The dilatometer test in sands: Use and limitations

Essai dilatométrique dans les sables: Domaine d'utilisation et limitations

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SYNOPSIS: The Flat Plate Dilatometer (DMT) is a soil displacing probe and its insertion alters the initial state (void ratio and mean stress) in cohesionless media. In order to assess the effect of disturbance on DMT data, laboratory tests in a small calibration chamber were conducted to obtain the DMT's response during the expansion phase in "undisturbed" and fully disturbed Ottawa sand. The experimental results demonstrate that DMT data are best interpreted in terms of normalized state parameter. Relationships obtained from large calibration chambers allow to infer the in-situ state of undisturbed sands from the DMT's stress index and the value of mean stress.

1 INTRODUCTION

The use of in-situ tests to determine design parameters is particularly important in sands where undisturbed sampling is difficult. Unfortunately, most in-situ tests do no measure actual soil properties but instead yield some index parameters which are converted to design values by means of empirical correlations. As pointed out by Wroth (1984), the choice of properties is crucial and should ideally be based on a physical appreciation of why the properties can be expected to correlate.

The flat plate dilatometer (DMT) is a rugged in-situ testing device, relatively inexpensive and rapidly gaining interest in recent years, both on-shore and offshore. The DMT is a soil displacing probe and its insertion alters the initial state (void ratio and mean stress) in cohesionless media. The fields of stress change and strain induced around the device vary significantly with distance from the membrane and are soil-type dependent. Furthermore, because of the geometry of the probe and its small dimensions, the problem is three-dimensional and a theoretical solution for an unequivocal interpretation of the results is not yet available.

The purpose of the paper is to discuss the intrepretation and use of the DMT in sands, as well as the limitations associated with the uncertainties of the key parameters controlling the soil's behaviour.

2 CURRENT INTERPRETATIONS OF DMT DATA

The design, operation and the subsequent determination of parameters from the test results has been described by Marchetti (1980) and Schmertmann (1986). Briefly, it consists of a stainless steel blade, 94 mm wide and 14 mm thick with a sharp edge and a 60 mm steel membrane on one side of the blade. Tests are performed by pushing the probe vertically into the soil and measuring the lift-off pressure and the pressure required to expand the membrane 1.1 mm at the test depths. Both readings are corrected for membrane stiffness to obtain P_o and P_1. In addition to these measurements, Schmertmann (1986) suggests to estimate the in-situ vertical effective stress,

$$\sigma_v' \approx \sigma_v - u_o,$$

and the thrust during pushing. From these field data DMT indices are defined:

Material Index $I_D = (P_1 - P_o)/(P_o - u_o)$

Horizontal Stress Index $K_D = (Po - uo)/\sigma_v'$

Dilatometer Modulus $E_D = 34.7(P_1 - P_o)$

For sands, the following engineering properties can be extracted from the field data and the DMT indices using empirical and semi-empirical relationships:

Soil Type $= f(I_D)$

Lateral Stress, $K_o = f(K_D, \phi')$

Strength $\phi' = f(K_o, \sigma_v', \text{Thrust})$

Compressibility, $M = f(I_D, E_D)$

Modulus, $E_{25} = f(E_D)$

Finally, correlations of dilatometer and calibration chamber test results led to tentative methods for the assessment of liquefaction potential of saturated sands (Marchetti, 1982; Robertson and Campanella, 1986) and to estimate foundation settlement from DMT data (Schmertmann, 1986). Other uses of DMT derived parameters include determining pile friction for design, evaluating p-y curves for laterally loaded piles, and providing quality control for ground improvement methods such as dynamic compaction.

3 DMT INTERPRETATION IN TERMS OF STATE PARAMETER

3.1 Normalized state parameter

Sand behaviour during shear depends primarily upon fabric and initial state. The state of a cohesionless soil is defined by its void ratio and its effective mean stress as shown on Figure 1. Current state, ψ, must however, be compared to a reference condition which divides the state space into two regions, leading to either a contractive or a dilative behaviour during shear. This condition can be taken as the steady state line (SSL) (Castro and Poulos, 1977; Been and Jefferies, 1985). The latter authors showed that well-defined relationships existed between ψ and the peak friction angle, volumetric strain, and dilation rate for sub-rounded to sub-angular sands. Konrad (1988) showed that these relationships could be extended to very compressible sands if the data are expressed in terms of normalized state parameter ψ/ψ_1, where ψ_1 is defined as $e_{max} - e_{min}$. This new parameter is close to the definition of relative density, D_r, except that it includes the effect of stress and of the slope of SSL. As illustrated on Figure 1, points A and B have different void ratios and thus different relative densities, yet identical normalized state parameters.

