INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

The paper was published in the proceedings of the 9th Australia New Zealand Conference on Geomechanics and was edited by Geoffrey Farquhar, Philip Kelsey, John Marsh and Debbie Fellows. The conference was held in Auckland, New Zealand, 8 – 11 February 2004.

Relationship between Dilatometer Test Parameters and In Situ Sand Stiffness

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Summary: The paper describes a series of field tests and numerical analyses that are aimed at establishing the link between the stiffness measured using a dilatometer in sand and the *in situ* (undisturbed) stiffness. The field experiments showed that the dilatometer modulus was typically about three times higher than *in situ* stiffness. The same ratio of three was also deduced from a simplified numerical approach, suggesting that this approach may be used to deduce improved relationships between the dilatometer modulus and *in situ* sand stiffness.

INTRODUCTION

The geotechnical profession relies heavily on *in situ* tests to assess design parameters for cohesionless soil. Many of the *in situ* test devices in common use, however, do not provide a direct measure of the non-proportional relationships between stress and strain changes in a soil (i.e. its non-linear stiffness) and, to estimate ground movements, practitioners generally resort to the derivation of a single 'operational' stiffness from empirical relationships with a single *in situ* test parameter. The actual 'operational' stiffness relevant to foundation settlement predictions is extremely difficult to quantify as it depends on the combined influence in the vicinity of foundations of many factors such as strain, stress level, density, stress history, anisotropy and ageing. Given this range of dependencies and the tenuous link between stiffness and many *in situ* test parameters (such as penetration tests, which involve a shear failure of the soil), it is not at all surprising that empirical relationships between operational stiffness and *in situ* test parameters are not generally applicable and have a relatively poor reliability.

Fahey (1998) proposed a simplified rational and practical approach to the *in situ* determination of the operational stiffness of cohesionless soils, which required measurement of the initial (very small strain) tangent shear stiffness (G_o) using seismic methods (seismic cone or surface wave) and the 'unload-reload' shear stiffness at intermediate strain levels in self boring pressuremeter tests (SBPTs). Although well designed self-boring pressuremeters impose minimal disturbance to the *in situ* sand, SBPTs are rarely employed for routine applications in view of their expense and the high level of operator expertise required. In contrast to the SBPT, the flat dilatometer test (DMT), which also provides a measure of soil stiffness at intermediate to large strains, does not contain any strain gauge circuits, and the test is simple and cheap to execute. This paper therefore examines the potential of employing the DMT as an alternative to the SBPT to provide a measure of lateral soil stiffness at strains levels well above those measured in seismic tests.

The DMT is described, in detail, in numerous references by its inventor, Prof. Silvano Marchetti (e.g. Marchetti 1980; www.marchetti-dmt.it). The test essentially involves the pushing of a 15mm thick, 95mm wide and 250mm high stainless steel blade into the ground and subsequent (pneumatic) measurement of (i) the lateral stress required to cause lift-off of a 60mm diameter steel membrane located at the centre of one side of the blade (p_o) and (ii) the stress required to cause movement at the membrane centre of 1.1mm (p_1). The increase in pressure ($p_1 - p_o$) required to induce this membrane movement in the adjacent soil is used, together with the theory of elasticity, to derive an equivalent DMT Young's modulus *(ED)* from:

$$E_D = 34.7\,(p_1 - p_o) \tag{1}$$

Installation of the DMT blade clearly causes disturbance to the *in situ* sand and it is vital that the relationship between E_D and the *in situ* stiffness is understood and quantified. Such a relationship is examined here in an initial study comprising carefully executed field experiments in Perth dune sand and simplified numerical analyses.

It is conceivable that the disturbance induced by installation of the dilatometer blade in sand is such that the subsequent measurement of stiffness bears little or no relationship to the *in situ* stiffness. Fahey and Lehane (2004) addressed this concern by comparing the very small strain Young's moduli (E_0) inferred from seismic cone tests (which do not contain any implicit disturbance effects) with E_D values measured recently at 7 sand sites in the Perth area. Apart from differences in absolute magnitude, these results indicated that E_0 and E_D vary in a similar way with the Cone Penetration Test (CPT) end resistance (q_c) and the vertical effective stress (σ'_v). Such equivalence in dependency suggests that E_D, like E_0, provides a measure of *in situ* stiffness.

