A Study of the One-Dimensional Consolidation Test

Une étude sur l'essai de consolidation uni-dimensionnel

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Summary

The influence of load increment ratio, nature of pore fluid, and side friction on the results obtained from one-dimensional consosidation tests was studied with the aid of pore pressure measurements.

Conclusions are drawn regarding (a) the nature of secondary compressions and the principal factors that control the rate at which they occur, (b) apparatus requirements necessary to substantially eliminate side-friction effects, and (c) the test conditions for which the Terzaghi theory can reliably predict the rate of pore pressure dissipation.

Sommaire

A l'aide de mesures de pressions d'eau interstitielle, on étudie l'influence du rapport de l'augmentation de charge, de la nature du fluide interstitiel et du frottement latéral sur les résultats obtenus dans des essais de consolidation uni-dimensionnels.

Des résultats obtenus, on tire des conclusions concernant : a) la nature des compressions secondaires et les facteurs principaux qui règlent la vitesse avec laquelle elles se produisent, b) les appareils nécessaires pour éliminer essentiellement les effets du frottement latéral, et c) les conditions d'essai pour lesquelles la théorie de Terzaghi est susceptible de prévoir avec assurance la vitesse de dissipation de la pression interstitielle.

Introduction

One-dimensional consolidation tests are widely used for the measurement of soil parameters (m_v and c_v) in the Terzahgi theory of consolidation. On the basis of earlier studies (for example, Taylor, 1942, and Van Zelst, 1948), certain procedures for conducting the test have been generally accepted; these involve the use of samples at least 3/4″ high and 2″ in diameter, a load increment ratio equal to one, and an increment duration of one day. Although aberrations from the Terzaghi theory were recognized at an early date (cf. Gray, 1936) — their causes are poorly understood; nor have the deviations due to test procedures been clearly delineated. A study to this end is reported herein.

Tests were performed in consolidometer rings 4-7/16″ in diameter (100 sq. cm.) with heights varying from 3/4″ to 1 ½″. The influence of load increment ratio, nature of the pore fluid, and side friction were studied with the aid of pore pressure measurements. Teflon-lined consolidometers were used in an effort to minimize the effects of side friction. To assist in delineating the phenomena involved, it was desired to investigate cases in which aberrations from the Terzazhi theory are large. Accordingly, most of the tests were conducted on undisturbed samples of Mexico City clay.

Load increment ratio

The effect of load increment ratio on compressibility, particularly its influence on the interpretation of the effective in-situ preconsolidation pressure, has been reported elsewhere (Leonards and Ramiah, 1959). It was concluded that a normally consolidated clay could sustain a small but definite (and important) pressure increment before volume changes would begin to occur; moreover, it was found that this "quasi-preconsolidation pressure" could be closely approximated by testing undisturbed samples of high quality using reduced load increment ratios — a practice that is prevalent in testing Mexico City clays (Zeevaert, 1957). This phenomenon is of practical importance in the case of highly compressible clays and for *deep* deposits of all "normally consolidated" clays.

Figure 1 illustrates the effects of load increment ratio on the time-rate of consolidation. For large load increment ratios, a dial reading-log time curve is obtained which, with exception of secondary compressions, is characterized by the Terzaghi theory (type I curve). For small load increment ratios, a type III curve is obtained, while for intermediate load increment ratios a transition curve (type II) is obtained. Type II and type III curves are also characteristic of the load increment that straddles the effective preconsolidation pressure. These curve shapes have previously been delineated by Marsal, et al (1950). The writers are of the opinion that they represent a general phenomenon, as they were found to develop also in such widely different soil types as glacial till and limestone residual clay. The heavy dots on the curves in Fig. 1 show the (typical) times at which the measured pore pressures have substantially dissipated. It was found that when a type I curve develops, the Casagrande construction delineates the

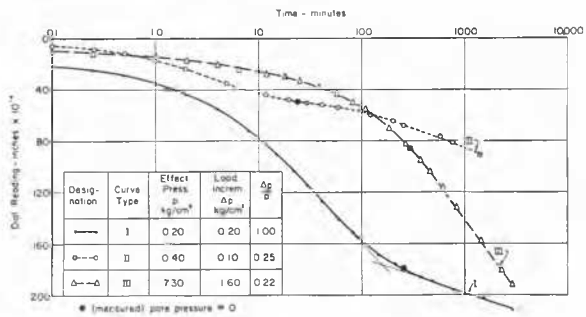

Fig. 1 Effect of load increment ratio on shape of dial reading-time curves. Undisturbed Mexico City clay.

Effet du rapport de l'augmentation de charge sur la forme des courbes de lecture du cadran en fonction du temps. Argile non remaniée de Mexico.

dial reading corresponding to 100 per cent primary consolidation to a good approximation, even when secondary compressions are large.

