Interrelationship between small strain modulus G_0 and operative modulus

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ABSTRACT: This paper presents experimental diagrams constructed using same-depth values of the small strain modulus G_0 and of the working strain modulus (constrained modulus) M determined by seismic dilatometer (SDMT) at 34 different sites in a variety of soil types, in order to investigate the interrelationship between the two moduli. The ratio G_0 /M is plotted as a function of the DMT horizontal stress index K_D (stress history) and of the DMT material index I_D (indicative of clay, silt or sand). Such experimental diagrams offer some elements of reply to the questions: (1) Is it feasible, as sometimes suggested, to estimate the *operative modulus* as G_0 divided by a constant? (2) Is it feasible, for a seismic classification, to use s_u or N_{SPT} as a substitute for V_S – when V_S has not been measured? Lines of research on the possible use of SDMT for deriving the in situ G-γ decay curves are also outlined.

1 INTRODUCTION

The seismic dilatometer (SDMT) is the combination of the traditional "mechanical" Flat Dilatometer (DMT) introduced by Marchetti (1980) with a seismic module placed above the DMT blade. The SDMT module is a probe outfitted with two receivers, spaced 0.5 m, for measuring the shear wave velocity V_S. From V_S the small strain shear modulus G_0 may be determined using the theory of elasticity. Motivations of the combined probe:

- V_S and G_0 are at the base of any seismic analysis.
- The G-γ decay curves of stiffness with strain level are an increasingly requested input in seismic analyses and, in general, in non linear analyses.
- Increasing demand for liquefiability evaluations.
- Seismic site classification using directly V_S rather than the SPT blow count N_{SPT} or the undrained shear strength s_u.
- Availability of the usual DMT results (e.g. constrained modulus M_{DMT}) for common design applications (e.g. settlement predictions).

The SDMT equipment and test procedure are briefly described in the paper. Comments on SDMT results and applications can be found in previous papers, in particular in Marchetti et al. (2008).

This paper is focused, essentially, on the experimental interrelationships between the small strain shear modulus G_0 and the operative (working strain) constrained modulus M_{DMT}, investigated by use of SDMT results obtained in the period 2004-2007 from a large number of tests at 34 sites, in a variety of soil types.

It must be emphasized the well known notion that, while the small strain shear modulus is unique, the *operative modulus* varies with strain. Hence, in theory, such comparison is impossible. However the term *operative modulus* sounds very familiar to practicing engineers, because they use it very often in design and would find useful methods providing even rough estimates of it. The price to pay is to accept (non negligible) approximation in the definition of the *operative modulus*, which however maybe still useful in practice, in view of the often very large errors in estimating such modulus.

2 THE SEISMIC DILATOMETER (SDMT)

The seismic dilatometer (SDMT) is the combination of the standard DMT equipment with a seismic module for measuring the shear wave velocity V_S.

Initially conceived for research, the SDMT is gradually entering into use in current site investigation practice. The test is conceptually similar to the seismic cone (SCPT). First introduced by Hepton (1988), the SDMT was subsequently improved at Georgia Tech, Atlanta, USA (Martin & Mayne 1997, 1998, Mayne et al. 1999). A new SDMT system (Fig. 1) has been recently developed in Italy.

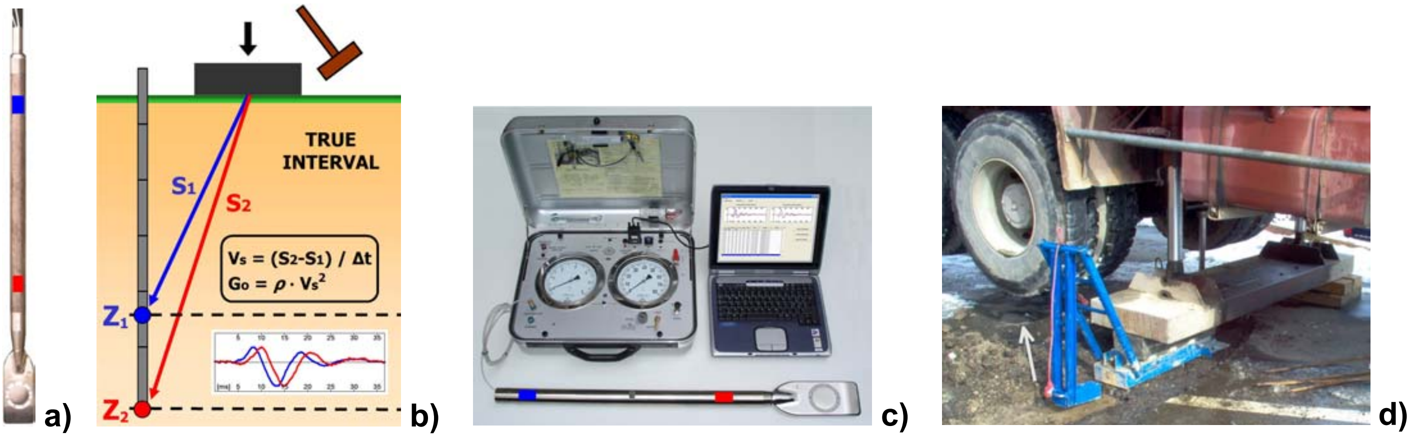


Figure 1. (a) DMT blade and seismic module. (b) Schematic layout of the seismic dilatometer test. (c) Seismic dilatometer equipment. (d) Shear wave source at the surface.

