REFERENCES

1) Davis, N. S. (1969): Porosity and Permeability of Natural Materials, Flow through Porous Media, Edited by Roger, J. M. Dewiest, Academic Press, New York, N. Y.
2) Gradshteyn, I. S. and Ryzhik, I. M. (1965): Table of Integrals, Series and Products, Academic Press, New York, N. Y.
3) Harr, M. E. (1962): Groundwater and Seepage, McGraw-Hill Book Company, Inc., New York, N. Y.
4) Krizek, R. J. and Anand, V. D. (1968): "Flow around a vertical sheetpile embedded in an inclined stratified medium," Water Resources Research, Vol. 4, pp. 113-123.
5) Leliavsky, S. (1955): Irrigation and Hydraulic Design, Vol. 1, Chapman and Hall, Ltd., London.

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A COMPUTATIONAL METHOD FOR CONSOLIDATION-COEFFICIENT

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ABSTRACT

The theoretical consolidation curve based on Terzaghi's theory has been successfully represented by a simple explicit algebraic equation. The use of this equation has been extended by obtaining an expression for consolidation-coefficient involving selected three oedometer test data. This method, unlike the existing one, does not require the use of graphs or charts and it can be effectively used on a digital computer.

Key words: clay, compression, consolidation, consolidation test
IGC: D5

INTRODUCTION

Clayey soils would undergo considerable consolidation upon sustained foundation loads. A settlement analysis is generally carried out to obtain total and time rate of settlement, of which, major component is from consolidation of underlying layers. The time rate of settlement is generally computed using Terzaghi's (4) one dimensional consolidation theory. This is essentially a linear one-dimensional theory, which yields the familiar diffusion type equation, viz

$$\frac{\partial u}{\partial t}=C_V\frac{\partial^2 u}{\partial z^2} \tag{1}$$

in which u=excess pore pressure, C_V=coefficient of consolidation, z=depth and t=time.

It is widely accepted that both the field and the laboratory consolidation curves have the primary as well as the secondary consolidation components. The contribution of the later to settlement becomes more and more significant towards the end of the primary and continues for very long time. The dimensionless time factor is defined by

$$T=C_V\,t\,H^{-2} \tag{2}$$

in which H is the effective drainage path.

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The degree of consolidation, U, is a ratio of settlement ρ, at any instant, to the total final settlement, ρ_f the component due to primary consolidation, i.e.

$$U=\rho/\rho_f \tag{3a}$$

with u_0=the initial pore-pressure (assumed constant throughout the height), U is expressed as

$$U=\frac{1}{H}\int_0^H\left(1-\frac{u}{u_0}\right)dz \tag{3b}$$

The solution of Eq. (1) for initial condition $U=0$ at $t=0$, is given by

$$U=1-8\pi^{-2}\sum_{n=1}^{\infty}(2n+1)^{-1}\exp(-0.25\pi^2(2n+1)^2T) \tag{4a}$$

The theoretical consolidation curve is expressed by the Eq. 4(a). The following two empirical equations have been suggested to provide an implicit relationship for T.

$$T=0.25\pi U^2, \quad U<0.53 \tag{4b}$$

and

$$T=1.781-0.9332\log(1-U), \quad U>0.53 \tag{4c}$$

Using any one of the conventional mothods, the coefficient of consolidation, C_V, can be obtained. In inis paper an expression for C_V as a function of three selected oedometer test readings has been obtained. Direct computation of C_V is now possible without any need of graph or chart.

AVAILABLE METHODS

Taylor (3) and Casagrande (1) proposed graphical methods for determination of C_V which are conventionally used. Both these methods utilise the characteristic properties of the theoretical consolidation curve. The oedometer dial gauge readings of sample compression are plotted as function of $\sqrt{t}$ or log t respectively, in the above two methods and a correction in the initial reading is graphically applied. Next, a point on this curve is obtained to which a fixed T value is assigned based on the typical characteristics of the theoretical consolidation curve. C_V is then computed using Eq. (2). There can be error in locating the above point on the plot because of the following reasons: (a) There is no theoretical basis; (b) The methods rely on use of readings in lower portion of the curve, where the values are a result of sum of primary and secondary consolidation; and (c) these methods being graphical leave enough scope for variation because of the error due to judgement.

