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Analytical interpretation of dilatometer penetration through saturated cohesive soils

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A three-dimensional numerical solution to the problem of penetration of a flat plate dilatometer through saturated cohesive soil is presented. Axisymmetric stream functions are used with those corresponding to a uniform velocity field to approximate the geometry of the stream lines during penetration. After the source strengths have been determined, velocities and strains are computed. The computed strain fields are compared with those for axisymmetric and plane strain penetrations to show the need to use a three-dimensional analysis. Effective stresses are computed from the strains based on assumed constitutive response (in this case an anisotropic bounding surface model) and total stresses are computed based on equilibrium considerations. The method provides computed horizontal stress indices that compare favourably with field data. The effect of penetration on the horizontal stress index measured by the dilatometer is evaluated. This index is shown to be most sensitive to changes in overconsolidation ratio and at-rest earth pressure coefficient, which reflect the initial in situ stresses.

KEYWORDS: **earth pressures; in situ testing; pore pressures; site investigation.**

L'article présente une solution numérique tridimensionnelle au problème de pénétration d'un dilatomètre-plaque dans un sol cohérent saturé. Des fonctions de flux symétriques, associées à des fonctions décrivant un champ de vitesse uniforme, sont utilisées pour approcher la géométrie des lignes de courant durant la pénétration. Après résolution des résistances initiales, les vitesses et les déformations sont calculées. Les champs de déformation calculés sont comparés à ceux obtenus pour des pénétrations induisant des déformations planes asymétriques et démontrent la nécessité d'une analyse tridimensionnelle. Des contraintes effectives sont calculées à partir de déformations basées sur une réponse supposée constitutive (dans notre cas, un modèle anisotrope de surfaces frontières). Les contraintes totales sont calculées à partir d'hypothèses d'équilibre. La méthode permet de calculer des indices de contraintes horizontales tout à fait comparables aux données in-situ. L'influence de la pénétration sur l'indice des contraintes horizontales mesuré par dilatométrie est évaluée. Cet indice semble être très sensible aux variations du rapport de surconsolidation et du coefficient de poids des terres au repos qui traduisent les contraintes initiales in-situ.

INTRODUCTION

The flat plate dilatometer is gaining acceptance as a routine sounding test for site explorations. In many cases, rapid estimates of sub-surface conditions and soil parameters are made by way of this probe. Empirical correlations have been developed that relate pressures measured during a dilatometer test to soil type, at-rest earth pressure coefficient K_0, overconsolidation ratio (OCR), constrained modulus M, friction angle ϕ and undrained shear strength S_u. While there should be, in general, a relation between the ease with which a probe is inserted in the ground or the pressures needed to inflate a membrane attached to that probe and the strength and stiffness of an in situ soil, there is no reason to expect a one-to-one correspondence between the measured pressures and engineering characteristics of an in situ soil, because of the effects of disturbance during insertion. In the case of the dilatometer, a membrane is inflated immediately after penetration and thus the resulting pressures p_0 on the membrane depend on the amount of disturbance associated with penetration.

Progress in understanding of the effects of insertion disturbance on in situ test results was accelerated when Baligh (1985) introduced the strain path method to evaluate the strains around a rigid probe advancing through an inviscid fluid. This method is based on the assumption that during deep penetration soil is forced to follow a certain deformation path independent of soil resistance. If inertial effects are ignored, the penetration process is reduced to a flow problem where soil particles move along stream lines around a fixed rigid body. The method has been

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applied to axisymmetric problems including cone penetration and the effects of disturbance on thin-walled samplers and driven piles (Baligh, 1984, 1985, 1986; Teh & Houlsby, 1991; Baligh, Azzouz & Chin, 1987).

Huang (1989) has implemented a numerical technique to conduct strain path analysis for arbitrary three-dimensional penetrometers. His technique used a source–density distribution on the surface of a body and solved for the distribution necessary to make the normal component of fluid velocity equal to zero on the boundary. The surface of a body was approximated by a series of plane quadrilaterals. The integral equation for the source density was replaced by a set of linear equations which solved for the source densities on the quadrilaterals. Strain fields were computed based on these source densities. Huang (1989) made computations for both the cone and the dilatometer, and found that the resulting strain fields are fundamentally different and that the levels of strain induced by the dilatometer are smaller than those induced during cone penetration.

The purpose of this Paper is to compute the strain field around a penetrating dilatometer, to evaluate resulting effective and total stress fields, and to correlate model-computed horizontal stress indices K_d, with field data. K_d is based on the first dilatometer reading after penetration P_0, and should reflect disturbance effects as well as in situ horizontal stress. The method presented here does not allow evaluation of the second dilatometer reading P_1.