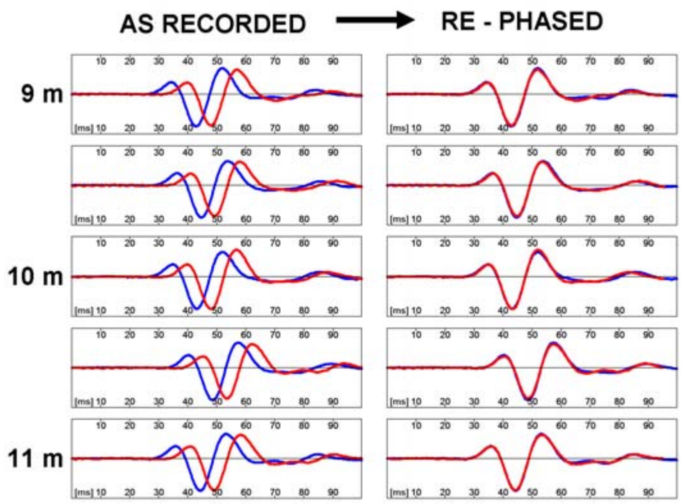


Figure 2. Example of seismograms obtained by SDMT at the site of Fucino (Italy)

The seismic module (Fig. 1a) is a cylindrical element placed above the DMT blade, outfitted with two receivers spaced 0.5 m. The signal is amplified and digitized at depth. The *true-interval* test configuration with two receivers avoids possible inaccuracy in the determination of the "zero time" at the hammer impact, sometimes observed in the *pseudo-interval* one-receiver configuration. Moreover, the couple of seismograms recorded by the two receivers at a given test depth corresponds to the same hammer blow and not to different blows in sequence, which are not necessarily identical. Hence the repeatability of V_S measurements is considerably improved (observed V_S repeatability ≈ 1-2 %).

V_S is obtained (Fig. 1b) as the ratio between the difference in distance between the source and the two receivers (S_2 - S_1) and the delay of the arrival of the impulse from the first to the second receiver (Δt). V_S measurements are obtained every 0.5 m of depth.

The shear wave source at the surface (Fig. 1d) is a pendulum hammer (≈ 10 kg) which hits horizontally a steel rectangular base pressed vertically against the soil (by the weight of the truck) and oriented with its long axis parallel to the axis of the receivers, so that they can offer the highest sensitivity to the generated shear wave.

The determination of the delay from SDMT seismograms, normally carried out using the cross-correlation algorithm, is generally well conditioned, being based on the two seismograms – in particular the initial waves – rather than being based on the first arrival time or specific marker points in the seismogram. Figure 2 shows an example of seismograms obtained by SDMT at various test depths at the site of Fucino (it is a good practice to plot side-by-side the seismograms as recorded and re-phased according to the calculated delay).

Figure 3 (Fiumicino) is an example of the typical graphical format of the SDMT output. Such output displays the profile of V_S as well as the profiles of four basic DMT parameters – the material index I_D (soil type), the constrained modulus M, the undrained shear strength s_u and the horizontal stress index K_D (related to OCR) – obtained using current DMT correlations. (Information on the mechanical DMT, not described in this paper, can be found in the comprehensive report by the ISSMGE Technical Committee TC16 2001). It may be noted in Figure 3 that the repeatability of the V_S profile is very high, similar to the repeatability of the other DMT parameters.

V_S measurements by SDMT have been validated by comparison with V_S measurements obtained by other in situ seismic tests at various research sites. As an example Figure 4 shows V_S comparisons at the research site of Fucino, Italy (NC cemented clay), extensively investigated at the end of the '80s. The profile of V_S obtained by SDMT in 2004 (Fig. 4) is in quite good agreement with V_S profiles obtained by SCPT, Cross-Hole and SASW in previous investigations (AGI 1991). Similar favourable comparisons are reported e.g. by Hepton (1988), McGillivray & Mayne (2004) and Młynarek et al. (2006).

