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DMT-PREDICTED VS OBSERVED SETTLEMENTS: A REVIEW OF THE AVAILABLE EXPERIENCE

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Abstract: This paper presents a compilation of documented case histories including comparisons of DMT-predicted vs observed settlements, in order to review the available experience in the use of DMT for settlement calculations and to evaluate the accuracy of settlement predictions based on DMT. The available data indicate that, in general, the constrained modulus obtained by DMT (M_{DMT}) can be considered a reasonable "operative modulus" (relevant to foundations under "working conditions") for settlement predictions based on the traditional linear elasticity approach. Attention is also given to the determination of the strain range appropriate to M_{DMT}, in view of the possible use of M_{DMT} for settlement predictions based on non-linear methods taking into account the decay of soil stiffness with strain level.

1. INTRODUCTION

Predicting settlements of shallow foundations is probably the number one application of the DMT, especially in sands, where undisturbed sampling and estimating compressibility are particularly difficult.

This paper presents a compilation of documented case histories (available to the writers) including comparisons of DMT-calculated vs observed settlements, in order to evaluate the accuracy of settlement predictions based on DMT. The database includes several contributions, ranging from well-documented cases to semi-qualitative assessments of DMT-predicted vs observed behaviour or simple comparisons between moduli/settlements obtained by DMT and by other methods. The data are critically reviewed and summarized.

The available experience, reviewed in this paper, indicates, in general, satisfactory agreement between DMT-predicted and observed settlements. In most cases, the constrained modulus obtained by DMT (M_{DMT}) proved to be a reasonable "operative modulus" (relevant to foundations under "working conditions") for settlement predictions based on the traditional linear elasticity approach.

2. CONSTRAINED MODULUS *M* FROM 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} (the same as $E_{oed} = 1/m_v$ obtained by oedometer).

M_{DMT} is obtained by 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 $M_{DMT} = R_M E_D$. The equations defining R_M as a function of the material index I_D and the horizontal stress index K_D were established by MARCHETTI [13]. $R_M = f(I_D, K_D)$ is not a unique proportionality constant relating M_{DMT} to E_D. The value of R_M varies mostly in the range of 1–3 and increases with K_D (major influence).

The causes of applying the correction R_M to E_D are listed in TC16 [28]. In general, the "uncorrected" modulus E_D should not be used as such in deformation analyses, but only in combination with I_D, K_D by use of M_{DMT}, primarily because E_D lacks information on stress history and lateral stresses, reflected to some extent by K_D. The necessity of stress history for a realistic assessment of settlements has been emphasized by many researchers (e.g., LEONARDS and FROST [12], MASSARSCH [17]).

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 $\nu = 0.2$ provides $E = 0.9\ M$, a factor not very far from unity. (Indeed M and E are often used interchangeably in view of the involved approximation).

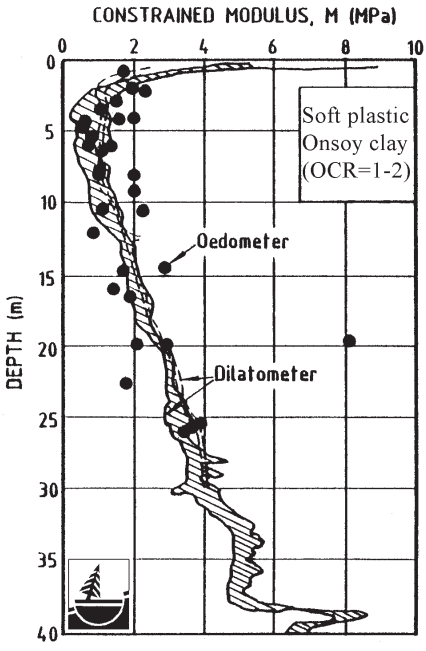


Fig. 1. Comparison between M determined by DMT and by high-quality oedometers, Onsøy clay, Norway (LACASSE [10])

Experience has shown that M_{DMT} is highly reproducible and in most sites variable in the range of 0.4–400 MPa. Comparisons both in terms of M_{DMT} vs reference M (e.g., M from high-quality oedometers, see the example in figure 1, LACASSE [10]), and in terms of predicted vs measured settlements have shown that, in general, M_{DMT} is reasonably accurate and dependable for everyday design practice.

3. 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 $\Delta\sigma$ 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 under "working conditions", i.e., for a safety factor $Fs \approx 2.5$ to 3.5.

MARCHETTI [15] (see also TC16 [28]) recommended that settlements of shallow foundations should be calculated by DMT by means of the classic 1-D method:

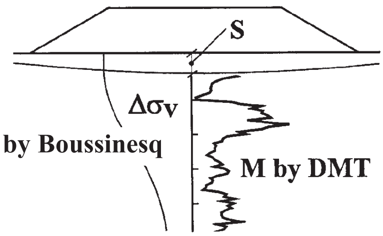
$$S_{1-DMT} = \sum \frac{\Delta\sigma_v}{M_{DMT}} \Delta z \,, \tag{1}$$

with $\Delta\sigma_v$ calculated, e.g., by Boussinesq (figure 2).

