Analysis of the dilatometer test in undrained clay

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The Marchetti dilatometer is being used increasingly in geotechnical practice to obtain design parameters for a variety of soils. Various authors have claimed success in obtaining strength and deformation parameters from this test, as well as knowledge of the stress state in the ground. All of these parameters are important for the prediction of soil behaviour in practical application. To date, the interpretation of the test has been performed almost exclusively using empirical methods. Curiously, there seems to have been little attempt so far to develop rigorous theoretical methods of the dilatometer. In this paper, a theoretical treatment of the dilatometer test in undrained clays is presented. Results of a series of numerical analyses have been used to develop an interpretation of the field test, that is not based on empiricism but on the rigorous application of an elastoplastic soil model to the behaviour of undrained clay soils.

Introduction

Site investigation and assessment of the characteristics of soils are essential parts of the geotechnical design process. The principal parameters of interest to designers are strength, deformation moduli, in situ horizontal stress and permeability. In situ testing to complement laboratory tests in obtaining these fundamental soil properties is becoming increasingly important in practice. Demand for in situ testing has developed with a growing appreciation of the inadequacy of conventional laboratory testing. Inevitable sample disturbance affects laboratory test results and raises questions as to the validity of the soil strength and deformation properties measured. Difficulties associated with the sampling of undisturbed soil specimens have led to the development of indirect methods in which the strength and deformation characteristics of the soil under field conditions are related to parameters derived from in situ penetration tests. Because of the complex behaviour of the soil when subject to the sophisticated loading conditions imposed by the in situ tests, the interpretation of test data is beset with difficulties (see, for example, Wroth (1984)). The quality of the interpretation, however, directly affects the accuracy of the soil properties obtained from the in situ tests. It is therefore vital to develop rigorous methods for the interpretation of in situ penetration tests so that the accuracy of the derived soil properties can be assured.

A relatively new in situ penetration test device, the flat dilatometer, is being used increasingly in geotechnical practice to obtain design parameters for a variety of soils because

(*a*) it is simple to operate and maintain
(*b* it does not rely on minimizing disturbance during insertion
(*c*) it provides a repeatable and continuous profile of the measured parameters.

The dilatometer is a flat-bladed penetrometer 14 mm thick, 95 mm wide, 220 mm long, which has a flexible stainless steel membrane 60 mm in diameter located on one face of the plate (Marchetti, 1980). Usually the dilatometer is inserted into the ground in a quasi-static manner and then its circular membrane is pressurized by way of a control console. Pressure expansion of the membrane occurs at a given rate and pressures are recorded at two instants: at the first to initiate movement of the membrane off the plane of the blade into the soil, and at the second to cause a membrane deformation of 1 mm against the soil.

In the past, the interpretation of the dilatometer test has been performed almost exclusively using empirical correlations, but this is not considered to be ideal. It is now considered preferable to interpret in situ tests using a rigorous analysis, based on a well-defined soil model and taking proper account of the appropriate boundary conditions. This has not always been possible due to the lack of suitable analytical or numerical solutions.

This paper presents a preliminary study aimed at the development of rigorous theoretical models of the dilatometer test in clay. In particular, the behaviour of undrained clay has been modelled as an elastic–perfectly plastic material obeying the Tresca yield criterion, and the dilatometer test has been analysed as a boundary value problem using the finite element technique.

Methods of analysis

As is the case with other mechanical in situ tests, the dilatometer does not measure any particular properties of the soil directly; rather, the load response to an imposed deformation is measured.

As mentioned previously, the conventional interpretation of the dilatometer test data is based predominantly on empirical correlations, using measurements of the lift-off pressure of the membrane P_0 and the pressure required to cause a further 1 mm expansion of the membrane P_1. These two pressures are related to the undrained shear strength (S_u), the initial total horizontal stress (σ_{h0}), the soil rigidity index (G/S_u, where G is the elastic shear modulus of the soil) and the stress history. Before using any data from the dilatometer tests it is important to account for the fact that the dilatometer is a soil displacing probe. The initial state of stress in the soil is altered by the installation of the dilatometer. The magnitude of these changes depends on many factors such as stress history and soil stiffness. Thus, a sensible interpretation of the dilatometer test data requires a more fundamental understanding of the soil behaviour during penetration as well as during membrane expansion.