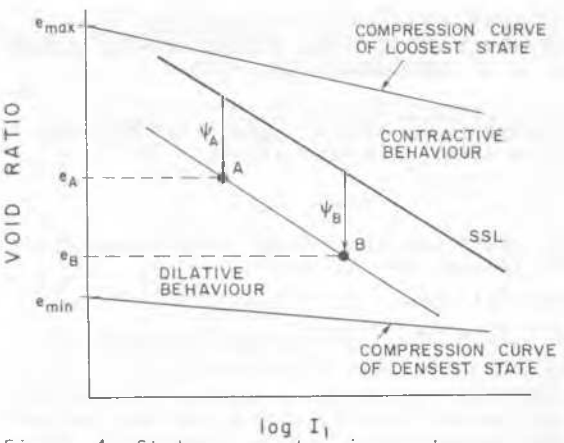

Figure 1. State parameter in sands.

3.2 Calibration chamber test results

3.2.1 Undisturbed Case. In an attempt to gain an understanding of the processes involved in DMT testing during the membrane expansion stage, laboratory tests were conducted in a small calibration chamber on "undisturbed" Ottawa sand under a given stress field. In near ideal laboratory conditions, i.e. uniform void ratio and fairly uniform stress field, tests results showed that there is a unique relationship between the expansion pressure ($P_1 - P_o$), the mean stress state, I'_1 , and the normalized state parameter (Fig. 3). For highly dilative sands, the ratio $(P_1-P_o)/I'_1$ is very large owing to the large stiffness of sands in its densest state while extremely loose sands would be characterized by values of $(P_1-P_o)/I'_1$ close to zero if their representative point would be in the contractive domain.

3.2.2 Fully Disturbed Case. Pushing the DMT into a cohesionless medium creates state and stress changes around the probe, which, in turn affect the properties of the surrounding soil and complicates the interpretation of the test results. To evaluate the void ratio changes induced by the insertion of the DMT, the experimental set-up used for the undisturbed case was modified to allow for the horizontal introduction of the DMT into a medium at an initial void ratio and under


Figure 2. View of experimental set-up

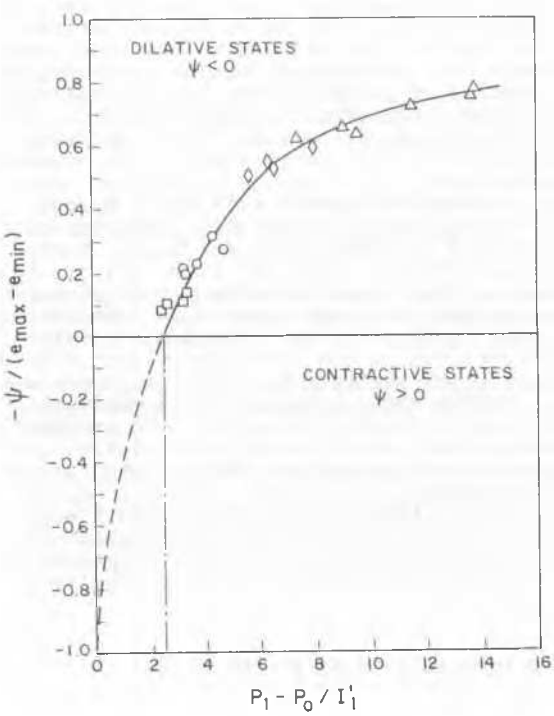

Figure 3. Relationship between normalized state parameter and expansion pressure from DMT test

a given stress field (Figure 2). During penetration, the vertical load was maintained constant by adjusting the pressure in the hydraulic jack. Multiple-sieve pluviation was used to control the placement of dry Ottawa sand in the container at three relative densities of about 34, 73 and 88 percent. As vertical stress is applied, the void ratio changes and the initial state is shown on Figure 4 for each test. The state after insertion was obtained from the DMT data in conjunction with the relationship given in Figure 3. The experimental results given in Figure 4 clearly show that sand in a loose state contracts around the DMT's probe while it dilates when in a dense condition. The changes are not as significant for sand in a medium state of compaction. It appears furthermore that the induced void ratio changes are not only a function of initial state but also of stress magnitude. This is especially noted for very dense sand in which void ratio change increased with increasing stress levels. For medium and dense conditions, the lift-off pressure was fairly close to the applied vertical stress but was about systematically lower than the applied stress in loose sands. Moreover, the difference increased with increasing stress levels. It is thought that the combined effects of arching and rigid inclusion may account for these non-uniform stress distributions.

