Geotechnical Site Characterization, Robertson & Mayne (eds) © 1998 Balkema, Rotterdam, ISBN 90 5410 939 4

In situ determination of c_h by flat dilatometer (DMT)

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Totani G., Calabrese M. and Monaco P (1998). "In situ determination of Ch by Flat Dilatometer (DMT)", Proc. First Intnl Conf. On Site Characterization ISC '98, Atlanta, Georgia (USA), Apr 1998, Vol. 2, 883-888.

ABSTRACT: This paper deals with the use of the flat dilatometer test (DMT) for evaluating the in situ horizontal coefficient of consolidation (c_h) by dissipation tests. Two different procedures developed for this purpose, the DMTC method by Robertson et al. (1988) and the DMTA method by Marchetti & Totani (1989), are briefly recalled and some comparative results discussed. Four case histories are presented where c_h values determined by DMT dissipation tests performed at different well documented NC to OC clay sites in Italy are compared with the corresponding values determined in the laboratory or backfigured from interpretation of field measurements.

1 INTRODUCTION

Different procedures have been developed for evaluating the horizontal coefficient of consolidation (c_h) by means of DMT dissipation tests (Robertson et al. 1988; Schmertmann 1988; Lutenegger 1988; Marchetti & Totani 1989). Particular reference is made herein to the "DMTC" method developed by Robertson et al. (1988) and to the "DMTA" method proposed by Marchetti & Totani (1989). The procedures and formulations adopted by the two methods are briefly recalled and some results comparatively discussed in this paper. Other procedures, such as the "A_2" method used by Schmertmann (1994) (consisting in a series of *A* readings after one *A-B-C* cycle), are just mentioned, since no direct comparative experience is available to the authors at the present time.

In all the proposed methods, the DMT blade penetration is stopped at a given depth, then some form of decay with time of the total contact horizontal stress (σ_h) is observed and plotted to infer c_h. The target of these procedures is c_h since, as shown by the piezocone (CPTU) research, the water flow occurs predominantly in the horizontal direction.

Research has also indicated that c_h determined this way generally applies to the overconsolidated (OC) range. Expected values of the correction factors for estimating c_h in problems involving loading in the normally consolidated (NC) range have been indicated by Schmertmann (1988) and Marchetti & Totani (1989).

2 DMT DISSIPATION TESTS: PROCEDURE AND INTERPRETATION

2.1 *DMTC dissipation test*

This method, developed by Robertson et al. (1988), consists in stopping the blade at a given depth and taking, at different times, the sequence of readings *A-B-C*. *C* is the closing pressure, determined by slowly deflating the membrane after the *B* reading, until the contact is reestablished.

The DMTC method is based on the assumption that p_2 (p_2 = closing pressure *C* corrected for membrane stiffness) is essentially the DMT penetration pore pressure in the soil facing the membrane, hence the resulting p_2 - $\log t$ plot is treated as the dissipation curve of the excess pore pressure and the final p_2 after complete dissipation represents the equilibrium piezometric pressure (u_o). This assumption was verified in a number of soft NC to slightly OC clay sites by researchers at the University of British Columbia and the Norwegian Geotechnical Institute.

- The procedure recommended by Robertson et al. (1988) for estimating c_h is the following: (a) plot the p_2 values obtained from *A-B-C* cycles versus $\log t$; (b) identify the time for 50 % dissipation (t_{50}); (c) use equation (1) to estimate c_h:

$$c_h = \frac{R^2 \cdot T_{50}}{t_{50}} \tag{1}$$

where R = 20.57 mm (equivalent radius for a standard 14 mm by 95 mm DMT blade) and $T_{50} \approx$ 4 (DMT time factor obtained from comparison with the theoretical solutions for CPTU), hence $R^2 \cdot T_{50} \approx 17\ \text{cm}^2$.

