C_h evaluations from DMTA dissipation curves

L'évaluation de C_h à partir des courbes de dissipation de DMTA

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SYNOPSIS: The paper presents a tentative method for inferring rate - of - consolidation properties - in particular the horizontal coefficient of consolidation C_h - from the A(t) dissipation curves determined by a standard Dilatometer. The method uses the time T_{flex} at the contraflexure point of the A vs log t dissipation curve as an index of the rate of consolidation. DMTA dissipation curves determined at a number of deposits, among which the Fucino clay and Pisa clay, are presented. Since theories relating T_{flex} to C_h are presently unavailable, a tentative empirical correlation between T_{flex} and C_h has been suggested. The paper is concerned with the evaluation of C_h in NC or moderately OC cohesive soils, with reference to decisions concerning the necessity of vertical drains adoption and drain space design.

1 INTRODUCTION

This paper presents a tentative method for evaluating the horizontal coefficient of consolidation C_h from the decay rate of the DMTA dissipation curve. Such curve is obtained by plotting, vs log time, a sequence of first readings A determined with a standard Dilatometer.

The DMTA dissipations referred to herein are performed by taking only the lift-off A reading, deflating the pressure immediately thereafter, thus omitting the expansion of the membrane and the B reading (DMT blade used as a "passive" spade cell).

The method is diverse from the "DMTC" method based on expansion-deflation cycles ABC, ABC etc. studied by other researchers (Schmertmann, 1988; Robertson, 1988; Lutenegger, 1988).

Consideration herein is restricted to NC or moderately OC cohesive soils.

2 BASE OF THE METHOD

DMTA dissipation curves have already been presented in the past (Marchetti et al., 1986) in a study concerned with the prediction of skin friction of piles driven in clay. Already at that time it was evident that the decay rates of A in soils of different permeability varied widely.

Since, at least in soft clays, an important proportion of σ_h against the blade is pore pressure u, and the σ_h decay corresponds, to a large extent, to the u decay, it seems logical to expect the existance of at least an approximate relationship between the rate of decay of σ_h and C_h (C_v having little effect, as demonstrated by CPTU research).

It may be appropriate to remind that the determination of the coefficient of consolidation does not necessarily require that the quantity measured be u (an example is the oedometer, where the speed of settlement is linked to C_v via the 1 - D consolidation theory).

The idea of inferring C_h from the decay rate of σ_h against in situ probes is not new. E.g. Clarke et al. (1979) studied such method in connection with the interpretation of the Pressuremeter Holding Test (in this test the membrane is held fixed automatically at the inflated radius by adjusting the applied pressure, controlled by the electronic output of the strain arms).

Theoretical solutions for the decay of σ_h (total) against cylindrical probes have been obtained by Carter et al. (1979).

Given the preliminary nature of the outlined method, the contribution of drained creep to the σ_h decay has been ignored.

3 THE EXPERIMENTAL DETERMINATION OF THE DMTA CURVES

The DMTA dissipation curves can be determined with high accuracy and regularity, as illustrated by various examples in this paper, thanks to the following circumstances:

- The method of σ_h determination is a balance - of - zero method.
- The membrane, being flat, opposes a very small resistance to lift - off.
- The membrane is an air-soil separator, not a measuring organ. Thus no zero drift is originated in the blade, affording stability over long periods of time, if required.
- The only measuring organ is the gage at surface. Since the A-readings in this kind of test are generally taken using the low scale gage, very high accuracy is obtained naturally, without particular efforts.
- Monitoring the total σ_h is inherently much simpler than monitoring u (especially in very impermeable clays).

The time sequence generally adopted by the authors for taking the A-readings is (in minutes): (0.25), 0.5, 1, 2, 4, 8, 15, 30 etc. The time origin is taken, and the stopwatch started, at the time when the blade reaches the DMTA test depth.

4 FITTING METHOD

By analogy to CPTU, one might base the interpretation of the DMTA dissipation curve on the time necessary for 50% decay of A (i.e. time to reach A_{50}). However, to identify A_{50}, one would need A_0 (initial value of A) and A_{100} (final value of A). But:

- The first portion of the curve, up to 30 to 60 sec, is generally missing, due to the reading method.

- A_{100} is generally unknown (unlike the final equilibrium u_0 with CPTU) unless the dissipation is carried out until stabilization of the A-reading (too time consuming).

