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# DMT-predicted vs measured settlements under a full-scale instrumented embankment at Treporti (Venice, Italy)

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ABSTRACT: This paper presents the preliminary results of field studies based on data from flat dilatometer tests (DMT) and the comparisons of measured vs DMT-predicted settlements. The study is part of a research project aimed at the characterization/modeling of the Venetian soils. A key feature of the project was the construction of a full-scale instrumented embankment (40 m diameter, 6.7 m height, applied load = 104 kPa) at the site of Treporti. The soil, typical of the Venice lagoon, is highly stratified and remarkably non homogeneous. Deformation moduli *M* obtained from DMT were used to predict settlements by using the "traditional" 1-D approach.

## 1 INTRODUCTION

This paper presents the preliminary results of field studies based on data from dilatometer tests (DMT) carried out by the geotechnical group of L'Aquila University at the site of Treporti (Venice, Italy).

The paper also presents the results of settlement calculations based on DMT moduli, carried out before the field measurements were available, and the comparison between DMT-predicted and measured settlements.

The study is part of a research project, involving the Italian Universities of Padova, Bologna and L'Aquila, aimed at the characterization/modeling of the Venetian soils for the preservation of Venice and its lagoon.

The most notable experimental feature of the project was the construction of a full-scale instrumented embankment at the research site of Treporti, in the Venice lagoon. A sand embankment of cylindrical shape (40 m diameter, 6.70 m height, applied load 104 kPa) was built over the period 12th September 2002 – 10th March 2003. The embankment was heavily instrumented for monitoring total settlements, local vertical strains, pore pressures and horizontal deformations down to ≈ 50-60 m depth.

## 2 BASIC PROPERTIES OF THE VENETIAN SOILS

The soil deposits in the lagoon area are composed of a complex system of interbedded sands, silts and silty clay sediments. Due to their complex geological history (Ricceri and Butterfield 1974), the sediments exhibit great non-homogeneity even in the horizontal direction.

The cohesive layers are predominantly silts and very silty clays (ML and CL of the Unified Soil Classification System) characterized by low plasticity (PI = 14 ± 7 %). Granular layers are mainly composed of medium-fine sands and fine silty sands (SP-SM) (Simonini and Cola 2000). Some thin peat layers are found embedded in the soil profile.

The sediments are of unique mineralogical origins, product of a combined effect: evolution of particle crushing and common sedimentation environment (Ricceri et al. 2001).

## 3 FLAT DILATOMETER TESTS AT TREPORTI

The research site of Treporti was extensively investigated before and after the construction of the instrumented embankment by means in situ flat dilatometer tests (DMT), piezocone tests (CPTU), boreholes and laboratory tests on samples. Seismic piezocone tests (SCPTU) and seismic dilatometer tests (SDMT, Martin and Mayne 1998) were also performed.

Fig. 1 shows the plan layout of the embankment and the location of all DMT, CPTU, SDMT and SCPTU soundings carried out at Treporti.

Ten DMT soundings to ≈ 44-46 m depth (DMT 11 – DMT 20) were performed before the embankment construction (January 2002) at various locations within the embankment area (center,

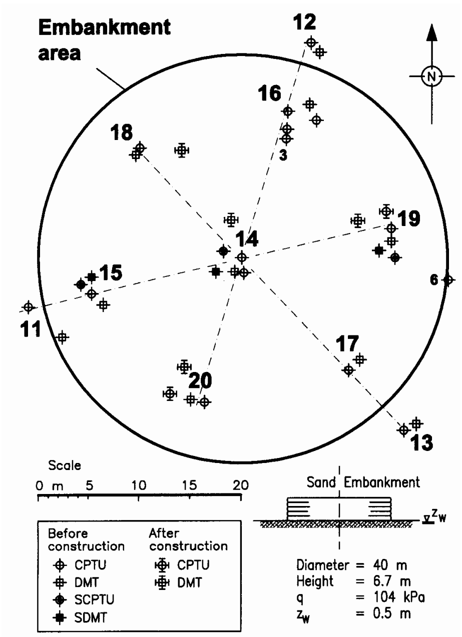


Fig. 1 – In situ tests location

perimeter and intermediate locations). *C* readings were taken every 20 cm, besides *A* and *B* readings, to obtain more detailed soil profiles and distinguish layer of different permeability. A large number of DMTA dissipation tests was carried out to estimate the in situ coefficient of consolidation in the cohesive layers.

