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EVALUATION OF FIELD CPTU DISSIPATION DATA IN OVERCONSOLIDATED FINE-GRAINED SOILS

EVALUATION DES DONNEES DE LA DISSIPATION DE CHAMP CPTU DANS DES SOLS FINS SURCONSOLIDEES

J.P. Sully[1] **R.G. Campanella**[2]

[1]Senior Geotechnical Engineer, INTEVEP, S.A., Caracas, Venezuela
[2]Professor, University of British Columbia, Vancouver, Canada

SYNOPSIS: In stiff overconsolidated clays, the interpretation of piezocone dissipation data is complicated by the large pore pressure gradients that exist. These large pore pressure gradients around the tip of the cone modify the response such that, at locations behind the tip, the measured values may initially increase rather than dissipate. The form of the dissipation curve is thus non-standard and cannot be interpreted according to existing theories, developed for soft normally consolidated soils. However, it is possible to correct the non-standard curves, in a theoretically acceptable manner, in order to produce dissipation curves whose shape is in agreement with the existing interpretation methods and assumptions. Four generic types of dissipation curve are identified, three of which are specifically for stiff overconsolidated soils. The correction procedures for interpretation of dissipation results in OC soils are presented and applied to data from three stiff clay sites. The results are compared with the coefficient of consolidation obtained from laboratory oedometer tests.

BACKGROUND

Cone penetration testing with pore pressure measurement (CPTU or piezocone testing) is becoming a regular investigation technique in geotechnical site investigation practise. The penetration of the piezocone can be halted at any instant and the variation with time of the measured parameters can be monitored. It is usually the time variation of the pore pressure that is of interest as the results can be interpreted to provide estimates of the *in situ* horizontal coefficient of consolidation, c_h (Torstensson, 1977). Rather than the total pore pressure, it is the change in the excess pore pressure (δu) with time that is required for the evaluation of c_h, where δu is defined as:

$$\delta u = u_i - u_o \qquad (1)$$

u_i is the measured pore pressure at the depth of interest and u_o is the equilibrium *in situ* pore pressure at the depth of the porous element on the piezocone.

Interpretation of dissipation records is generally based on a normalized excess pore pressure ratio, U, defined as:

$$U = \delta u(t)/\delta u_i = (u(t)-u_o)/(u_i-u_o) \qquad (2)$$

where $\delta u(t)$ is the excess pore pressure at any time t after penetration is stopped, δu_i is the initial excess pore pressure at t=0, i.e. immediately on stopping penetration and u(t) is the total pore pressure at any time t.

Three specific filter locations will be discussed in this paper and the excess pore pressure will be subscripted according to where the measurements are obtained (Fig. 1a):

$$\delta u_{1,2,3} = u_{1,2,3} - u_o \qquad (3)$$

(Here it is assumed that since all the porous filter locations are very close, the same value of u_o can be used to calculate δu.)

It is usual practise to continue taking dissipation measurements until at least half the initial excess pore pressure has dissipated (U = 0.5).

Interpretation of the dissipation results can be achieved using either cavity expansion theory or the strain path approach. Comparisons of the available solutions and results from field studies suggest that the methods of Torstensson (1977), Levadoux (1980) and Teh (1987) all provide similar predictions of consolidation parameters from CPTU dissipation data in normally consolidated soils. The relevance of any of the above solutions depends on many factors, the most important of which relates to how well the initial pore pressure distribution around the cone compares with the theoretical idealization employed by each of the models. In overconsolidated soils, large pore pressure gradients exist around the cone (Robertson et al., 1986; Sully et al., 1988) which may give rise to non-standard type dissipation curves. A typical set of excess pore pressure dissipations (Type I) in soft normally consolidated clay for the three above-mentioned filter locations are presented in Fig. 1(a). The corresponding normalized dissipation curves are shown in Fig. 1(b). All three pore pressure dissipation curves show a monotonic decrease in the excess pore pressure with time and agree with the theoretical dissipation curve. Under these conditions, the data can be interpreted according to any of the available theories to estimate the *in situ* consolidation parameter, c_h, which primarily governs the rate of dissipation for CPTU tests (Baligh and Levadoux 1980).

However, in overconsolidated soils with filters located at the u_2 and u_3 positions, the pore pressures on stopping penetration do not decrease immediately, rather they show an initial increase over a definite period of time before finally beginning to dissipate. At the u_1 filter location, the dissipation record may also be modified due to the unloading that occurs when penetration is stopped. The interpretation of these dissipation records to obtain predictions of c_h in overconsolidated soils are the subject of this paper.

