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Finite element modeling of cone penetration test in weakly cemented sand

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ABSTRACT: A stress-strain model has been developed for weakly cemented sand using Drucker-Prager yield and failure criteria modified to account for the strain dependencies of friction angle, dilation angle and cohesion. The model was calibrated against drained triaxial compression test data obtained from laboratory tests of water pluviated weakly cemented sand samples. Miniature cone penetration tests were conducted in the laboratory to check the performance of the calibrated model. Weak cementation for performing miniature cone test samples were introduced in an identical process that used for introducing cementation in triaxial sand samples. The 2.75-mm diameter model cone used in these tests had a non-standard apex angle 18°. The model cone was pushed through samples of weakly cemented sand prepared within a steel cylinder with 200 mm diameter and 170 mm height. Miniature cone resistances were calculated numerically using ABAQUS/EXPLICIT version 6.11 which showed good agreement with experimental test data.

1 INTRODUCTION

Weakly cemented sands and silts widely occur in nature. In general, cementation typically develops due to either chemical precipitation of calcium carbonate, microbial metabolic products or dissolution and deposition of soluble salts from groundwater (van Paasen LA, 2009). Natural cementation creates bonds between soils grains due to various geological processes such as chemical precipitation, weathering by-products and welding effect (Clough et al., 1981). Naturally cemented materials typically have variable densities and degrees of cementation. Characterization of cemented sand in the laboratory is often difficult due to sampling difficulties. Disturbance during sampling damages or breaks intergranular cementation render the soil weak. To overcome these difficulties, artificially cemented sand has been investigated via laboratory tests that simulate the cemented sand present in natural soil deposit.

In this study, weak cementation was introduced by pluviating sand particles in an aqueous medium reflecting typical groundwater mineral salt contents inoculating with a strain of calcifying bacteria obtained from a cemented sand site on the east coast of India. Isotropically consolidated drained triaxial tests were conducted on these weakly cemented sand samples in the laboratory. A stress-strain model was then developed and calibrated using ABAQUS (version 6.11) for the drained response of the artificially prepared weakly cemented sands. Subsequently, a miniature cone penetration test (MCPT) model was developed using the calibrated stress-strain model and then compared with the results of MCPT conducted in the laboratory.

2 DRAINED TRIAXIAL TEST

A series of isotropically consolidated drained triaxial tests were conducted on water pluviated sand samples. Triaxial samples, approximately 37 mm in diameter and 74 mm in height, were prepared by pouring poorly-graded siliceous sand within a mixture of mineral salt media and EPS (Extracellular polymeric substances), calcite producing bacteria obtained from a cemented sand site on the east coast of India. Specimens were prepared for introducing microbially induced cementation through three different bio-processes namely non-ureolytic calcifying, ureolytic calcifying and EPS only. Microbe produces EPS along with calcite in non-ureolytic and ureolytic calcifying processes in the absence and presence of urea in the nutrient media respectively. On the other hand, in “EPS only” process microbe produces only EPS as extracellular metabolic products leads to cementation. Specimens were prepared in such a manner that the post consolidation relative density was approximately 40 %. Bacteria-inoculated samples were sheared under a constant strain rate of 0.012 mm/min.

3 STRESS-STRAIN MODEL

A stress-strain model has been developed by modifying the Drucker-Prager model implemented in the general purpose continuum mechanics software package in ABAQUS 6.11 to account for the mobilization of friction angle, dilation angle and cohesion as the material hardens/softens. The model was used via explicit finite element algorithm incorporated in ABAQUS/explicit together with arbitrary Lagrangian Eulerian (ALE) approach to accommodate very large distortion. The model was first calibrated using drained stress-strain and volumetric behaviour of weakly cemented soil sample obtained from three processes non-urelolytic, urelolytic and EPS for isotropic confining pressures of 100 kPa and 300 kPa. Soil was modeled as elastic-plastic material. The Young's modulus, which controls the elastic behaviour, was estimated from small strain shear modulus, G_0, using

$$G_0 = \rho \times v_s^2 \qquad (2.1)$$

Where, ρ is the total mass density and V_S is the shear wave velocity. Shear wave velocities used in the model were estimated following Baxter and Sharma (2012). In Drucker-Prager constitutive model, the ratio of flow stress in triaxial tension to flow stress in triaxial compression was assumed to be 0.778 (Abaqus keyword reference manual).