The penetration of the dilatometer can be regarded as a complex loading test on the soil. A possible way of analysing the penetration process is to model it as the expansion of a flat cavity, tractable as the enforcement into the soil of an opposing pair of rigid vertical strips. The penetration of the dilatometer causes a horizontal displacement of the soil elements originally on the vertical axis of 7 mm (the half thickness of the dilatometer). During the penetration of the dilatometer there is a

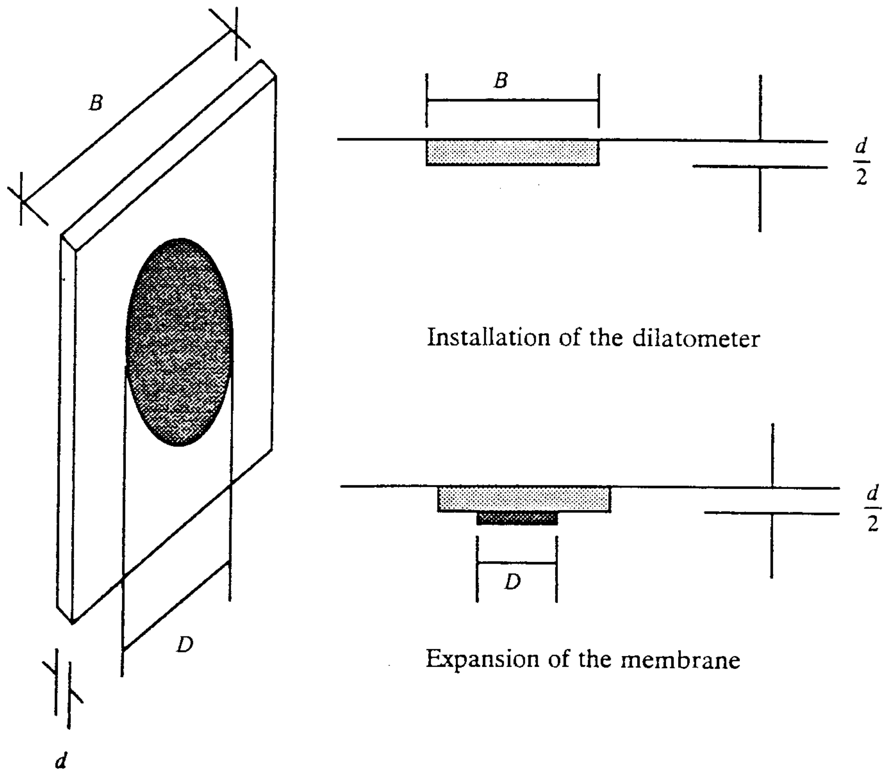

Fig. 1. Modelling of the dilatometer test process

concentration of shear strain near the edges of the blade, so that the volume of soil facing the membrane undergoes a smaller shear strain than other areas. The subsequent expansion of the circular membrane to 1 mm outward displacement generates smaller increments of strain in the soil and this expansion may be satisfactorily modelled as a continued loading of a circular area after the penetration stage. This approach is shown graphically in Fig. 1.

Analysis of the dilatometer test

To gain a better understanding of the dilatometer test process, numerical simulations have been carried out for the test in undrained clay. The soil mass has been idealized as an elastic–perfectly plastic medium which obeys the Tresca yield criterion and deforms under constant volume conditions. The numerical work was carried out using a general finite element program, AFENA, developed at the University of Sydney (Carter and Balaam, 1989). Figure 2 shows the geometry and boundary conditions used for modelling the installation of the dilatometer. A mesh that consists of 400 eight-noded plane strain elements and 1281 nodes was used. The outer boundaries of the mesh were placed at a distance of approximately 25 times the width of the dilatometer from its centre so that the behaviour of an infinite medium could be appropriately modelled. Since only a quarter of the dilatometer is analysed and due to the symmetric nature of the problem, a rigid vertical boundary condition is used for the upper boundary of the finite element mesh. Care was taken in designing the mesh so that regions likely to have high stress gradients had a higher density of elements. A reduced integration scheme (2 × 2) was used to approximate the stiffness matrix of the soil mass so that the incompressibility condition could be adequately approximated (Sloan and Randolph, 1982; Yu, 1991). Furthermore, elastic incompressibility was approximated by assigning a value of 0.49 to Poisson's ratio.

