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Use of DMT to predict settlements of shallow foundations

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ABSTRACT: The paper focuses on the use of the DMT to predict settlements of shallow foundations especially for sands where undisturbed sampling and estimating compressibility are particularly difficult and make field tests the method of choice in site investigations. In the last decades the use of DMT to predict settlements has increased, due to the capability of the DMT to determine the constrained modulus M_{DMT} with reliable accuracy and the capability of M_{DMT} to incorporate the beneficial effects of stress history and aging. This paper presents example comparisons of DMT-calculated *vs* observed settlements of shallow foundations in working conditions. In the case of high rise buildings, it is of particular interest the entity of the predicted settlements that may affect the choice of the foundation, with substantial economical consequences.

1 INTRODUCTION

More and more, today, the factor controlling the design of a foundation is not the bearing capacity, but the necessity of limiting settlements. Often the selection of a suitable foundation (e.g. shallow or deep foundation) is based on the amount of the expected settlements. If the predicted settlements are very limited, i.e. if the foundation soil is relatively stiff), a high rise building may be safely supported by a foundation constituted by several underground floors, a more economical solution than piles. Hence accurate prediction of settlements is crucial, having substantial economical consequences. Predicting settlements of shallow foundations is probably the most important application of the DMT, especially in sands, where undisturbed sampling and estimating compressibility are particularly difficult. The available case histories indicate, in general, satisfactory agreement between DMT-predicted and observed settlements. The importance of stress history for a realistic assessment of settlements has been emphasized by numerous researchers (e.g. Leonards & Frost 1988, Massarsch 1994). The higher sensitivity of DMT to stress history, compared with other in situ tests, has been repeatedly observed and pointed out in literature (e.g. Schmertmann 1984, Jamiolkowski 1988, Jendeby 1986). As showed in this paper the significant sensitivity of the DMT parameter K_D (Stress History Index) was observed both in the calibration chamber and in the field (Lee et al. 2011. The case of a large mat foundation constructed to support a 13-storeys dormitory building in Atlanta, Georgia (Mayne 2005) is a representative example showing that simple elastic solutions with input modulus derived from DMT provide estimates of settlements in good agreement with measured settlements.

2 THE CONSTRAINED MODULUS M FROM DMT (M_{DMT})

The most significant stiffness parameter for settlement analyses obtained from DMT is the constrained modulus *M* (often designated as M_{DMT}), defined as the vertical drained confined (1-*D*) tangent modulus at σ'_{v0} (same as E_{oed} obtained by oedometer). M_{DMT} is obtained by

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applying to the dilatometer modulus E_D=34.7 (p_1-p_0) – "intermediate" modulus derived from the DMT readings p_0 and p_1 by simple theory of elasticity – the correction factor R_M, according to the expression $M_{DMT}=R_M \cdot E_D$. The equation defining R_M as a function of the material index I_D and the horizontal stress index K_D, $R_M=f(I_D, K_D)$, were established by Marchetti (1980). The reasons for applying the correction R_M to E_D are listed in TC16 (2001).

M_{DMT} is to be used in the same way as if it was obtained by oedometer and introduced in one of the available procedures for calculating settlements. If required, the Young's modulus E (not to be confused with the dilatometer modulus E_D) can be derived from M_{DMT} using the theory of elasticity, that, e.g. for a Poisson's ratio ν = 0.2, provides E=0.9 M, a factor not very far from 1. (Indeed M and E are often used interchangeably in view of the involved approximation). Comparisons both in terms of M_{DMT} *vs* reference M (e.g. M from high quality oedometers, see example in Fig. 1, Lacasse 1986) have shown that, in general, M_{DMT} is reasonably accurate and dependable for everyday design practice.

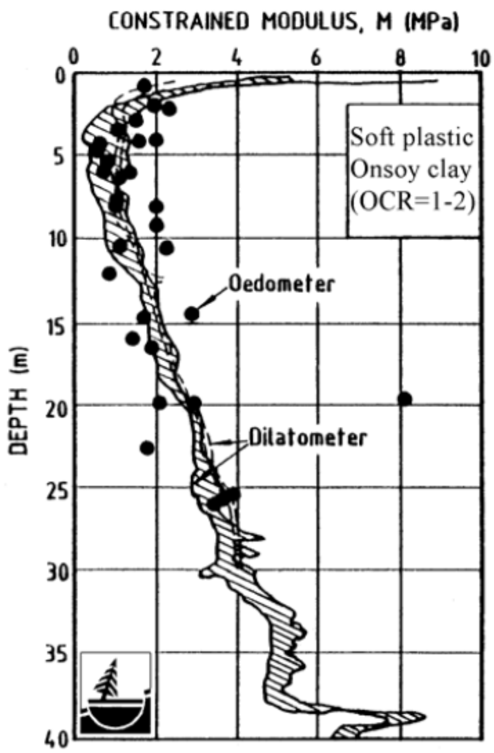

Figure 1. Comparison between M determined by DMT and by high quality oedometers, Onsøy clay, Norway (Lacasse 1986)