A cylindrical assemblage comprised of 952 eight-noded elements with one reduced integration point (C3D8R), 76 mm in height and 38 mm in diameter, was used in these simulations. The bottom plate of Specimen was restrained in vertical and horizontal directions. Equal radial and axial pressures were applied in the next step. In the subsequent step, the axial pressure was removed, a rigid surface was placed on the top surface and a velocity was applied so as to deform the sample at a compressive axial deformation of 0.12 mm. Triaxial model was initialized to isotropic states of stress of 100 kPa and 300 kPa.

The peak friction and dilation angles and peak cohesion for cemented specimens as well as the manner in which these parameters depend on plastic strain were obtained by fitting the computed stress-strain response to laboratory test data by trial and error. The observed and simulated deformation behavior of weakly cemented sand samples in drained triaxial compression at 100 kPa and 300 kPa are presented in figures 3.1, 3.2 and 3.3. The results indicate that the stress-strain model developed in this study captures soil behavior reasonably. Friction angles, cohesion and dilation angles back figured from calibrated model are presented in Figure 3.4, 3.5 and 3.6 respectively. The parameters thus obtained indicated that the mobilized friction angle is an increasing function of plastic strain of approximately hyperbolic nature. The variation in friction angle and dilation angle with plastic strain is accommodated in this study through a user-defined subroutine. The cohesion, on the other hand, increases at small strain and found to decrease at larger strain.

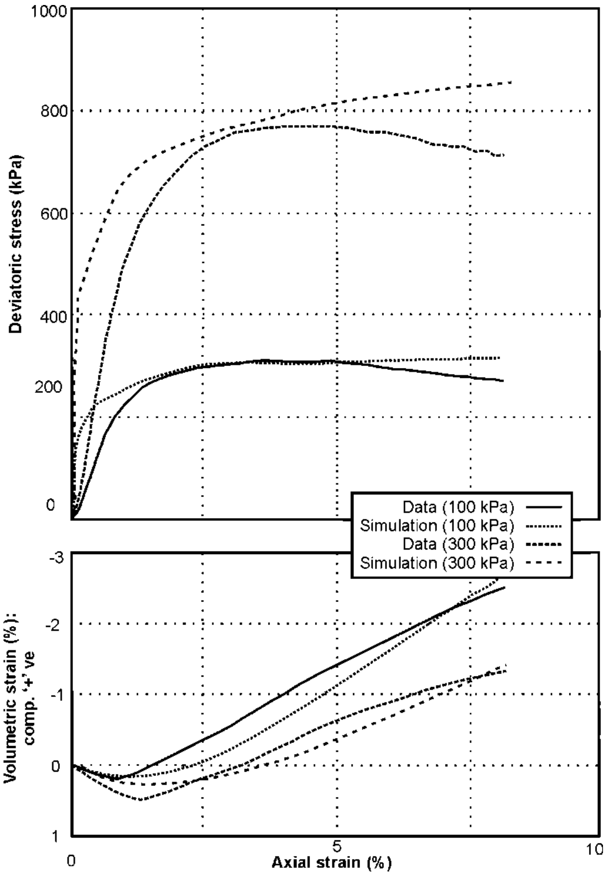

Figure 3.1: Observed and simulated triaxial compression behaviour of non-urelolytic soil sample at 100kPa and 300kPa cell pressure