Schmertmann (1988), by combining the work by Baligh & Levadoux (1986), Gupta (1983), Lutenegger (1988) and Robertson et al. (1988), presented a similar procedure for evaluating c_h from DMTC dissipation tests: (a) plot the $C - \sqrt{t}$ curve; (b) identify t_{50}; (c) use equation (1) to estimate c_h, assuming $R^2 \approx 600\ \text{mm}^2$ and T_{50} = time factor depending on the rigidity index (E/s_u), ranging between 1.5 ÷ 2 (from Gupta 1983), hence $R^2 \cdot T_{50} \approx 9 \div 12\ \text{cm}^2$ versus $17\ \text{cm}^2$ proposed by Robertson et al. (1988).

2.2 *DMTA dissipation test*

This method (Marchetti & Totani 1989) consists in stopping the blade at a given depth, then taking a sequence of *A* readings at different times (usually 0.5, 1, 2, 4, 8, 15, 30, 60 etc. minutes after stopping the blade at the required depth, until stabilization). Only the *A* reading is taken, without performing the expansion to *B* as in the standard DMT test, i.e. deflating immediately as soon as *A* is reached (this method is also called "*A* & deflate" dissipation).

- The steps suggested by Marchetti & Totani (1989) for evaluating c_h are: (a) plot the $A - \log t$ curve; (b) identify the contraflexure point in the curve and the associated time (t_{flex}); (c) use equation (2) for an average estimation of $c_{h,OC}$ (Marchetti 1997):

$$c_{h,OC} \approx \frac{7\ \text{cm}^2}{t_{flex}} \qquad (2)$$

3 DMT DISSIPATION TESTS IN DIFFERENT CLAY SITES IN ITALY

3.1 *Fucino*

Several standard DMT and DMTA / DMTC dissipation tests were performed at the Fucino site, in center Italy (Totani & Marchetti 1988; Marchetti & Totani 1989), as a part of an extensive investigation program. A detailed characterization of the soil (a thick, quite homogeneous deposit of soft, highly structured, cemented, NC lacustrine clay) is illustrated by A.G.I. (1991). The results of a typical DMT test are shown in Figure 1.

A comparison between decay curves obtained from DMTA (A - $\log t$) and DMTC (p_2 - $\log t$) dissipation tests performed at about the same depths (5 - 10 - 15 m) is shown in Figure 2.

The in situ c_h values determined by DMTA and DMTC are plotted versus depth in Figure 3, compared to the values of c_v and c_h determined in the