3 THE IMPORTANCE OF STRESS HISTORY ON SETTLEMENTS PREDICTION AND POSSIBLE REASONS FOR THE HIGHER SENSITIVITY OF K_D TO STRESS HISTORY

The necessity of stress history for a realistic assessment of settlements has been emphasized by many researchers and the importance of the stress history parameter K_D on settlements prediction is pointed out by Yoshimi *et* al. (1975), Leonards (1988), Jamiolkowski (1988) and Robertson (1986).

It is fundamental that DMT is a two-parameter test, because, for a reasonably accurate settlement prediction, both E_D and K_D are necessary. If K_D were not available, no correction accounting for stress history would be possible. R_M - and M_{DMT} are not proportional to K_D. However the increase of M_{DMT} with K_D is not far from linear proportionality. As E_D is only slightly sensitive to stress history, the increase of the calculated M_{DMT} with stress history is essentially caused by the increase of K_D.

Ignoring the benefits of stress history, inevitable when the investigation is carried out with probes not very sensitive to stress history, has an effect on settlement prediction namely scatter and conservative design. Again K_D makes it easier to distinguish between a freshly deposited low-K_D site and a prestressed high- K_D site, and to take advantage of that distinction when predicting settlements.

Numerous researchers have found that DMT readings are considerably more sensitive than CPT to stress history, including ageing. The first researcher to point out in 1984 the higher sensitivity of DMT to stress history was Schmertmann. He explained that the cone appears to destroy a large part of the modification of soil structure caused by the overconsolidation and it therefore measures very little of the related increase in modulus. In contrast the lower strain penetration of the DMT preserves more of the effect of overconsolidation. Using the CPT to evaluate modulus changes e.g. after ground treatments by vibrations, surcharging etc. may lead to large overestimate of the settlement. Some of the reasons of the higher sensitivity of K_D to stress history are physically intuitive.

One of the effects of one-dimensional overconsolidation is an increment of σ'_h.

Penetration probes of circular cross section are moderately sensitive to $\Delta\sigma'_h$ because of the formation during penetration, of a highly stressed stiff ring of sand surrounding the tip, Hughes and Robertson (1985). This "parasitic" ring acts as a screen, obstructing the access of σ'_h to the probe. Moreover, the laterally suspended floating ring also reduces σ'_v at the tip level, resulting in a less than linear q_c versus z profile. This kind of arching is very small in the DMT blade which has a rectangular cross section with a sides ratio ≈ 6.

A systematic calibration chamber research, specifically aimed at comparing the effects of stress history on CPT and DMT on sands, was recently carried out by Lee *et* al. (2011). The results indicate a substantially higher capability of the DMT parameter K_D to reflect *OCR*, i.e to discern overconsolidated sands from normally consolidated sands (Fig. 2).

Ignoring or disregarding the benefits of stress history, inevitable when the investigation is carried out with probes modestly sensitive to it, leads to inaccurate-often excessive-settlement, resulting in an overconservative and uneconomical design.

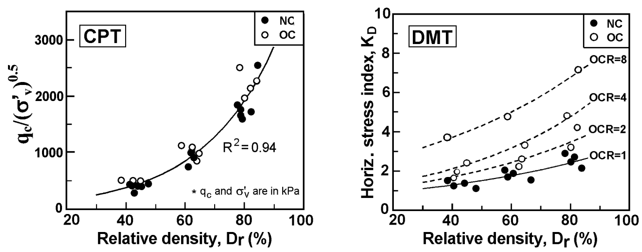

Figure 2. Sensitivity of CPT and DMT to stress history (Lee *et* al. 2011)

4 PREDICTING SETTLEMENTS OF SHALLOW FOUNDATIONS BY DMT

Settlements of shallow foundations using DMT are generally calculated by means of the traditional linear elastic approach (1-D or 3-D formulae), with stress increments $\Delta\sigma_v$ calculated by elasticity theory (Boussinesq) and soil moduli determined from DMT (constrained modulus M_{DMT} or Young's modulus E derived from M_{DMT} via elasticity theory). This approach, being based on linear elasticity, provides a settlement proportional to the load and is unable to provide non linear predictions. The calculated settlement is meant to be the settlement in "working conditions", i.e. for a safety factor Fs ≈ 2.5 to 3.5.