Scott (1961) proposed a different scheme for obtaining C_V-values, however, the initial correction of readings is applied using Taylor's method. This method uses a chart of a set of curves deduced from Eq. (4a); however an accurate use of the same is not possible.

EQUATION OF CONSOLIDATION CURVE

For low values of time, the empirical equation which is given as Eq. (4b), very closely follows the theoretical consolidation curve and can be represented by another form

$$U=(4.\ \pi^{-1}T)^{0.5}, \quad T\ll 1 \tag{5}$$

and for high values of time, the curve is asymptotic to the line

$$U=1, \quad T\gg 1 \tag{6}$$

Combining Eqs. (5) and (6) through a method of curve fitting, the following explicit equation valid for all values of U has been obtained

$$U=\frac{\left[4\frac{T}{\pi}\right]^{0.5}}{\left[1+\left(\frac{4T}{\pi}\right)^{2.8}\right]^{0.179}} \tag{7}$$

Eq. (7) can be converted to the following implicit form

$$T=\frac{\frac{\pi}{4}U^2}{(1-U^{5.6})^{0.357}} \tag{8}$$

For small values of U, Eq. (8) takes the form of Eq. (4b). The variation of the percentage error in Eq. (7) compared to theoretical consolidation curve has been depicted in Fig. 1. A perusal of the curve shows that the maximum percentage error is only three, which is within the permissible engineering accuracy. It is thus justified to use Eqs. (7) and (8) in place of the theoretical consolidation equation, i.e. Eq. (4a).

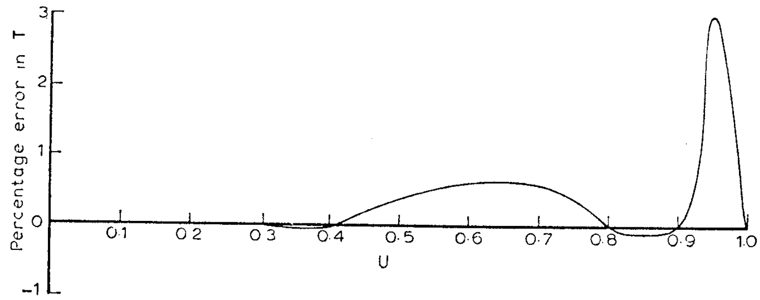

Fig. 1. Error diagram

DETERMINATION OF C_V

From an oedometer test two readings R_1 and R_2 corresponding to time t_1 and t_2 are taken during the early phase of consolidation. This permits the use of Eq. (4b), for the respective dimensionless time T_1 and T_2:

$$T_1 \text{ or } C_V t_1/H^2=\pi/4[(R_1-R_i)/(R_f-R_i)]^2 \tag{9}$$

and

$$T_2 \text{ or } C_V t_2/H^2=\pi/4[(R_2-R_i)/(R_f-R_i)]^2 \tag{10}$$

in which R_i and R_f are the initial and final oedometer readings excluding the secondary consolidation effects. Combining the Eqs. (9) and (10), the following equation is obtained

$$R_i=(R_1-R_2\sqrt{t_1/t_2})/(1-\sqrt{t_1/t_2}) \tag{11}$$

giving the corrected initial dial gauge reading.

The third dial gauge reading R_3 is taken at time t_3, with corresponding T_3 such that considerable consolidation of the sample has taken place. Using Eq. (8) for this reading

$$T_3 \text{ or } \frac{C_V t_3}{H^2}=\frac{\pi}{4}\frac{[(R_3-R_i)/(R_f-R_i)]^2}{\{1-[(R_3-R_i)/(R_f-R_i)]^{5.6}\}^{0.357}} \tag{12}$$

with the use of Eqs. (9), (10) and (12), R_f and C_V can be obtained as

$$R_f=R_i-\frac{R_i-R_3}{\{1-[(R_i-R_3)(\sqrt{t_2}-\sqrt{t_1})/(R_1-R_2)\sqrt{t_3}]^{5.6}\}^{0.179}} \tag{13}$$

and

$$C_V=\frac{\pi}{4}\left[\frac{R_1-R_2}{R_i-R_f}\frac{H}{\sqrt{t_2}-\sqrt{t_1}}\right]^2 \tag{14}$$

Eqs. (11), (13) and (14) give the values of R_i, R_f and C_V respectively in terms of three data.