Settlements in sand are generally calculated using the 1-D formula (large rafts) or the 3-D formula (small isolated footings). However, MARCHETTI [14] observed that the 1-D and the 3-D formulae give generally similar answers (in most cases the 1-D settlements are within 10% of the 3-D calculated settlements), therefore it appears preferable to use the 1-D formula in all cases, as being simpler and "engineer independent" (no need of subjective guesses of ν or horizontal stresses as required by the 3-D formula). On the other hand, BURLAND et al. [3] observed that errors introduced by simple classical methods are small compared with errors in deformation parameters. Hence, the emphasis should be on the accurate determination of simple parameters, such as the one-dimensional compressibility coupled with simple calculations. Similarly, POULOS et al. [22] emphasized that simple elasticity-based methods appear capable of providing reasonable estimates of settlements, and the appropriate choice of soil moduli is the passport to success rather than the details of the method of the analysis used.

The 1-D method (equation (1)) is also used for predicting settlements in clay. It should be noted that the calculated settlement is the primary settlement (i.e., it does not include immediate and secondary settlements), 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 [15], in some highly-structured clays, whose oedometer curves exhibit a sharp break and a dramatic reduction in slope across the preconsolidation pressure p'_c, M_{DMT} can be an inadequate average if the loading straddles p'_c. However, in many common clays (and probably in most sands) the fluctuation of M across p'_c is mild, and M_{DMT} can be considered an adequate average modulus.



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

Fig. 2. Recommended method for settlement calculation using DMT
(MARCHETTI [15], TC16 [28])

$S_{1\text{-}DMT}$ calculated by equation (1) should still be corrected for rigidity and depth, using the Skempton–Bjerrum correction. In 3-D problems in OC clays, the Skempton–Bjerrum correction often ranges from 0.2 to 0.5. However, considering that (a) the application of the Skempton–Bjerrum correction is tantamount to reducing $S_{1\text{-}DMT}$ by a factor 2 to 5, and (b) in OC clays "the modulus from even good oedometers may be 2 to 5 times smaller than the in situ modulus" (TERZAGHI and PECK [29]); MARCHETTI [15] observed that these two factors approximately cancel each other out and suggested to adopt directly $S_{1\text{-}DMT}$ from equation (1) as primary settlement (even in 3-D problems in OC clays), without the Skempton–Bjerrum correction (while adopting, if applicable, the rigidity and depth corrections, typically from ca. 0.8 to 1).

The methods for settlement calculations using DMT were presented by other authors. SCHMERTMANN [24] suggested to calculate settlements using the classic 1-D method, assuming $M = M_{DMT}$ (Ordinary Method). (This method coincides, in practice, with the method recommended by MARCHETTI [15]). Schmertmann also introduced a procedure (Special Method) for adjusting M_{DMT} (1-D tangent modulus at σ'_{v0}) with varying effective vertical stress during loading, in the virgin compression or recompression range. However, Schmertmann observed that the Ordinary Method, with no adjustment of M_{DMT}, is adequate in most cases.

LEONARDS and FROST [12] proposed a procedure for estimating settlements of footings on granular soils that takes into account the effects of overconsolidation on compressibility. The procedure uses a combination of DMT and CPT results to identify the preconsolidation pressure, while soil moduli (E or M) are obtained from DMT. However, the method by Leonards and Frost is not used as frequently as the other mentioned DMT-based methods.

4. COMPARISON OF DMT-CALCULATED VS OBSERVED SETTLEMENTS

This section presents a compilation of documented case histories (available to the writers), including comparisons of DMT-calculated vs observed settlements. The database includes both Class-A and Class-C predictions. Contributions by various authors (listed in chronological order) range from well-documented cases, with detailed description of soil properties, foundation characteristics and measurements, to semi-qualitative assessments of DMT-predicted vs observed behaviour, with no quantitative data, or simple comparisons between moduli/settlements obtained by DMT and by other methods.

LACASSE and LUNNE [11]

LACASSE and LUNNE [11] report very good agreement between constrained moduli obtained from DMT and moduli backfigured from measured settlements of soils and determined from screw plate and cone penetration tests in Drammen sand (Norway), a 40 m deposit of medium to medium coarse loose sand with occasional silty and organic layers (figure 3).