Marchetti (1997) recommended to calculate settlements of shallow foundations by DMT by means of the classic 1-D method (Eq. 1):

$$S_{1-DMT} = \sum \frac{\Delta\sigma_v}{M_{DMT}} \Delta z \qquad (1)$$

with $\Delta\sigma_v$ calculated e.g. by Boussinesq (Fig. 3).

Settlements in sand are generally calculated using the 1-D formula (large rafts) or the 3-D formula (small isolated footings). However, Marchetti (1991) observed that, since the 1-D and the 3-D formulae give generally similar answers. On the other hand, Burland *et* al. (1977) had observed that errors introduced by simple classical methods are small compared with errors in deformation parameters. Similarly, Poulos *et* al. (2001) emphasized that simple elasticity-based methods appear capable of providing reasonable estimates of settlements, and the key to success lies more in the appropriate choice of soil moduli than in the details of the method of analysis used.

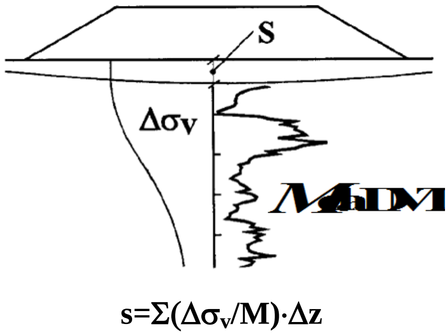

Figure 3. Recommended method for settlement calculation using DMT (Marchetti 1997, TC16 2001)

The 1-D method (Eq. 1) is also used for predicting settlements in clay. It should be noted that the calculated settlement is the primary settlement (i.e. does not include immediate and secondary), and M_{DMT} is to be treated as the average E_{oed} derived from the oedometer curve in the expected stress range.

As noted by Marchetti (1997), in some highly structured clays, whose oedometer curves exhibit a sharp break and a dramatic reduction in slopes across the preconsolidation pressure p'_c, M_{DMT} could be an inadequate average if the loading straddles p'_c. However in many common clays (and probably in most sands) the M fluctuation across p'_c is mild, and M_{DMT} can be considered an adequate average modulus.

5 COMPARISON OF DMT-CALCULATED VS OBSERVED SETTLEMENTS

Fig. 4 summarizes the available comparisons of DMT-calculated vs observed settlements. The over 40 datapoints are representative of the case histories, limited to the cases reporting numerical values of DMT-calculated and measured settlements. Fig. 4 shows that settlements predicted by DMT are generally in good agreement with observed settlements for a wide range of soil types (including sands, silts, clays and organic soils), settlements (from a few mm to over 300 mm) and footing sizes (from small footings to large rafts and embankments). The average ratio DMT-calculated/observed settlement for all the case histories summarized in Fig. 4 is ≈ 1.3. The band amplitude (ratio between maximum and minimum) of the datapoints is less than 2, i.e. the observed settlement is within ± 50 % from the DMT-predicted settlement.

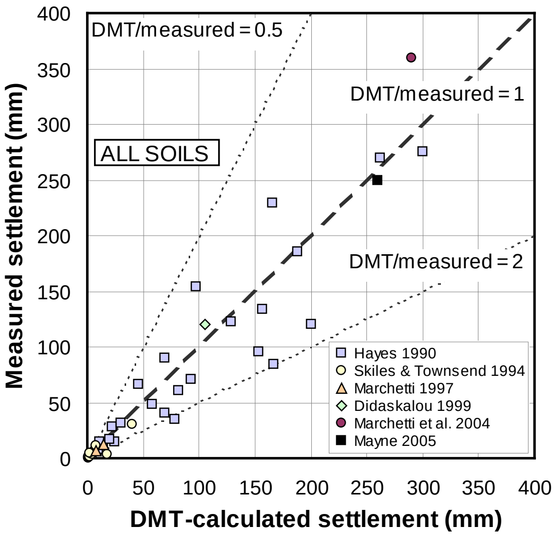

Figure 4. Summary of available comparisons of DMT-predicted *vs* observed settlements (Monaco *et* al. 2006)

