PIEZOPROBE DETERMINED COEFFICIENT OF CONSOLIDATION

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ABSTRACT

This paper describes a procedure for determining the insitu coefficient of consolidation by observing the dissipation of excess pore pressures generated during piezometer probe penetration. The procedure consists of a curve matching between the computer-generated plots and the field piezometer probe dissipation plot. The computer plots are developed by means of a two-dimensional uncoupled axisymmetric consolidation dissipation of an assumed initial excess pore water pressure distribution. The initial excess pore pressure distribution, calculated using cavity expansion theory, is related to the field penetration generated pore pressures. Computations are made in an incremental manner which permits pore pressure dissipation to occur during tip penetration. The new procedure was applied in studies of three different sites and the resulting coefficients of consolidation showed reasonable agreement with laboratory-determined values.

Key words : clay, coefficient of consolidation, consolidation, in-situ test, penetration test, piezocone, pore pressure (IGC : C 3/D 5)

INTRODUCTION

Consolidation and permeability characteristics of soil can be determined by observing the dissipation of the excess pore pressures generated during piezometer probe penetration.

Schmertmann (1974) and Janbu & Senneset (1974) reported on the first investigations of the pore pressures generated during cone penetration tests. Torstensson (1975, 1977) determined the initial excess pore pressure distribution due to cone penetration, using

cylindrical and spherical cavity expansion theory. He then used a linear, uncoupled, one-dimensional finite difference consolidation analysis to develop normalized excess pore pressure dissipation curves. The insitu coefficient of consolidation could then be estimated by matching prediction and field measurement curves.

Levadoux (1980), Levadoux & Baligh (1980) and Baligh & Levadoux (1980), used an approximate strain path method to predict initial excess pore pressures around the piezocone. Then they performed a two-dimen-

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sional uncoupled consolidation analysis to develop dissipation curves. The coefficient of consolidation in the horizontal direction, c_h , could be determined by matching field and prediction curves.

The procedure introduced in this paper predicts the initial excess pore pressure distribution by considering the probe at several successive locations, with intervals equal to the radius of the piezocone. Cavity expansion theory is used, but is corrected for the actual insitu probe measurements. The initial excess pore pressures developed during penetration start to dissipate while the piezocone is still advancing. This effect is taken into account in the proposed procedure. The axisymmetric uncoupled consolidation problem, with both radial and vertical drainage and isotropic or anisotropic conditions, is then solved with assumed values of insitu

coefficient of consolidation. A matching of field and program dissipation curves allows for the determination of the insitu properties.

Piezoprobes or Piezocones

Piezoprobes, e.g., the Wissa piezometer probe, measure only pore pressures during penetration. Piezocones, like those developed by Baligh et al. (1981), Campanella et al. (1983), Goudsche Machinefabriek/Hogentogler (see Robertson & Campanella, 1984), Fugro (see Zuidberg et al., 1982), Tuma et al. (1981), measure cone bearing capacity, q_c , friction, f_s , and the penetration pore pressures, Δu . Fig. 1(a) illustrates the Wissa piezoprobe, Fig. 1(b) the Fugro piezocone, and Fig. 1(c) the Wissa 60° piezocone. The Wissa type piezoprobes and piezocones, e.g. Baligh et al. (1981) and Wissa et al. (1975), measure the pore pressures at the cone tip. The GMF/Hogentogler and Campanella & Robertson (1983) piezocones measure them just above the cone base, while the latest Fugro piezocones, (Zuidberg et al., 1982) have the porous element on the cone face.

A friction reducer, which is 6 to 10 mm larger in diameter than the cone, is usually provided on the first push rod connected to the Dutch cone, piezoprobe or piezocone. This reduces the side friction on the push rods and decreases the total load required during deep subsurface investigations. Goudsche Machinefabriek, Sanglerat (1972), places the friction reducer 0.2 m above the top of the Dutch cone penetrometer tip. At the University of Florida, it is usually placed 0.1 m above the lower end of the first push rod. In the study reported in this paper, however, the friction reducer was placed at the lower end of the second push rod, a vertical distance of 1.25 m above the cone tip.

