Correlation of Maximum Shear Modulus with DMT Test Results in Sand
Corélation du Module de Cisaillement Maximum Avec Resultats d'Essais DMT Dans Un Sable

SM #125

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SYNOPSIS: Seismic cone penetration test (SCPT) and dilatometer (DMT) data from a Lower Mainland site in B.C. are compared to provide data on the correlation between dilatometer modulus, E_D, and maximum shear modulus, G_o. The results obtained are compared with published data. It would appear that the dilatometer modulus, E_D, may provide reasonable estimates of the small strain shear modulus through empirical correlations. The correlation factor, R_G, is, however, sensitive to variations in soil type and, to a lesser extent, overconsolidation ratio. In sand, the R_G value appears to be noticeably affected by fines content. The evaluation of the lateral stress coefficient, k_o, from DMT and CPT is also considered because of the effect of in situ stress on modulus.

1 INTRODUCTION

The flat dilatometer test (DMT) introduced by Marchetti (1980) is becoming increasingly more popular in geotechnical practice. The soil parameters derived are obtained from empirical correlations. Increased use in a broader range of soils has led to various refinements to the initial interpretation proposed by Marchetti. Furthermore, the test technique has been modified to enable in situ pore pressures generated by insertion of the DMT and their subsequent dissipation to be monitored. Test repeatability has been shown to be good.

Using the three measured pressures (P_o, P_1, P_2) and the thrust required to advance the blade, a multitude of soil parameters can be evaluated (Schmertmann, 1988). More recently, the DMT indices E_D and K_D have been correlated to the small strain shear modulus, G_o (Baldi et al, 1986; Hryciw and Woods, 1988). Most of the results have been obtained in calibration chambers (CC) where the effects of aging and structure cannot be practicably considered. However, for granular soils, where comparisons between CC and field results have been possible, the CC results require correction in order to agree with correlations obtained in the field (Baldi et al, 1986).

Results are presented here from a UBC research site where the correlation between G_o and DMT indices are evaluated. In order to evaluate the dependency of G_o on the average normal stress, the lateral stress coefficient, k_o, is evaluated from both CPT and DMT data.

Shear wave velocities, V_s, were determined by means of the seismic downhole method using the seismic cone penetration test (SCPT) as described by Campanella and Robertson (1984) and Campanella et al (1986). The maximum shear modulus, G_o, is obtained from the shear wave velocity according to

$$G_o = \rho V_s^2 \qquad (1)$$

where ρ is the average soil mass density over the depth considered. The analysis presented here uses averaged data at 1 m depth intervals. Shear wave velocities have been determined using the crossover method (Campanella et al, 1986).

2 BASIS OF CORRELATION

Deformation characteristics of soil are sensitive to stress-strain history which has resulted in limited success when correlating modulus with penetration resistance since no unique relationship exists. As discussed by Bellotti et al (1989), the small strain shear modulus, G_o, is an exception and appears to be insensitive to stress-strain history. Yu and Richart (1984) suggest that:

$$G_o = f\ (\sigma'_a,\ \sigma'_b,\ D_r) \qquad (2)$$

where:

σ'_a - effective stress in direction of wave propagation
σ'_b - effective stress in direction of soil particle displacement
D_r - relative density of soil.

For the downhole seismic cone penetration test, σ'_a and σ'_b can be replaced by the vertical, σ'_v, and the horizontal, σ'_h, effective stresses. Defining the average normal stress, σ'_o, as

$$\sigma'_o = (\sigma'_v + \sigma'_h)/2 = (1 + k_o)\ \sigma'_v/2 \qquad (3)$$

equation (1) can be rewritten as:

$$G_o = f\ (\sigma'_o,\ D_r) \qquad (4)$$

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These same variables have been shown to influence penetration resistance; a property also insensitive to the stress strain history of the soil.

The stress dependent modulus can be considered to vary according to the empirical relationship:

$$G_o = K_g \, p_a \, (\frac{\sigma'_o}{p_a})^n \qquad (5)$$

where K_g is the shear modulus number. Since p_a = 1 bar, the equation may be simplified to:

$$G_o = K_g \, (\sigma'_o)^n \quad \text{(bar)} \qquad (6)$$

and

$$K_g = f \, (D_r) \qquad (7)$$

Seed and Idriss (1970) present data relating K_g and D_r.