As mentioned above, the analysis can be divided into two different stages. First of all, the installation of the dilatometer was modelled as a pair of opposing rigid strips. The expansion of the dilatometer membrane could also be modelled as a continuous loading of a smaller circular area. Obviously, the modelling of the second stage involving the expansion of the dilatometer membrane is more complex than the first stage. This is mainly due to the fact that accurate modelling of the expansion of the membrane would require a three dimensional analysis. As this paper represents the first stage of an on-going research programme on the analysis of the dilatometer, only the installation process has been considered here. The analysis of the expansion of the dilatometer membrane is currently in progress and will be treated in a later paper.

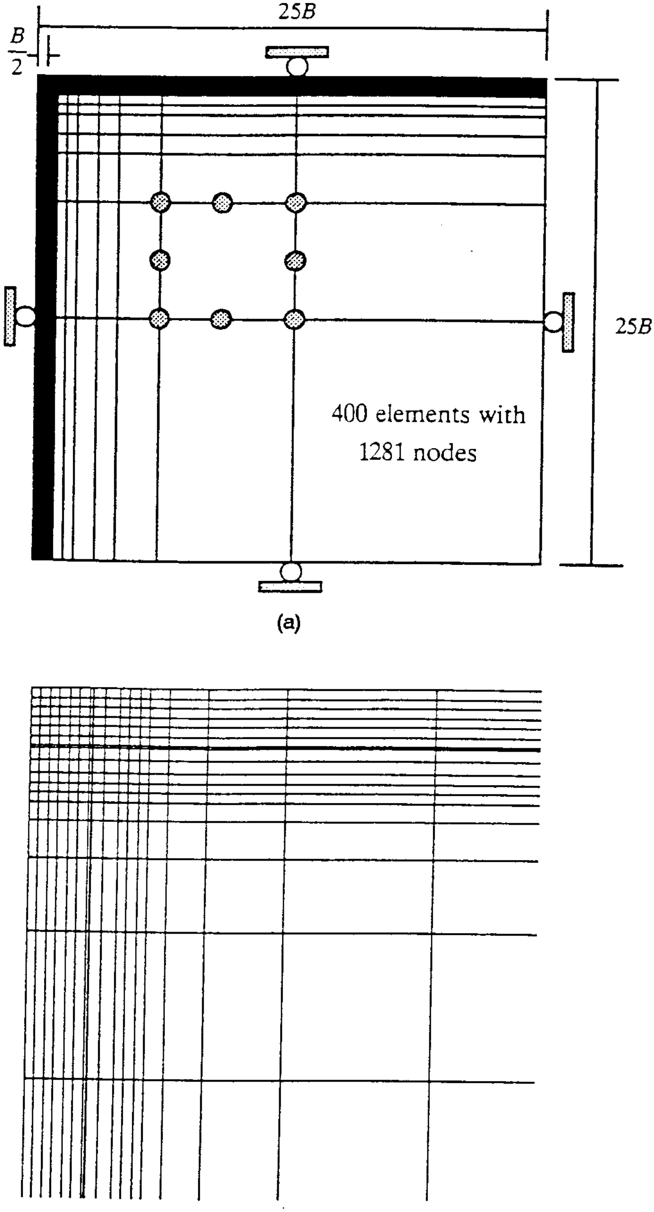

Fig. 2. (a) The overall mesh and boundary conditions for the dilatometer analysis, and (b) the detailed mesh for the region around the dilatometer

The dilatometer installation is modelled as a plane strain problem with no strain in the vertical direction. For simplicity in this preliminary study, it is also assumed that the initial state of stress in the ground is isotropic.

The dilatometer analysis simulates the full-displacement penetration of a flat spade into the ground, and in some respects this is similar to the installation of a full-displacement pressuremeter and a cone. Recent research suggests that the installation of the full-displacement pressuremeter can be satisfactorily modelled as the expansion of a cylindrical cavity within the soil (Houlsby and Withers, 1988; Yu, 1990; Houlsby and Yu, 1990). It has been pointed out (Baligh, 1986) that this modelling of installation provides only an approximate solution, but nevertheless, this simple approach has been largely supported by other theoretical studies on the cone penetration test (e.g. Teh (1987)). Teh showed that the stress distribution far behind the cone-tip predicted from Baligh's strain path method is similar to the distribution created by the expansion of a cylindrical cavity from zero initial radius. In detail, the stresses seem to correspond more closely to a cavity expansion followed by a small contraction, but the magnitude of the appropriate contraction is difficult to assess. According to the cavity expansion theory, the lift-off pressure of the cone-pressuremeter test in undrained Tresca materials, P_i, can be expressed in a normalized manner as follows:

$$N_{P_i} = \frac{P_i - \sigma_{h0}}{S_u} = 1 + \ln \frac{G}{S_u} \tag{1}$$

Equation (1) indicates that the stress changes due to the installation are mainly controlled by the rigidity index and undrained shear strength. Because of the similarity between the installation of the dilatometer and the full-displacement pressuremeter (or cone-pressuremeter), it would be expected that the lift-off pressure of the dilatometer should also be primarily controlled by the undrained shear strength and the rigidity index of the soil. It is being increasingly recognized that the rigidity index is one of the most important parameters in the understanding of many in situ tests in undrained clays (Houlsby and Wroth, 1989; Yu, 1992; Yeung and Carter, 1990). It is for this reason that the effects of the rigidity index of the soil will be studied in detail in this paper.

Numerical results

Figure 3 shows the typical result of a numerical simulation of the dilatometer test in undrained clay. The pressure–expansion curve from each numerical simulation is interpreted as if it were derived from a real test. The average value of the dilatometer–soil contact pressure at end of

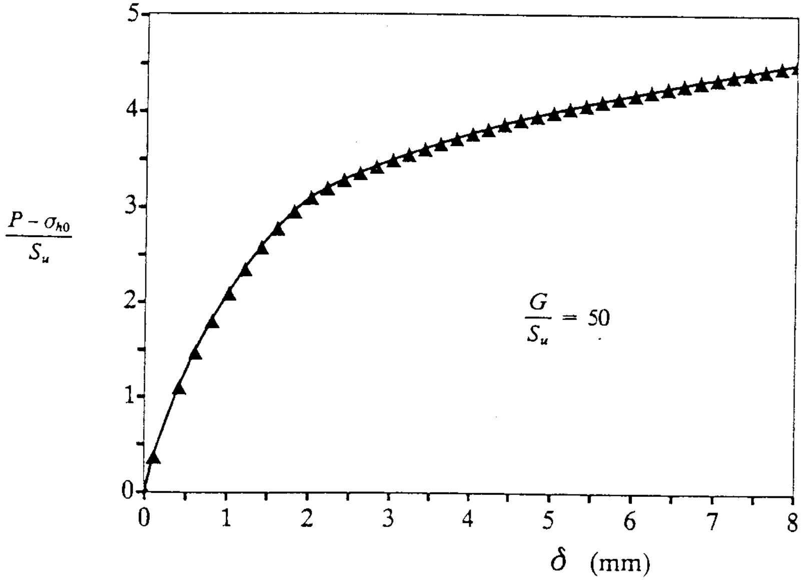

Fig. 3. Typical result of a numerical simulation of the dilatometer test

installation, i.e. when the outward horizontal displacement of each rigid strip (δ) reaches 7 mm, is denoted by P_0. The values of 25, 50, 100, 200, 300 and 500 have been selected for the rigidity index in the calculations so that its effects could be fully investigated.

As discussed earlier, the lift-off pressure P_0 against the side of a penetrating dilatometer is generally a function of initial total horizontal stress σ_{h0}, the undrained shear strength and the rigidity index of the soil. The results of the analyses can be represented by a non-dimensional parameter defined by $N_{P_0} = (P_0 - \sigma_{h0})/S_u$.

Figure 4 shows the predicted variation of the normalized lift-off pressure N_{P_0} with the rigidity index. It is found that N_{P_0} increases significantly with the rigidity index. The value of N_{P_0} ranges from 3.64 for very soft clays to 8.3 for stiff soils. The numerical data presented in Fig. 4 may be approximately represented by the following expression

$$N_{P_0} = \frac{P_0 - \sigma_{h0}}{S_u} = -1.75 + 1.57 \ln \frac{G}{S_u} \tag{2}$$

To highlight the significance of the numerical correlation (2), the results of field dilatometer tests in clays reported by Marchetti (1980) have been reanalysed. A total of 16 tests which have independent measurements of K_D, K_0, OCR and S_u/σ'_{v0} are particularly useful for this purpose. The quantity K_D denotes the lateral stress index of the