During soundings, the enlarged diameter of the friction reducer creates an annular hollow space along the cone rods. Experience at the University of Florida indicates that this annular space is certain to be found in over-consolidated clays, silts, clayey sands and

Fig. 1. Pore pressure sounding instruments

- (a) Wissa 60° piezometer probe
- (b) Fugro piezocone
- (c) Wissa 60° piezocone

dense sands, both below and above the ground water table. In soft clays and loose sands, there is a tendency for caving in of the soil, resulting in partial clogging or filling of the annular space. In such cases, it is advisable to use a larger diameter friction reducer, 10 to 19 mm greater than the cone.

INITIAL EXCESS PORE PRESSURE DISTRIBUTION

A number of theoretical and experimentally measured initial excess pore pressure distributions have been reported in the literature. Theoretical solutions have been developed by Soderberg (1962), Vesic (1972) and Levadoux & Baligh (1980). Koizumi & Ito (1967) and Roy et al. (1979) measured the excess pore pressures generated during field pile installation. Clark & Meyerhof (1972) and Steenfelt et al. (1981), measured pore pressures around model piles penetrated into laboratory samples. Within this literature there is divergence as to the extent, and in some cases even the sign, of the pore pres-

sure distribution generated by a penetrating probe or pile.

In predicting the initial excess pore pressure distribution around the cone, the authors of this paper have made the following assumptions:

1. As the cone advances, it produces in its immediate vicinity the series of successive spherical cavity expansions schematically shown in Fig. 2.
2. In saturated impervious materials (permeability less than 1×10^{-7} m/s) each of these cavity expansions produces excess pore pressures, which occur under undrained conditions.
3. The excess pore pressure distribution around the tip can be represented by the spherical cavity expansion logarithmic distribution developed by Vesic (1972).
4. When the cone, during its advance, is at a particular location, the excess pore pressure distribution around it is related to the measured penetration pore pressures at that location.
5. The penetration pore pressures developed due to undrained cavity expansion are subjected to significant dissipation by the time the cone advances to its final location.

Assumption number 5 is important. For example, in Boston Blue Clay at a depth of 40 feet (12 m), the piezoprobe, when stopped after a 5 foot (1.5 m) penetration, recorded a 50% dissipation of excess pore pressure in 100 s, Baligh & Levadoux (1980). Since the probe was being penetrated at a rate of 2 cm/s it would take 75 s for 5 feet (1.5 m) of penetration and 60 s for 4 feet (1.2 m). The penetration pore pressures generated by the probe after its first one foot of advance will be subjected to dissipation for 60 s, before the probe completes its 5 foot (1.5 m) final penetration. Fig. 9 shows that these one foot pore pressures are subject to about 40% dissipation before the probe stops at its final location for observation of pore pressure decay.

In the current research the following procedure has been followed. During steady penetration of the piezocone into a soil, excess

Fig. 2. Schematic for predicting initial excess pore distribution

- (a) Successive undrained cavity expansions
- (b) Typical measured pore pressure-depth curve

pore pressures are assumed to be developed as shown in Fig. 2. When the piezocone is at point A, for example, the excess pore pressures around this point will be related to the measured pore pressure u_A , at point A. Using Vesic's (1972) logarithmic distribution, the excess pore pressure at any point B in the zone APQR is :

$$\Delta u_B = \frac{(u_A - u_{0A}) \left[0.943 \alpha_f + 4 \ln \left(\frac{R_p}{r_B} \right) \right]}{\left[0.943 \alpha_f + 4 \ln \left(\frac{R_p}{r_A} \right) \right]} \quad (1)$$