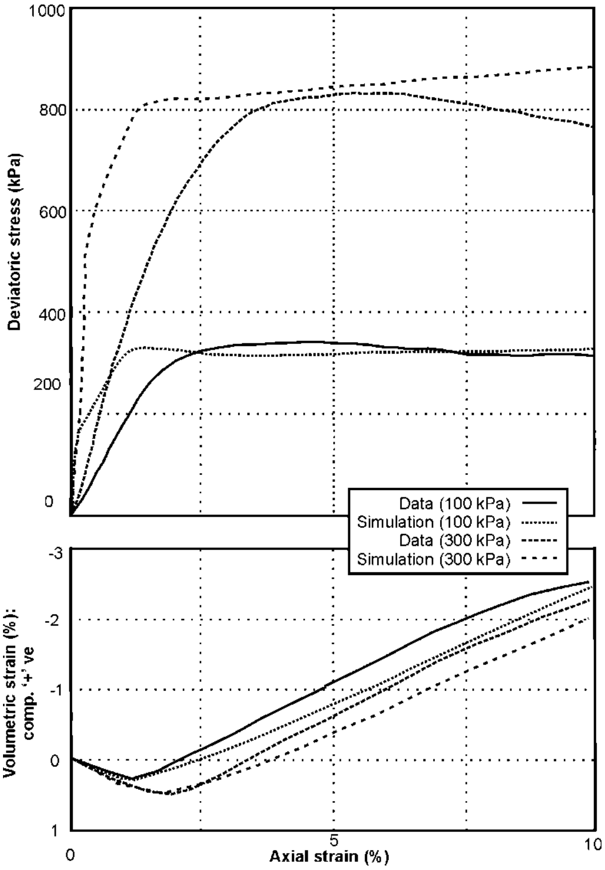

Figure 3.2: Observed and simulated triaxial compression behaviour of ureolytic soil sample at 100kPa and 300kPa cell pressure

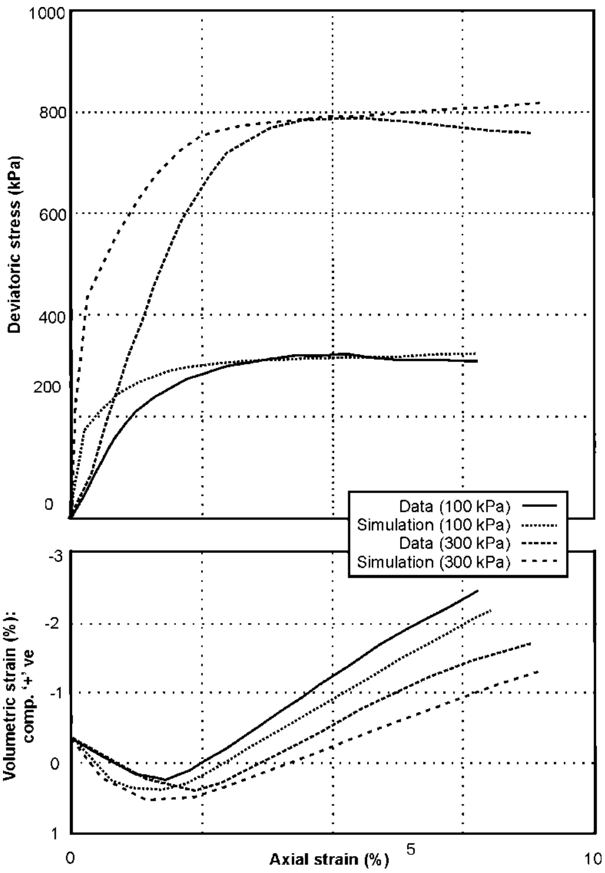

Figure 3.3: Observed and simulated triaxial compression behaviour of an EPS soil sample at 100kPa and 300kPa cell pressure

