An analytical study of cone penetration tests in granular material

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A numerical technique that couples the distinct-element and boundary-element methods was developed to simulate a granular soil deposit as a two-dimensional, circular disk assembly. A series of simulated penetration tests of a 60° apex angle cone was performed in normally consolidated and overconsolidated disk assemblies. The simulations allowed the cone penetration mechanisms to be evaluated from microscopic as well as the conventional, continuum mechanics points of view. Results show that the soil loading history can affect the characteristics of the soil failure mechanism and dilatancy. Lateral stress measurement behind the cone base is not sensitive to soil loading history. Finer particles appear to experience higher contact stresses and hence are more likely to be crushed by the cone penetration.

Key words: cone penetration, sand, shear strength, loading history, distinct-element method.

Une technique numérique qui couple la méthode d'élément distinct et la méthode d'élément de frontière a été développée pour simuler un dépôt de sol pulvérulent sous forme d'un assemblage en disque circulaire bidimensionnel. Une série d'essais de simulation de pénétration d'un cône ayant un angle de pointe de 60° a été réalisée dans des assemblages en disques normalement consolidés et surconsolidés. Les simulations ont permis d'évaluer les mécanismes de pénétration du cône autant sous l'angle microscopique que du point de vue de la mécanique conventionnelle des milieux continus. Les résultats montrent que l'histoire de chargement du sol peut affecter les caractéristiques du mécanisme et de la dilatance à la rupture du sol. La mesure de la contrainte latérale à l'arrière de la base du cône n'est pas sensible à l'histoire de chargement. Les particules plus fines semblent subir des contraintes de contact plus fortes et sont ainsi plus sujettes à l'écrasement lors de la pénétration du cône.

Mots clés : pénétration d'un cône, sable, résistance au cisaillement, histoire de chargement, méthode de l'élément distinct.

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Introduction

Field testing such as the cone penetration test (CPT) represents one of the few alternatives in characterizing a granular, cohesionless soil deposit because of the difficulty in obtaining undisturbed samples. The result of a typical CPT in granular soil includes the tip resistance (q_c), sleeve friction ratio (FR), and (or) lateral stress measurements behind the cone (e.g., Huntsman et al. 1986). The soil friction angle and compressibility are closely related to relative density, (D_r), which in turn can be estimated from q_c values. Empirical rules have been established to provide a stratigraphical description of the soil from CPT results (Robertson and Campanella 1983). Several correlations between q_c, D_r, vertical stress, and stress history for sands have been proposed (e.g., Durgunoglu and Mitchell 1975; Schmertmann 1978; Vilet and Mitchell 1981; Baldi et al. 1982; Tringale 1983; Jamiolkowski et al. 1988). However, there are significant discrepancies among these correlations.

Failure mechanisms of cone penetration

Many model tests have been conducted to elucidate failure mechanisms of flat-ended pile foundations. Some of the proposed failure mechanisms from these studies are shown in Fig. 1. Few of these early studies considered a wedged penetrometer such as the cone. In addition to bearing capacity type of failure mechanisms, it has also been proposed that advancement of the penetrometer takes place by the expansion of a spherical or cylindrical cavity (Vesic 1972).

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Based on their limited model tests of a wedged penetrometer, Durgunoglu and Mitchell (1975) concluded that the failure mechanism shown in Fig. 1*d* resembles their laboratory observations the most. According to Fig. 1*d*, a wedged penetrometer should induce a radial slip surface that reaches a vertical tangency. Following the failure mechanism of Fig. 1*d*, Durgunoglu and Mitchell developed empirical correlations between soil friction angle and q_c. Because of the nature of their assumed failure mechanism, an increase of depth or lateral stress (or overconsolidation ratio OCR) can cause a higher q_c value.