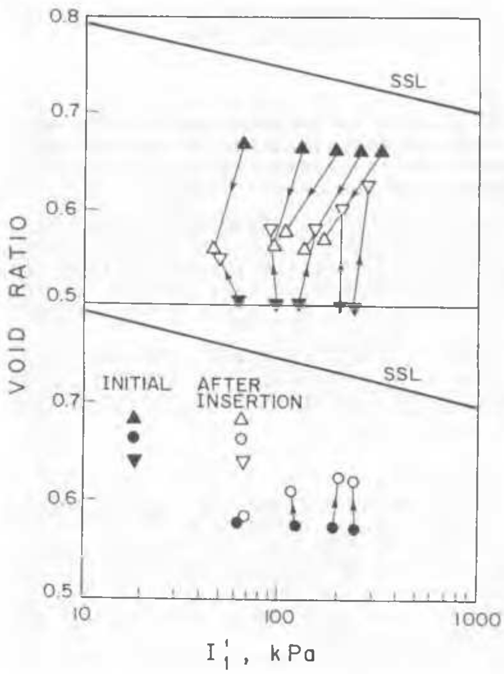

Figure 4. Effect of DMT insertion in Ottawa sand under constant stress

3.2.3 Large Calibration Chambers. Bellotti et al. (1979) and Marchetti (1982) reported DMT data obtained from tests conducted in chambers which are large enough so that boundary effects are not a serious limitation. Furthermore, the chambers used allow for adequate control of boundary stresses and displacements. Vertical insertion of the DMT in these chambers alters the state only over a certain distance from the probe as it may be assumed that far field conditions are unaffected. The sand mass is thus characterized by a locus of points in a state diagram. The lift-off pressure approximates the normal stress near the membrane while the expansion pressure ($P_1 - P_o$) reflects the complex distribution of stresses and void ratio around the probe.

A simplified interpretation of DMT data can be contemplated by considering a fictious soil condition characterized by a constant state producing the same expansion pressure as that obtained in the real situation. In order to obtain the equivalent ψ/ψ_1 from Figure 3, I'_1 must be specified. I'_1 is the average stress of the fictious soil and cannot be rigorously determined with the present analytical techniques. It is therefore proposed to relate I'_1 directly to the measured lift-off pressure as:

$$I'_1 = \alpha\,(P_o - u_o) \qquad (1)$$

where α is less than 1. The equivalent ψ/ψ_1 can then be obtained for various values of α. The range of α will be limited as the average void ratio must be physically admissible, i.e. between maximum and minimum values, and the average stress of the fictious system should never be smaller than the initial mean stress.

Figure 5 shows the values of ψ/ψ_1 for the equivalent system of the tests performed in the large calibration chambers. These values were obtained for α equal to 0.5 and 0.75. As expected, the insertion of the DMT produced an increase in void ratio and in stresses in fairly dense sand while it resulted in a decrease in average void ratio in loose sand with, however, still slight stress increases. The state path followed during insertion can be defined as the line between the initial state and the equivalent state of the fictious system. This path appears to depend upon the initial state, the stress level and fabric of the sand deposit.