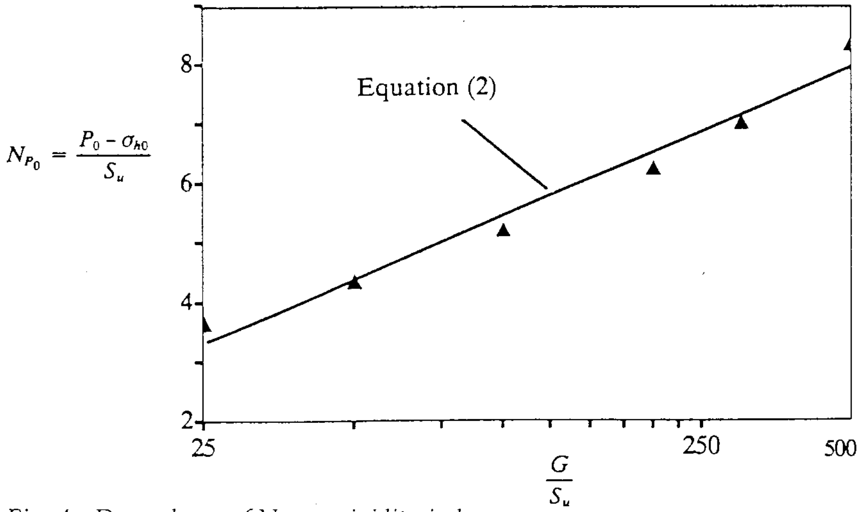

Fig. 4. Dependence of N_{P_0} on rigidity index

dilatometer test, defined as $(P_0 - u)/\sigma'_{v0}$, where σ'_{v0} and u are the vertical effective stress and the pore water pressure respectively prior to the dilatometer insertion. K_0 represents the initial lateral stress ratio given by $(\sigma_{h0} - u)/\sigma'_{v0}$ and OCR stands for the overconsolidation ratio of the soil. The normalized lift-off pressure defined previously in this paper for

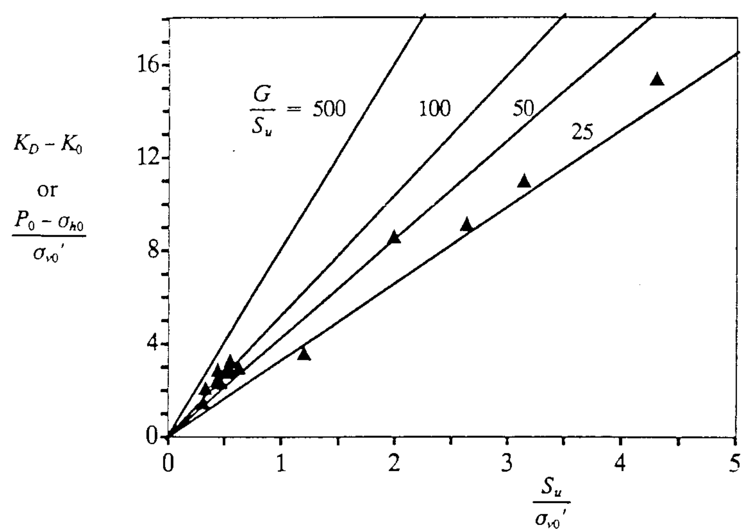

Fig. 5. Correlation between $K_D - K_0$ and S_u/σ'_{v0}

the dilatometer can be calculated using the known values of K_D, K_0 and S_u/σ'_{v0} according to $N_{P_0} = (P_0 - \sigma_{h0})/S_u = (K_D - K_0)/(S_u/\sigma'_{v0})$. Plotted in Fig. 5 is the variation of $K_D - K_0$ with S_u/σ'_{v0}. The triangles represent the actual test data reported by Marchetti (1980), while the solid lines drawn on this figure represent a form of the theoretical relationship expressed in eqn. (2), for selected values of rigidity index. It is easily shown that the slope of a line passing through the origin and each individual data point represents the value of N_{P_0} for that test. Using the correlation (2), the rigidity index for the soil in each test can be estimated from the measured value of N_{P_0}.

It has been well established by both experimental studies (Ladd et al., 1971; Ladd and Edgers, 1972) and theoretical research using the concepts of Critical State Soil Mechanics (Wroth and Houlsby, 1985) that the rigidity index of the soil increases with OCR until OCR is about 2.0, after which it starts to decrease with OCR. With the theoretical result (2), it is possible to estimate the variation of the rigidity index with overconsolidation ratio OCR from the field test results.