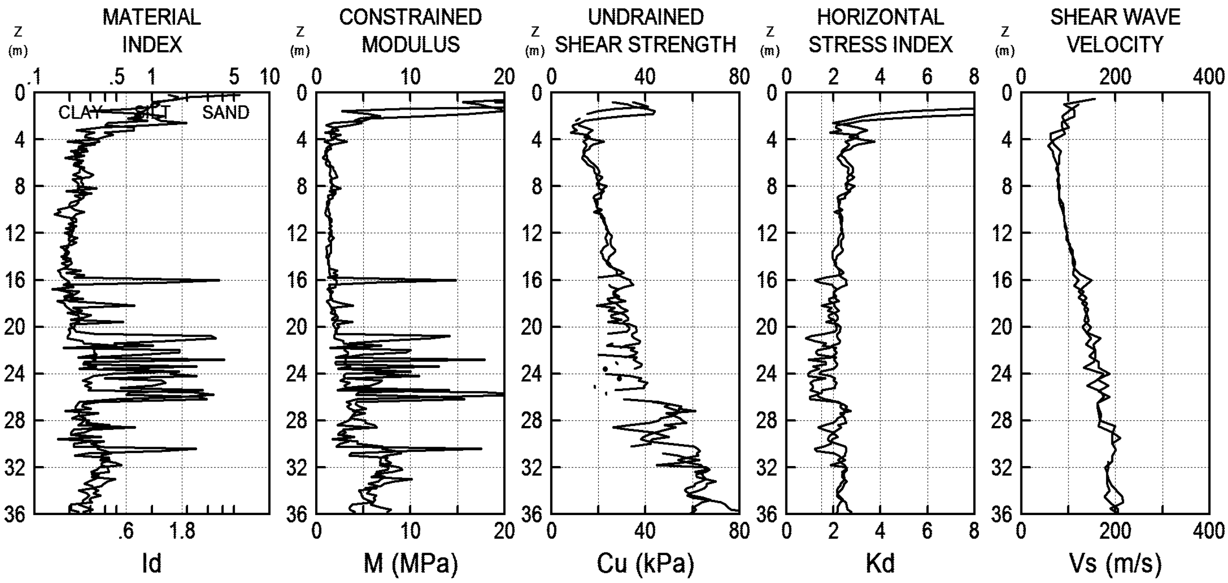


Figure 3. SDMT profiles from two parallel soundings at the site of Fiumicino (Italy)

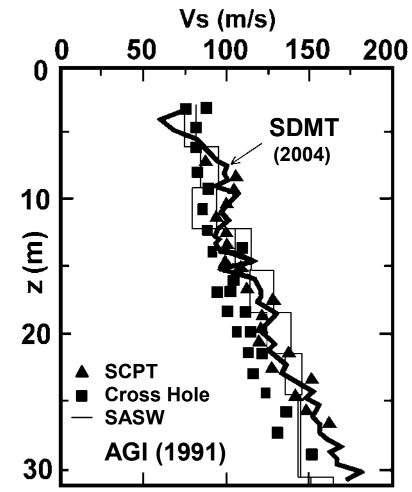


Figure 4. Comparison of V_S profiles obtained by SDMT and by SCPT, Cross-Hole and SASW (AGI 1991) at the research site of Fucino (Italy)

3 INTERRELATIONSHIPS BETWEEN EXPERIMENTAL G_0 AND M_{DMT}

The experimental diagrams presented in this section have been constructed using same-depth values of G_0 (small strain shear modulus from V_S) and M_{DMT} (constrained modulus from the usual DMT interpretation) determined by SDMT at 34 different sites, in a variety of soil types. The majority of the sites are in Italy, others are in Spain, Poland, Belgium and USA.

SDMT generates plentiful data points because each sounding routinely provides profiles of G_0 and M_{DMT}, in addition to other parameters. Of the over 2000 data points available, only 800 high quality data points have been considered, relative to "uniform" one-m soil intervals where log I_D, K_D, E_D (dilatometer modulus), M_{DMT}, V_S all differ less than 30 % from their average – used then to plot the data points – to insure a proper match of the data. The DMT parameters have been calculated with the usual DMT interpretation formulae (see Marchetti 1980 or Table 1 in TC16 2001).

3.1 *Diagrams of the ratio G_0/M_{DMT}*

The values of the ratio G_0/M_{DMT} (800 high quality data points from 34 sites) are plotted in Figure 5 as a function of the horizontal stress index K_D for clay (having material index $I_D < 0.6$), silt ($0.6 < I_D < 1.8$) and sand ($I_D > 1.8$). Best fit equations are indicated for each soil type.

Recognizable trends in Figure 5 are: (a) The data points tend to group according to their I_D (soil type). (b) G_0/M_{DMT} is mostly in the range 0.5 to 3 in sand, 1 to 10 in silt, 1 to 20 in clay. (c) The widest range and the maximum variability of G_0/M_{DMT} are found in clay. (d) For all soils G_0/M_{DMT} decreases as K_D (related to OCR) increases.

Considerations emerging from the diagram:

(1) The ratio G_0/M varies in a wide range (≈ 0.5 to 20 for all soils), hence it is far from being a constant. Its value is strongly dependent on multiple information, e.g. (at least) soil type and stress history. Therefore it appears next to impossible to estimate the operative modulus M by dividing G_0 by a constant, as suggested by various Authors.