where

u_{0A} = hydrostatic pore pressure at point A

R_p = radius of the plastic zone

$= \left(\frac{G}{S_u} \right)^{1/3}$ for spherical cavity

S_u = undrained strength

G = shear modulus $= E/3$ for Poisson's ratio $= 0.5$

α_f = Henkel's pore pressure parameter at failure $= 0.707 (3 A_f - 1)$

A_f = Shempton's pore pressure parameter at failure

When the piezocone reaches point C, the new value of the excess pore pressure at D in zone CP'Q'R' is found using Eq. (1), replacing the subscripts 'B' by 'D' and 'A' by 'C'. If the piezocone penetrates from A to C in time Δt , then the excess pore pressure calculated at points such as B, on the basis of the measured pore pressure at A, will dissipate. Dissipation depends upon the coefficient of consolidation, the pore pressure distribution around the point being considered, the time interval Δt and the drainage boundaries. This dissipation must be taken into account for all points that lie above the mid-height of the cone at its present location. The process is repeated at intervals equal to the radius of the piezocone, until the penetration is stopped at some point I, Fig. 2.

Initial excess pore pressure distributions around the cone and shaft when the tip reaches point I (Fig. 2), as predicted using the above method, are shown in Fig. 3. Δu is the excess pore pressure at any instant of time, while u_{ei} is the measured excess pres-

Fig. 3. Predicted normalized initial excess pore pressure contours

(a) $c = 1.0 \times 10^{-5} \text{ m}^2/\text{s}$

(b) $c = 1.0 \times 10^{-6} \text{ m}^2/\text{s}$, and Radial excess pore pressure distribution at cone base

(c) $c = 1.0 \times 10^{-5} \text{ m}^2/\text{s}$

(d) $c = 1.0 \times 10^{-6} \text{ m}^2/\text{s}$

sure at the time when the piezocone penetration stopped. In Figs. 3(a) and 3(b), the coefficients of consolidation, c , are $1.0 \times 10^{-5} \text{ m}^2/\text{s}$ and $1.0 \times 10^{-6} \text{ m}^2/\text{s}$, respectively. Symbols c_v and c_h are used to represent the coefficients of consolidation in the vertical and horizontal directions, respectively. In the computer program developed by the authors anisotropic conditions, i. e. different values of c_v and c_h , can be input. In those cases where isotropy is assumed, $c_v = c_h$ and the symbol c with no subscript is used. The friction reducer was assumed to be at a distance of $22R$ above the cone tip. This matches closely with the usual practice of

providing a friction reducer either at the lower end of the first push rod or at some short distance above this end. The typical penetration pore pressures shown in Fig. 2(b) were used in these predictions. It can be seen that the effect of dissipation is much less for the lower value of c . For the higher value of c , the 0.5 pore pressure contour extends to approximately $13R$ above the tip. For the lower value, it extends to $16.5R$. During the dissipation process, a decrease in pore pressure occurs near the probe, while at greater radial distances the pore pressure increases. Such radial distributions are shown in Fig. 3(c) and (d) at the level of the cone base. This phenomenon results in the

0.01 contour being at a greater distance from the shaft for the higher value of c . For example, at $20R$ above the tip and at a radius of $4R$, Fig. 3(a) and (b), the excess pore pressure prediction for the more pervious soil is greater than for the less pervious material. The effect of drainage along the cone shaft above the elevation of the friction reducer is also reflected in the pore pressure contours of these Figures.

Initial excess pore pressure distributions, predicted for the case when the friction reducer is $65R$ above the cone tip, are shown in Figs. 4(b) and 4(c). In this case the piezocone was advanced 1 m from its initial position. The penetration pore pressures recorded during the advance are shown in Fig. 4(a). Again, a significant dissipation effect is found for the higher value of c .

UNCOUPLED LINEAR CONSOLIDATION ANALYSIS

Theories of consolidation fall into two main categories. Those associated with the names of Terzaghi and Rendulic may be called the uncoupled or unlinked approaches. In these, it is assumed that the total stress remains constant everywhere, and strains are the result only of changes in porewater pressure. The theories in the second category are associated with the linked Biot (1941) theory, in which the interaction between skeleton and porewater is included in the formulation.