SOIL CONDITIONS AT EXPERIMENTAL TEST SITE

As part of the investigation described here, a number of standard and non-standard dilatometer installations and membrane expansions were carried out at a sand site at Shenton Park, which is a suburb to the west of Perth city centre. Previous research at this site had indicated that suction led to a strong seasonal dependency of *in situ* test parameters in areas with an abundance of native trees. All DMT investigations were therefore performed in an open area of the site, where suctions pressures within the sand were shown to be relatively insignificant (Lehane and Fahey 2003).

Soil Classification

The soil conditions at the test locations comprise between 8m and 12m of dry to moist, yellow sand overlying variably cemented limestone. Although the deposit is part of a calcareous dune system, the calcite has been leached out and the sand is primarily composed of quartz, containing only minor traces of feldspar and calcium carbonate. Sieve analyses of bulk samples retrieved at 0.5m depth intervals from a 3.5m deep trial pit indicate that the sand has a fines content (< 75µm) of less than 5% and effective particles sizes, D_{50}, D_{60} and D_{10} of 0.42 ±0.02mm, 0.47±0.02mm and 0.21±0.01mm respectively. The angularity of the sand grains varies from sub-rounded to sub-angular and the maximum and minimum void ratios (e_{max} and e_{min}) are 0.81±0.01 and 0.45±0.01 respectively.

In Situ Testing

Six sand replacement tests were performed during excavation of a 3.5m deep trial pit in the test area. The results from these tests, combined with water content determinations and the measured e_{max} and e_{min} values, indicated that *in situ* water contents (w) and degrees of saturation (S_r) were relatively constant at about 3.5% and 14% respectively to a depth of 3.5m. The inferred relative densities were a little more variable but essentially indicated that the deposit had an *in situ* relative density (D_r) of 50±5% and a bulk density of 1670±25 kg/m^3.

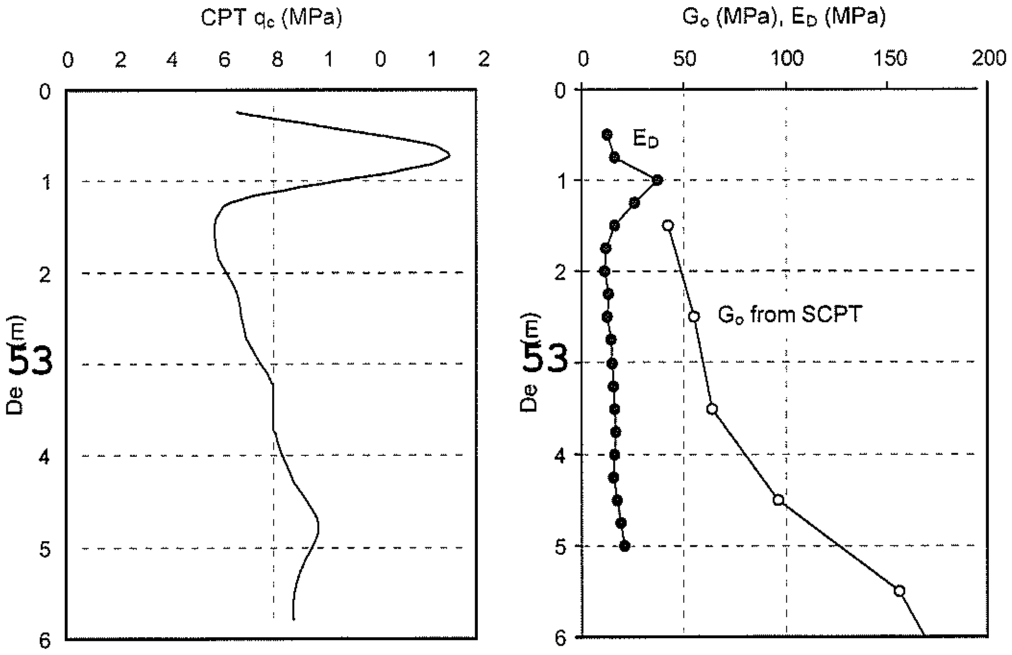

Figure 1: *In situ* test data at Shenton Park, Perth

The CPT q_c, seismic cone G_o and (standard) DMT E_D data recorded in the test area are plotted on Figure 1. These data are compatible with trends expected for an aged normally/lightly overconsolidated medium dense sand. The mean G_o/q_c and E_D/q_c ratios of 14±4 and 2.7±0.2 are consistent, for the observed CPT q_c values, with the trends indicate by the Perth sand database presented in Fahey and Lehane (2004).