An alternative "characteristic" time, adopted herein, is T_{flex}, the time to reach the contraflexure point in the A-log t curve. The use of T_{flex} has several advantages:

- T_{flex} is not affected by possible inaccuracies in ΔA, ΔB (membrane corrections), Z_m (zero of the gage) and u_0 (equilibrium pore pressure). A change in these quantities would result in a vertical shift of the curve, leaving unaffected T_{flex}.

- T_{flex} can be identified without the knowledge of A_0 and A_{100}, thus avoiding dubious back/forward extrapolations.

T_{flex} has the great practical advantage of being virtually independent both from the operator and from the engineer performing the interpretation.

5 INTERPRETATION

Ideally, the theoretical interpretation of T_{flex} would require the availability of a complete solution (total stresses, pore pressures, effective stresses distributions) immediately after blade penetration and during the subsequent reconsolidation. In particular the facet of the theoretical solution needed for interpreting T_{flex} would be the family of the σ_h vs time-factor curves. The contraflexure points of these curves would provide the theoretical link T_{flex} to C_h.

Despite fast advances in the field (e. g. "strain path method" solutions able to model the penetration of the DMT blade have just been developed, An - Bin Huang, 1988) the complete theoretical solution, as outlined above, is still unavailable. Therefore, at present, the C_h vs T_{flex} correlation can only be worked out empirically.
(It is possible that the introduction in the C_h vs T_{flex} correlation of the material index Id - a sort of stiffness over strength ratio - as a parameter, might improve the quality of the predictions. However, in order to evaluate such possible benefit, reference C_h values much more accurate than those presently available to the authors would be needed).

6 EXAMPLES OF DMTA DISSIPATION CURVES

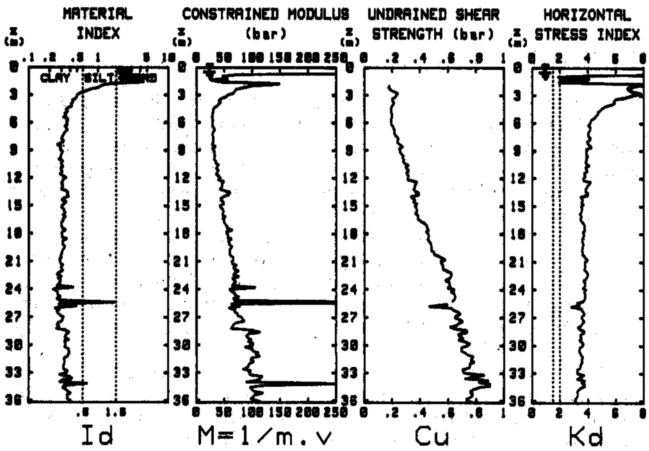
6.1 Fucino

The soil at this site is normally consolidated, lacustrine, slightly organic, markedly aged silty clay. Typically ρ = 1.5 to 1.6 t/m^3, PI$\approx$60.

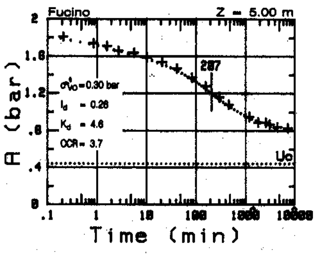
This site is currently being intensely investigated by several research teams. Expectably, various comparative research reports will soon appear in the literature.

Standard DMT results at this site are shown in Fig. 1a. The DMT - predicted C_u profile agrees well with Field Vane results. The results obtained from six different DMT soundings are pratically identical. Figs. 1b and 1c present examples of DMTA dissipations (the OCR values indicated in these figure, as well as in the similar ones that follow, are inferred from Kd using the Marchetti, 1980 correlations). The DMTA diagrams also show the least square 3rd degree polynomial through the data points and T_{flex} relative to such polynomial.

(a)



(b)



(c)

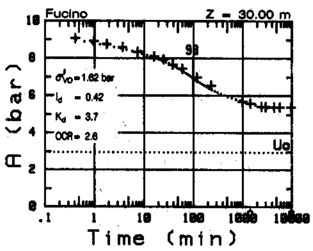


Fig. 1. Fucino: (a) Standard DMT results; (b) and (c) DMTA dissipations

The following comments can be made:

- The drop in A with time is considerable.

