vol. 33, No. 6, pp. 853-865.

Fakharian, K. and Evgin, E., 1993. A Three-Dimensional apparatus for Cyclic Testing of Interfaces. Proceedings, 46th Annual Canadian Geotechnical Conference, Saskatoon, Canada, pp. 485-493.

Fakharian, K. and Evgin, E., 2000. Elasto-plastic modeling of stress-path dependent behaviour of interfaces. International Journal for Numerical and Analytical Methods in Geomechanics, No. 24, pp. 183-199.

Huang, T.H. and Doong, Y.S., 1990. Anisotropic Shear Strength of Rock Joints. Rock Joints, Barton and Stephansson (eds.), Balkema, Rotterdam, pp. 211-218.

Itasca, 1999. PFC3D, Particle Flow Code in 3 Dimensions, Itasca Consulting Group Inc., Minneapolis, Minnesota, USA.

Mroz, Z., Norris, V.A., and Zienkiewicz, O.C., 1978. An Anisotropic Hardening Model for Soils and its Application to Cyclic Loading. Int. Journal of Numerical and Analytical Methods in Geomechanics, Vol. 2, pp. 203-221.

Navayogarajah, N., Desai, C.S., and Kiousis, P.D., 1992. Hierarchical single-surface model for static behavior of interfaces, Journal of Engineering Mechanics, ASCE, 118(5), pp. 990-1011.

Prevost, J.H., 1978. Anisotropic Undrained Stress-Strain Behavior of Clays, Journal of Geotechnical Engineering Division, ASCE, Vol. 104, No. GT8, pp. 1075-1090.

Uesugi, M. and Kishida, H., 1986. Influential Factors between Steel and Dry Sand, Soils and Foundations, Vol. 26, No. 4, pp. 139-149.