Three seismic piezocone tests (SCPTU) and three seismic dilatometer tests (SDMT) were carried out before the embankment construction (June 2002) by the Georgia Tech research group (Atlanta, USA).

After completion of the embankment (May 2003), four DMT soundings to ≈ 44 m were performed starting from the top surface of the embankment (Fig. 2), very close to the locations of pre-construction DMT soundings (≈ 2 m distance), in order to detect changes induced in the soil by the embankment load, particularly variations in moduli with stress level. Fig. 2 is a picture of the embankment taken during the lifting of the penetrometer.

## 4 DMT RESULTS BEFORE CONSTRUCTION

Fig. 3 shows the profiles versus depth of the main parameters (material index $I_D$, constrained modulus $M_{DMT}$, undrained shear strength $c_u$, horizontal stress index $K_D$) obtained from the interpretation of DMT 14, located at the center of the embankment.

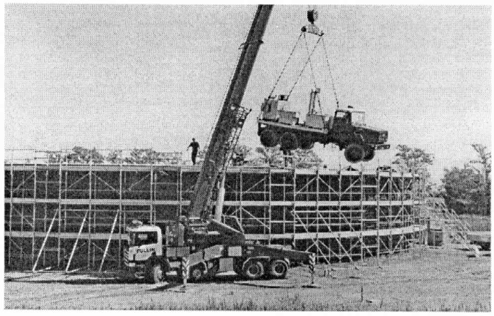

Fig. 2 – Positioning of penetrometer for tests after embankment construction

Fig. 4 shows the superimposed profiles of the above parameters obtained from all the ten pre-construction DMT soundings.

Fig. 5 shows the profiles of $p_0$ and $p_1$ (corrected *A* and *B* readings) obtained at the center of the embankment (DMT 14).

Fig. 5 also shows the profiles of $p_2$ (corrected "closing pressure" *C* reading), the pore pressure index $U_D = (p_2 - u_0) / (p_0 - u_0)$ (Lutenegger and Kabir 1988) and the material index $I_D = (p_1 - u_0)/(p_0 - u_0)$.

Details on the use of *C* readings and $U_D$ may be found in TC16 (2001).

Some comments on DMT results at Treporti are given here below.

### 4.1 *Stratigraphic profile*

$I_D$ profiles (soil type) indicate that layers of sand, silt and silty clay are intensely interbedded. The thickness of the single layers is highly variable, and homogeneous layers with thickness > 2 m are rarely found. A sand layer of significant thickness was found just below the ground surface, in the upper 6-8 m. A thin layer of very soft clay is present at ≈ 1.5-2 m depth.

$U_D$ profiles are a useful integration to the profiles of the material index $I_D$ in non homogeneous and highly stratified soils, like those found at Treporti and, in general, in the Venice lagoon area. The inspection of $U_D$ profiles permits to discern free-draining layers from non free-draining layers. In sand layers (high permeability) it was found $U_D \approx 0$, in high clay fraction layers (low permeability) $U_D \geq 0.7$, in silty layers (partially draining) $U_D$ values are in the range ≈ 0.2 to 0.4.