An accurate analysis of the dissipation of pore pressures around a cone would require a coupled and nonlinear consolidation procedure. However, uncertainties involved in estimating the initial conditions, i. e., the spatial distribution of pore pressures and total stresses, together with the nonlinear behavior of the deposit and the different variables that affect them, make such an analysis impossible.

The analyses presented in this paper were performed using a computer program, Gupta (1983), based on the alternating direction implicit method, Bruce et al (1953), Douglas (1962), Peaceman & Rachford (1955). The

Fig. 4. Excess pore pressure distributions
 (a) Typical normalized penetration pore pressure
 (b, c) Predicted normalized initial excess pore pressure contours for 1 m penetration of piezocone
 (b) $c = 1.0 \times 10^{-5} \text{ m}^2/\text{s}$
 (c) $c = 1.0 \times 10^{-6} \text{ m}^2/\text{s}$

program solves the linear transient uncoupled axisymmetric consolidation problem, with the governing equation :

$$c_v \frac{\partial^2 u_e}{\partial z^2} + c_h \frac{\partial^2 u_e}{\partial r^2} + \frac{c_h}{r} \frac{\partial u_e}{\partial r} = \frac{\partial u_e}{\partial t} \quad (2)$$

where

c_v = coefficient of consolidation in vertical direction

c_h = coefficient of consolidation in horizontal direction

u_e = excess pore pressure

t = time

r = radial distance from the central axis of the cone

The alternating direction implicit schemes, which lead to a perturbation of the Crank-Nicholson equation, are locally second-order correct in space and time, are unconditionally stable, and each of the algebraic systems is tridiagonal. The method first evaluates the r derivative at $n+1/2$ and obtains a first approximation u_{n+1}^* at time $n+1$ from

$$\frac{1}{2} c_h \delta_r^2 (u_{i,j,n+1}^* + u_{i,j,n}) + \frac{1}{2} \frac{c_h}{r} \delta_r (u_{i,j,n+1}^* + u_{i,j,n}) + c_v \delta_z^2 u_{i,j,n} = (u_{i,j,n+1}^* - u_{i,j,n}) / \Delta t$$

then moves the equation of the z derivative ahead by means of

$$\begin{aligned} & \frac{1}{2} c_h \delta_r^2 (u_{i,j,n+1}^* + u_{i,j,n}) + \frac{1}{2} \frac{c_h}{r} \delta_r (u_{i,j,n+1}^* + u_{i,j,n}) \\ & + u_{i,j,n} + \frac{1}{2} c_v \delta_z^2 (u_{i,j,n+1} + u_{i,j,n}) \\ & = (u_{i,j,n+1} - u_{i,j,n}) / \Delta t \end{aligned}$$

where δ is a central difference operator for the variables.

The solution of these equations is obtained in a straightforward manner by the use of the Thomas Algorithm, Bruce et al. (1953), Douglas (1962).

It was determined that taking zero excess pore pressure drainage boundaries at a radial distance of $100 R$, and at a vertical distance of $45 R$ below the tip, closely matched infinite boundaries. Because of the axial symmetry, the central axis of the cone shaft can be considered an impervious boundary.

The annular hollow space formed along the cone shaft, above the elevation of the friction reducer, acts as a zero excess pore pres-

Fig. 5. Normalized excess pore pressure at the tip versus time factor for various values of E/S_u and A_f

Table 1

Number (1)	Ratio, E/S_u (2)	A_f (3)	Time Factor (4)
1	100	0.9	0.70
2	200	0.9	0.97
3	300	0.9	1.19
4	400	0.9	1.33
5	200	0.7	0.93
6	200	0.5	0.75

sure drainage boundary, Fig. 3. The upper drainage boundary, at a distance of $30 R$ above the friction reducer, closely matches an infinite drainage boundary.