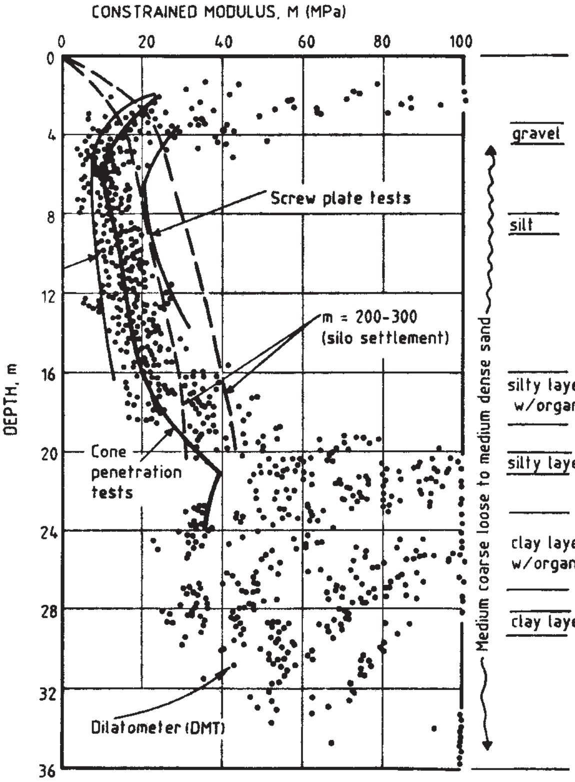


Fig. 3. Comparison of constrained moduli *M* from DMT and from other methods in Drammen sand (LACASSE and LUNNE [11])

SCHMERTMANN [24]

SCHMERTMANN [24] reports 16 case histories at various locations and for various soil types, including sands, silts, clays and organic soils, with measured settlements ranging from 3 to 2850 mm (table 1). In most of the cases, settlements from DMT were calculated using the Ordinary 1-D Method. The average ratio of DMT-calculated/observed settlements was 1.18, with the value of the ratio mostly in the range from ca. 0.7 to 1.3 and a standard deviation of 0.38.

Table 1

Comparison of DMT-calculated vs measured settlements from 16 case histories (SCHMERTMANN [24])

No.	Location	Structure	Compressible soil	Settlement (mm)			Ratio of DMT/ measured settlements
				DMT	**	Measured	
1	Tampa	bridge pier	highly OC clay	25*	b, d	15	1.67
2	Jacksonville	power plant (3 structures)	compacted sand	15*	b, o	14	1.07
3	Lynn Haven	factory	peaty sand	188	a	185	1.02
4	British Columbia	test embankment	peat & organic soils	2030	a	2850	0.71
5 a	Fredricton	surcharge	sand	11*	a	15	0.73
5 b	Fredricton	3' plate load test	sand	22*	a	28	0.79
5 c	Fredricton	building (raft foundation)	quick clayey silt	78*	a	35	2.23
6 a	Ontario	road embankment	peat	300*	a, o	275	1.09
6 b	Ontario	building	peat	262*	a, o	270	0.97
7	Miami	4' plate load test	peat	93	b	71	1.31
8 a	Peterborough	apartment building	sand & silt	58*	a, o	48	1.21
8 b	Peterborough	factory	sand & silt	20*	a, o	17	1.18
9	Peterborough	water tank	silty clay	30*	b, o	31	0.97
10 a	Linkoping	2×3 m plate	silty sand	9*	a, o	6.7	1.34
10 b	Linkoping	1.1×1.3 m plate	silty sand	4*	a, o	3	1.33
11	Sunne	house	silt & sand	10*	b, o	8	1.25

* Ordinary Method used (1-D settlement, no adjustment of M for vertical effective stress during loading).
** b Settlements calculated before the event.
** a Settlements calculated after the event.
** o Settlements calculated by other than the author.
** d Dilatometer advanced by driving with SPT hammer.

HAYES [8]

Figure 4 by HAYES [8], including the datapoints by SCHMERTMANN [24] in table 1 and additional datapoints, shows a remarkably good agreement between observed and DMT-calculated settlements for a wide settlement range.

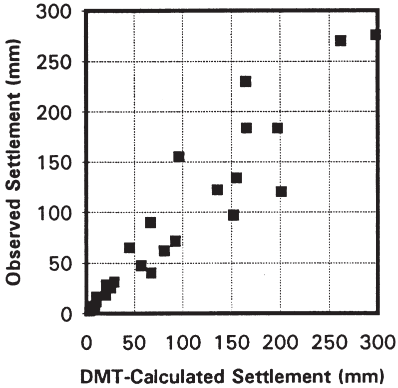


Fig. 4. Observed vs DMT-calculated settlements (HAYES [8])

DUMAS [5]

DUMAS [5] reports good agreement between settlements calculated by pressuremeter (PMT) and DMT in a silty-sandy soil in Quebec, Canada. However, Dumas notes that the time for PMT testing was about 4 as long as that for DMT testing. Similar remarks have been expressed by other authors. SAWADA and SUGAWARA [23] observed that the self-boring pressuremeter (SBPM) and the DMT are both valuable for estimating soil parameters in sands, but the SBPM is much time-consuming and too expensive. SCHNAID et al. [25] compared the parameters from SBPM and DMT in a granite saprolite (Kowloon Bay, Hong Kong) and concluded that the DMT proved to be a reliable tool that yielded good soil parameters at a fraction of the cost of other tests.