(2) If only mechanical DMT data are available, Figure 5 permits to obtain rough estimates of G_0 (and V_S) by use of the three parameters I_D, K_D, M. However there is no reason for not measuring directly V_S (e.g. by SCPT or SDMT).

(3) Figure 5 highlights the dominant influence of K_D on the ratio G_0/M. In case of non availability of K_D, all the experimental data points would cluster on the vertical axis. In absence of K_D – which reflects the *stress history* – the selection of the ratio G_0/M

would be hopelessly uncertain. Hence as many as *three* informations, i.e. I_D, K_D, M (though only two independent), are needed to formulate rough estimates of G_0 and V_S.

(4) In view of the consideration (3), the use of N_{SPT} or s_u alone as a substitute of V_S (when not measured) for the seismic classification of a site, as proposed e.g. by the Eurocode 8 and by various national codes, does not appear founded on a firm basis. In fact, if V_S is assumed to be the primary parameter for the classification of the site, then the possible substitute of V_S must be reasonably correlated to V_S. If three parameters (I_D, K_D, M) are barely sufficient to obtain rough estimates of V_S, then the possibility to estimate V_S from only one parameter appears remote.

Reason of plotting G_0/M (I_D, K_D) rather than G_0/E_D (I_D, K_D), i.e. reason of selecting a format not similar to the 1980 correlation M/E_D (I_D, K_D).

The first attempt by the writers was to plot G_0/E_D (I_D, K_D) – where E_D is the dilatometer modulus, as many researchers had done before (Tanaka & Tanaka 1998, Sully & Campanella 1989, Baldi et al. 1989, Lunne et al. 1989, Hryciw 1990, Baldi et al. 1991, Cavallaro et al. 1999, Ricceri et al. 2001). The plot G_0/E_D was expected to contain less dispersion than the plot G_0/M, since the relationship M from E_D has its own variability. However it was found, contrary to expectations, that the degree of correlation in the G_0/E_D plot was lower (see Figure 6).

3.2 *Diagrams of the ratio G_{DMT}/G_0*

The diagrams in Figure 7 show the same experimental information as in Figure 5, but involve the additional modulus G_{DMT} derived from M_{DMT} using the formula of linear elasticity:

$$G = M / [2 (1-\nu) / (1-2\nu)] \qquad (1)$$

For an often assumed value $\nu = 0.20$:

$$G_{DMT} = M_{DMT} / 2.67 \qquad (2)$$

All the G_{DMT} have been derived from M_{DMT} using Eq. 2, then the ratios G_{DMT}/G_0 have been calculated too and plotted vs. K_D for clay, silt and sand (Fig. 7).

The reason of constructing Figure 7 is the following. The ratio G/G_0 is the usual ordinate of the normalized G-γ decay curve and has the meaning of a strain decay factor. Since M_{DMT} is a *working strain modulus* one might hypothesize that G_{DMT} is a *working strain shear modulus* too, in which case G_{DMT}/G_0 could be regarded as the shear modulus decay factor at *working strains*.