Figure 6 presents the measured variation of N_{P_0} with OCR, obtained from the field tests. It is found that the experimental value of normalized lift-off pressure range from 3.03 to 6.72. As discussed before, an estimate can also be made of the rigidity index from the value of N_{P_0}, by using eqn. (2) for each test. The results obtained using this approach are shown in Fig. 7. Although there is a scatter in the data, it can be clearly seen that the variation of rigidity index with OCR deduced from the

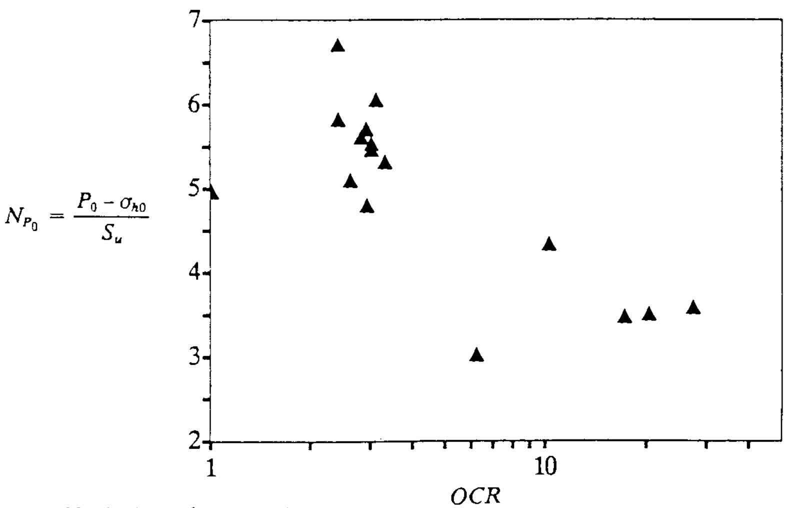

Fig. 6. Variation of N_{P_0} with OCR

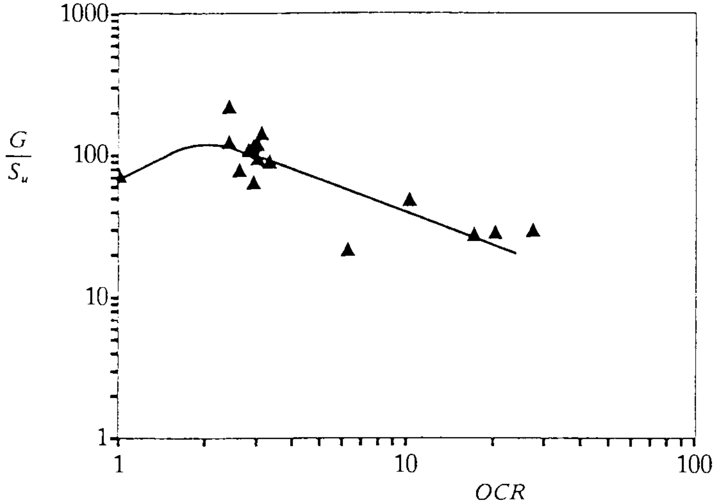

Fig. 7. Variation of rigidity index with OCR

dilatometer test results follows a pattern that is consistent with independent estimates, specifically the experimental data cited previously and the theoretical prediction using the concepts of Critical State Soil Mechanics.

It is interesting to compare the lift-off pressures predicted for the flat blade dilatometer and the full displacement pressuremeter (or cone-

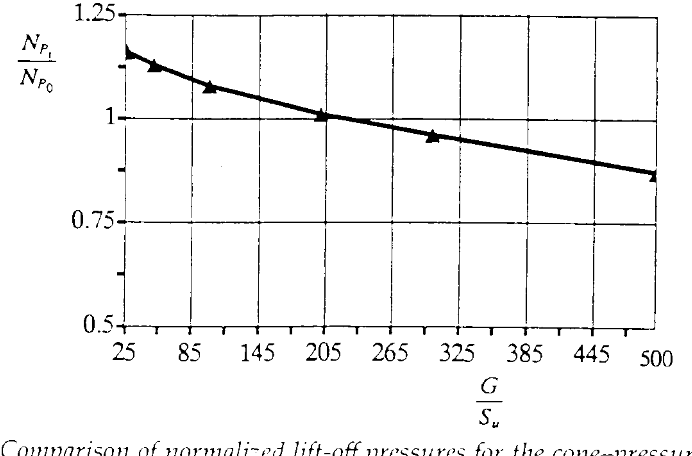

Fig. 8. Comparison of normalized lift-off pressures for the cone–pressuremeter and the dilatometer