- The curves are smooth and stable.

- The contraflexure point is well defined.

Most of the T_{flex} values at Fucino (see Fig. 6) are in the range 100 to 200 minutes, among the highest observed by the authors.

6.2 Pisa

The Pisa sub soil is by no means a uniform deposit. It contains many silty or sandy layers of very variable thickness. Moreover moving from one location to another the depths at which the main layers are found vary considerably.

In view of the above, only tests performed in well identifiable layers are usable for comparative purposes.

In particular only the "upper clay" and the "lower clay" layers (Fig. 2a) have been taken into consideration. (The DMT soundings, for practical constraints, had to be performed at some 100 m from the Tower). Data by Croce et al. (1981) indicate in the upper clay PI = 35 to 40, w≈50, in the lower clay PI = 25 to 35, w≈35. A comprehensive collection of soil properties can also be found in Mitchell et al. (1977). Unfortunately the authors have been unable to locate any published specific information on C_h.

DMTA dissipations in the upper and lower clay are shown in Figs. 2b and 2c respectively.

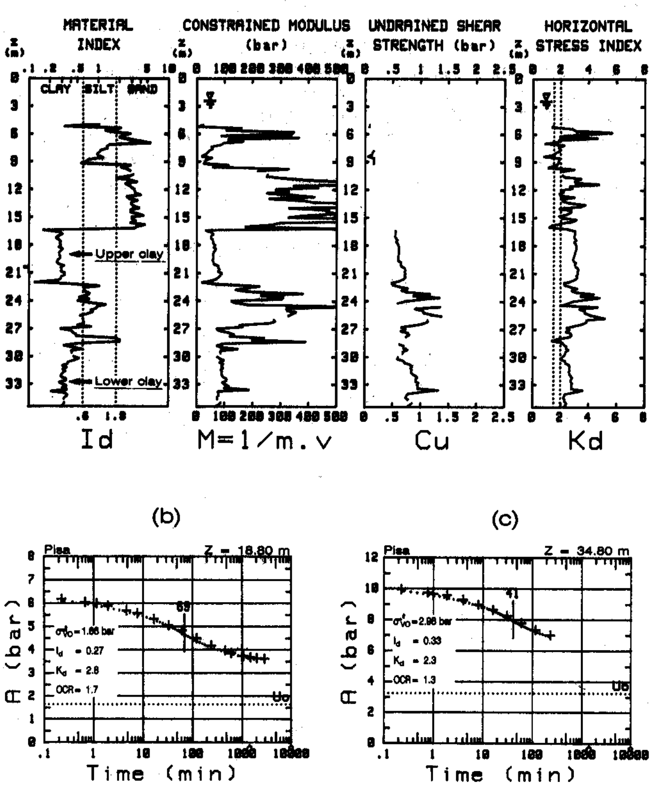


Fig. 2. Pisa: (a) Standard DMT results; (b) and (c) DMTA dissipations

6.3 Other Sites

Fig. 3 shows DMTA dissipations performed in other (non-research) sites, where only qualitative geotechnical information was available, preventing any quantitative comparison.

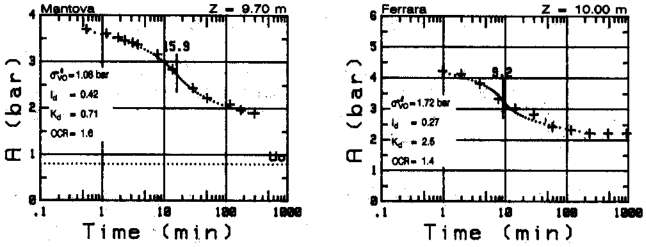


Fig. 3. DMTA dissipations at Mantova and Ferrara (Northern Italy)

These dissipations are reported herein merely for giving an idea of the various types of DMTA curves that may be encountered.

It can be noted:

- Though some data points do not appear perfect (these were commercial tests, performed by drillers with practically no previous experience) the general shape of the curve is well defined on the whole, and so is T_{flex}.
- T_{flex} at these sites (as in most of the other sites investigated) are considerably lower than at Fucino.

Fig. 4 shows the DMTA dissipation at the site (Quarantoli) where the highest value of T_{flex} (510 min) has been observed, sofar.