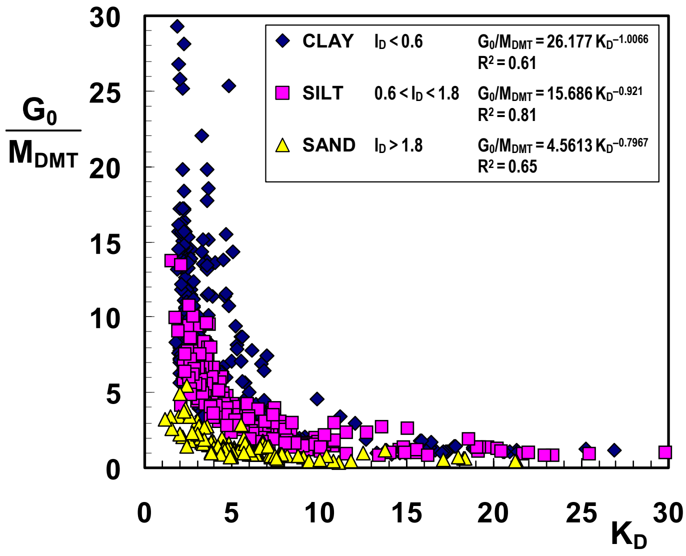


Figure 5. Ratio G_0/M_{DMT} vs. K_D (OCR) for various soil types

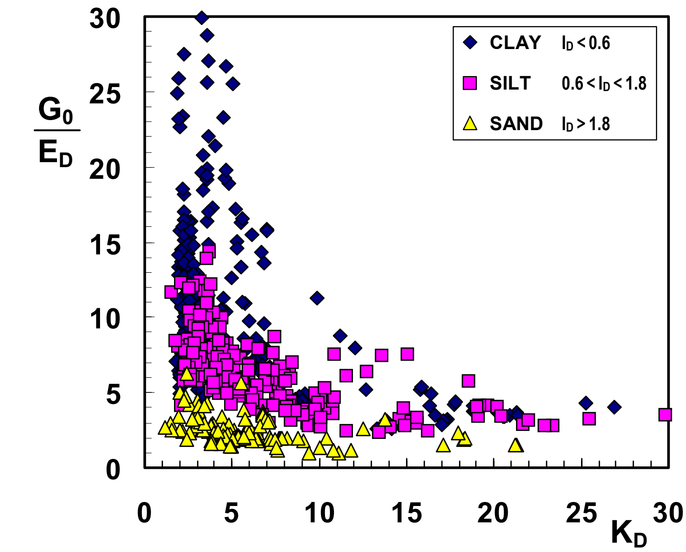


Figure 6. Ratio G_0/E_D vs. K_D for various soil types

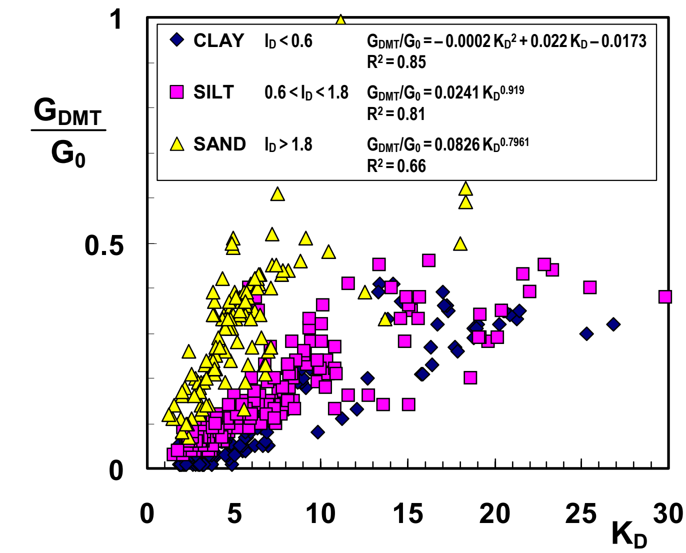


Figure 7. Decay ratio G_{DMT}/G_0 vs. K_D for various soil types

It is emphasized that, at this stage, the legitimacy of using linear elasticity for deriving G_{DMT} from M_{DMT} (Eq. 2) and the assumption that G_{DMT} is a *working strain shear modulus* are only working hypotheses, likely more difficult to investigate than verifying that M_{DMT} is a *working strain constrained modulus* (the matter is discussed later in the paper). The very designation *working strain shear modulus* (or operative shear modulus) requires clarification.

Anyway, if the above hypotheses were acceptable, Figure 7 could provide, if I_D and K_D are known, rough estimates of the decay factor at *working strains*. If complete SDMT are available, then said rough estimates of the *decay factor* could be skipped and the factor could be obtained directly as the ratio between G_{DMT} derived from M_{DMT} (Eq. 2) and G_0.

Experimental information on the *decay factor* could possibly be of interest to researchers in the area of the G-γ decay curves, who might find of interest experimental data indicating how fast G_0 decays depending on soil type and stress history.

Trends emerging from Figure 7 are: (a) The G decay in sands is much less than in silts and clays. (b) The silt and clay decay curves are very similar. (c) For all soils the decay is maximum in the NC or lightly OC region (low K_D).

4 IN SITU G-γ DECAY CURVES BY SDMT

Research in progress investigates the possible use of the SDMT for deriving "in situ" decay curves of soil stiffness with strain level (G-γ curves or similar).

Such curves could be tentatively constructed by fitting "reference typical-shape" laboratory curves (see Figure 8, where G is normalized to G_0) through two points, both obtained by SDMT: (1) the *initial modulus* G_0 from V_S, and (2) a *working strain modulus* G_{DMT} corresponding to M_{DMT} (Eq. 2).

To locate the second point it is necessary to know, at least approximately, the shear strain corresponding to G_{DMT}. Indications by Mayne (2001) locate the DMT moduli at an intermediate level of strain ($\gamma \approx 0.05$-0.1%) along the G-γ curve. Similarly Ishihara (2001) classified the DMT within the group of methods of measurement of soil deformation characteristics involving an intermediate level of strain (0.01-1 %). The above indications, to be supplemented by further investigations, could possibly help develop methods for deriving in situ G-γ curves from SDMT.

Lines of research on this topic were first outlined by Lehane & Fahey (2004).