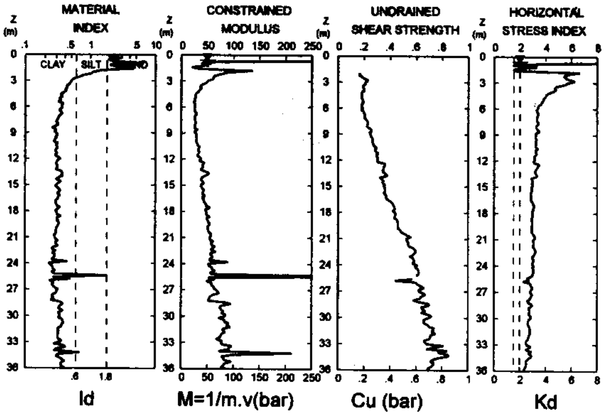

Figure 1. Fucino - Typical DMT profiles

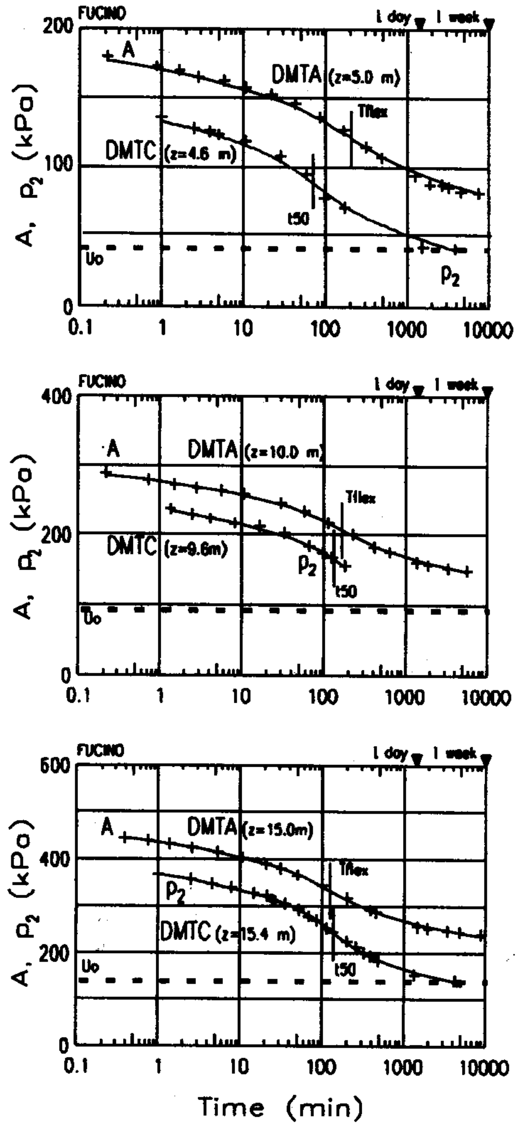

Figure 2. Fucino - Comparison between decay curves from DMTA and DMTC at the same depth

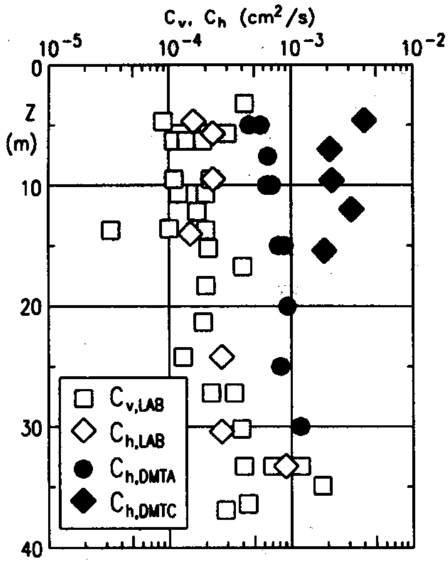

Figure 3. Fucino - Comparison between in situ c_h by DMT and laboratory c_v - c_h by oedometer tests (after A.G.I. 1991)

laboratory by oedometer tests at effective stresses equal to twice the yield stress (A.G.I. 1991), hence in the NC range.

The laboratory c_h values (horizontally trimmed specimens), though limited in number, indicate a ratio c_h / c_v ≈ 1 ÷ 1.5, hence a nearly isotropic behavior of the clay.

The ratio between in situ $c_{h,OC}$ from DMTA and laboratory $c_{h,NC}$ is nearly constant with depth (reflecting high reproducibility and stability of DMTA results) and equal to ≈ 3 ÷ 4. This could be explained as an effect of the different stress range (OC versus NC); anyway, the ratio $c_{h,OC}$ / $c_{h,NC}$ in this case is less than presumed previously (Schmertmann 1988; Marchetti & Totani 1989).

The c_h values from DMTC, determined according to Robertson et al. (1988), are one order of magnitude higher than the laboratory c_h and ≈ 4 times c_h from DMTA at the same depths, thus indicating a discrepancy between the two methods.

3.2 *Garigliano River*

Two standard DMT tests and two DMTA dissipation tests were performed in 1994 in an extensively investigated site located in center-south Italy, where a new bridge over the Garigliano River had to be constructed. The tests were performed nearby a large approach embankment, 6 to 8 m high, instrumented with piezometers and extensometers (Figure 4). Details about site characterization and instrumentation are reported by Mandolini & Viggiani (1992). The results of one DMT test are shown in Figure 5.