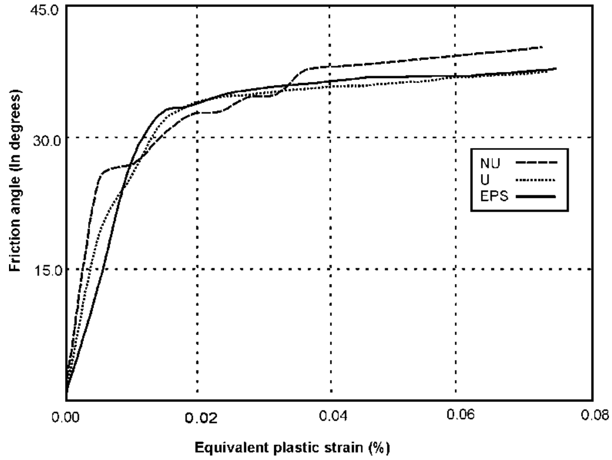

Figure 3.4: Variation of friction angle with equivalent plastic strain

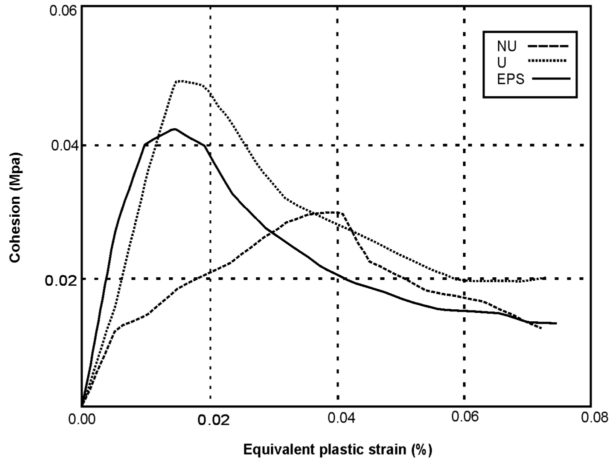

Figure 3.5: Variation of Cohesion with equivalent plastic strain

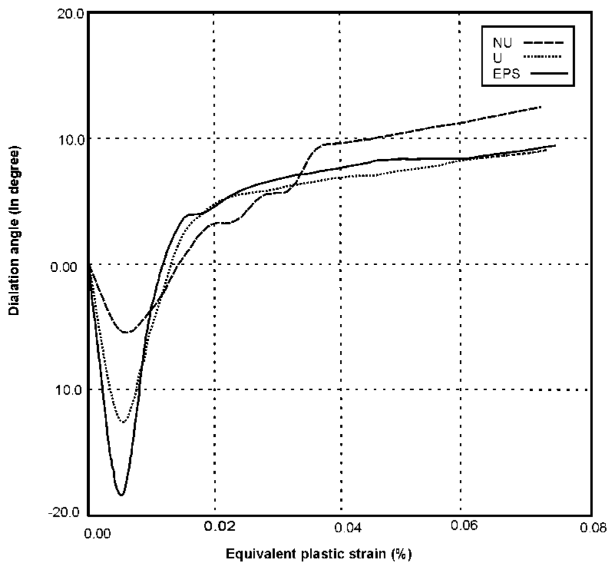

Figure 3.6: Variation of dilation angle with equivalent plastic strain

4 MINIATURE CONE PENETRATION TEST

The sample preparation procedure for miniature cone penetration test in laboratory was similar to drained triaxial test. Special precautions were made to maintain the relative density and biomass concentration to achieve certain degree of cementation. The sample is kept in a cylindrical container having diameter 200 mm and height 200 mm. An instrument similar to cone penetrometer was designed to measure tip resistance in penetrating the soil sample. The instrument was calibrated. The diameter of the needle was chosen in such a manner that ratio of the diameter of needle to that of sand sample remained less than 1:40 to minimize the effect of boundary on the result.

A 2.75-mm diameter cone used in these tests had an apex angle 18°. The diameter ratio was 36.5. The length of miniature cone was 238mm. The sleeve length was set to 1.25 times the diameter of cone. The soil sample was placed on triaxial frame and loaded at a penetration rate of 3mm/min. Load was measured from modified load cell ring at every 5 sec interval or 0.25mm penetration depth.

5 MINIATURE CONE MODEL

An axisymmetric model was created, the outer boundary of soil was 100mm from centerline and soil thickness was 170mm. In this study a diameter ratio of 72.73 was used which is more than the standard diameter ratio of 50 suggested by Lee et al. (2010) required to minimize boundary effects. An Elasto-plastic stress-strain model was used for soil with linear Drucker-Prager model defining the plastic behaviour. The cone was modeled as rigid body and soil as deformable. Initially, the cone was placed in a conical notch in the soil domain and was penetrated to a depth of 80mm at a rate of 3 mm/min. The bottom and side boundaries were restrained from moving vertically and horizontally, respectively. Adaptive Lagrangian Eulerian meshing is used to control element distortion in cases where large deformation or loss of material occurs. A master-slave relationship was used to model the penetrometer-soil contact, where the nodes of the master surface capable of penetrating through slave surface. The penetrometer was considered to be the master surface and soil as slave surface. The interface friction angle was chosen in accordance with Dietz and Lings (2006). The cone penetration resistance was calculated at an interval of 0.25mm numerically which shows good agreement with experimental test data. The comparisons of test data and simulated data were shown in Fig. 5.1, Fig. 5.2 and Fig. 5.3 for non-urelolytic, urelolytic and EPS respectively.