DISSIPATION IN OVERCONSOLIDATED SOIL

A typical example of pore pressure dissipation at the three filter locations in a lightly overconsolidated fine grained soil (OCR=4) is illustrated in Fig. 2 using results obtained at the Strong Pit site. Similar types of dissipation record (Type II) in OC soils for locations behind the tip have been reported by Lutenegger and Kabir (1987), Coop (1987) and Lunne et al. (1986). Assuming that the filter system has been saturated correctly, the initial rise in pore pressures measured behind the tip can be attributed to the redistribution that occurs around the tip due to the large gradients that are generated in OC soils.

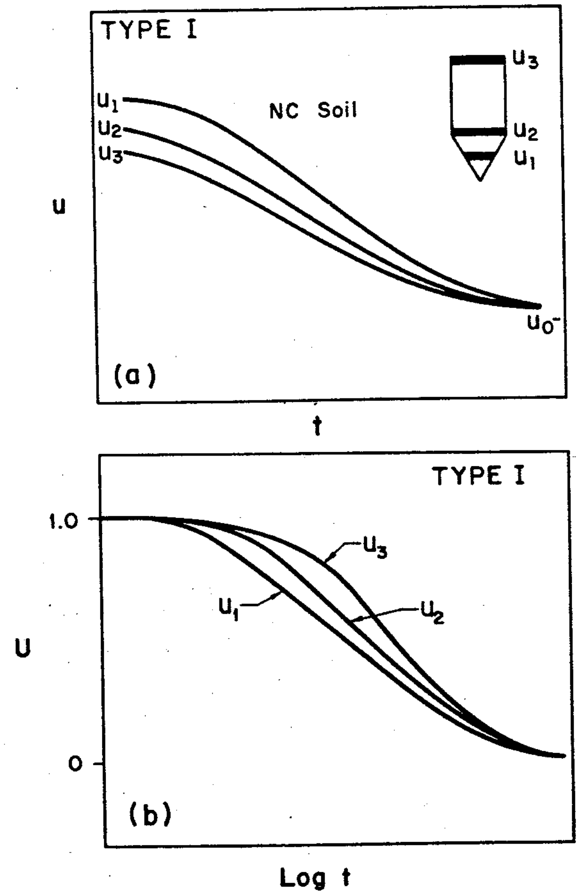

Fig. 1 Typical dissipation data for NC soil

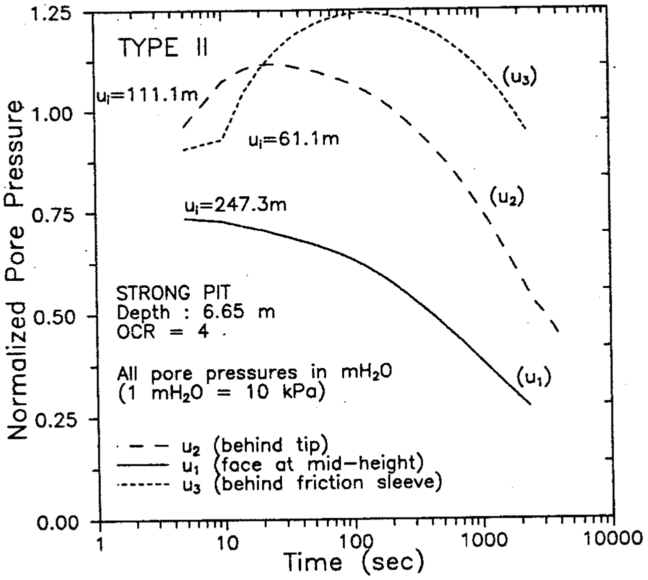

Fig. 2 Type II dissipation curves in OC soil

In moderately to heavily OC soils the pore pressures measured at locations behind the tip may be negative of hydrostatic or even below zero. In this case, on halting penetration the pore pressure increases to finally arrive at the *in situ* equilibrium value. Two types of dissipation curve may result depending on the soil characteristics:

-- the measured pore pressure may increase over and above the in situ equilibrium value if the rate of pore pressure redistribution is higher than the rate of dissipation. After reaching some peak value, the pore pressure then decreases until the equilibrium value is reached (Fig. 3, Type III).

--if the rate of dissipation is faster than the rate of redistribution, the pore pressure dissipation does not overshoot but directly arrives at the equilibrium value (Fig. 3, Type IV).

Types II and III pore pressure response can be evaluated using the correction technique outlined below. Type IV can be considered as inverted dissipation and treated in the standard way (as dissipation of a negative excess).