A note of some interest, useful for the interpretation of DMT results at Treporti, concerns the influence of the drainage conditions during the test. Like other penetration tests, the DMT is a drained test in a clean sand, while in a low permeability clay the test is undrained and the pore pressure excesses do not undergo any appreciable dissipation during the nor-

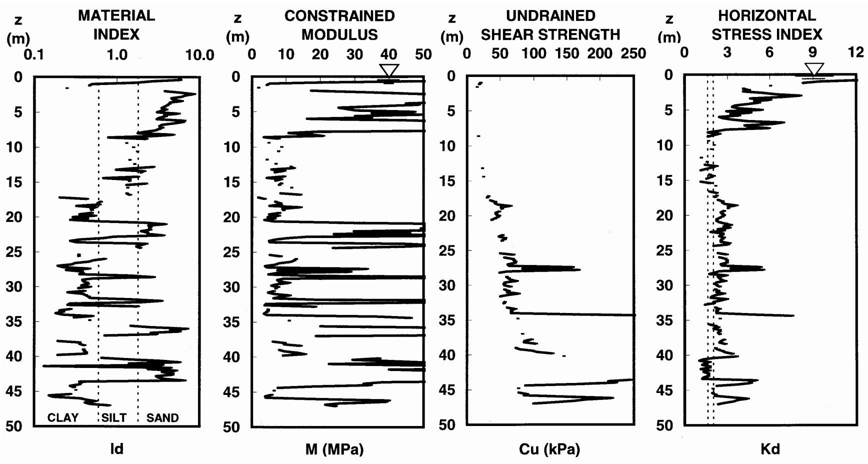


Fig. 3 – DMT profiles of the test at the center of embankment area (DMT 14)

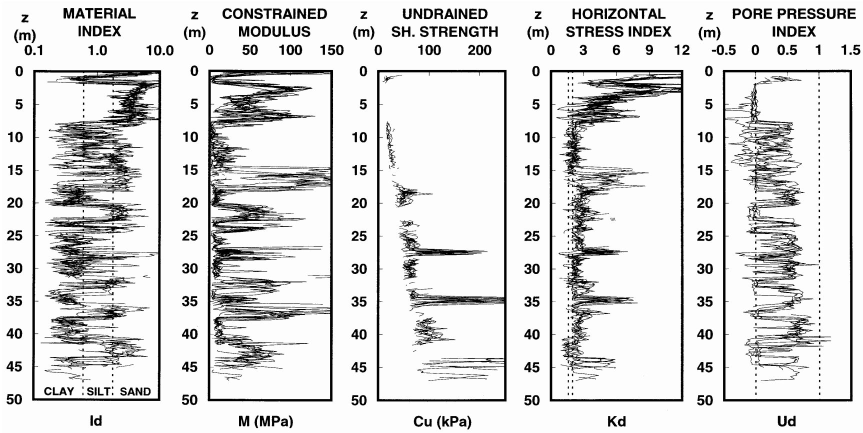


Fig. 4 – Superimposed DMT profiles of all tests (DMT 11, 12, …, 20)

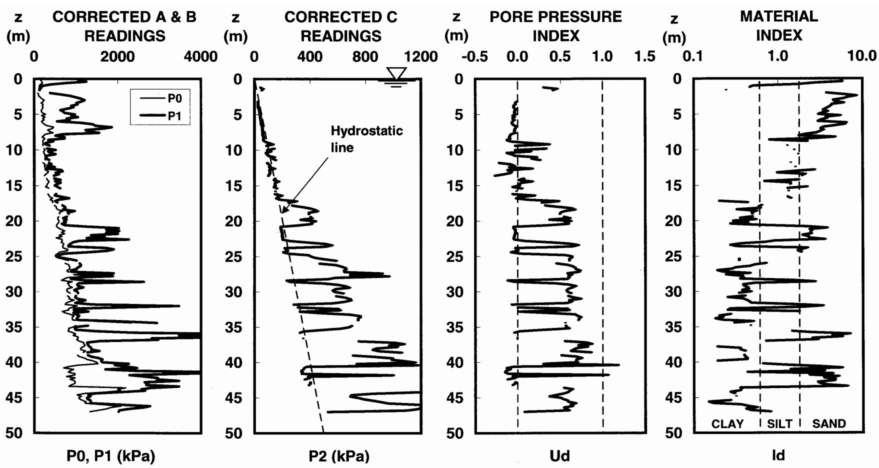


Fig. 5 – Profiles of $p_0$ & $p_1$, $p_2$, $U_D$ and $I_D$ of the DMT test at the center of embankment area (DMT 14)