PARAMETRIC STUDY FOR DISSIPATION ANALYSIS

The variables in the prediction of the initial excess pore pressure distribution are the ratio E/S_u and the parameter A_f . These have to be determined either from laboratory tests or from correlations with insitu tests. Fig. 5 and Table 1 show the variation of time factor T_{50} with values of the E/S_u ratio ;

$$T_{50} = \frac{ct_{50}}{R^2}$$

where

c = coefficient of consolidation of the assumed isotropic soil

t_{50} = the measured time to achieve 50% consolidation

Fig. 6. Normalized excess pore pressure versus time factor for various sensing element locations

R = an "equivalent" radius which simulates the cavity radius

An incorrect assessment of the ratio E/S_u , say 400 instead of 100, would result in a prediction of the value of the coefficient of consolidation, c , about twice the correct value. An incorrect assessment of the parameter, A_f , e.g. 0.9 in place of the correct value of 0.5, would result in a prediction of the value of c about 1.3 times the correct value.

Fig. 6 shows the predicted normalized excess pore pressure versus time factor, T , relationships for different locations of the pore pressure sensing element. The sensing element is located at the tip, at the cone base (about $2R$ above the tip), and along the shaft, at distances equal to $4R$ and $8R$ above the tip. A study made with two friction reducer locations ($22R$ and $66R$ behind the tip), showed that the pore pressure versus time factor relationships were practically identical.

In Fig. 6, Torstensson's (1977) spherical and cylindrical cavity expansion solutions, Randolph and Wroth's (1979) analytical solution, and Baligh & Levadoux's (1980) strain path method solution, have also been shown. The spherical solution (D) predicts a much faster consolidation than the cylindrical solution (E). The analytical (B) and cylindrical solutions (E) predict about the same trend. The strain path method (A) predicts the

Table 2

Depth of Measurement, in meters	Location of Sensing Element Roy et al. (1982)	Observed t_{50} , in minutes Roy et al.	Predicted T (Fig. 6)
(1)	(2)	(3)	(4)
4.6	At tip (type DPA)	6.5	0.942
4.6	At cone base, (type PA)	13.0	1.403
4.6	At $4R$ above tip (type RA)	18.5	1.68

slowest consolidation pattern.

Table 2 compares Roy's (1982 a, 1982 b) observed time for 50% dissipation, t_{50} , with those predicted using Fig. 6. The ratio of observed t_{50} at the cone base to that at $4R$ above the tip is 0.7, while the ratio of the corresponding predicted values is 0.83. The ratio of observed t_{50} at the cone base to that at the tip is 2, while the ratio of the corresponding predicted values is 1.49. These comparisons show a close agreement between measured and predicted values.

ANALYSIS OF PIEZOCONE DISSIPATION RESULTS

Lake Alice Clay

Piezcone soundings were performed in Lake Alice Clay in Gainesville, Florida. A 1.5 inch (38.1 mm) diameter Wissa 60° piezoprobe, Fig. 1(a), specially designed for the University of Florida, was used in the study. A friction reducer was provided at the upper

Fig. 7. Comparison of field and prediction curves for Lake Alice Clay

end of the first attached rod. This special rod had a diameter equal to that of the piezocone. The rods in the string above the friction reducer were somewhat smaller. The porous element was fully saturated by first applying a vacuum and then supplying deaired water into the system. Typical plots of normalized excess pore pressure versus time of dissipation are shown in Fig. 7.

It can be seen that the predicted and field curves do not match each other. This is to be expected in view of the several assumptions necessary for such a complex problem. Even in relatively simple problems, like one dimensional consolidation testing, the form of actual time versus compression curves are similar to, but not exactly the same as the theoretical curves predicted from consolidation theory. The absence of a perfect match (i.e., over their entire extent) between the field and prediction curves means that the predicted value of c is dependent on where a match between the curves is chosen. At this site, a match was made at about 50% consolidation. The ratio E/S_u was selected from available triaxial tests. Values of the coefficient of consolidation ($c=c_v=c_h$) were chosen by trial, until the computer generated prediction curves approximately matched the field curves at t_{50} , Fig. 7.

The measured and predicted curves at a

Fig. 8. Comparison of laboratory and prediction coefficients of consolidation for Lake Alice Clay

depth of 23.1 feet (7.05 m) are parallel to each other throughout the dissipation. A further minor adjustment of c would have produced a perfect match. At all other depths, the predicted curves show a faster dissipation in the beginning and a slower dissipation later.