Correction to Non-Standard Dissipation Curves for Initial Distribution Effects

Two alternative data manipulation approaches have been used to correct the above-type dissipation curves so that the available dissipation theories can be used to estimate values of the coefficient of consolidation. One approach is based on a log-time plot while the other is based on a square-root time representation.

Log-time plot correction

The data in Fig. 2, obtained in a lightly overconsolidated clay at Strong Pit, have to be corrected according to the location of the pore pressure measurement, i.e. either on the cone tip or behind the cone tip, since the redistribution that occurs affects the two sets of pore pressures in different ways.

On the tip, a sudden decrease in pore pressure occurs on halting penetration. In Fig. 2 the normalized pore pressure (as defined in Eq. (2)) 5 seconds after dissipation begins is already reduced by 25% due to the reduction in the bearing stress acting on the face of the cone. For this location, the initial maximum pore pressure used for normalizing the dissipation record is taken as the peak value once the initial unload has occurred, i.e. for this case the maximum value corresponds to the 5 sec. measurement and this time is taken as the zero time point (5 sec. are subtracted from the time register throughout the record).

For the behind tip locations, the maximum pore pressure is taken as the peak value that occurs during the post-penetration increase and the time at which this peak occurs is taken as the zero time of the dissipation record and all other times adjusted accordingly.

The data from Fig. 2, corrected in this way are replotted in Fig. 4 to show the new form of the normalized dissipation plot, adjusted to account for unloading and redistribution effects. Figure 4 does highlight the problems associated with the execution and interpretation of dissipation data in fine-grained soils for filter locations behind the tip. The time for 50% dissipation increases from 1100 seconds to approximately 10000 seconds as the filter moves from u_1 to u_3.

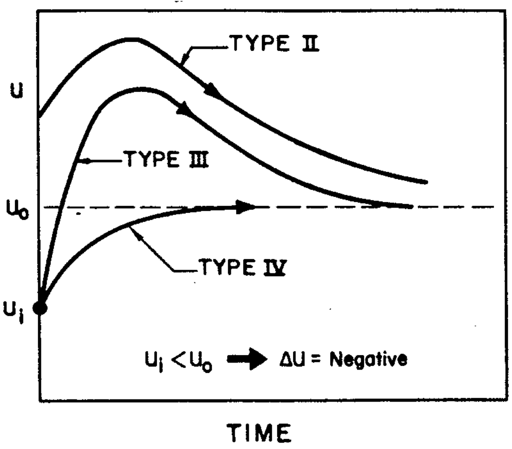

Fig. 3 Type III and IV dissipation curves in OC soil

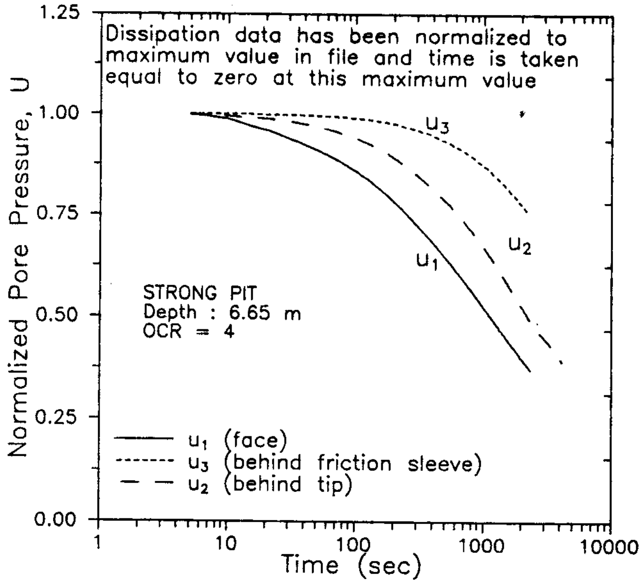

Fig. 4 Log-time corrected Type II data from Strong Pit

Root-time plot

In a similar fashion to the Taylor approach for interpreting oedometer data, it is also possible to adjust the dissipation data of Fig. 2 using a back-extrapolation technique on a square-root time plot. In the root-time plot, the dissipation that occurs after the initial peak caused by redistribution of pore pressure, depicts a straight line which can be back-extrapolated to t=0 in order to obtain a u_i for the corrected dissipation curve. This back-extrapolated value is then used to produce the normalized dissipation curve. The basis of the above correction technique is illustrated in Fig. 5 for measurement locations behind the tip. The principle is the same for measurement locations on the tip except that instead of an increasing pore pressure, the initial pore pressure suddenly drops as discussed previously.