mal duration of the test (say 1 minute). There is however a *niche* of soils (in the silts region) for which 1 minute is insufficient for full drainage, but sufficient to permit some dissipation. In these *partial drainage* soils the data obtained can be misleading. In fact the reading $B$, which follows $A$ by ≈ 15 seconds, is not the "proper match" of $A$, because in the 15 seconds from $A$ to $B$ excess has been dissipating and $B$ is too low, with the consequence that the difference $B$-$A$ is also too low and so are the derived values $I_D$, $E_D$ and $M_{DMT}$, depending on $B$-$A$. In such soils $I_D$ will possibly end up in the extreme left hand of its scale ($I_D$ = 0.1 or less) and $M_{DMT}$ will also possibly be far too low.

*Niche* soils of very low $I_D$ and $E_D$ were sporadically observed at Treporti in various DMT soundings. The $U_D$ values in such "low $B$-$A$" layers are intermediate between those found in the free-draining layers and those found in the non free-draining layers, thus confirming the above interpretation of "partial drainage". For this reason, for the layers with $I_D \leq 0.15$ it was decided to ignore all the results dependent on the difference $B$-$A$, in particular $E_D$ and $M_{DMT}$. However this occurrence concerns just a few points for each sounding, as shown e.g. by the "blanks" in the $M_{DMT}$ profile in Fig. 3.

### 4.2 *Stress history and OCR*

The $OCR$-$K_D$ correlation commonly used for clay (Marchetti 1980) indicates that the deposit at Treporti is normally consolidated to slightly overconsolidated ($K_D \approx 2.5$, $OCR \approx 1.2$-2).

In the upper ≈ 6-8 m an overconsolidated "crust" ($K_D > 5$-6), maybe due to desiccation, is present.

The "peaks" observed in $K_D$ and $c_u$ profiles in all soundings, more or less at the same depths (27-28 m, 34-35 m and 43-44 m), are due to the presence of thin stiff peat layers.

### 4.3 *Constrained modulus $M_{DMT}$*

The constrained modulus $M$ determined from DMT ($M_{DMT}$) is the vertical drained confined (one-dimensional) tangent modulus at $\sigma'_{vo}$ and is the same modulus which, when obtained by oedometer, is called $M_{oed} = 1/m_v$.

The profiles of $M_{DMT}$ at Treporti reflect the vertical and horizontal disuniformity of the deposit. $M_{DMT}$ varies between ≈ 5 MPa in soft clay layers and 100-150 MPa in sand layers.

### 4.4 *Small-strain shear modulus $G_0$*

Fig. 6 shows the profiles of the shear wave velocity $Vs$ obtained from the seismic flat dilatometer tests and the seismic piezocone tests at the locations 14, 15 and 19. SDMT and SCPTU tests were performed and interpreted by the Georgia Tech research group.

Fig. 7 shows the profiles of the small-strain shear modulus $G_0$ obtained from $Vs$ along the section 15–14–19 across the embankment. $G_0$ has been obtained from $V_S$ using $\gamma_{DMT}$.

The profiles of $G_0$ are more uniform than $M_{DMT}$. $G_0$ increases almost linearly with depth from ≈ 30 MPa to ≈ 150 MPa at 40 m depth.

### 4.5 *Coefficient of consolidation and permeability*

The horizontal coefficient of consolidation $c_h$ was obtained from DMTA dissipations as $c_h \approx 7$ cm$^2/t_{flex}$, where $t_{flex}$ is the time at the contraflexure point of the $A$-log $t$ curves (Marchetti and Totani 1989). The horizontal coefficient of permeability $k_h$ was derived from $c_h$ as $k_h = c_h \gamma_w / M_h$, where $M_h = K_0 M_{DMT}$ (Schmertmann 1988, see also TC16 2001).

Figs. 8 and 9 show the values of $c_h$ and $k_h$ obtained from all DMTA dissipations. The oscillations in the values of $c_h$ and $k_h$ reflect the marked heterogeneity of the deposit. Higher values are influenced by the presence of more permeable silt/sand layers close to the dissipation depths.