WOODWARD and MCINTOSH [31]

WOODWARD and MCINTOSH [31] report the case of a 4-storey steel-framed office building in Jacksonville, Florida, supported on a shallow foundation. The soil was made by an upper ≈ 3–4 m thick layer of loose to firm clean sand overlying a ≈ 2–6 m thick layer of compressible very loose silty fine sand (N_{SPT} from 0 to 5). Total settlements (up to 5 cm) and differential settlements (up to 2.5 cm) estimated using SPT data were considered intolerable. DMT tests were then performed to refine settlement estimates. Total and differential settlements re-evaluated using DMT data (up to 3.2 cm and 1.9 cm, respectively) were considered acceptable to the structural engineer. Settlements measured during construction were slightly less than these predicted by DMT, in general with reasonably good agreement. The use of the DMT at this site enabled the structure to be constructed on a conventional shallow foundation system, avoiding costly and time-consuming soil improvement techniques.

SKILES and TOWNSEND [26]

SKILES and TOWNSEND [26] report comparisons of settlements predicted by DMT and measured in 11 load tests conducted in a controlled test pit filled with a uniformly graded subangular sand. The load tests and the DMT tests were conducted at four separate times, corresponding to different densities of the sand. Square concrete footings of various sizes (12, 18, 24 and 36 in.) were pushed into the sand and the full load–settlement curves were recorded and compared to the predicted settlements at the allowable bearing capacity and near failure. Settlements predicted by DMT were generally in good agreement with the settlements measured at "working loads" of about 1/3 of the ultimate bearing capacity (table 2). The ratio of DMT-predicted/measured settlements was 1.87 on average, with values mostly in the range from ≈ 1 to 2.5. The predictions appeared more conservative for low sand density and small footing size. A trend towards unconservative predictions was noted as the footing size and the sand density increased.

Table 2

Comparison of settlements predicted by DMT (using Schmertmann's Ordinary Method) and measured at allowable bearing capacity in 11 load tests on square footings in sand (modified from SKILES and TOWNSEND [26])

Series	Sand density	Footing size (m)	Allowable bearing capacity (kPa)	Settlement (mm)		Ratio of DMT/ measured settlements
				DMT	Measured	
Sept 1990	very loose	0.61	35	18.3	3.3	5.54
		0.91	53	40.4	30.2	1.34
May 1991	medium dense	0.30	39	1.3	0.5	2.50
		0.46	59	2.5	1.0	2.50
		0.61	78	3.8	3.0	1.25
		0.91	117	6.6	6.4	1.04
June 1992	loose to medium dense	0.30	20	1.3	0.8	1.67
		0.46	30	2.8	1.3	2.20
		0.61	40	4.1	3.0	1.33
		0.91	61	7.9	11.4	0.69
July 1992	heavily compacted	0.91	169	2.3	4.3	0.53

Spread Footing Prediction Symposium at Texas A&M University (1994)

A well-known documented case is the Spread Footing Prediction Symposium held in June 1994 at Texas A&M University, as part of the ASCE Conference Settlement'94 (ASCE, BRIAUD and GIBBENS [1]). Five square footings, ranging in size from 1 to 3 m, were constructed at the Texas A&M University test site. The soil profile at this site consists of 11 m of medium dense (D_R = 50–60%) silty fine sand underlain by a very hard clay layer.

Based on the results of a large number of laboratory and in situ tests (including DMT) carried out at the site, the predictors were asked to formulate a Class-A prediction of the load–settlement behaviour of all the five footings.

Various predictors used DMT data for estimating Q_{25} (load measured in the load test curve at a settlement of 25 mm on the 30 minute load–settlement curve of each footing), using in general the methods by SCHMERTMANN [24] and by LEONARDS and FROST [12]. Figure 5 shows the comparison of DMT-predicted vs measured values of Q_{25} for footing 1 (north) of 3×3 m size. The average ratio of DMT-predicted/measured Q_{25} for all the five footings was generally between ≈ 0.7 and 1.2, i.e., within ± 30% of the measured value. (Note that the "benchmark" settlement $S = 25$ mm, for the footing size B from 1 to 3 m, corresponds to a ratio of $S/B = 0.8–2.5\%$).