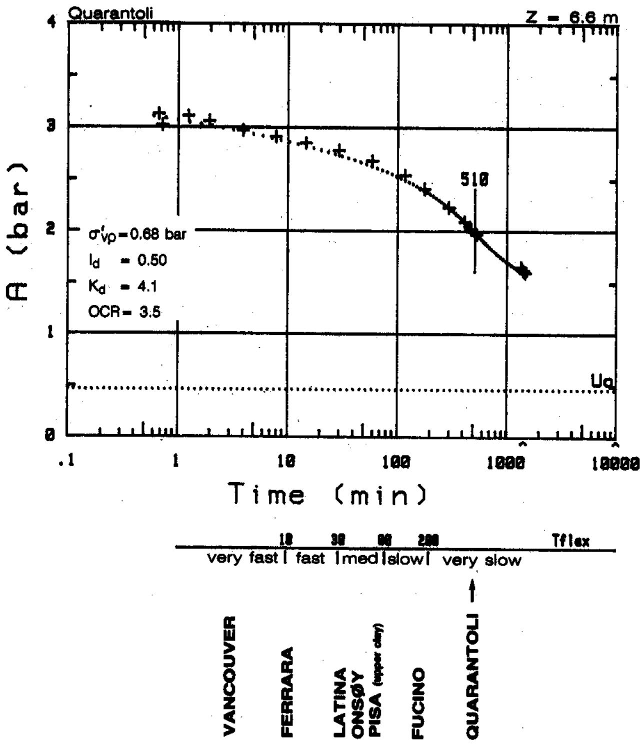


Fig. 4. DMTA dissipation at Quarantoli (Verona) with the scale providing a rating

A number of additional examples of DMTA dissipations can be found in Marchetti et al. (1986).

6.4 Non S-shaped DMTA curves

A relatively small proportion (say 20%) of all the DMTA curves known to the authors resemble more to a straight line than to an S. Two examples are given in Fig. 5.

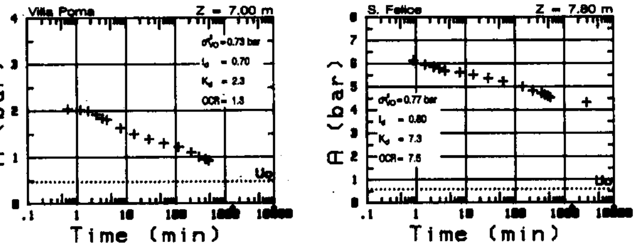


Fig. 5. DMTA results at Villa Poma and S. Felice Po (near Verona)

Among the soil properties possibly responsible of such shape one may consider secondary compressibility, organic content, permeability and possibly others. Unfortunately the available geotechnical information was insufficient to investigate in depth the problem, in particular to explore if a straight DMTA curve may be indicative of some property of interest.

7 RATING ON CONSOLIDATION RATE PROPERTIES BASED ON T_{FLEX}

Since DMTA curves (and T_{flex}) are easy to obtain, the authors have collected the results of some 60 DMTA dissipation at some 20 sites in a relatively short period. In contrast, difficulties were found when trying to locate reliable reference C_h values (a common complaint).

In view of the above difficulties, a first step considered of some usefulness was to subdivide soils in groups according to T_{flex}, setting up Table 1 (equivalent to the scale at the bottom of Fig. 4) providing an evaluation of the rate of consolidation property of a material.

Table 1. Rating on consolidation speed based on T_{flex}

T_{flex} (minutes)	Consolidation rate
< 10	very fast
10 to 30	fast
30 to 80	medium
80 to 200	slow
> 200	very slow

In essence, what the scale in Fig. 4 does is to associate T_{flex} to various sites. T_{flex} is then used as a link to extrapolate experience from one site to another.

The indications from Table 1 are obviously broad, but they may already be of help in design decisions. E.g. the authors would today consider unnecessary the use of vertical drains in deposits characterized by $T_{flex} < 10$ to 15 min.

8 DURATION OF THE DMTA DISSIPATIONS

In order to determine T_{flex} it is not necessary to carry out the dissipation until the A-reading is stabilized. To avoid unneeded loss of time, the dissipation can be stopped as soon as the contraflexure point is clearly identifiable. This generally occurs within two data points after T_{flex} (assuming a time increment ratio of 2 between subsequent readings), i.e. within 3 to 4 times T_{flex}. Thus in most soils the test requires 1 to 3 hours. In very "slow" clays a convenient alternative may be to perform dissipations in parallel, using two or more blades.