The dilatometer modulus, E_D, has been correlated to G_o in the following manner (Baldi et al, 1986; Hryciw and Woods, 1988)

$$R_G = G_o/E_D \qquad (8)$$

Jamiolkowski et al (1985) suggest an alternative definition of R_G in the form:

$$R_G = G_o/G_D \qquad (9)$$

$$G_D = \frac{E_D}{2(1+\nu)} \qquad (10)$$

where ν is usually assigned a value of 0.1 for a low strain drained test in sand.

Bellotti et al (1986) report the following values for the G_o/E_D ratio:

- NC Ticino Sand -

$$R_G = \frac{G_o \text{ (RCT)}}{E_D} = 2.72 \pm 0.59 \qquad (11)$$

where G_o (RCT) is the G_o value from a resonant column test.

- Po River Sand -

$$R_G = \frac{G_o \text{ } (V_s\text{-CH})}{E_D} = 2.2 \pm 0.7 \qquad (12)$$

where G_o is obtained from in situ crosshole seismic wave velocity determination. Hryciw and Woods (1988) present data from an overconsolidated silty sand where:

$$R_G = \frac{G_o \text{ } (V_s\text{-CH})}{E_D} = 1.53 \text{ to } 6.08 \qquad (13)$$

The following comments can be made regarding Hryciw and Woods data:

- the larger values of R_G were due to low E_D values and the insensitivity of the cross hole G_o to a soft layer in the soil profile.
- ignoring the higher anomalous data, the mean and standard deviation of R_G was 1.66 ± 0.14.

No data is given relating to the in situ D_r % of the soils but judging from the difficulties of penetrating the DMT blade, estimated values were considered to be higher than 80%.

Evaluation of the published CC data would thus suggest that the G_o/E_D ratio for clean sand is approximatly 2.5 and increases slightly with overconsolidation ratio. Limited field data on the other hand suggests a ratio of 1.66 for OC sand. Presumably for NC sand R_G is lower. Due to a lack of related data, this anomaly cannot be resolved. Field data from a UBC research site is evaluated to try and resolve the apparent anomaly.

3 SITE CHARACTERISTICS

The seismic cone and dilatometer tests were performed at the Laing Bridge South (LBS) research site of the In Situ Group of the University of British Columbia. The soil profile is very similar to that of the more established McDonald Farm site which is nearby. The upper fine to medium sand layer is, however, more uniform than at McDonald Farm and generally contains less fines both within the sand and as isolated lenses or pockets.

The sediments at the site are post glacial Holocene deltaic deposits which are essentially normally consolidated. The surficial soils (<2 m) are underlain by granular marine and tidal flat deposits (fine to medium sand) to a depth of around 20 m. Underlying the sands are 40 m of soft to firm marine silts and clayey silts. Only the results in the sand deposits are considered here.

Typical DMT data for the site are shown in Fig. 1. The cone bearing profile is also indicated on the figure. Figure 2 presents the variation in G_o with depth. Also shown are E_D and G_D from the DMT and G_o estimated from N(SPT) using the Ohta and Goto (1978) equation.