Laboratory Testing

Triaxial compression tests were performed on samples of the Shenton Park sand that were reconstituted to the *in situ* D_r of 50% with degrees of saturation (S_r) varying from 3% to 100%. Samples were equipped with bender elements to facilitate measurement of the vertical shear wave velocity (and hence G_o) at various stages of the test, and with local strain instrumentation to record the degradation of stiffness with strain and mobilised strength. Data from a typical test performed on a fully saturated sample that was isotropically consolidated to 100 kPa and subsequently mobilised a peak friction angle (ϕ'_p) of 38° in drained triaxial compression are plotted on Figure 2. Figure 2a presents a summary of the G_o values determined following various (small) deviator stress (q) unloading stages performed for a range of mean effective stress levels (p') attained during the test. The observed trend is consistent with the following commonly assumed form:

$$G_o/p_{atm} = C\,(p'/p_{atm})^{0.5} \qquad \text{where } p_{atm} \text{ is atmospheric pressure} \qquad (2)$$

The best-fit value of the constant, C, for the reconstituted data on Figure 2a (with D_r=50%) is 1100. Figure 2a also plots the corresponding variation with p' of the *in situ* G_o values measured in seismic cone tests (SCPTs) assuming $K_o = 0.5$. Evidently, the *in situ* C value is about 30% higher than that of the reconstituted material; such a discrepancy may be explained by ageing phenomena (e.g. Fahey 2001) and by the probable presence of light suctions within the partially saturated *in situ* sand.

The sample's secant shear stiffness (G_{sec}) measured during the triaxial compression is plotted on Figure 2b in the form of the variation of G„ normalised by the initial tangent stiffness (G_o) with the ratio (q/q_f), where q_f is the peak deviator stress (recorded at an axial strain of 5%). This trend is compatible with the following formulation proposed by Fahey and Carter (1993):

$$G_{sec}/G_o = 1 - f(q\,/\,q_f)^g \qquad (3)$$

Equation (3) is plotted using f and g parameters of 0.99 and 0.25 respectively and is seen to provide an excellent representation of the stiffness data, especially when q/q_f >0.1 (corresponding to axial strains in excess of 0.02%). It should be noted that the G_{sec}/G_o values that are in excess of unity on Figure 2b arise as the (perhaps less reliable) local strain instrumentation at very low strains indicated higher G values than those inferred from the bender elements.