9 COMPARISON OF T_{FLEX} (DMTA) WITH T_{50} (CPTU) AT FUCINO

With the initial aim of linking T_{flex} to C_h, the values of T_{flex} (DMTA) have been compared with the values of T_{50} (CPTU). (In the CPTUs the pore pressure was measured on the face of the tip). Such comparison (Fig. 6 and Table 2) has highlighted several unexpected features (and problems), to which this section is entirely devoted. (It remains however to be found out if the particular case reported herein reflects a general trend).

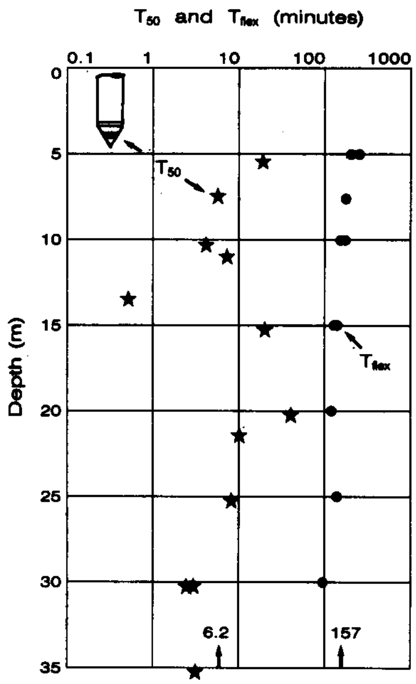


Fig. 6. Values of T_{flex} (DMTA) compared with values of T_{50} (CPTU) at Fucino

TABLE 2. Values of T_{50} (CPTU) and T_{flex}(DMT) at Fucino

CPTU No.	Z (m)	T_{50} (min)
2	7.30	5.95
2	11.00	7.50
2	21.40	10.10
2	30.30	3.10
2	35.30	3.18
3	5.50	18.97
3	10.30	4.13
3	13.55	0.52
3	15.30	20.75
3	20.30	42.95
3	25.30	8.30
3	30.30	2.57

DMT No.	Z (m)	T_{flex} (min)
3	5.0	207
3	15.0	133
4	20.0	125
4	30.0	98
5	10.0	179
5	25.0	143
6	5.0	256
6	7.6	180
6	10.0	153
6	15.0	148

From inspection of Fig. 6 and Table 2 it may be noted:

1. The average (geometric mean) T_{flex} (157 minutes) is 25 times the average T_{50} (CPTU) (6.2 minutes). This trend is in the same direction as indications obtainable (indirectly) from the works of Robertson et al. (1988) and Lutenegger et al. (1988), though the factor 25 appears rather high.
2. Probably the most striking feature in Fig. 6 is the ***huge difference in variability*** of T_{flex} and T_{50}. E.g. the ratio maximum to minimum (after discarding the extremes) is 1.66 for T_{flex}, 8.1 for T_{50}.

These observations raise several questions, particularly concerning the difference in variability. This may be explained by different answers, which however remain to be investigated:

1. CPTU profiles more finely stratigraphic details, while DMTA reflects the average consolidation of the soil bulb facing the membrane. (However if a say 10 cm thick seam of the more permeable soil - or of the more impermeable soil - existed, it would have shown up as a very-different-from-average T_{flex}. Hence this explanation may not be the whole answer).
2. At least part of the T_{50} (CPTU) variability may be due to inherent u measurement uncertainties (especially in clays of low permeability, as the Fucino clay) due to imperfect saturation, gas in the soil, smear, rod clamping effects etc.
3. CPTU dissipations reflect the dissipations of u in the seams and fissures, while DMTA reflects the dissipation of the average value of u (average in the fissures and in the soil lumps).
4. The avarage strain in the "volume of soil controlling the decay" is probably less with DMT than it is with CPTU. This because, in the case of DMT, the characteristic dimension controlling the thickness of distorted soil (blade thickness) is several times less than the characteristic dimension (membrane diameter) to which the diameter of the consolidating soil bulb is proportional (for cylindrical probes such characteristic dimension is unique).