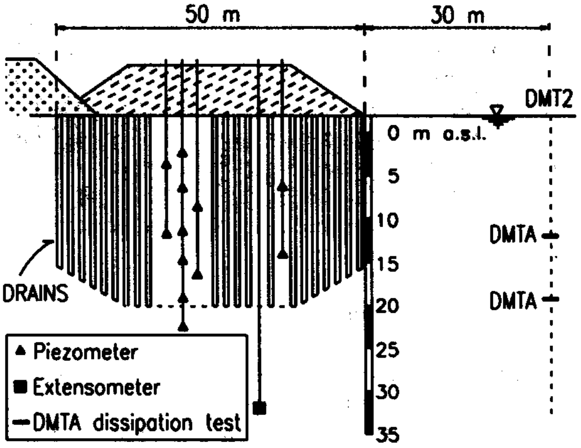

Figure 4. Garigliano - Instrumented embankment (after Mandolini & Viggiani 1992) and location of DMT dissipation tests

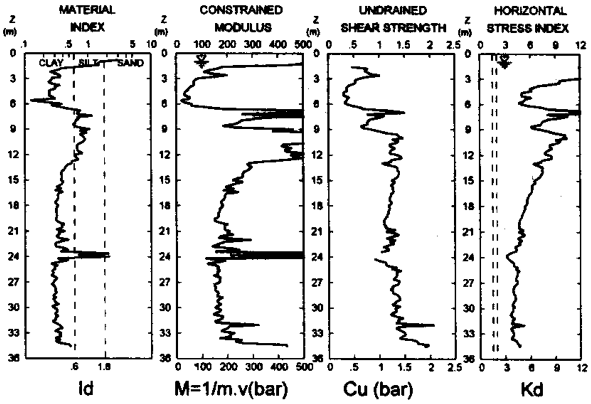

Figure 5. Garigliano - Typical DMT profiles

The soil is a thick, slightly OC (*OCR* ≈ 6 ÷ 8 in the upper 20 ÷ 30 m, decreasing with depth) silty sandy clay deposit. Considering the stress level involved by the problem, consolidation occurs predominantly in the OC range.

Since calculations carried out based on an average c_v determined from laboratory tests ($c_v = 4.5 \cdot 10^{-4}$ cm²/s) had indicated a very long time to achieve a significant amount of consolidation, prefabricated vertical drains, 12 to 25 m long, had been installed in order to fasten settlements below the embankment.

An average value of the in situ $c_h \approx 0.9$ to $1.9 \cdot 10^{-3}$ cm²/s (i.e. 2 ÷ 4 times larger than the average laboratory c_v) was backfigured by Mandolini & Viggiani (1992) from interpretation of the radial (due to the vertical drains) consolidation process based on piezometers and extensometers measurements.

The in situ c_h values determined from the two DMTA dissipation tests, performed at 13.90 m and

21.40 m depth, ($c_{h,OC} = 0.4 \cdot 10^{-3}$ - $2 \cdot 10^{-3}$ cm^2/s), fall in the range of the in situ $c_{h,OC}$ values estimated by back analysis. The difference between the two c_h values from DMTA probably reflects, in this case, some small scale heterogeneity of the deposit. This points out the necessity of performing an adequate number of dissipations, particularly in non homogeneous sites, in order to obtain representative data.

3.3 *Santa Barbara mine*

In 1994 three standard DMT tests and one DMTA dissipation test were performed in a large clay waste disposal (Forestello) located in the area of Santa Barbara open-pit mine (center Italy), where a considerable consolidation process, monitored over a long period by piezometer cells installed at different depths and locations, was still in progress (Figure 6).

The disposal is formed by the material resulting from excavation of the mine slopes, a heavily OC jointed pliocenic clay, which, due to softening and water content redistribution, is turned into a remoulded, isotropic, compressible NC clay (D'Elia et al. 1994). In this case, consolidation occurs in the NC range.

The results of a typical DMT test are shown in Figure 7. The *A* - *log t* curve from DMTA (33.20 m depth) is shown in Figure 8.