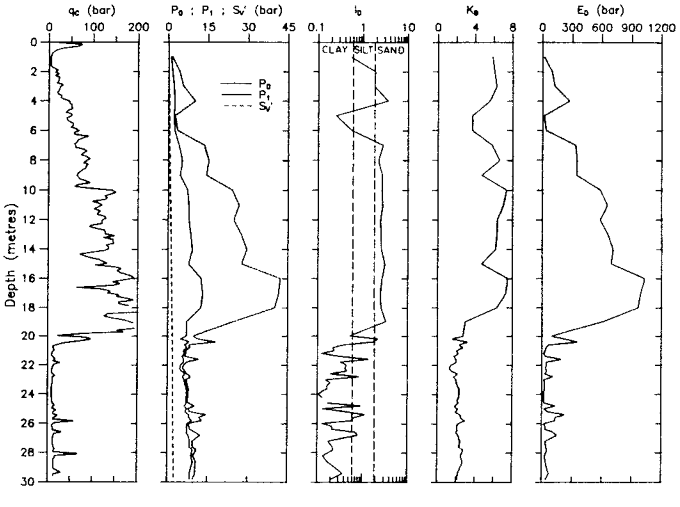

Figure 1. DMT data and cone bearing profile for Laing Bridge South site

G_D (= $E_D/2.2$) values from the DMT (eqn. 9) underestimate the measured G_o by a factor of just over 2. This results from the good G_o-E_D correspondence. G_o obtained from the N(SPT) results is overestimated by as much as 50%. The correlation between G_o and E_D is discussed later.

4 EVALUATION OF LATERAL STRESS CONDITIONS

As mentioned earlier the maximum shear modulus is stress dependent and controlled by σ'_o. In order to evaluate σ'_o some estimate of the in situ lateral stresses is required.

The site has only recently been investigated by the In Situ Group at UBC and hence no sophisticated in situ stress measurements are available. The lateral stress coefficient, k_o, was estimated in three ways:

(1) use of the simplified Jaky expression

$$k_o = 1 - \sin \phi' \qquad (14)$$

with ϕ' being obtained from DMT data and corrected for triaxial conditions.

(2) via correlations with the DMT horizontal stress index, K_D. Of the various existing correlations, that by Baldi et al (1986) was used. The equation between K_D and k_o is

$$k_o = 0.376 + 0.095\ K_D - 0.00461\ (q_c/\sigma'_{vo}) \qquad (15)$$

This relationship was obtained from adjustment of CC data to correctly predict k_o from self boring pressuremeter tests performed in Po river sand. The correlation is considered appropriate due to the very similar age and characteristics of the LBS and Po river sands.

(3) establishing a correlation between cone bearing, q_c, and k_o using published CC data on similar sands.

Houlsby and Hitchman (1988) suggest the following relationship based on CC tests performed on dry Leighton Buzzard sand:

$$q_c = A\ (\sigma'_h)^{0.6} \quad \text{(bar)} \qquad (16)$$

where A is an empirical constant related to the relative density of the sand. Evaluation of their data gives a linear relationship between A and D_r according to:

$$A = 2.87\ (D_r\ \%) - 13.03 \qquad (17)$$

By relating D_r and q_c using the Baldi et al (1986) correlation, and obtaining values of the dimensionless parameter, A, at any depth, k_o can be evaluated from the expression:

$$q_c = A\ (k_o)^{0.6} \cdot (\sigma'_v)^{0.6} \qquad (18)$$

The estimated values of k_o by the three methods are shown in Fig. 3. The agreement is remarkably good. Methods (2) and (3) were used to obtain an average k_o at successive depths for determining the average effective normal stress, σ'_o.

These estimated k_o values will be verified in the near future by means of self-boring pressuremeter tests.