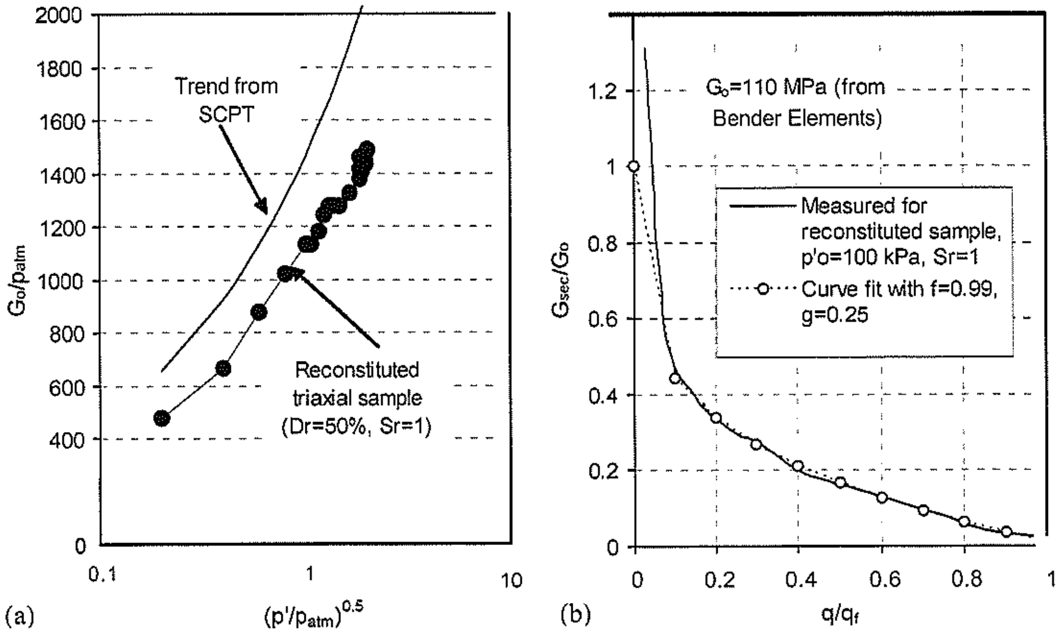

Figure 2: Triaxial Compression Test Results for Shenton Park Sand

DMT EXPERIMENTS AT SHENTON PARK

The programme of dilatometer experiments performed at Shenton Park comprised standard DMTs (i.e. the results for which are plotted on Figure 1) and a series of non-standard DMTs, which involved expansion of the DMT membrane in three trial pits following (i) pit excavation to a depth of 1.25m, 2m or 3m and placement of excavated sand around the dilatometer blade after locating it at the pit base and (ii) installation of the DMT into the backfilled sand to the base of each pit. A variety of sand placement techniques were employed around the DMT blade and sand replacement density tests were conducted to assess the corresponding D_r values.

The values of p_o and p_l measured in each of the experiments are plotted on Figure 3, which also indicates the backfill relative densities and shows p_o and p_l stresses obtained at the corresponding depths during standard DMT installations. The following general trends are apparent:

(i) Values of p_o and p_l (and hence also E_D) measured after installing the DMT into loose and medium dense backfill are typically about three times higher than those values measured for the 'wished in place' dilatometer. It is clear therefore that installation effects are significant and need to be accounted for when assessing *in situ* stiffness from E_D.

(ii) Sand density has an important effect on measured DMT parameters e.g. for DMT installations into the backfill, E_D values recorded for initial backfill D_r values of 2.5%, 26% and 53% were 2.9 MPa, 4.3 MPa and 9.2 MPa respectively.

(iii) DMT parameters measured after installation into backfill are only about 60% of the corresponding values measured following installation into *in situ* sand at the same relative density; e.g. see test results on Figure 3 at a depth (z) of 3m. This result is analogous to the trend indicated on Figure 2a and is presumably due to the effects of ageing and (possible) suctions on the stiffness of the natural material.

(iv) Evidently, E_D values are strongly related to the initial lift off pressure (p_o). For DMT installations into the backfill and into the natural *in situ* sand, E_D/p_o values were remarkably constant at 100±25. The material index (I_d) proposed by Marchetti (1980) embodies such a dependence, and he uses it as means of soil classification e.g. Marchetti (1980) shows that, when the ambient pore pressure (u_o) is zero, E_D/p_o exceeds 70 in sands and is less than 20 in clays.