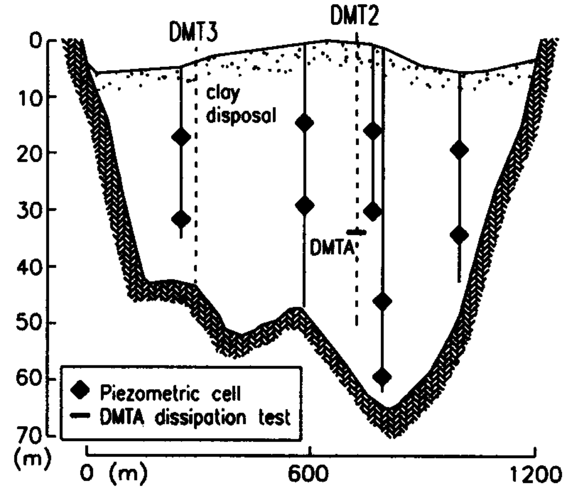

Figure 6. Santa Barbara - Instrumented cross section (after D'Elia et al. 1994) and location of DMT dissipation tests

The values of c_v determined from laboratory tests on undisturbed clay samples taken from the disposal and backfigured by modeling the consolidation process based on piezometer measurements (D'Elia et al. 1994) are plotted versus the effective vertical stress (σ'_v) in Figure 9. The in situ c_h from DMTA ($c_{h,OC} = 1.2 \cdot 10^{-3}$ cm^2/s), also indicated in Figure 9, falls within the range of c_v (NC) values determined in the laboratory and estimated by back analysis at the same stress level ($c_v \approx 1 \div 3 \cdot 10^{-3}$ cm^2/s).

In this case, since the clay may be considered isotropic ($c_h \approx c_v$), the ratio $c_{h,OC} / c_{h,NC}$ is ≈ 1.

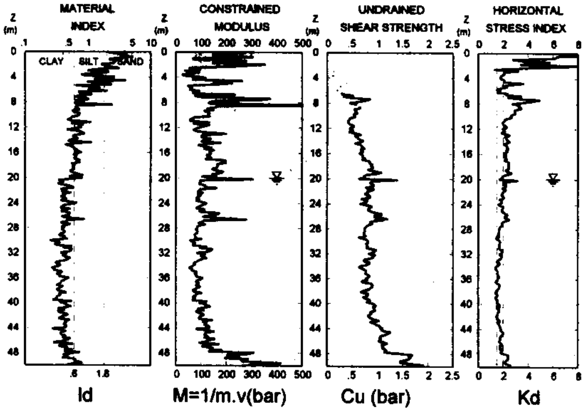

Figure 7. Santa Barbara - Typical DMT profiles

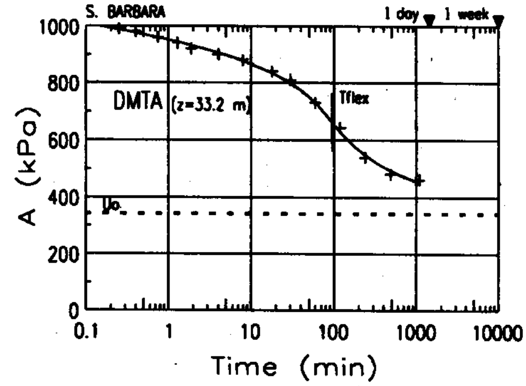

Figure 8. Santa Barbara - Decay curve from DMTA dissipation test

3.4 *Parma*

In 1997 a comprehensive site investigation program, including several standard DMT and DMTA dissipation tests, was carried out near Parma, in the Po River plain (north Italy), in order to characterize a site where a new important railway structure had to be constructed.

The soil is a slightly OC clayey silt with frequent thin sandy layers. The results of a typical DMT test are shown in Figure 10. Figure 11 shows a sample DMTA *A* - *log t* curve.