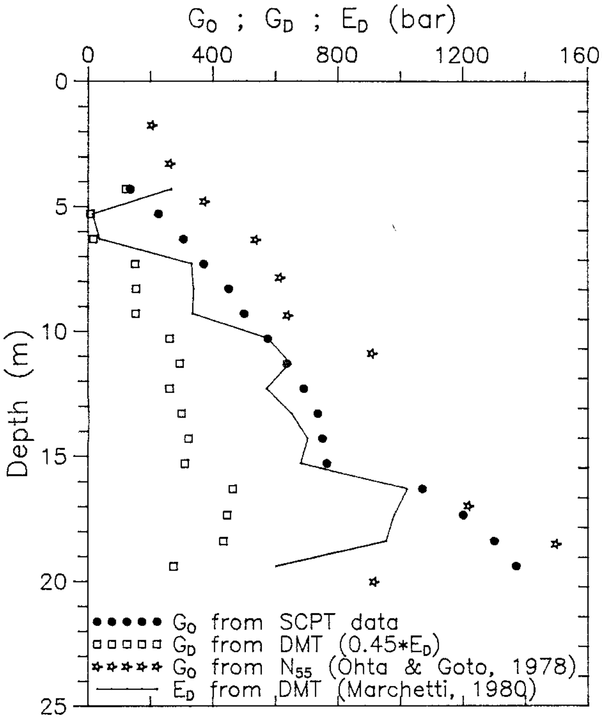

Figure 2. Variation in G_o with depth at Laing Bridge South

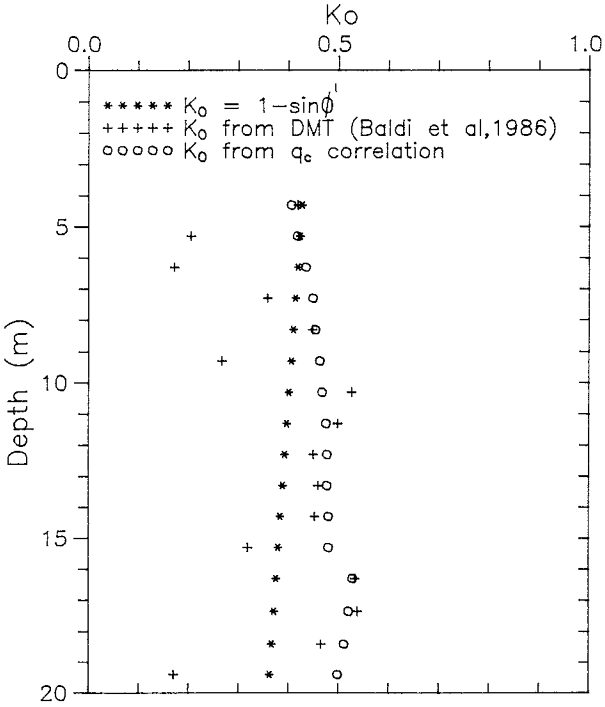

Figure 3. Evaluated k_o profiles from DMT and CPT data for Laing Bridge South site

5 SHEAR MODULUS RELATIONSHIPS

The G_o variation shown in Fig. 2 can be correlated to both depth and vertical effective stress. However, for consistency, the average effective stress, σ_o', was used resulting in:

$$G_o = 893\ (\sigma_o')^{0.67} \quad \text{(bar)} \qquad (19)$$

where both G_o and σ_o' are in bar. The value of 893 for K_g in Eqn. (19) is on average 30% lower than that predicted from the Seed and Idriss (1970) relationship.

Between 7 m and 18 m, comparison of E_D and G_o gave the following:

$$R_G = G_o/E_D = 1.17 \pm 0.15 \qquad (20)$$

This same ratio attained values of 8 to 15 where the soft layer is present at 4 m to 6 m. These higher values are characteristic of fine grained soils and were not included in the above determination for sand.

Figure 4 presents the range of G_o/E_D ratios for LBS (Laing Bridge South) as compared to results obtained by Bellotti et al (1989) and Hryciw and Woods (1988). Various differences between the soil types exist which may explain the distribution of the data, namely, OCR, k_o, fines content, etc. Furthermore, the apparent agreement between results for Ticino and Po river sands may be fortuitous considering the different test methods used (CC versus in situ and cross hole versus resonant column). It would also appear, based on the limited information available, that R_G is not inversely related to k_o as suggested by Hryciw and Woods (1988), and is in fact relatively insensitive to any change in the lateral stress condition. This would seem to be intuitively correct since both E_D $(P_1 - P_o)$ and G_o themselves are reasonably independent of k_o in the broad sense.

6 DISCUSSION

In situ DMT and SCPT data have been used to evaluate the parameters controlling the small strain shear modulus, G_o. The following comments can be made in this respect:

(1) the shear modulus number, K_g, determined from the field data is approximately 30% lower than values predicted from SPT N values corrected to N_{55} using the Seed and Idriss (1970) relationship.