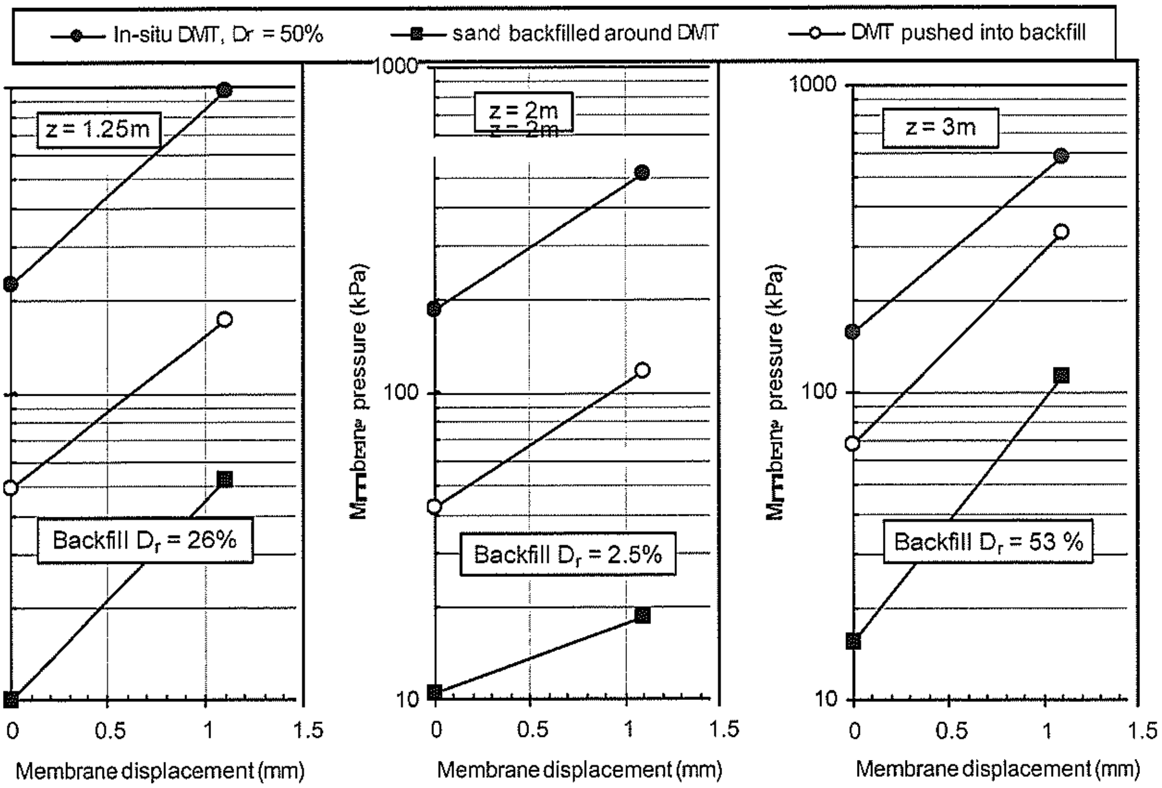

Figure 3: p_l and p, Values Determined During DMT Investigations

NUMERICAL ANALYSES

A series of finite element (FE) analyses using AFENA (Carter and Balaam, 1996) were performed to assist understanding of the DMT Shenton Park experiments. The analyses, summarised here, are confined to examination of the tests performed in the backfill with D_r = 53% at z = 3m. as the triaxial data, summarised previously, matched this relative density. All analyses employed the f-g soil shear stiffness formulation (as given by Equation 3) and used parameters derived directly from the triaxial test (i.e. C=1100. f=0.99, g=0.25. ϕ'_p=38°). Full details concerning this constitutive model and its application in FE analyses are provided in Fahey and Carter (1993).

Analysis for 'Wished In Place' Dilatometer in Backfill

Axisymmetric analyses employing 720, eight noded quadrilateral elements were performed to model expansion of the 60mm diameter *(D)* flexible membrane. The stress conditions in the mesh were assumed isotropic with an initial mean effective stress (p'_o) of 10 kPa, equivalent to the lift-off pressure in the 'wished in place' field test under consideration. A uniform pressure applied to the circular membrane simulated the membrane expansion, and restraining the nodes in the area corresponding to the blade simulated the rigid blade. Analysis was also carried out using a rigid blade. This would give a very different pattern of deformation in a linear elastic soil, but in the non-linear elastic soil used (the f-g soil model), the deformed shape of the flexible membrane is not that far from uniform (i.e. almost identical to a rigid blade).