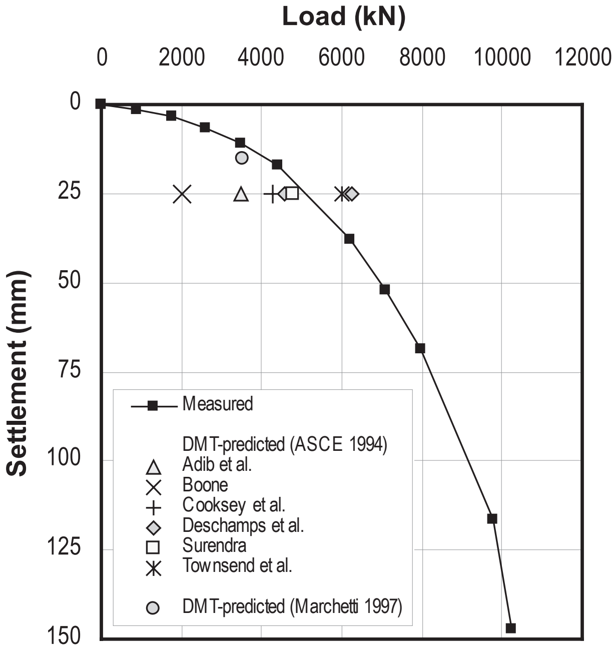


Fig. 5. ASCE Settlement'94 Spread Footing Prediction Symposium. Measured load–settlement curve for footing 1 (3×3 m) vs values of load Q_{25} predicted by DMT by various authors (ASCE [1]) and additional prediction by MARCHETTI [15]

Subsequently MARCHETTI [15] formulated a Class-C prediction using the 1-D method (equation (1)). For the 3×3 m footing he calculated a load of 3519 kN to cause a "working conditions" settlement $S = 0.5\%$ B equal to 15 mm. For this load, S_{observed} (figure 5) was 12 mm, while $S_{1-DMT} = 15$ mm, with a DMT overprediction of +25%. Similarly, for the 1.5×1.5 m footing the calculated load to cause the settlement $S = 0.5\%$ B (7.5 mm) was 844 kN, while $S_{\text{observed}} = 6.5$ mm, with a DMT overprediction of + 15%.

STEINER [27]

STEINER [27] reports the case of a backfilled retaining wall of an avalanche protection gallery in the Swiss Alps, founded on a strip footing on loose silty-sandy soil.

The settlements observed were substantially higher than these anticipated based on soil borings. An additional boring was then drilled to detect the exact depth of the bedrock at the wall position and DMT tests were performed. Settlements re-evaluated using DMT moduli agreed well with monitored settlements of the wall.

DIDASKALOU [4]

DIDASKALOU [4] reports good agreement between DMT-predicted and observed settlements of the Hyatt Regency Hotel in Thessaloniki (Greece), supported on a shallow foundation on a very compressible silt. The maximum settlement predicted by DMT was 105 mm, while the settlement measured near the hotel inauguration (probably including some secondary) was ≈ 120 mm.

FAILMEZGER et al. [6]

FAILMEZGER et al. [6] present 5 case histories with comparisons of settlements predicted by DMT and by SPT. At Route 460 Bypass, Blacksburg, Virginia, SPT predicted 100 mm settlements, while DMT predicted 27 mm (confirmed by oedometer), leading to change in design and cost savings. Generally SPT overpredicted settlements (in one case by a factor of 10).

PELNIK et al. [21]

PELNIK et al. [21] present the examples of use of CPTU and DMT in the sedimentary soils in the Atlantic Coastal Plain region of Virginia, with a subjective rating of the relative value of CPTU and DMT for several design applications in these soils. The DMT is rated as “excellent” for evaluating settlements in sands and soft clays. At Hoskins Creek (new bridge at US Route 17), a very soft NC clay site, PELNIK et al. [21] report good agreement of M_{DMT} with oedometer moduli. Also, settlements estimated by DMT were in agreement with presumed settlements of the road leading to the existing bridge.

TICE and KNOTT [30]

TICE and KNOTT [30] describe the case of moving the Cape Hatteras Lighthouse about 900 m from its original location to protect it from a receding coastline. Tice and Knott found that DMT data provided reliable settlement estimates in the predominantly sandy soils along the path and at the final destination of the lighthouse.

FAILMEZGER [6]

FAILMEZGER [6], in a discussion on probability analysis of settlement predictions of footings in sand, analyzed the standard deviation of settlement predictions by SPT and DMT. According to Failmezger the overall standard deviation is a combination of three independent sources of uncertainty: model uncertainty, measurement noise (test repeatability) and spatial variability of the site. Various studies have indicated that the uncertainty of measurement noise for the SPT can be as high as 45–100%, while the measurement noise for the DMT is much less (6%). Failmezger analyzed the different probability distributions and the test and analysis methods to determine their effects on the probability of unsatisfactory performance of exceeding a threshold settlement. Assuming the standard deviation from spatial variability equal to 20% of the average settlement for both SPT and DMT, the standard deviations from measurement noise and model uncertainty of SPT were much larger than those of DMT. The overall standard deviation for the SPT was 86% of the average value compared with only 29% for the DMT. Failmezger questioned the value of using the SPT as a method to compute settlements altogether and concluded that, in view of the above high SPT variability, the engineer should select for design the best available test and analysis method and attempt to minimize model uncertainty and measurement noise, then focus on the spatial variability of the site, e.g., by use of probabilistic methods.