The values of $c_h$ are mostly of the order of $1 \cdot 10^{-1}$ cm$^2$/s. The minimum values of $k_h$ (in silty clay layers) are higher than usually found in most soft clays ($k_h \approx k_v \approx 1 \cdot 10^{-7}$ cm/s, Mesri et al. 1994).

The above results suggest a rather fast primary consolidation.

## 5 COMPARISON OF DMT RESULTS BEFORE / AFTER CONSTRUCTION

Fig. 10 shows the profiles of before / after DMT soundings at the center of the embankment. The comparison shows the following effects of the embankment load:

- A reduction in $K_D$ (i.e. in $OCR$) is particularly evident in the OC crust located at shallow depth (in the upper ≈ 6-8 m). This "rejuvenation" is due to the fact that the vertical stress increase in the soil approaches the preconsolidation pressure, leading the soil to a nearly NC state.
- A slight increase in $c_u$, more evident in the soft clay layer at ≈ 2 m below the ground surface.
- $M_{DMT}$ remains unchanged or shows only a very light increase. The application of the load produces an increase in $E_D$ but, at the same time, a reduction in $K_D$. Since $M_{DMT} = f(K_D, E_D)$, the two opposite variations approximately compensate each other and the before / after values of $M_{DMT}$ are very similar. This result, apparently in contradiction with the common notion that $M$ should increase with stress, can be explained observing that, in oedometer tests, $M$ stops to increase as the vertical stress approaches the preconsolidation pressure, or rather, in the case of a pronounced break, $M$ decreases when the vertical stress exceeds the preconsolidation pressure.

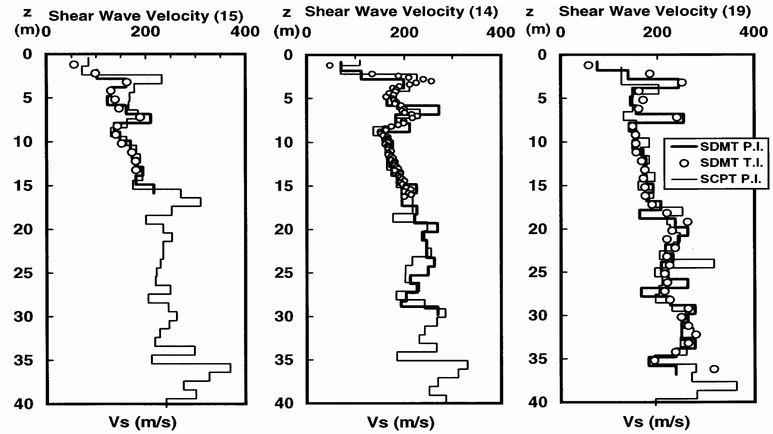


Fig. 6 – Profiles of shear wave velocity *Vs* for the cross section 15-14-19

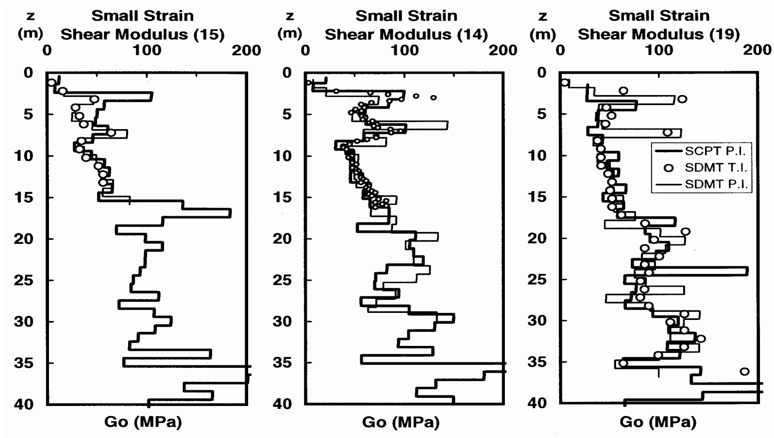


Fig. 7 – Profiles of small strain shear modulus $G_0$ for the cross section 15-14-19