Lines of research currently under investigation (Marchetti et al. 2008) are:

(a) Enter the G_{DMT}/G_0 ratios of Figure 7 in the vertical axis of "reference typical-shape" G-γ curves recommended in the literature for the corresponding

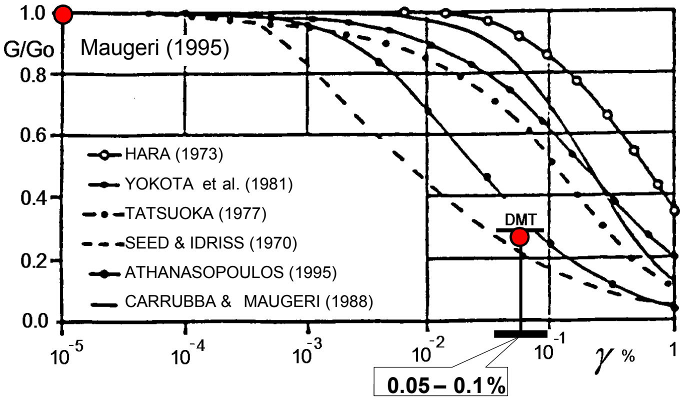


Figure 8. Tentative method for deriving G-γ curves from SDMT

soil type. The range of abscissas of the intersection points with the G-γ curves could possibly help to better define the shear strain corresponding to G_{DMT}.

(b) Develop a procedure for selecting the G-γ curve, among the typical curves recommended in the literature, making use of I_D for choosing the band of curves recommended for the soil type (sand or silt or clay), and K_D (possibly G_0/M_{DMT} too) for selecting one curve in the band.

(c) Evaluate for each of the 800 data points in Figure 5 the settlement under a simple loading scheme using the simple linear analysis with input M_{DMT} (operation equivalent to converting a DMT investigation into a "virtual" load test). Then calculate the settlement by non linear analyses with G-γ curves having variable rates of decay as input. By trial and error identify the G-γ curve (originating in G_0) producing agreement between the two predicted settlements. Consider such G-γ curve reasonably correct and use it in the development of procedures for selecting the G-γ curves from SDMT data.

5 M_{DMT} AS AN OPERATIVE OR WORKING STRAIN MODULUS

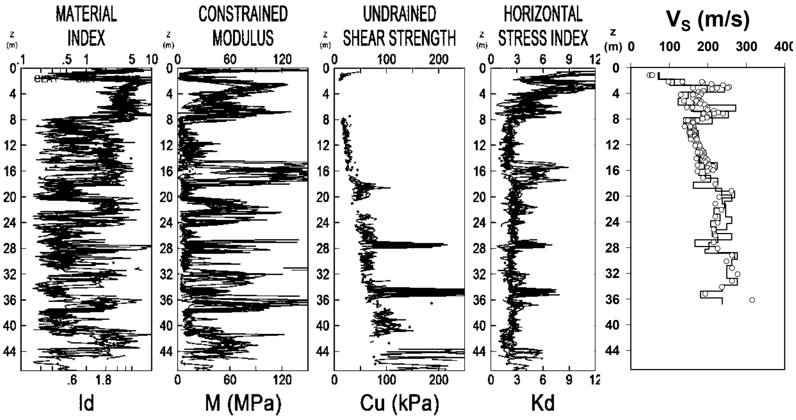
The possible use of the SDMT for deriving "in situ" G-γ decay curves is heavily founded on the basic premise that M_{DMT} is as a reasonable estimate of the *operative* or *working strain modulus*, i.e. the modulus that, introduced into the linear elasticity formulae, predicts with acceptable accuracy the settlements under working loads. (The terms *operative modulus* and *working strain modulus* are considered synonyms and used interchangeably in this paper).

It is therefore considered appropriate to recall here the presently available evidence.

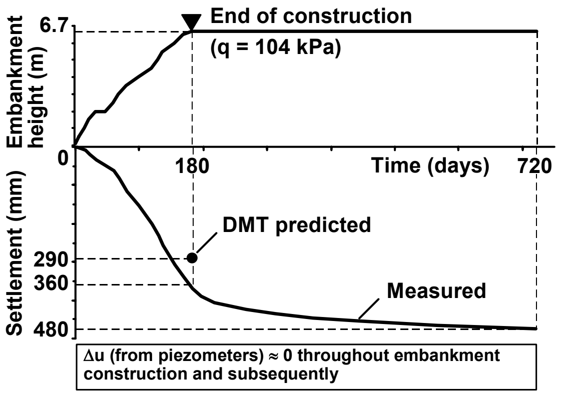
(a) Comparisons of surface settlements

Schmertmann (1986) reported 16 case histories at various locations and for various soil types, with measured settlements ranging from 3 to 2850 mm.

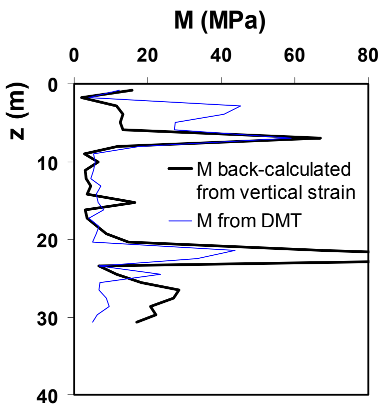
(a) Test embankment. Penetrometer truck for testing after construction.