The model tests by Durgunoglu and Mitchell (1975) were performed in a rigid box, at shallow depths and in a dense sand to assure a general shear failure mechanism. It is known that the lateral boundary condition affects q_c values (Parkin 1988). It is not clear, however, if the lateral boundary condition can influence the penetration mechanism. Most of the field CPTs are clearly in the category of deep penetration. Previous studies (e.g., Vesic 1967) on deep foundations have indicated that beyond a critical depth there is a change of failure mechanism from shear to compression of soil under the penetrometer base, arching action of soil around the base, and grain crushing. There have been few analytical studies to verify these findings, especially for cone penetrations.

CPTs and loading history

The shear strength of granular materials in terms of the friction angle is often more than sufficient for most geosolutions, the ratio of limit cavity expansion pressure over that of the initial normal stress in a cohesionless soil increases with soil dilatancy. If cone penetration is considered as a cylindrical cavity expansion, then the maximum normal stress in the y direction, $\boldsymbol{\sigma}_{yy(\mathrm{peak})}$ below the cone tip should relate to the limit cavity expansion pressure and q_c. As shown in Fig. 12, the disks below the cone tip contract in the OC assembly, whereas in the NC assembly they dilate. Based on the aforementioned stress computations, $\boldsymbol{\sigma}_{yy(\mathrm{peak})}/\sigma_{h(\mathrm{in\ situ})}$ is 8 in the NC assembly and 3 in the OC assembly. It appears that the effects of higher $\sigma_{h(\mathrm{in\ situ})}$ as OCR increases are offset by the gradual decrease of dilatancy within the disks. Consequently, the cavity expansion pressure does not increase proportionally with $\sigma_{h(\mathrm{in\ situ})}$ and causes a negative relationship between $\boldsymbol{\sigma}_{yy(\mathrm{peak})}/\sigma_{h(\mathrm{in\ situ})}$ (or $q_c/\sigma_{h(\mathrm{in\ situ})}$) ratio and OCR.

The limit analysis by Durgunoglu and Mitchell (1975) assumes a failure surface that resembles a general shear bearing capacity failure. The simulations show that overconsolidation results in a more localized failure surface. It is known that the bearing capacity factors for the general shear failure condition are higher than those for the local shear failure. If we analyze CPT as a bearing capacity problem, the increase of OCR would invoke two conflicting factors, namely higher in situ lateral stress and a more localized failure mechanism. The effect of higher in situ lateral stress is offset by the lower bearing capacity factors associated with a more localized failure surface. As a result q_c does not increase proportionally with OCR, which is consistent with the interpretation of CPT from a cavity expansion point of view.

The simulations have indicated that neither $\boldsymbol{\sigma}_{yy}$ nor $\boldsymbol{\sigma}_{zz}$ above the cone base is sensitive to the soil loading history. The results do not support the idea of relating lateral stress measurements behind the cone to the in situ lateral stress. It appears that FR values are sensitive to the soil loading history. However, typical FR values in sand are small and subject to significant fluctuations as indicated in the simulations. The practicality of using FR to correlate soil loading history may be questionable.

Due to the complicated nature of the penetration mechanism, a rigorous interpretation of CPT results is not likely. Empirical or semiempirical correlation has been the norm and will likely remain in the future. It appears that either the cavity-expansion or bearing-capacity theory can be used as a basis to establish these correlations. However, improvement should be made in recognizing the importance of soil dilatancy and its effects on the penetration mechanism.

Conclusions

The coupled DEM–BEM numerical technique provided an environment where the cone penetration mechanisms can be evaluated without the complication caused by boundary effects. Based on the numerical simulations, the following observations are made.

The cone penetration mechanism and soil dilatancy in a granular material are both affected by the loading history. These two factors offset one other. As a result, OCR is not expected to have a significant effect on q_c values.

The lateral stress measurement behind the cone base is not expected to be sensitive to the in situ lateral stress. The FR is too low to be a useful index for the soil in situ lateral stress.

For CPTs in graded sands, the study indicates that crushing is more likely to occur in smaller particles.