MARCHETTI et al. [16]

MARCHETTI et al. [16] present the comparison of DMT-predicted vs measured settlements under a full-scale instrumented test embankment (40 m diameter, 6.7 m height, applied load of 104 kPa) at the research site of Treporti (Venice, Italy). The site, typical of the Venice lagoon, consists of highly stratified silts or silty clays and sands, remarkably heterogeneous even in the horizontal direction. The moduli M_{DMT} are highly variable, from ≈ 5 MPa in soft clay layers to ≈ 150 MPa in sand layers.

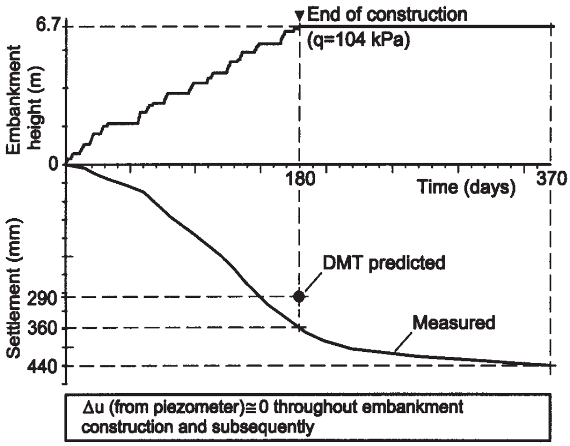


Fig. 6. DMT-predicted vs measured settlement under the center of Treporti test embankment (MARCHETTI et al. [16])

The total settlement measured under the center of the embankment at the end of construction (180 days) was ≈ 36 cm (figure 6). Significant additional settlements were measured after the end of construction (≈ 44 cm at 370 days), hence the 36 cm settlement measured at the end of construction presumably includes, besides immediate and primary, also a significant amount of secondary settlement developed during construction (occurred essentially under drained conditions, as indicated by almost zero excess pore pressure measured by piezometers). The settlement predicted by M_{DMT} using the 1-D approach (equation (1)), before the field measurements were available, was 29 cm net of secondary one, i.e., 7 cm less (–20%) than the 36 cm measured (also including secondary settlement during construction). Hence the settlement predicted by DMT (net of secondary) was in good agreement with the settlement observed.

MAYNE [19]

MAYNE [19] presents the case of a large mat foundation (104×18 m in size, 1.1 m thickness) constructed to support a 13-storey dormitory building on the Piedmont residual silty soils in Atlanta, Georgia. The maximum expected settlement of the mat estimated prior to construction was 46 mm, while the building proceeded to deflect as much as 250 mm at the center and 100 to 140 mm at the corners near the end of construction. Mayne attributes such an incorrect settlement prediction to an over-reliance on SPT data, coupled with a poor choice of the model for analysis and other bad judgments, and shows that simple elastic continuum solutions with input moduli derived from DMT tests (conducted by the independent engineering firm) and finite layer thicknesses are in excellent agreement with measured settlement profiles (figure 7). If carried out before, such calculations would have given essentially the correct answer and warned the designers of excessive displacements.

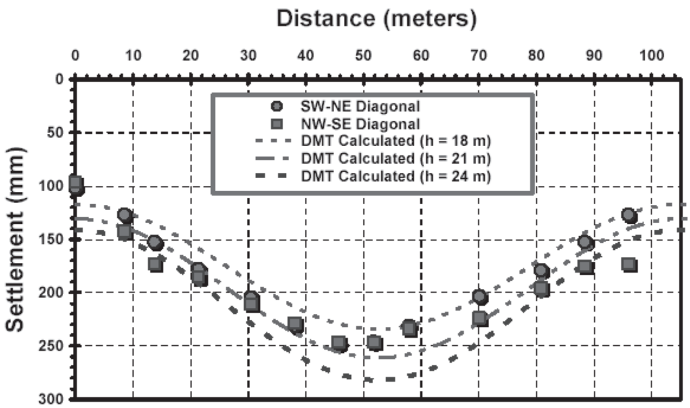


Fig. 7. Measured vs DMT-calculated settlement profiles along the diagonal axes of the mat foundation of a 13-storey dormitory building in Atlanta, Georgia (MAYNE [19])

5. SUMMARY OF AVAILABLE EXPERIENCE ON DMT-CALCULATED VS OBSERVED SETTLEMENTS

Figure 8 summarizes the available comparisons of DMT-calculated vs observed settlements. Over 40 datapoints in figure 8 are representative of the case histories previously described, limited to the cases reporting numerical values of DMT-calculated and measured settlements.