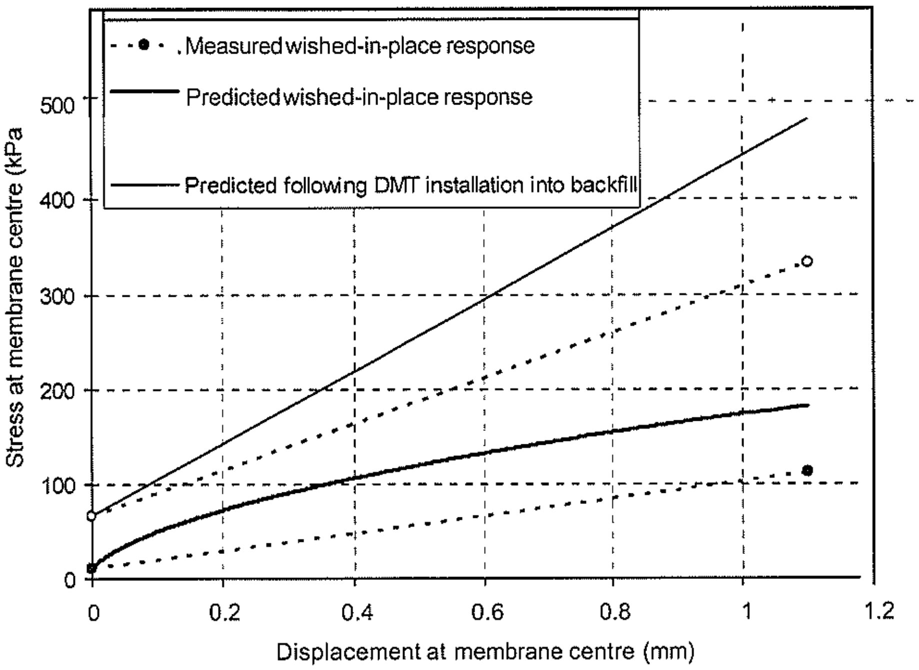

Figure 4: Predicted and Measured DMT Expansion Curves

The predicted membrane stress *vs.* membrane maximum displacement curve is plotted on Figure 4 and compared with the measured p_o and p_1 values. The prediction is seen to overestimate the measured E_D value by about 50%. Such a level of over-prediction is not surprising given the errors associated with the *in situ* measurement of very low p_o values and the assumed isotropic stress state in the vicinity of the membrane. In addition, some arching of the sand around the DMT blade may be expected to have occurred during sand placement.

The equivalent shear modulus of the soil at a displacement at the membrane centre (s_c) may be evaluated from the following expression for an elastic half space:

$$s_c = q\,D\,(1-\nu)/2G_{eq} \tag{4}$$

A G_{eq} value of 3.3MPa is inferred using this equation for the FE prediction on Figure 4 at $s_c = 1.1$mm. Equating this G_{eq} value with the expression for element stiffness given in Equation (3) indicates that its value corresponds with an average element q/q_f value of 0.7; this q/q_f ratio was developed at an axial strain of 0.68% in the triaxial test. The operational shear modulus around the membrane therefore equates to the elemental stiffness at a strain level of about 0.7%. which is approximately 0.4 s_c/D. This observation is consistent with a procedure proposed by Atkinson (2000). and others, for the estimation of equivalent stiffness beneath foundations from triaxial stiffness data. It is also noted that, even if the DMT did not induce disturbance, the E_D value measured is representative of a stiffness at a strain that is about seven times higher than the strains induced during typical unload-reload loops in SBPTs.

Analysis for Dilatometer Installation in Backfill and Subsequent Membrane Expansion

Despite significant recent advances made in numerical approaches to model penetrometer installation in clay (e.g. van den Berg 1996, Finno 1993, Hu and Randolph 1998, Yu et al. 2000), these approaches have not developed to a stage that allow a thorough analysis of dilatometer installation in sand. The simplified approach adopted here models the dilatometer blade installation as the expansion by 7.5mm (half of the blade thickness) of a circular area with a diameter of 150mm (the equivalent diameter of the side area of the blade) and subsequent contraction so that the stresses at the membrane location correspond to the lift off pressure measured in the field tests. The membrane expansion is then simulated, as before, by application of a uniform stress on a 60mm diameter area, which is located at the centre of the 150mm diameter blade.