The values of $c_{h,OC}$ from DMTA have been compared with the values of c_v determined in the laboratory from oedometer tests on undisturbed samples taken at the same depth at σ'_{vo} in the recompression (OC) range (Figure 12). Despite the large scattering of the data, reflecting the marked

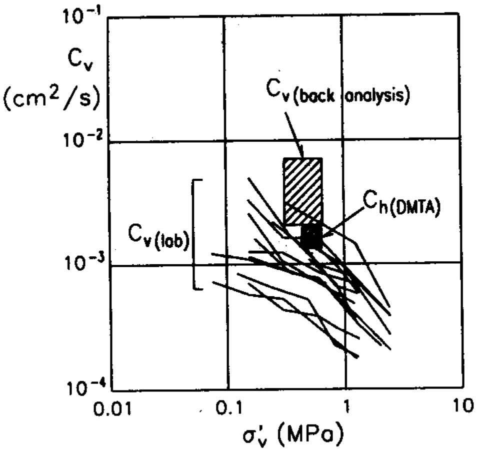

Figure 9. Santa Barbara - Comparison between c_v from laboratory tests, in situ c_v from back analysis (D'Elia et al. 1994) and in situ $c_{h,OC}$ from DMTA

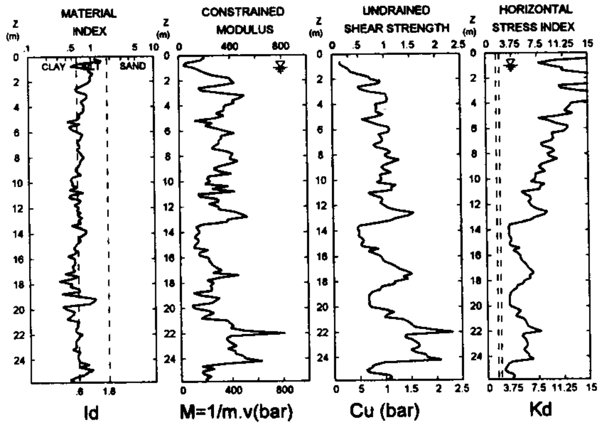

Figure 10. Parma - Typical DMT profiles

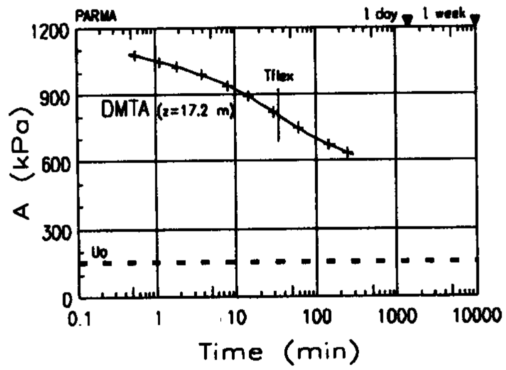

Figure 11. Parma - Sample DMTA decay curve

heterogeneity of the deposit, an average ratio $(c_{h,OC})_{DMTA} / (c_{v,OC})_{LAB} \approx 1.5$ may be detected in this case.

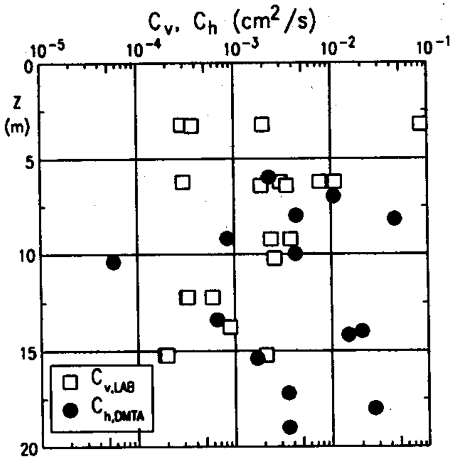

Figure 12. Parma - Comparison between in situ $c_{h,OC}$ from DMTA and $c_{v,OC}$ from oedometer tests

4 CONSIDERATIONS ABOUT DMT DISSIPATION TESTS RESULTS

Favourable aspects of DMT dissipation tests are believed to be:

- absence of problems of filter smearing / loss of saturation / clogging (the DMT membrane is anyway a non draining boundary);
- while pore pressures *u(t)* vary from point to point, settlements (like in the oedometer) and total contact horizontal stresses $\sigma_h(t)$ (the membrane can be regarded as a "mini lateral embankment") have a more stable trend, being some kind of integral, thus providing a more stable evaluation of c_h (see Fig. 6 by Marchetti & Totani 1989).