Figure 8 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 of DMT-calculated/observed settlements for all the case histories summarized in figure 8 is ca. 1.3. The band amplitude (the ratio between maximum and minimum) of the datapoints in figure 8 is less than 2, i.e., the settlement observed is within ±50% of the DMT-predicted settlement.

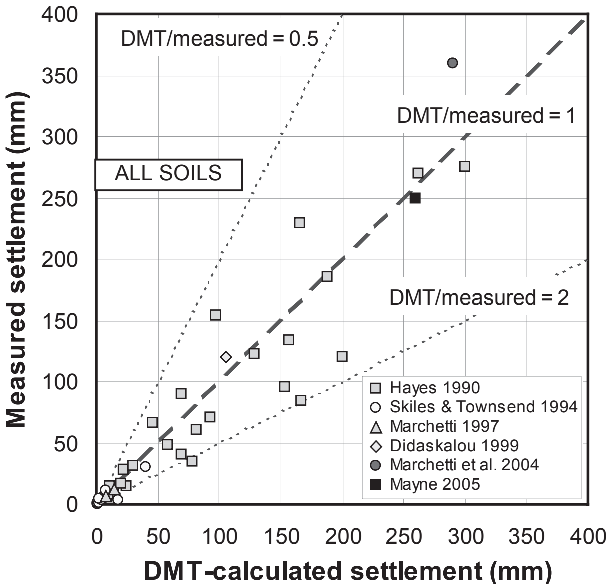


Fig. 8. Summary of available comparisons of DMT-predicted vs observed settlements

6. M_{DMT} AS "OPERATIVE MODULUS" AND POSSIBLE USE OF M_{DMT} FOR NON-LINEAR SETTLEMENT PREDICTIONS

The global experience from several case histories reviewed in this paper indicates that M_{DMT} can be considered a reasonable "operative modulus", i.e., a modulus that, introduced into the linear elasticity theory formulae, provides reasonably accurate settlement predictions for foundations under "working conditions" (say for a safety factor $Fs \approx 2.5$ to 3.5).

In the linear elasticity approach, soil moduli are assumed as constant (not dependent on variations in stress and strain level). Research currently in progress investigates the possible use of M_{DMT} for settlement predictions based on non-linear methods taking into account the decay of soil stiffness with strain level. The objective is to develop the methods for evaluating in situ the decay curves of soil stiffness with strain level (G–γ curves or similar). This approach should permit us to bypass the effect of sample disturbance on G_0 and G–γ curves determined in the laboratory. In situ G–γ curves could be tentatively derived by the use of the seismic dilatometer (SDMT), recently entered into current practice, by fitting "reference" laboratory curves through 2 points: (1) the initial shear modulus G_0 obtained from shear wave velocity V_S measurements, and (2) a modulus at "operative" strains, corresponding to M_{DMT} – provided the strain range appropriate to M_{DMT} is defined. This approach is expected to provide more realistic estimates compared to other methods proposed for deriving in situ G–γ curves (e.g., MAYNE et al. [20]), since the second point for the curve-fitting (given the first point G_0) is not located "at failure", but in the range of "operative" strains (i.e., the strain range of "well designed foundations").

YAMASHITA et al. [32] have shown that OCR significantly influences soil moduli, mostly in the strain range from ≈0.05 to 0.1% (figure 9), where the E_{OC}/E_{NC} ratio (secant Young's moduli from triaxial tests on NC and OC sand specimens) was found as high as from ≈4 to 7 (for K_0 consolidation), while at very small and at very large strains the E_{OC}/E_{NC} ratio is ≈1, i.e., moduli are much less influenced by OCR.

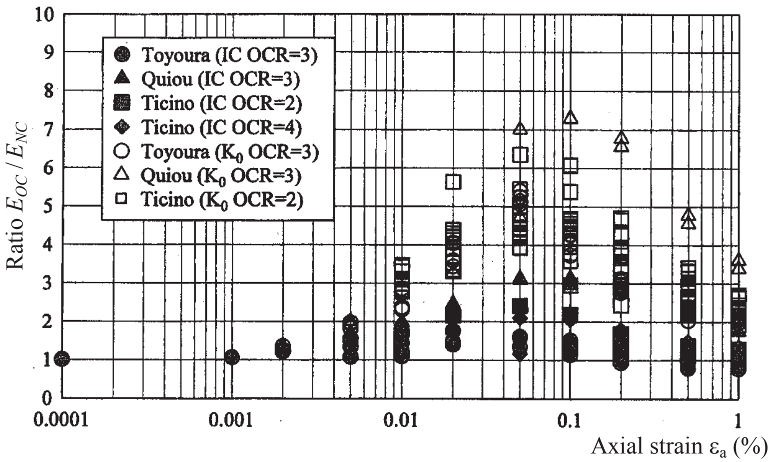


Fig. 9. Effect of OCR on secant Young's modulus from triaxial tests on NC and OC sand specimens (YAMASHITA et al. [32])

Yet, as is well-known, OCR has a strong influence on settlements. Hence G_0, scarcely sensitive to OCR, appears inadequate, if used alone, to correctly predict settlements.