Figure 5 shows the prediction for the pressure at the centre of the membrane during expansion of the 150mm diameter 'blade' by 7.5mm followed by unloading to the measured lift-off stress (p_o) of 65 kPa and subsequent expansion of the membrane centre by 1.1mm to a p_1 value of about 490 kPa (the expansion was then continued well past this point). The membrane expansion component of these predictions is also plotted on Figure 4, where it is compared with the measured p_1 and p_o values following dilatometer installation into the backfill.

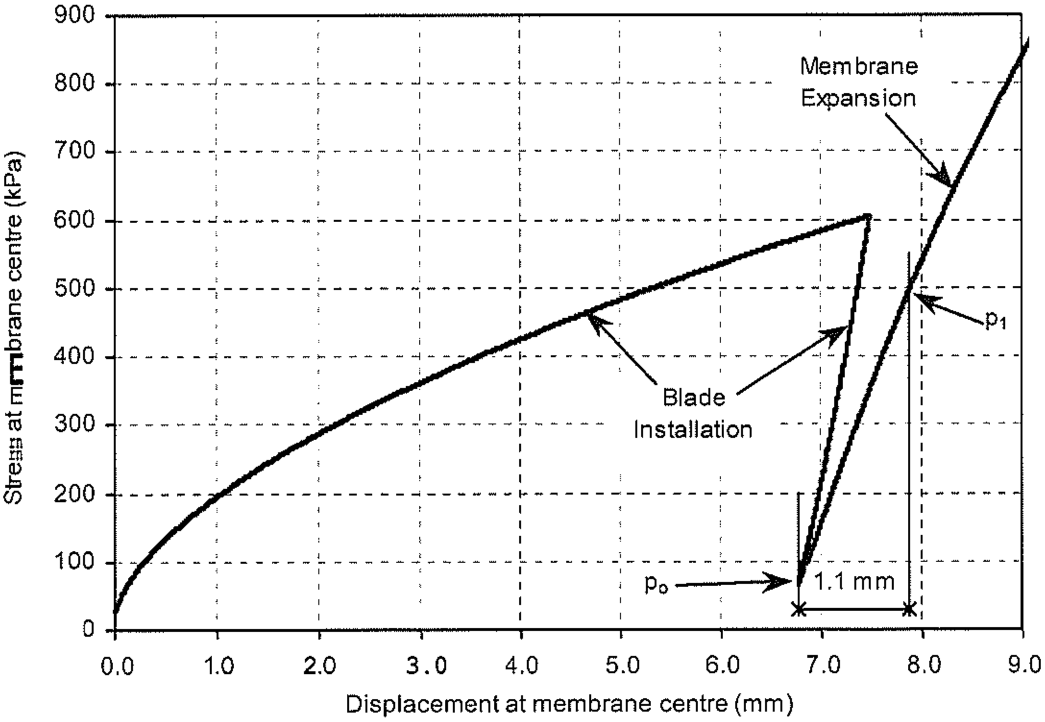

Figure 5: Stress Changes Predicted by Simplified DMT Installation Model

The FE analyses are seen to over-predict the p_l and p_o values for both the wished-in-place and pushed-in dilatometer by about 50%; a match between measurements and predictions is obtained if a lower *C* value (see Equation *2)* of 750 is employed. The FE analyses do, however, predict that, as for the field measurements at a depth of 3m, the E_D value for the pushed-in case is *2.5* times E_D for the wished-in-place case. The ability of the analysis to predict this ratio is encouraging and supports the validity of the simplification adopted to model the DMT installation process. Further FE analyses indicated that, for the soil model and parameters employed, this ratio is insensitive to the assumed initial *in situ* stress and DMT lift-off stress.

CONCLUSION

It has been shown experimentally that the E_D value measured following installation of a dilatometer in sand is about *2.5* to 3 times higher than the E_D value measured for a wished-in-place dilatometer. A simplified numerical approach to model dilatometer has been shown to predict a similar installation effect. This suggests that it may be possible to carry out a complete numerical study of the process of installation of the DMT blade, and expansion of the DMT membrane, using the non-linear elastic-plastic model of Fahey and Carter (1993), thereby allowing a full parametric study of the links between the DMT parameters and the non-linear model parameters. This approach therefore offers the possibility of a rational assessment of *in situ* stiffness (at intermediate to large strain levels) using DMT data.

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