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Baldi, G., Bellotti, R., Ghionna, V., Jamiolkowski, M., and Pasqualini, E. 1982. Design parameters for sands from CPT. *In* Proceedings of the 2nd European Symposium on Penetration Testing, May 24–27, 1982, Amsterdam. *Edited by* J. de Ruiter. A.A. Balkema, Rotterdam. Vol. 2. pp. 425–432.

Been, K., Crooks, J.H.A., and Rothenburg, L. 1988. A critical appraisal of CPT calibration chamber tests. *In* Proceedings, 1st International Symposium on Penetration Testing, March 20–24, 1988, Orlando, Fla. *Edited by* J. de Ruiter. A.A. Balkema, Rotterdam, The Netherlands, pp. 651–660.

Biarez, J., Burel, M., and Wack, B. 1961. Contribution à l'étude de la force portant des fondations. *In* Proceedings of the 5th International Conference on Soil Mechanics and Foundation Engineering, Paris. Vol. 1. pp. 603–609.

Brinch-Hansen, J. 1961. A general formula for bearing capacity. Danish Geotechnical Institute, Copenhagen, Bulletin 11, pp. 38–46.

Christoffersen, J., Mehrabadi, M.M., and Nemat-Nasser, S. 1981. A micromechanical description of granular material behavior. Journal of Applied Mechanics, **48**: 339–344.

Cundall, P.A. 1974. A computer model for rock-mass behavior using interactive graphics for the input and output of geometric data. United States National Technical Information Service Report AD/A-001 602.

Dayal, U., and Allen, J.H. 1975. The effect of penetration rate on the strength of remolded clay and sand samples. Canadian Geotechnical Journal, **3**: 336–348.

Durgunoglu, H.T., and Mitchell, J.K. 1975. Static penetration resistance of soils. I. Analysis. II. Evaluation of theory and implications for practice. *In* Proceedings of the Specialty Conference in In-Situ Measurements of Soil Properties, ASCE, June 1–4, 1975, Raleigh, N.C. *Edited by* H.E. Wahls. ASCE, New York. Vol. 1. pp. 151–189.

Huang, A.-B. 1989. Strain path analyses for arbitrary 3-D penetrometers. International Journal for Numerical and Analytical Methods in Geomechanics, **13**: 551–564.

Huntsman, S.R. 1985. Determination of in-situ lateral pressure of cohesionless soils by static cone penetrometer. Ph.D. thesis, University of California at Berkeley, Berkeley.

Huntsman, S.R., Mitchell, J.K., Klejbuk, L.W., and Shinde, S.B. 1986. Lateral stress measurements during cone penetration. *In* Proceedings of In Situ '86, ASCE, Blacksburg, Va. pp. 617–634.

Jamiolkowski, M., Ghionna, V.N., Lancellotta, R., and Pasqualini, E. 1988. New correlations of penetration tests for design practice. *In* Proceedings, 1st International Symposium on Penetration Testing, March 20–24, 1988, Orlando, Fla. *Edited by* J. de Ruiter. A.A. Balkema, Rotterdam, The Netherlands, pp. 263–296.

Lambrechts, J.R., and Leonards, G.A. 1978. Effects of Stress history on deformation of sand. ASCE Journal of the Geotechnical Engineering Division, **104**: 1371–1387.

Masood, T. 1990. Determination of lateral earth pressure in soils by in situ measurement. Ph.D. thesis, University of California at Berkeley, Berkeley.

Meyerhof, G.G. 1951. The ultimate bearing capacity of foundations. Géotechnique, **2**: 301–332.

Parkin, A.K. 1988. The calibration of cone penetrometers. *In* Proceedings, 1st International Symposium on Penetration Tests, March 20–24, 1988, Orlando, Fla. *Edited by* J. de Ruiter. A.A. Balkema, Rotterdam, The Netherlands, pp. 221–244.