Comparisons between DMTA and DMTC have been attempted, whenever possible. The two methods differ for test procedure, type of "reference time" and formulation. Since only a few data are available of parallel c_h from DMTA / c_h from DMTC (generally one opts for DMTA or DMTC) in sites where reliable reference c_h are available too (as at the Fucino site), it is not possible today to evaluate comparatively the quality of the two methods. However, the authors preference goes to the DMTA method for the following reasons:

- DMTA is perfectly analogous to the well established pressuremeter "holding test" (in the case of the DMT, the fixity of the probe is 100 % insured, being the DMT blade a solid object). While theoretical σ_h decay curves are not available for the DMT shape, such curves are expected to be similar to the theoretical curves found for the cylindrical case, since the phenomenon is the same. Waiting for the theory, the most effective way appears to use an experimentally calibrated relation such as the above equation (2).

- The DMTC method relies on the assumption (which may not always be sufficiently approssimate) that $C \approx u$, using $C(t) \approx u(t)$ decay curves in an attempt to reproduce the interpretation of c_h from CPTU.
- In DMTC the C reading is affected by the travel of the membrane during the expansion (Powell & Uglow 1988), which suggests some "procedure dependence" of the results.
- Being the DMT blade rectangular, the selection of the DMT equivalent radius involves further uncertainty, requiring an experimental calibration anyway.
- Determining t_{flex} (DMTA) is, generally, simpler and more stable than t_{50} (DMTC): usually t_{flex} is very clearly identifiable (except in non S-shaped curves), while t_{50} is often of dubious determination due to the uncertainties which in many cases exist at start / end of the decay curves.

Comparing equations (1) (assuming an average product $R^2 \cdot T_{50} \approx 14$ cm^2) and (2), it can be noted that they imply t_{50} (DMTC) ≈ 2 t_{flex} (DMTA). The authors have attempted, based on a few available data, some comparisons t_{flex} (DMTA) - t_{50} (DMTC), in order to evaluate if and to what extent the relation t_{50} (DMTC) ≈ 2 t_{flex} (DMTA) is verified. It has been observed that these values are usually similar, but not systematically one larger than the other. Some cases are reported where the ratio t_{flex} (DMTA) / t_{50} (DMTC) is found to be ≥ 1 (at Fucino t_{flex} (DMTA) / t_{50} (DMTC) $\approx 1 \div 3$; Chang (1994) illustrates a case in Singapore marine clay where this ratio is $\approx 1.6 \div 5.6$). Obviously, larger amount of parallel DMTA-DMTC data is needed in order to draw general conclusions about this point.

5 CONCLUSIONS

- The persisting scarcity of adequate reference data still does not permit to evaluate adequately the c_h predictions by DMT. However, in the cases presented in this paper, the values of c_h from DMTA are in relatively satisfactory agreement with the corresponding values determined in the laboratory or backfigured from interpretation of field measurements.
- The comparative data presented in this paper, obtained for both NC and OC clay sites, show that c_h values from DMTA dissipations are highly reproducible, stable, procedure and operator independent.
- The ratio $(c_{h,OC})_{DMTA}$ / $(c_{h,NC})_{LAB}$ has been found to vary significantly from site to site, in the range 1 to $3 \div 4$ (i.e. DMTA predictions 1 to $3 \div 4$ times faster than predictions based on laboratory). Such range of variation is high, but not as high as presumed previously (Schmertmann 1988; Marchetti & Totani 1989). Further insight is needed into the problem of the identification of "correction factors" from OC to NC state (and, in general, from field to laboratory).
- In the examined cases, predictions of the settlement rate based on c_h from DMTA, without applying any correction factor, would have been not too far from field behavior, being the DMTA predictions slower by a factor 1 to 3 (c_h from "real life" back calculations $\approx$ 1 to 3 times c_h from DMTA).

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