The additional advantage of the root-time method is that the initial straight line portion can be extrapolated to 50% pore pressure reduction if short dissipation periods are used in the field and measured data to longer periods are not available (Fig. 6).

Alternately, the initial linear slope in the normalized pore pressure root time plot can be analysed to provide estimates of c_h using the theoretical approach suggested by Teh (1987). These extrapolations however require further verification prior to general use.

The two correction methods (log time and root time) described above will give rise to slightly different normalized dissipation curves since the initial corrected u_i values are, by definition, not the same. The resulting corrected dissipation data are compared in Fig. 7 (the root time plot has been reproduced in log time space for comparison purposes). While the dissipation curves for U less than 25% for both corrections may be different (as would be expected from the different u_i values) at U=50% the error is relatively small. In essence, the two correction techniques give the same values for t_{50}. The curves in Fig 7 do, however, indicate the importance of the initial pore pressure value at t=0 on the normalized form of the dissipation curve.

EVALUATION OF PROCEDURE IN OC SOILS

Basis of Comparison

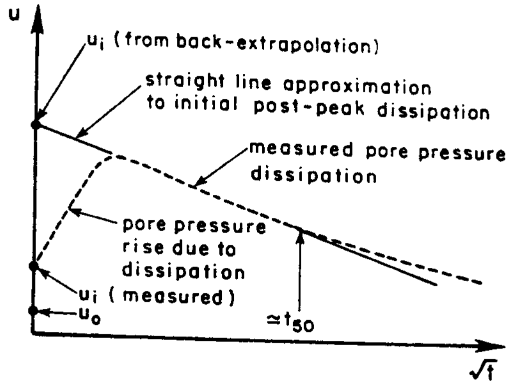

Fig. 5 Root-time correction procedure for Type II data

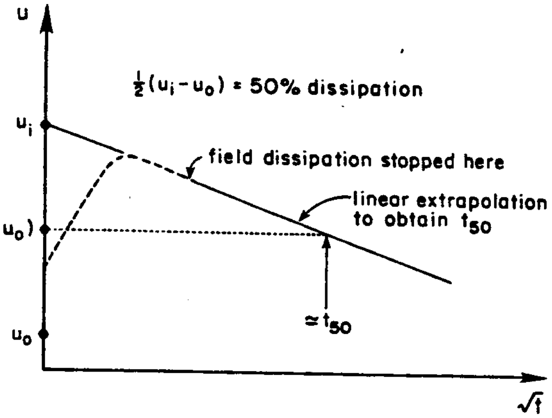

Fig. 6 Extrapolation of data in root-time plot to obtain t_{50}

The log time correction procedure has been applied to CPTU dissipation data from three University of British Columbia research sites where overconsolidated soils are present in the profile. The results of comparisons between the log t correction and laboratory derived consolidation parameters are considered below. The root time method is not presented here since the difference between the resulting times from the two methods is only significant for short dissipation periods. All the results presented here are for 50% dissipation of the excess pore pressure.

The horizontal coefficient of consolidation can be evaluated from the corrected CPTU data using any of the available theories. For this study, the method proposed by Teh (1987) has been used. The advantage of this method is that it considers the effect of the rigidity index on the pore pressure dissipation and can be applied to any filter location. The c_h value is determined from:

$$c_h = (T^* R^2 I_R^{0.5})/t_{50} \qquad (4)$$

where T^* is the Teh and Houlsby (1988) modified time factor, R is the cone radius at the measurement location and I_R is the rigidity index of the soil. Results presented by Danziger (1990) suggest that the Houlsby and Teh (1988) approach provides more consistent c_h estimates than the other available methods.

For comparison with the CPTU interpretation, consolidation coefficients from incremental laboratory oedometer tests are presented. While these laboratory determined of c_v values may not be wholly representative of in situ conditions, the results do provide a basis on which the relative CPTU magnitudes can be compared. Also, at the OC clay research sites no field data from full-scale monitoring are available and so laboratory reference values form the basis for comparison.

Laboratory c_v values are determined from root time plots at each incremental loading stage, so that both OC and NC data are available. Furthermore 1-D oedometer tests have also been performed on samples cut so as to obtain estimates of c_h. Hence the c_h/c_v ratio can be evaluated from the laboratory tests in order to correct the CPTU c_h values to c_v for direct comparison with the laboratory data.