Laboratory consolidation tests were performed on undisturbed samples, obtained using a Swedish piston sampler. In Fig. 8, the range of laboratory c_v values obtained at different loads has been plotted, along with the values predicted by the numerical analysis. Although there is considerable scatter in both the laboratory and predicted results, the plot shows a reasonable agreement between them.

Boston Blue Clay

Data from 60° piezometer probe soundings, performed in Boston Blue Clay, Baligh & Levadoux (1980), were also analyzed by the method presented in this paper. In this probe, the sensing element was at the tip and the cone diameter was 1.5 inches (38.1 mm). Ladd (1976) recommends a permeability ratio, k_h/k_v , of between 2 and 5 for clays with "occasional silt dustings to random lenses". In view of this, the ratio c_h/c_v for the Boston Blue Clay was assumed to be 3. The ratio E/S_u was taken as 200. The predicted normalized excess pore pressure dissipations are compared with the measured field

Fig. 9. Comparison of field and prediction curves for Boston Blue Clay

Fig. 10. Comparison of laboratory and prediction coefficients of consolidation for Boston Blue Clay

curves in Fig. 9. These curves match at about 40% consolidation. Contrary to the trend noticed in the Lake Alice plots, these predicted curves show a slower dissipation in the beginning and a faster dissipation later.

It can be seen in Fig. 10 that the predicted values of c_v between 39 feet (11.9 m) and 46 feet (14 m) were very close to the laboratory values. However, at 62.5 feet (19 m) and 87.5 feet (26.7 m) the predicted values were somewhat higher than the laboratory values.

Richmond and Burnbay Sites

Gillespie & Campanella (1981) performed piezocone tests at two sites, Richmond and Burnbay. They used a standard 1.4 inch (35.6 mm) diameter, 60° cone with the porous element at the base of the conical tip. They reported excess pore pressure versus time dissipation curves at one depth at each site. At the Richmond site, at a depth of 83.6 feet (25.5 m) in a clayey silt, the time to achieve 50% dissipation was 4 minutes. Using Fig. 6 for the porous element at the cone base, the time factor T is 1.44. This gives a predicted value of c of 0.18 inch²/min (1.9×10^{-6} m²/s). The reported laboratory value of c_v (normally consolidated-loading) was 0.12 inch²/min (1.3×10^{-6} m²/s).

At the Burnbay Site, at a depth of 50.8 feet (15.5 m) in a soft silty clay, the observed t_{50} was 45 min. The predicted value of c , using Fig. 6, is 0.015 inch²/min (1.7×10^{-7} m²/s). The reported laboratory value of c_v (normally consolidated-loading), was 0.013 inch²/min (1.4×10^{-7} m²/s). The predicted

and laboratory values in both cases were very close.

CONCLUSIONS

As a penetrometer is steadily pushed into the soil, it is believed that the cone produces in its immediate vicinity a series of successive deformation patterns which are similar to that produced in the spherical cavity expansion problem. The symmetry of displacement contours along the shaft is a result of successive summation of these spherical expansions.

In saturated impervious materials, these successive spherical cavity expansions produced excess pore pressures under undrained conditions.

The positive excess pore pressure distribution around a cone in a non-dilating soil can be represented by the logarithmic distribution of spherical cavity expansion theory applicable to undrained conditions.

When the cone during its advance is at a particular location, the excess pore pressure distribution around it is related to the measured penetration pore pressure at that location.

The generated pore pressures start to dissipate during the cone advance. These pressures, developed due to undrained cavity expansion during the initial advance, are subjected to significant dissipation by the time the cone reaches and stops at its final location. The effect of this dissipation is more pronounced in soils with higher values of coefficient of consolidation.

The length of time for any percent dissipation increases with increasing distance of the pore pressure sensing element from the tip.

The analysis procedure which is described in this paper has been developed on the basis of the above conclusions and appears to provide reasonable predictions of the coefficient of consolidation.

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