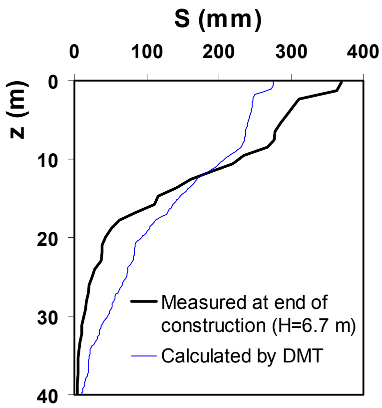
(b) Superimposed profiles of all SDMT data



(c) Settlement vs. time at the center of the embankment and comparison of measured vs. DMT-predicted settlements at the end of construction



(d) M_{DMT} vs. M back-calculated from local ε_v measured at 1 m depth intervals under the center at the end of construction



(e) Observed vs. DMT-predicted settlement under the center at the end of construction

Figure 9. Venezia-Treporti Research Embankment. SDMT profiles. Predicted vs. observed moduli and settlements (Marchetti et al. 2006).

In most cases settlements from DMT were calculated using the Ordinary 1-D Method. The average ratio DMT-calculated/observed settlement was 1.18, with the value of the ratio mostly in the range 0.7 to 1.3 and a standard deviation of 0.38.

Monaco et al. (2006) reviewed numerous real-life well documented comparisons of DMT-predicted versus measured settlements. The average ratio DMT-calculated/observed settlement for all the cases reviewed by Monaco et al. (2006) is ≈1.3, with an observed settlement within ±50% from the DMT-predicted settlement.

The above settlements comparisons appear to support the assumption that M_{DMT} is a reasonable estimate of the constrained *working strain modulus*.

(b) Comparisons of moduli

Even more direct, but rarely available, are data comparing M_{DMT} with moduli back-figured from local vertical strain measurements – by far more realistic and preferable for calibration or comparison purposes.

In 2002 a major research project, funded by the Italian Ministry of University and Scientific Research and by Consorzio Venezia Nuova, was undertaken by a consortium of three Italian Universities (Padova, Bologna and L'Aquila). A full-scale cylindrical heavily instrumented test embankment (40 m diameter, 6.7 m height, applied load 104 kPa – Fig. 9a) was constructed at the site of Venezia-Treporti, typical of the highly stratified, predominantly silty deposits of the Venezia lagoon (Fig. 9b). The loading history, the progression of the settlements and the drainage conditions – practically fully drained – are shown in Figure 9c.

A specific aim of the research was to obtain a profile of the observed 1-D operative modulus M under the center of the embankment. For this purpose a high precision sliding micrometer was used to accurately measure the *local* vertical strain ε_v at 1 m depth intervals.

M values were back-calculated from local vertical strains ε_v in each 1 m soil layer as $M = \Delta\sigma_v / \varepsilon_v$, with vertical stress increments $\Delta\sigma_v$ calculated at the mid-height of each layer by linear elasticity formulae