This Paper presents the theoretical basis and describes the approximations associated with the equations used to compute the strain field during dilatometer penetration of saturated cohesive soils, compares computed three-dimensional strains with the limiting cases of axisymmetric and plane strain penetration, summarizes the computations of effective and total stress fields during penetration, and presents an evaluation of the computed stresses by comparing the model-computed K_d values with those observed in the field at a well-documented test section and with Marchetti's (1980) data which were used to derive commonly-used empirical correlations. The influence of various parameters on computed response is also shown, and the sensitivity of the computed K_d values to these parameters is indicated.

THEORETICAL BACKGROUND

Strain fields

In accordance with the strain path approach developed by Baligh (1985), to compute the strain field around a penetrating dilatometer: initial stress conditions are established, a velocity field that satisfies conservation of volume and specified boundary conditions is computed, deformation rates along stream lines are evaluated by differentiation of computed velocities with respect to spatial co-ordinates, and the strain rates along stream lines are integrated to compute a strain path for various soil elements. Dilatometer geometry, the co-ordinate system and the location of sources and body points used in the analyses are shown in Fig. 1.

Stream lines. Two stream functions, Ψ and X, are in general required in order to define three-dimensional flow. If an analytical expression can be found for these functions such that the boundary conditions for the dilatometer are satisfied, then the stream functions can be differentiated to compute velocity fields (Rutherford, 1959). However, analytically definition of the two stream functions for three-dimensional flow in general, and for the dilatometer geometry in particular, is quite problematic. The approach taken here is a numerical one in which superposition is used to establish a grid of spherical point sources, which, when placed in a uniform velocity field v_0 and subjected to proper boundary conditions, represents flow around a penetrating dilatometer.

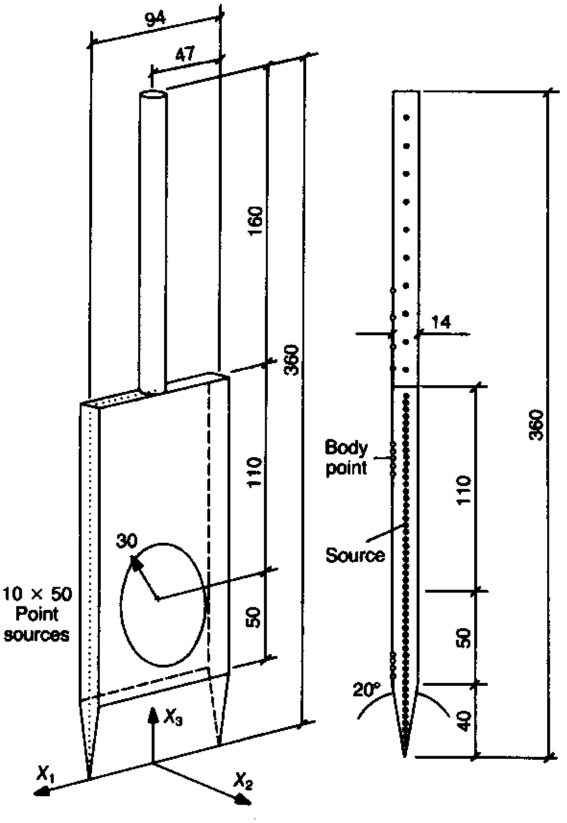

Fig. 1. Problem definition and dilatometer geometry: dimensions in mm

OCR, K_o is varied over a range of reasonable values defined by variation of the terms in (Schmidt, 1966)

$$K_{o(oc)} = K_{o(nc)} \mathrm{OCR}^m \qquad (19)$$

where $K_{o(nc)}$ varies between the limits defined by $(1 - \sin \phi)$ for ϕ of 17–37°, and m varies between 0·3 and 0·5 for a cohesive soil (Ladd, Foott, Ishihara, Schlosser & Poulos, 1977).

The results of these computations are shown in Fig. 9, where OCR is plotted against measured K_d for a number of cohesive soil sites (Mayne, 1987). The ranges of computed K_d values from this parametric study are superposed on the field data; the former follow the trend of the latter, providing a measure of how well the model accounts for disturbance effects. Because site-specific soil parameters were not used to compute the K_d values numerically, the agreement between the field and model-computed values emphasizes the primary dependence of K_d on the initial soil conditions and the minor influence of strength and compressibility.