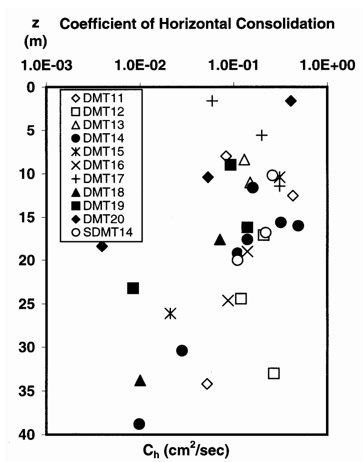


Fig. 8 – Coefficient of horizontal consolidation

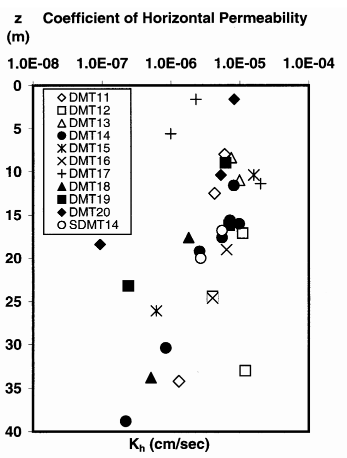


Fig. 9 – Coefficient of horizontal permeability

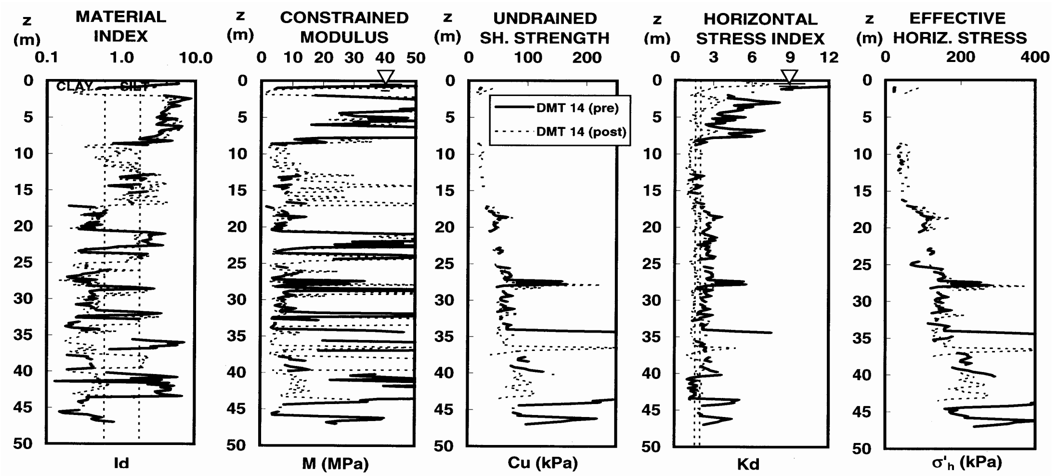


Fig. 10 – DMT profiles of the test at the center of embankment area (DMT 14) before and after the embankment construction

- An increase in $\sigma'_h$ calculated based on $K_0$ estimated from DMT in clay. The increase of $\sigma'_h$ is similar to the corresponding $\Delta\sigma_h$ calculated by Boussinesq. This is a broad confirmation of the DMT $K_0$ correlation for clay.

## 6 DMT PREDICTED SETTLEMENTS

### 6.1 *Primary consolidation settlements*

Deformation moduli obtained from DMT were used to predict settlements below the embankment − before the field results were available.

Settlements were calculated adopting the "traditional" 1-D approach: vertical stress increments were calculated by linear elasticity and "operative" soil 1-D (constrained) moduli were assumed as constant (not dependent on the variations in stress and strain level).

Consolidation (primary) settlements were calculated with the classical 1-D formula $s = \Sigma\,(\Delta\sigma_v / M)\,\Delta z$, assuming $M = M_{DMT}$.

The values of $\Delta\sigma_v$ were calculated from the solutions derived from Boussinesq elastic homogeneous halfspace theory for a circular loading area (Poulos and Davies 1974).