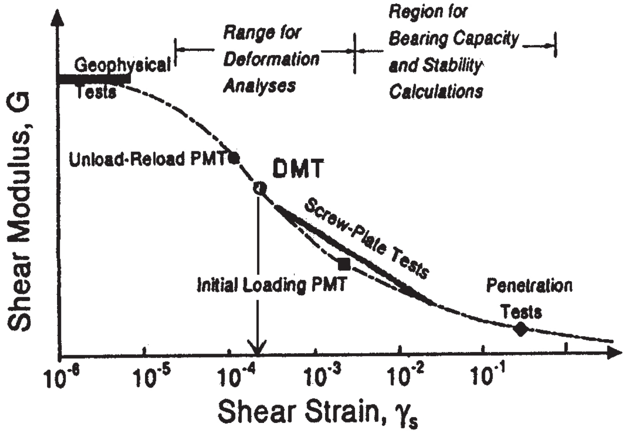


Fig. 10. Decay of shear modulus with strain level and possible strain range of moduli from various in situ tests (MAYNE [18])

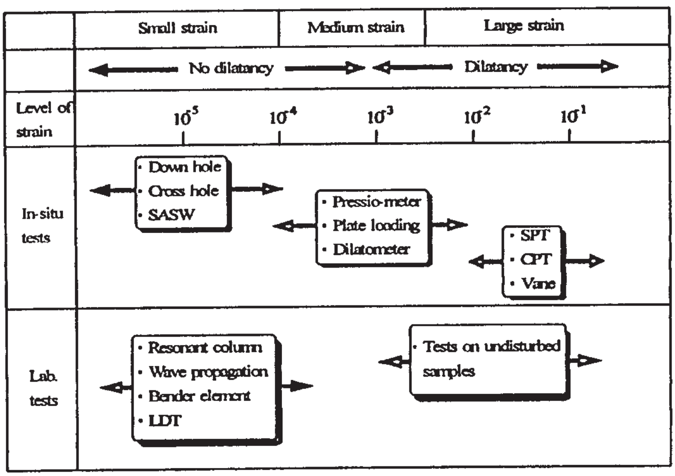


Fig. 11. Classification of methods of measurement of soil deformation characteristics according to the strain level involved (ISHIHARA [9])

In order to use M_{DMT} for locating the second point of the G–γ curve, it is necessary to know at least approximately the shear strain – i.e., the abscissa – corresponding to M_{DMT}. The following indications have been advanced so far.

MAYNE [18] observed that correlations, developed between some in situ tests (e.g., PMT, DMT) and performance monitored data of full-scale structures or reference laboratory values, provide a modulus "somewhere along the stress–strain–strength curve" (figure 10), generally at an "intermediate" level of strain (≈0.05–0.1% in figure 10). A similar indication is given in figure 11 (ISHIHARA [9]), where the

DMT is classified within the group of methods of measurement of soil deformation characteristics involving an intermediate level of strain (0.01–1%).

In most of the cases reviewed in this paper, M_{DMT} predicted well settlements for the values of the S/B ratio (measured settlement/width of footing) mostly in the range of ≈0.5–1%. This observation, supplemented by further investigations, could possibly help develop criteria for deriving in situ curves of decay of soil stiffness with strain level from SDMT to be used for non-linear settlement predictions. Such curves could be expressed, e.g., in form of decay of Young's modulus E/E_0 vs foundation settlement to width ratio of S/B (as proposed, e.g., by ATKINSON [2]).

7. CONCLUSIONS

Many researchers, practitioners and investigation firms have presented case histories comparing observed vs DMT-predicted settlements, reporting generally satisfactory agreement.

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 under "working conditions" (say for a safety factor $Fs \approx 2.5$ to 3.5).

The accuracy of settlement predictions by M_{DMT} is believed to be mostly due to the fact that M_{DMT} routinely takes into account overconsolidation and possible existence of high lateral stresses (incorporated via the stress history parameter K_D) that reduce considerably soil compressibility.

According to POULOS et al. [22] the methods for estimating footing settlements can be evaluated in terms of: (1) accuracy (ratio of calculated/measured settlement), (2) reliability (percentage of cases in which the calculated settlement was equal to or greater than the measured settlement), and (3) ease of use (length of time required to apply the method). Based on the available data, the ability of the DMT to predict settlements proved in general quite satisfactory from all the above points of view.

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