6 CASE HISTORY

Mayne (2005) presents the case of a large mat foundation (104×18 m size, 1.1 m thickness) constructed to support a 13-story dormitory building on residual silty soil in Atlanta, Georgia. The dormitory buildings is located in downtown Atlanta and it is composed by four buildings. Building "Dorm B" underlain by approximately 2 to 5 m of fill and alluvial soils (residual silts and sands). Dormitory B was constructed on a reinforced concrete mat foundation having a breadth of 104 m, width of 18 m, and thickness of 1.1 m. The 13-storeys structure is shown in Fig. 5. Results of flat dilatometer tests (DMT) carried out at Dorm B site are presented in Fig. 6. In particular, the Material Index I_D, the Stress index K_D and the Dilatometer Modulus E_D profiles with depth of typical DMTs conducted at Dorm B site are reported.

Figure 5. Completed Dormitory Building B

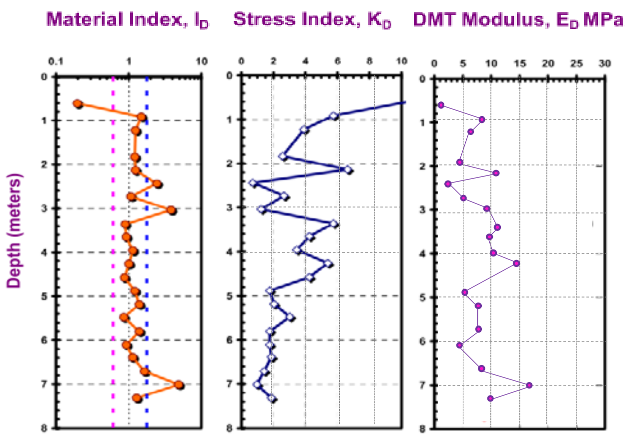

Figure 6. Results of DMT sounding at Dorm B site, Atlanta, GA.

The material index I_D correctly falls within the category for silty soils, with some variation into the silty sands and sandy silt regimes.

Settlements are calculated using the elastic continuum theory and adopting a soil stiffness variation with depth, derived from DMT tests. A good agreement between DMT–calculated *vs* measured settlements for Dorm B mat foundation is observed at the end of construction (Fig. 7). The measured settlements of the Dorm B mat are shown in Fig. 7; a maximum settlement of 250 mm was observed near the center and the four corners showed settlements of between 100 mm and 140 mm.

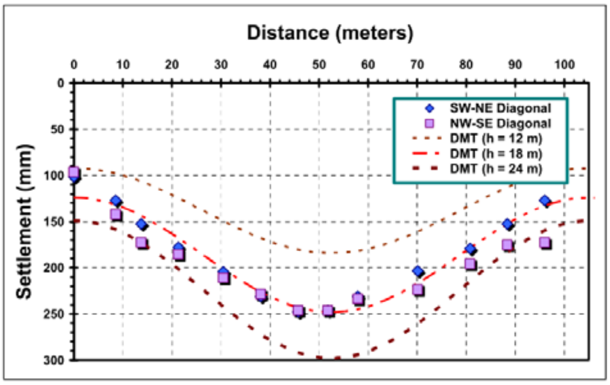

Figure 7. Measured *vs* DMT-Calculated settlement profile along the diagonal axes of the mat foundation of a 13-story Dorm B in Atlanta, Georgia.

7 CONCLUSION

The available experience indicates that the constrained modulus M_{DMT} can be considered a reasonable "operative modulus", i.e. introduced into the traditional elasticity theory formulae predicts settlements with reasonably good accuracy for foundations in "working conditions" (say for a safety factor Fs ≈ 2.5 to 3.5). The accuracy of settlement predictions by M_{DMT} is believed to be due mostly to the fact that M_{DMT} routinely takes into account stress history and possible existence of high lateral stresses (incorporated via the stress history parameter K_D), that reduce considerably soil compressibility.

The most significant results obtained at Dorm B site from comparison of DMT results with the in situ observed behaviour, presented in this paper, is that the settlement predicted by DMT along the diagonal axes of the mat foundation of a 13-story Dorm B in Atlanta is in good agreement with the measured settlement. Simple elastic continuum solutions with input moduli derived from flat dilatometer tests represent a good tool for predicting settlements.

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