The above questions are not academic, but have strong design implications:

- Which T profile, if any, reflects more realistically the variations of the operative C_h?
- Since the selection of design profiles is generally preceeded by some "averaging" treatment, would the "average" C_h evaluated from DMTA be an appropriate base for the choice of such profiles?

10 QUANTITATIVE LINK T_{FLEX} - C_h

Before attempting any correlation with the coefficient of consolidation C, it is necessary to specify clearly the "target" C. It is in fact well known that $C_h \neq C_v$ (by a factor that can easily be e.g. 5 - of course widely variable in various deposits) and that $C_{NC} \neq C_{OC}$ (by another large factor that can easily be e.g. 7 - again widely variable). Thus in a given deposit, and already with considerable simplification, one should distinguish at least 4 values of C, namely $C_{v,NC}$, $C_{v,OC}$, $C_{h,NC}$, $C_{h,OC}$, with $C_{h,OC} = 35\ C_{v,NC}$ for the above exemplified values of the factors. (The generally high, and variable, $C_{h,OC}/C_{v,NC}$ ratio makes the conventional oedometer inadequate to evaluate $C_{h,OC}$).

Indeed, when attempting to link DMTA to C for the Fucino clay, it was found that the evaluations of C reported in the literature (D'Elia et al., 1974; AGI, 1979) ranged between 0.1 and 4.5 • 10^{-3} cm^2/sec. This factor 45 is not overly surprizing considering that the reported C estimates were derived from oedometers, CPTUs and back analysis of foundation settlement. (Particularly when back analysing foundation settlements, a lot of subjective judgment is involved to determine which one of the C values is being estimated, because one has to evaluate if the water flow was mostly vertical / horizontal / in between and if the stresses were below / above / straddling σ'_p).

Since the value of T_{flex} (DMTA) in a given layer is unique, while the values of C are many, the correlation should be attempted with the physically closest C value, which, for DMTA, is $C_{h,OC}$ (as demonstrated by CPTU research).

By analogy to oedometer and CPTU methods, it seems logical to search the correlation in the form:

$$C_{h,OC} \cdot T_{flex} = \text{constant} \qquad (1)$$

which, to be defined quantitatively, just requires the evaluation of the constant.

By analysis of all available comparative $C_{h,OC}$ - T_{flex} data (unfortunately in quantity and quality considered unsatisfactory - especially because considerable subjective judgment had to be exercised to indirectly evaluate $C_{h,OC}$), including data by Lutenegger (1988), Lutenegger et al. (1988), Robertson et al. (1988), the constant was evaluated to be in the range 5 to 10 cm^2, i.e.:

$$C_{h,OC} \cdot T_{flex} = 5 \text{ to } 10\ cm^2 \qquad (2)$$

Eq. 2 should be regarded very cautiously, and should be considered a starting point for catalyzing further experience.

In order to avoid any conceptual misunderstanding, the user of Eq. 2 should clearly bear in mind that the coefficient of consolidation that Eq. 2 tries to evaluate is $C_{h,OC}$. $C_{h,OC}$ (however obtained) should be decreased by several times (in general) for application to a problem of essentially vertical flow and further (considerably) decreased in problems where the settlement takes place predominantly in virgin compression.

11 CONCLUSIONS

(1) The DMTA dissipation curves, obtained with a simple procedure by using a standard dilatometer, are in general stable and smooth.

(2) The decay rates of such curves vary considerably in deposits of different permeabilities. This paper suggests using T_{flex} (time to reach the contraflexure point in the DMTA curve) as an index of the consolidation speed of the soil.

(3) The time T_{flex}, in NC to moderately OC cohesive soils, is generally well defined, virtually independent both from the operator and from the engineer performing the interpretation. T_{flex} has also been observed to be highly reproducible.

(4) T_{flex} represents an index which may be used for extrapolating, approximately, field experience from one site to another. The proposed Table 1 subdivides soils in groups according to T_{flex}, and provides approximate ratings of the consolidation speed of the tested material.

(5) The tentative correlation $C_{h,OC}$ vs T_{flex} presently used by the authors, based on the limited reference $C_{h,OC}$ information available to them, has been indicated (Eq. 2).

(6) Eq. 2 needs considerable further evaluation, which requires performing DMTA dissipations at a number of sites where reliable $C_{h,OC}$ reference data are available.

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