Example

In order to illustrate the use of the method, the following three data from Taylor (3) shown in Table 1, have been selected:

$$R_1=2025 \qquad t_1=\ \ 15\text{ sec.}$$
$$R_2=1953 \qquad t_2=\ \ 60\text{ sec.}$$
$$R_3=1615 \qquad t_3=1200\text{ sec.}$$

and $H=1.21$ cm

Using Eqs. (11), (13) and (14) the following values have been obtained

$$R_i=2097, \quad R_f=1595.64$$

and $C_V=16.43\times10^{-4}\text{ cm}^2/\text{sec.}$

The value of C_V computed by this method is in close corres pondence with the one obtained by using Scott's method

$$C_V=21.5\times10^{-4}\text{ cm}^2/\text{sec.}$$

Table 1, further shows the computed C_V values based on the present method selecting R_3 and t_3 values from one of the oedometer test readings of Taylor (3). For the above R_3 and t_3 values, C_V based on Scott's method have been shown. The computed values from the present method are fairly close to the one found using Scott's method. The present method gives reasonable values of C_V, whereas Scott's method yields higher values which is associated with difficulties in use of the suggested chart.

Table 1. Oedometer computations

	1	2	3	4	5	6	7	3	9	10
Time min	0.0	0.25	1.0	2.4	4.0	6.0	9.0	15	20	30
Dial gauge reading (Taylor)	2125	2025	1953	1882	1815	1750	1700	1638	1615	1593
C_V (Scott) (10^{-4} cm²/sec.)	—	—	—	—	36.1	—	24.7	22.8	21.5	—
C_V (present method) (10^{-4} cm²/sec.)	—	—	—	—	29.3	18.6	19.5	17.2	16.4	

CONCLUSION

From the foregoing investigation, the following conclusions can be drawn.

An analytical method utilising three oedometer test readings has bee proposed for determination of C_V. The computed values are in close agreement with those obtained by existing methods.

NOTATION

C_V = consolidation coefficient

H = effective drainage path

R_f = final oedometer reading for primary consolidation alone

R_i = corrected initial oedometer reading

R_1, R_2, R_3 = three selected oedometer readings at time t_1, t_2 and t_3

= dimensionless time

t = time

t_1, t_2, t_3 = time readings

U=degree of consolidation
u=pore pressure
u_0=initial pore pressure
z=depth
ρ=settlement
ρ_f=final settlement

REFERENCES

1) Casagrande, A. and Fadum, R. C. (1940): "Notes on soil testing for engineering purposes," Soil Mechanics Series No. 8, Pub. No. 268, p. 37, Harvard University, Cambridge, Mass.
2) Scott, R. F. (1961): "New Method of consolidation-coefficient evaluation," Journal of Soil Mechanics and Foundation Division, ASCE, Vol. 87, pp. 29-39.
3) Taylor, D. W. (1948): Fundamentals of Soil Mechanics, John Wiley and Sons, Inc. New York.
4) Terzaghi, K. (1923): "Dic berechnung der durchlassigkeitsziffer des tones ans dem verlanf der hydrodynamischen spannungserschernungen," Akad. Wiss. Wien Abt, Ila, n 132.

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ULTIMATE RESISTANCE OF DEEP VERTICAL ANCHOR IN SAND

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ABSTRACT

Model test results of a vertical square anchor plate in loose, medium and dense sand are presented. The ultimate anchor resistance has been expressed in terms of a nondimensional breakout factor, $N_q=P_u/\gamma AH$. For shallow anchors, the breakout factor increases with embedment ratio. Beyond the critical embedment ratio, when the anchor behaves as a deep anchor, the breakout factor remains approximately constant. The critical embedment ratio is about 5 for loose sand and increases to about 8 for dense sand. The variation of the experimental breakout factor for deep anchor with the angle of friction of sand has been compared with that predicted by the existing theories.

Key words: anchorage, angle of internal friction, bearing capacity, compaction, load, laboratory test, sandy soil

IGC: E3/K11

INTRODUCTION

Vertical anchor slabs are used in several cases for design and construction of earth retaining structures. The geometric parameters of a vertical anchor are shown in Fig. 1. When an anchor is placed at a shallow depth, at ultimate pullout load, the shear failure extends to the ground surface and it is defined as a shallow anchor. However, when the

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