(2) The G_o/E_D ratio (R_G) averages 1.17 for the NC slightly silty sand tested at LBS (D_{50} = 0.3 - 0.45 mm; 5% <200 μm). For soils of greater fines content this ratio can be expected to increase since E_D is more sensitive than G_o to a decrease in grain size. The R_G value obtained for this site does not concur with the trend presented by Bellotti et al (1989). The CC data for Ticino sand may overpredict R_G values as in the case of CC predictions of k_o. Also the increased fines content of Po river sand (Bruzzi et al, 1986) as compared to the LBS sand may be one factor accounting for the different R_G values in these two natural deposits. For similar deposits, R_G may increase slightly with OCR. Additional field data is required to verify the above points.

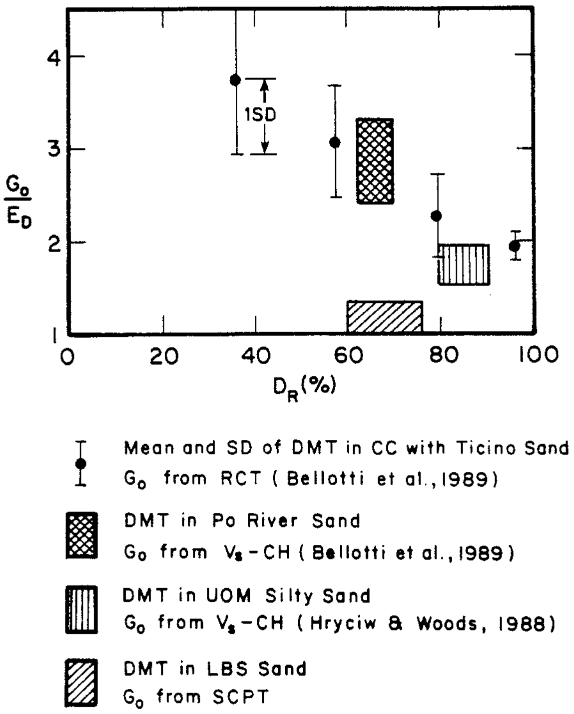

Figure 4. G_o-E_D ratios for published data on sand

(3) The relationship proposed by Baldi et al (1986) for predicting k_o from DMT results (eqn. (15)) provides reasonable estimates of the lateral stress coefficient for the LBS site. The disadvantage of the relationship is that it incorporates both DMT and CPT data. A comparison was made of the thrust, T, required to advance the DMT and the cone bearing, q_c, for the LBS site. The following relationship was found

$$T(\text{kg})/q_c(\text{kg/cm}^2) = 20.6 \pm 3.6\ \text{cm}^2 \qquad (21)$$

This suggests that the effective area of the DMT with respect to the pushing force is approximately twice the effective cone area. This concurs with results obtained by Tsang (1987) that the DMT requires almost twice the pushing force required by the 10 cm^2 cone. Consequently, an equivalent cone bearing, q_D, can be obtained from DMT data by dividing the thrust by a constant equal to 20 cm^2 (T/20 kg/cm^2). This equivalent cone bearing can then be used in eqn. (13), thus reducing the need to perform both DMT and CPT soundings. Similarly, q_D can be used with CPT q_c relationships to estimate D_r%, a parameter not evaluated in the present correlations for DMT interpretation.

(4) A methodology has been presented for estimating k_o from the cone bearing in NC unaged clean sand. The method relies on two empirical correlations derived from CC data. The method gives consistent estimates of k_o for the LBS site. Further validation is, however, required.

7 CONCLUSIONS

The small strain shear modulus, G_o, has been successfully correlated to large strain indices such as the SPT N value and the CPT cone bearing. Similarly it would appear that consistent estimates of G_o may be obtained using correlations with the DMT modulus, E_D, provided important factors such as fines content and test method are considered. Unfortunately, it is not yet possible to establish a clear relationship between G_o and E_D. The correlation factor, R_G, would appear to be sensitive to variations in soil type and, to a lesser extent, overconsolidation ratio. In sand R_G is noticeably affected by fines content.

8 ACKNOWLEDGEMENTS

Primary funding for this research was provided by the Natural Sciences and Engineering Research Council, Canada.

J.P. Sully is on leave from INTEVEP, S.A., Venezuela, while carrying out graduate study at UBC. Funding was provided by an SERC (UK) overseas NATO scholarship which is gratefully acknowledged.

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