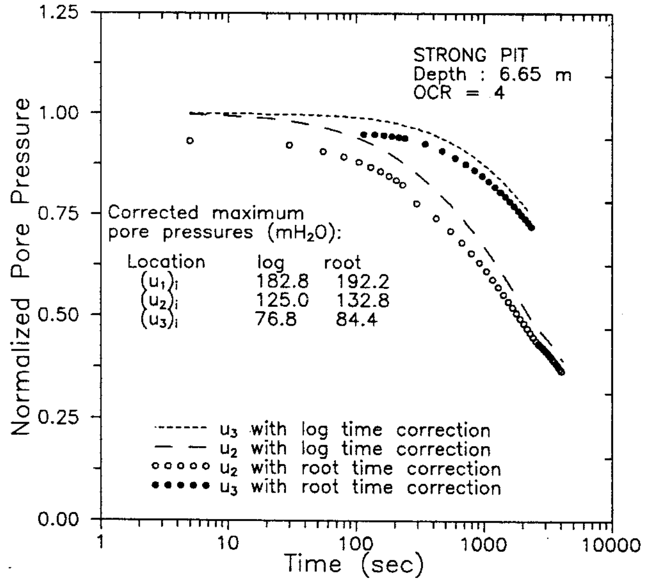

Fig. 7 Comparison of log and root-time corrected dissipation curves

Geotechnical Review of Sites Considered

The general geotechnical characteristics of the sites under consideration are presented in Table 1. The soils at Lr. 232 St. are soft sensitive clay silts. At the other two sites the clay silts are non-sensitive with undrained strengths up to 200 kPa.

Table 1 Geotechnical characteristics for sites considered.

Site	Depth range (m)	PI (%)	OCR	Range of σ_v'(kPa)	Range of σ_{vm}'(kPa)
Lr 232 St	1-5	21-30	3-10	16-40	90-205
Strong Pit	1-9	11-20	2-15	16-180	350-500
200th St	1-5	20	2-17	16-51	115-300

σ_{vm}' is the maximum past vertical pressure from oedometer tests

Results of Comparison

Only data from pore pressure locations u_1 and u_2 have been used for the purposes of comparison. The times required for 50% dissipation of the excess pore pressure measured at the u_3 location are prohibitively long and the use of piezocone dissipation tests at this location is not considered by the authors to be of practical interest unless graphical extrapolation techniques can be employed.

The coefficients of consolidation from CPTU (c_h) and laboratory oedometer (c_v) tests have been determined as described above. The obtained values are compared in Table 2.

Table 2 Comparison of field and laboratory coefficients of consolidation

Site	Measure. location	c_h from CPTU(cm²/s)	c_v from oedom.(cm²/s) OC range	NC range
Lr 232	u_1	0.002-0.005	0.006-0.1	0.0005-0.001
	u_2	0.005-0.016		
Strong	u_1	0.007-0.004	0.002-0.005	0.0006-0.001
	u_2	0.01-0.006		
200 St	u_1	0.014-0.047	0.05-0.18	0.001-0.03
	u_2	0.045-0.054		

The c_h values from the two pore pressure measurement locations (u_1 and u_2) are in very good agreement with each other. Furthermore, the CPTU values would suggest that the t_{50} dissipation provides an estimate of the c_h corresponding to the OC condition, i.e. the in situ condition of the soil. Hence, it would appear that at degrees of dissipation of 50% or more, the theory provides estimates of the coefficient of consolidation relevant to the in situ stress history condition, $(c_h)_{OC}$, at the sites studied. In addition to this, it is apparent from the types of dissipation curve considered, that stress history may be an important factor to be considered when interpreting CPTU dissipation data. The dissipation curve itself may be useful as a stress history indicator.

CONCLUSIONS

The c_h values from CPTU generally fall into the range suggested by the laboratory data. The correction method proposed here does give rise to consistent estimates of c_h based on a theoretically acceptable technique. Due to the limited data available, it is not possible to recommend a preferential pore pressure measurement location in terms of performing CPTU dissipation tests. The u_3 location would appear to involve prohibitively long dissipation times to be of practical use.. On the other hand, the u_1 position would appear to be a good location due to the higher rate of dissipation involved. In fine-grained soils, the time required for dissipation of CPTU excess pore pressures may be very long and as a result impractical to perform in the field. In this respect, a graphical extrapolation technique would be useful whereby data from an initial short period of dissipation could be mathematically modelled to predict the complete dissipation curve. Alternatively, the root-time interpretation method can be used to extrapolate short duration dissipation tests.

The results presented here are preliminary and further evaluation is being performed.

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