Settlements were calculated at the center and at various points at the edge of the embankment, based on $M_{DMT}$ profiles obtained from each DMT sounding (Fig. 1). Such settlements were then "averaged" to take into account approximately the horizontal variability of the soil across the embankment.

The settlement predictions are reported in Fig. 11. In particular DMT predicted a primary settlement of 267 mm at the center of the embankment, 101 to 160 mm at the edge.

### 6.2 *Immediate (undrained) settlements in clay*

It should be noted that the settlements predicted by DMT are "*the primary settlements (i.e. net of immediate and secondary)*" as emphasized in the TC16 (2001), (section 13.1.2). To obtain the total values, the immediate and secondary settlements need to be added.

An approximate estimate of the immediate settlement was carried out, based on the general geotechnical characteristics of the deposit.

The immediate settlement of the clay layers was estimated using the undrained moduli $E_u$ determined according to Duncan and Buchigani (1976), assuming $E_u/c_{u\,DMT}$ = 600 ("typical" value for NC clays of low plasticity). $E_u$ was also estimated assuming $E_u = 4\,M_{DMT}$ ("typical" ratio between undrained and drained moduli, see e.g. Mitchell et al. 1977).

The immediate (undrained) settlement of the sole clay layers at the center of the embankment was estimated as ≈ 20-23 mm, i.e. ≈ 8-9 % of the consolidation settlement.

### 6.3 *Secondary settlements*

A quantitative method for estimating the secondary settlement by DMT is at present not available, hence no quantitative prediction of secondary settlement was made.

However the DMTA dissipations gave a possible signal that the secondary contribution could be important. Such signal came from the shape of a number of DMTA dissipation curves in silty clay layers exhibiting, instead of the typical "S-shape", a rather "outstretched" nearly rectilinear shape, moreover with $\sigma_h$ continuing to decrease after the dissipation of the excess pore pressures $\Delta u$. Possibly such "non-

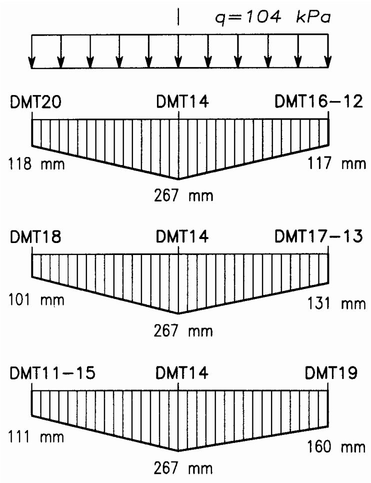


Fig 11 – Consolidation settlements predicted for three cross sections (see also Fig. 1)

S shape" of the DMTA curves could be due to the fact that the decay of $\sigma_h$ depends not only on the dissipation of $\Delta u$, but also on significant creep of the soil skeleton.

The importance of the secondary settlement was later confirmed by the field measurements, indicating a secondary settlement of the same order of the primary settlement.

## 7 COMPARISON OF PREDICTED VS OBSERVED SETTLEMENTS

The total settlement measured under the center, the day of embankment completion, i.e. 180 days after the beginning of construction, was ≈ 36 cm. Excess pore pressure from piezometers was ≈ 0 (< 3 kPa) throughout embankment construction and subsequently. This settlement includes, besides immediate and primary, also the secondary settlement developed in the 180 days of construction (occurred essentially in drained conditions). Secondary during construction was presumably significant, because in the 190 days following the end of construction additional 8 cm of secondary developed (at 370 days the measured settlement was ≈ 44 cm).

DMT had predicted a settlement, under the center, net of secondary (DMT does not predict secondary) of 29 cm (Fig. 12).