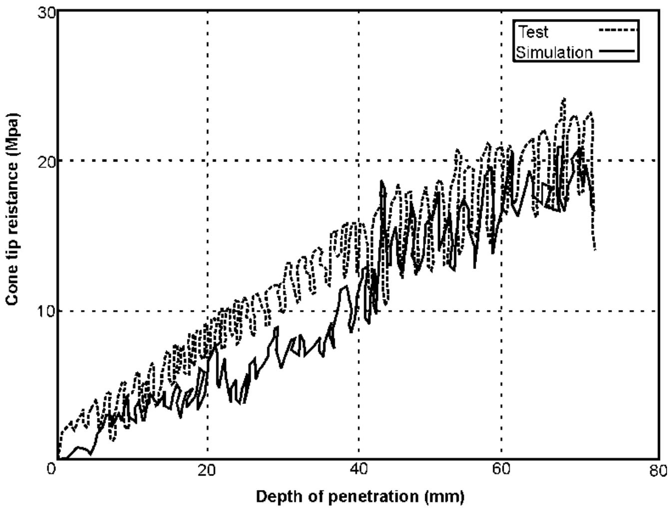

Figure 5.1: Observed and simulated cone tip resistance of non-urelolytic soil sample.

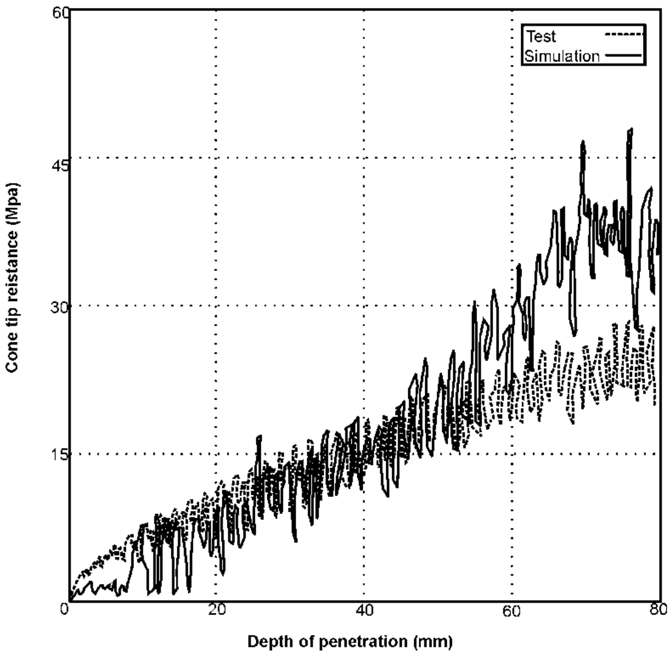

Figure 5.2: Observed and simulated cone tip resistance of urelolytic soil sample

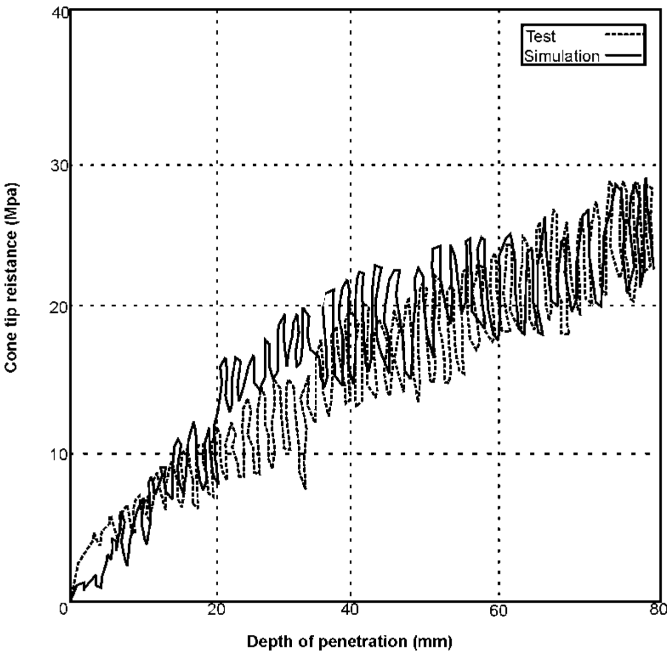

Figure 5.3: Observed and simulated cone tip resistance of EPS soil sample

6 CONCLUSIONS

It was observed that the drained triaxial compression test data and numerically simulated data shows good agreement for isotropically consolidated weakly cemented soil samples. The test data conducted in laboratory on miniature cone and simulated data from finite element analysis shows good agreement between them. The cone penetration resistance obtained in the case of EPS sample is greater in comparison with non-urelolytic and urelolytic samples due to high cementation bonding between particles.

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