The parametric studies also indicate that the effective stress and pore pressure responses during penetration differ as OCR increases. Fig. 10 shows σ_{22}^T and σ_{22} for OCRs of 1·3 and 8 computed at the stream line initially located $x_2 = 10$ mm from the centre of the blade. In contrast to the lightly overconsolidated conditions where the total stress increase is primarily a result of pore pressure increase during penetration, both total and effective stresses increase during penetration for an OCR of 8. In general, the model computes positive u_e for OCRs that vary from 1 to 8. Fig. 11 shows computed u_e normalized by the change in σ_{22}^T during penetration. The shaded zone is based on the range of values used in the parametric study, with the exception of ϕ, which is summarized in Table 3. The effect of ϕ is shown

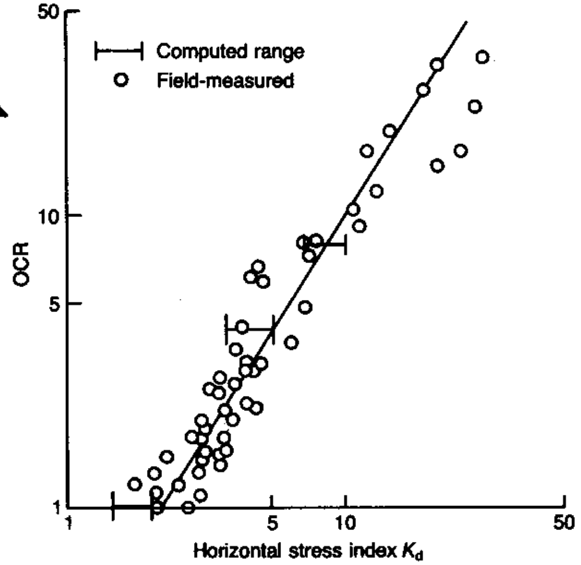

Fig. 9. Computed and observed K_d values (adapted from Mayne (1987))

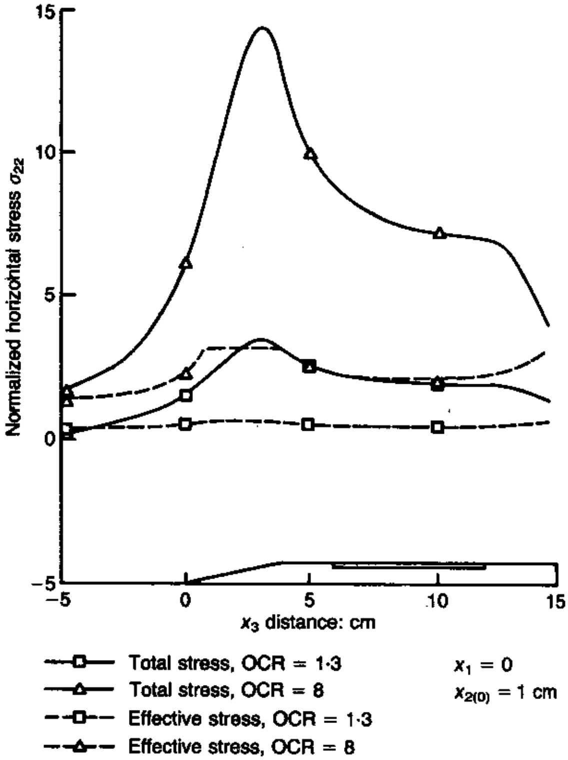

Fig. 10. Computed horizontal stresses for OCRs of 1·3 and 8 at the centre of the membrane: normalized by initial effective overburden pressure

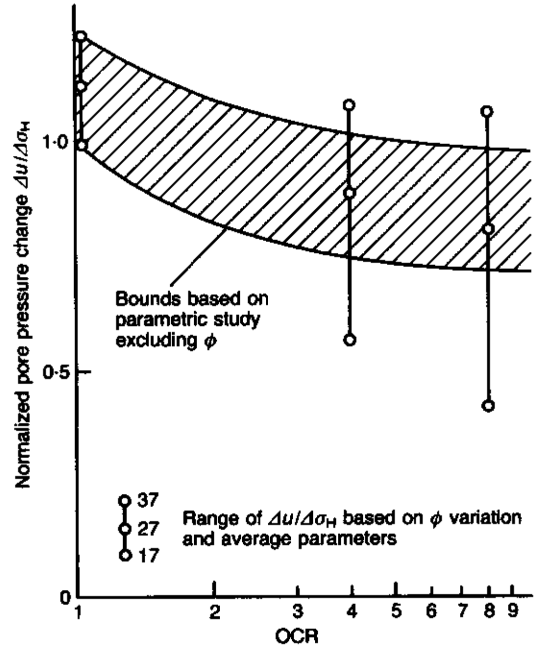

Fig. 11. Computed normalized excess pore pressure