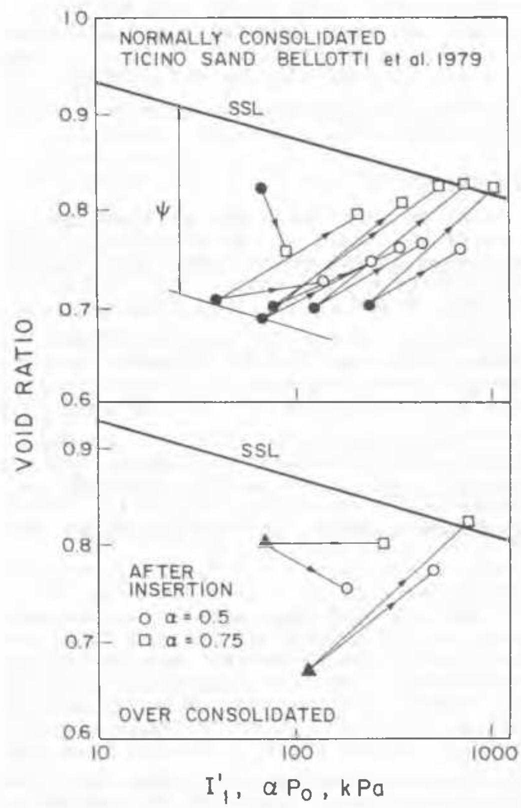

Figure 5. Effect of DMT insertion in large calibration chambers

4 IN-SITU STATE FROM DMT TEST

In view of the above mentioned results, it is suggested to relate the measured effective lift-off pressure normalized with respect to the effective vertical stress, i.e. K_D, to the initial normalized state parameter $(\psi/\psi_1)_o$ and to the magnitude of the in-situ mean stress, $(I_1)'_o$. Available chamber test data processed in terms of $(\psi/\psi_1)_o$, $(I'_1)_o$ and K_D are presented in Figure 6. It appears that there is indeed a correlation between the normalized state parameter of the undisturbed condition subjected to a given stress state and the DMT's K_D. For instance, in dilative soils, i.e. $\psi < 0$, K_D increases with increasing values of $(\psi/\psi_1)_o$. However, for a given normalized state, K_D increases also with the increasing stress level of undisturbed sand mass. It is noted that test 47 in Bellotti et al. (1979) was corrected in order to account for the self-weight component at a depth of 0.75 m which was about 18 percent of the applied vertical stress.

The results shown in Figure 6 indicate that the same relationships appear to hold for both normally and over-consolidated samples. This leads the author to believe that the effects of fabric and stress history must be accounted for adequately when assessing the mean stress state of the undisturbed medium in order to obtain the actual value of the in-situ state parameter.

The fact that good correlations were obtained in terms of normalized state parameter and DMT data points out that sand compressibility is of utmost importance since it controls the value of ψ_1. Ignoring its effect may explain the poor correlations obtained between K_D and relative density.

5 SUGGESTED USE OF DMT

Potential users of the flat plate dilatometer should be aware that most of the empirical correlations developed so far do not take into account the compressibility of the sands. For instance, the relationship M versus (I_D, E_D) proposed by Marchetti (1980) to obtain the constraint modulus of undisturbed sand from the DMT modulus (disturbed condition) is only related to stress change (via K_D) and the compressibility of the sand, i.e. the slope of the steady state line, is ignored. As discussed by Konrad (1988), the large scatter in the proposed correlation can be accounted for by differences in the value of the initial and final state parameter, which in turn depend on soil type.

An alternative approach is to use the inferred value of the normalized in-situ state from DMT field data combined with the correlations presented in Figure 6. It should be stressed that the use of normalized state parameter does not require a prior knowledge of the actual steady state line of the soil under investigation. Maximum and minimum densities, however, allow to back-calculate the actual state parameter, ψ_0, which can be used to determine required engineering properties from relevant laboratory tests conducted on samples at the same state. This procedure does not reproduce in-situ fabric.

Finally, it is recommended to use the DMT in conjunction with other in-situ devices, such as the piezo-cone, the pressuremeter, or the plate bearing test and to develop site specific correlations rather than more general ones.

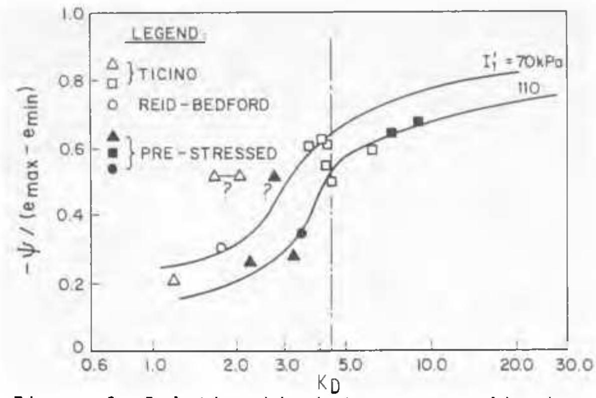

Figure 6. Relationship between normalized state parameter and DMT horizontal stress index.

6 CONCLUSIONS

It is suggested that interpretation of DMT tests in sands should be done in terms of normalized state parameter which is defined as the ratio of state parameter and the quantity $(e_{max} - e_{min})$.

The expansion pressure is dependent upon the normalized state parameter and the stress state.

It is proposed to correlate the normalized state parameter of the undisturbed sand deposit to the horizontal stress index, K_D and the mean effective stress.

Once the in-situ state is known, engineering properties should be obtained from existing correlations expressed in terms of the state parameter.

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