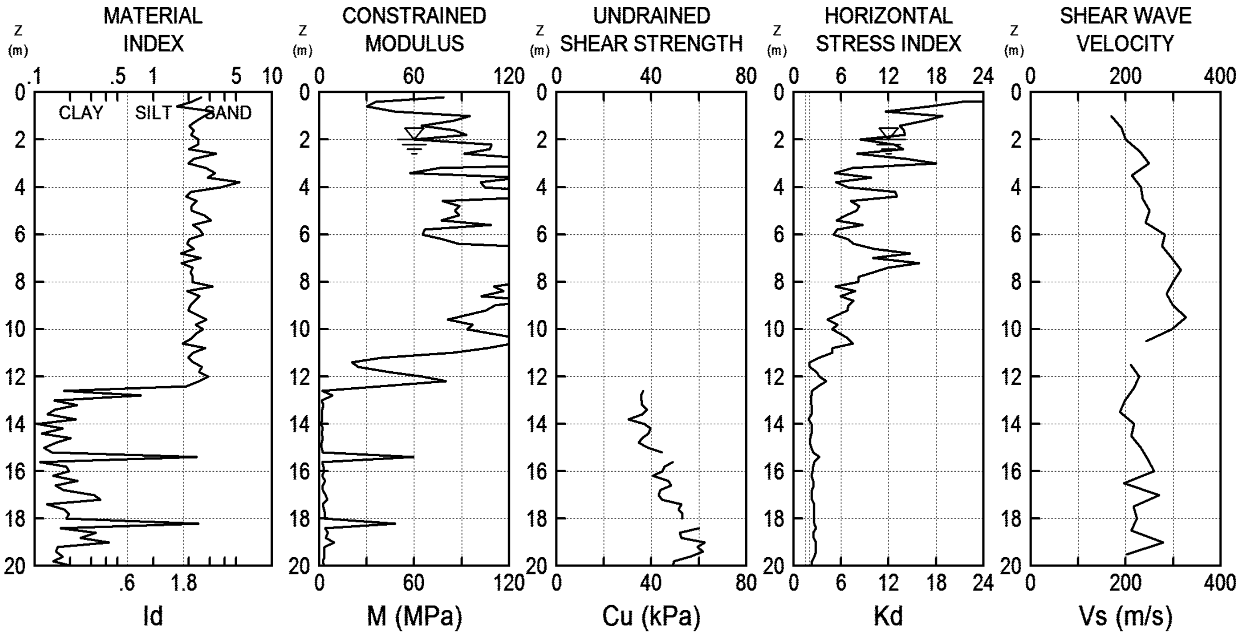


Figure 10. SDMT profiles at the site of Barcelona – El Prat Airport (Spain)

(approximation considered acceptable in view of the very low ε_h). Figure 9d, which is believed to be one of the *most important results* of the Venezia-Treporti research, shows an overall satisfactory agreement between M_{DMT} and moduli back-figured from the test embankment performance, also considering the marked soil heterogeneity. Figure 9e compares the observed versus DMT-predicted settlements at each depth. Again the agreement is rather satisfactory, considering that the DMT predicted settlements were calculated using the simple linear 1-D conventional approach $s = \Sigma\ (\Delta\sigma_v / M_{DMT})\ \Delta H$, where $\Delta\sigma_v$ is calculated by Boussinesq linear elasticity formulae.

As to the surface settlements, the total settlement measured under the center of the embankment at the end of construction (180 days) was ≈ 36 cm (Fig. 9c). The settlement predicted by M_{DMT} using the 1-D approach (before knowing the results) was 29 cm. Hence the 29 cm predicted by DMT (which does not include secondary) are in good agreement with the 36 cm observed settlement (which includes some secondary during construction).

More details on the Venezia-Treporti research can be found in Marchetti et al. (2006), also containing numerous additional bibliographic references.

In conclusion also the Venezia-Treporti case-history supports the assumption that M_{DMT} is a reasonable estimate of the constrained *working strain modulus*.

6 DERIVABILITY OF THE OPERATIVE MODULUS *M* FROM G_0

Figure 10 (Barcelona airport site) shows that at ≈ 12 m depth (transition from an upper stiff sand layer to a lower very soft clay layer) the modulus M_{DMT} exhibits a drastic drop, while V_S shows only a minor decrease. Hence $G_0 = \rho\ V_S^2$ (even considering the power 2) is far from being proportional to the *working strain modulus M*.

Similar lack of proportionality, with variations of the ratio G_0 / M_{DMT} often of one order of magnitude, has been observed at many sites (including Venezia, Figure 9d), suggesting that it is next to impossible (at least without local layer-specific correlations) to derive the *working strain modulus* by simply reducing the *small strain modulus* by a fixed percent factor (e.g. 50 %, Simpson 1999).

On the other hand the poor correlability *M* to G_0 was expected, since at small strains the soil tendency to dilate or contract is not active yet. Such tendency substantially affects the operative modulus *M*, but does not affect G_0. Said in a different way, *M* includes some stress history information, G_0 does not (Powell & Butcher 2004). It may be noted that the high variability of the ratio G_0 / M is already clearly expressed by Figure 5.

7 CONCLUSIONS

The seismic dilatometer SDMT provides routinely at each depth both a *small strain modulus* (G_0 from V_S) and *working strain modulus* (constrained modulus M_{DMT} – as indicated by numerous favourable real-life comparisons of DMT-predicted vs. measured settlements or moduli).

Based on a large number of results by SDMT, diagrams showing experimental interrelationships G_0 - M_{DMT} have been constructed. Figure 5 illustrates the most significant observed trends.

Figure 5 permits to obtain rough estimates of G_0 (and V_S) when V_S is not measured and only mechanical DMT results are available (I_D, K_D, M). Moreover Figure 5 indicates:

(1) Deriving the operative modulus M for settlement predictions from G_0, by dividing G_0 by a fixed number (as suggested by various Authors), appears arduous. Often to drastic variations in the M profile correspond barely visible variations in the G_0 profile. The ratio G_0/M varies in the wide range 0.5 to 20, hence it is far from being a constant, especially in clays and silts. Its value is strongly dependent on multiple information, e.g. soil type and stress history.

(2) To use only one information (e.g. N_{SPT} or s_u) as a substitute of V_S (when not measured) for the seismic classification of a site, as suggested by various codes, appears of dubious validity.

Current research investigates the possible use of the SDMT for deriving "in situ" decay curves of soil stiffness with strain level, by fitting "reference G-γ curves" through two points provided by SDMT at different strain levels: the *small strain* shear modulus G_0 (from V_S) and a *working strain* modulus corresponding to M_{DMT}.

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