pressuremeter). As argued before, the lift-off pressure P_i for the full-displacement pressuremeter may be estimated by eqn. (1), and this estimate has been obtained from the theory for a cylindrical cavity expansion. The numerical results presented in Fig. 4 (or eqn. (2)) may be used to provide an approximation for the lift-off pressure for the dilatometer P_0. Figure 8 shows the predicted variation of the ratio of the normalized lift-off pressures for the cone-pressuremeter and the dilatometer with the rigidity index. It can be seen that the predicted lift-off pressure for the cone pressuremeter is slightly higher than that of the dilatometer for soft clays, but the reverse is true for stiff clays. In general, however, the lift-off pressures for both the cone–pressuremeter and the dilatometer are very close. This predicted trend is consistent with the field data reported by Lutenegger and Blanchard (1990), who conducted many field with tests both the full-displacement pressuremeter and the flat dilatometer at a number of different clay sites. The soils tested ranged in stiffness from very soft sensitive marine clays to very stiff glacial clay tills. The comparison of measured lift-off pressures for the cone-pressuremeter and the dilatometer is shown in Fig. 9.

Conclusion

This paper has described a numerical study of the flat dilatometer test in undrained clay. It represents the first stage of an on-going research

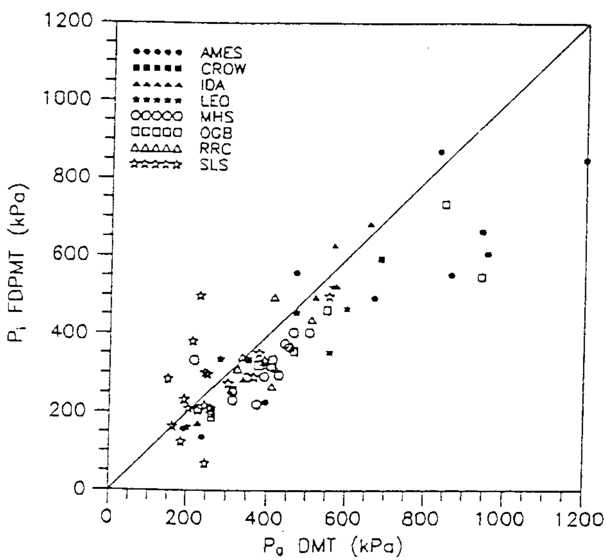

Fig. 9. Comparison of measured lift-off pressures for the cone–pressuremeter and the dilatometer (after Lutenegger and Blanchard (1990))

programme on the analysis of the dilatometer test, and so attention has been focused on the modelling of the dilatomer installation. The penetration of the dilatometer into the ground was modelled as the expansion of a flat cavity. A plane strain condition was assumed, with no strain permitted in the vertical direction.

The results of a series of numerical analyses indicate that the lift-off pressure of the flat dilatometer is a function of initial horizontal stress, undrained shear strength and rigidity index of the soil. It was found that the normalized lift-off pressure of the dilatometer, as defined by $N_{P_0} = (P_0 - \sigma_{h0})/S_u$, is not a constant but increases very significantly with the rigidity index of the soil. With the numerical correlation between the normalized lift-off pressure and the rigidity index, the shear modulus can be calculated provided K_D, K_0 and S_u can be estimated. The application of the numerical predictions to field test results leads to a similar pattern for the variation of the rigidity index with overconsolidation ratio OCR as observed in laboratory tests. The theoretical correlation has also been used to predict the relative magnitudes of the lift-off pressures for both the full-displacement pressuremeter and the flat dilatometer. In particular, it suggests that the lift-off pressure of the full-displacement pressuremeter is generally close to that of the dilatometer, with the lift-off pressure of the pressuremeter being slightly lower for stiff clays. This prediction is validated by the results of many field tests in clays carried out with both the full-displacement pressuremeter and the dilatometer.

The numerical study presented in this paper is of limited scope. A comprehensive method for the interpretation of the dilatometer test will not be achieved until the expansion of the circular membrane has also been analysed. This task will form a second stage of the theoretical study of the dilatometer test in undrained clay. Because of the complex boundary conditions corresponding to the expansion of the circular membrane, a three dimensional analysis may be necessary. In addition, it is also proposed to extend the analysis of the dilatometer test to include a treatment of purely frictional materials, so that a rigorous method for the interpretation of the test in sand may be available. This work will form the subject of future papers.

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