The DMT-predicted 29 cm is 7 cm less (20 % less) than the 36 cm measured. However, if homologous quantities have to be compared, the 36 cm developed during the 180 days of construction should be reduced of the contribution of the secondary during construction. Quantifying such contribution would require a specific analysis separating primary

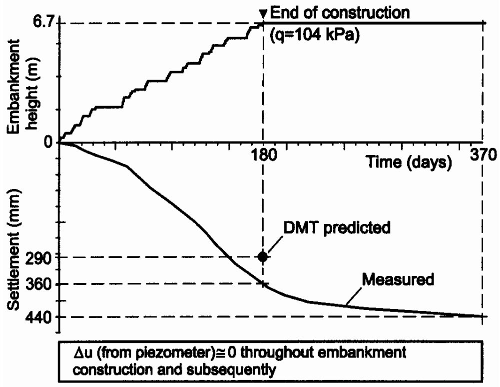


Fig 12 – Comparison of predicted vs measured settlement under the center of the embankment

from secondary, based on back fitting the full time-settlement curve. This analysis will be possible after stabilization of the slope of the time-settlement curve (and possibly when values of $c_\alpha$ from laboratory will be available). The secondary detraction, however, should end up not very different from the above mentioned difference. If this expectation is correct, the ability of DMT to predict settlement (net of secondary) proved in this case quite satisfactory.

## 8 CONCLUSIONS

An experimental instrumented cylindrical embankment, 40 m in diameter, 6.70 m high (104 kPa), was built at a site "representative" of the soil conditions in the Venice area. The complete results of the numerous in situ and laboratory tests and of field monitoring will be published in a comprehensive Report.

This paper concentrates on the DMT results and on the comparisons of measured vs DMT-predicted settlements.

The DMT investigation indicated the following:

– The site consists of highly stratified clays (or very fine silts) and sands, remarkably heterogeneous even in the horizontal direction. The 1-D moduli are highly variable too, in the range 5 to 150 MPa.
– The DMTA dissipations indicate fast consolidation characteristics, hence, in the field, very short duration of the undrained conditions. Actually the construction of the embankment (in 180 days) occurred practically in drained conditions, as demonstrated by the zero excess pore pressure read at the piezometers throughout construction and subsequently.
– The nearly rectilinear shape of the DMTA dissipations curves (in contrast with the more usual S-shape) represented a warning that the secon-

dary settlement could be important. Such importance was later confirmed by the field measurements, indicating a secondary settlement of the same order of the primary settlement.

The soil variations due to the load of the embankment were reflected by the following changes of DMT results before / after construction:

- The horizontal stress index $K_D$ (also representing a "stress history index") decreased, indicating a rejuvenation of the foundation soil. In fact *OCR* decreases as the vertical stress increases under the weight of the embankment, approaching the preconsolidation stress.
- While $K_D$ decreased, $E_D$ increased, so that $M_{DMT}$ remained substantially unchanged. It appears fitting that the DMT correlations have indicated no change in modulus, as the tendency of modulus to increase with stress was compensated by the tendency of modulus to decrease nearing the NC state.
- An increase of: $p_0$ (first DMT reading), $c_u$ and $\sigma'_h$.

The comparisons measured settlements vs DMT-predicted (before the field results were available) indicated the following:

- The total settlement measured under the center, the day of embankment completion, was ≈ 36 cm. This settlement includes, besides immediate and primary, also the secondary settlement developed in the 180 days of construction (occurred essentially in drained conditions). Secondary during construction was presumably significant, because in the 190 days following the end of construction additional 8 cm of secondary developed (at 370 days settlement ≈ 44 cm).
- DMT had predicted a settlement, under the center, net of secondary (DMT does not predict secondary) of 29 cm.
- The DMT-predicted 29 cm is 7 cm less (- 20 %) than the 36 cm measured. However, if homologous quantities have to be compared, the 36 cm developed during the 180 days of construction should be reduced of the contribution of the secondary during construction. Such detraction − once evaluated from a specific analysis based on back fitting the full time-settlement curve − should end up not very different from the above mentioned difference. If this expectation is correct, the ability of DMT to predict settlement (net of secondary) proved in this case quite satisfactory.

The data presented in this paper are the base for subsequent studies. $M_{DMT}$ will have to be compared to $M$ backfigured from measurement of local vertical strains. The analysis of the local vertical strains under various embankment loads, starting from the origin, should permit to reconstruct the in situ $G$-$\gamma$ or $E$-$\varepsilon_v$ curves.

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