Fig. 2 shows a plot of the secondary compression per cycle on the log time scale (R_s), per unit of pressure increment (Δp), per unit height of sample (H) vs. the total effective pressure at the end of the increment (p_t) for values of p_t in excess of the preconsolidation pressure. As load increment ratio was varied for another purpose, the curves are incomplete; however, it is seen that (for example) at a total pressure

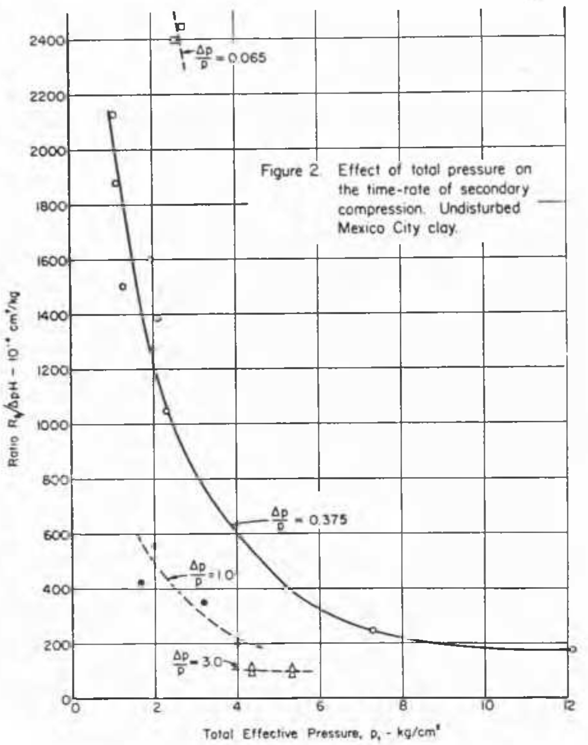

Fig. 2 Effect of total pressure on the time-rate of secondary compression. Undisturbed Mexico City clay.

Effet de pression totale sur la vitesse de la compression secondaire. Argile non remaniée de Mexico.

of 2·7 kg/cm², $R_s/\Delta p.\ H$ increases six-folds as the load increment ratio is reduced from 1·0 to 0·065. Table 1 shows a typical set of test results for values of p_t below the preconsolidation pressure. If the load increment ratio in-situ varies with depth, the use of a constant value of $R_s/\Delta p{\cdot}H$ (as determined by any particular test procedure) can lead to substantial discrepancies in the predicted settlement rate.

Table 1

Effect of Load Increment Ratio on Rate of Secondary Compression

p_t kg/cm²	$\Delta p / p$ *	$\frac{R_s \times 10^{-4}}{\Delta p{\cdot}H}$ $\frac{\text{cm}^2}{\text{kg}}$
0·2	1·00	33
0·3	0·50	45
0·4	0·33	47
0·5	0·25	192
0·6	0·20	348
0·7	0·167	532
0·8	Preconsolidation Pressure	

* p=effective press. at beginning of increment Δp.

The influence of total pressure and sample height on the rate of secondary compression can be eliminated by plotting the ratio of R_s to R_{100} (the amount of "primary" consolidation during the increment) vs. the load increment ratio $\Delta p/p$, as shown in Fig. 3. The numbers adjacent to the points are the total effective pressures p_t; the solid point corresponds to $p_t \approx p_c$, the preconsolidation pressure. The reasons why three typical shapes of dial reading vs. time curves are obtained is evident. The phenomena shown in Fig. 1 to 3 are viewed as a deterrent to the possibility of representing the consolidation process by rheological models, as suggested by Tan (1957).

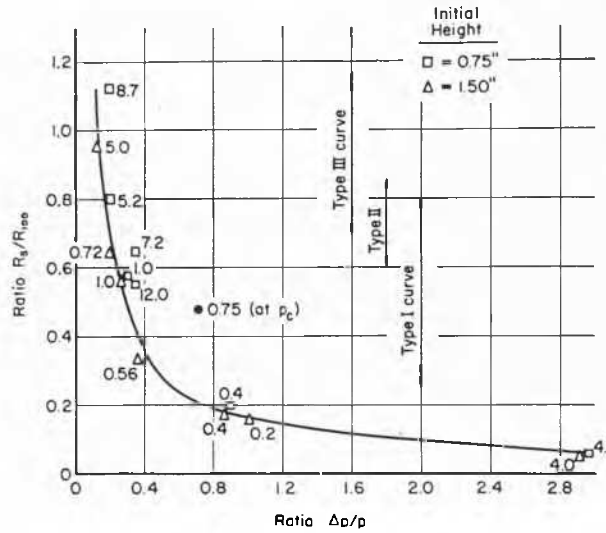

Fig. 3 Effect of load increment ratio on rate of secondary compression. Undisturbed Mexico City clay. (Numbers opposite points are total pressures).

Effet du rapport de l'augmentation de charge sur la vitesse de la compression secondaire. (Les chiffres en face des points représentent les pressions totales). Argile non remaniée de Mexico.

Nature of pore fluid

The pore water in undisturbed samples of Mexico City clay was replaced with carbon tetrachloride (CCl_4) by successively circulating alcohol, acetone, and CCl_4 through the sample until tests showed the effluent to be pure. A comparison of pertinent properties of these liquids is shown in Table 2. Water of the same ionic concentration as the pore water was circulated through companion samples under the same head.

Table 2

Comparison of Certain Properties of Pore Fluids Used

Liquid	*Dielectric Constant*	*Dipole Moment Debyes*
Water	80·4	1·85
Ethyl Alcohol	24·3	1·70
Acetone	21·4	2·70
Carbon tetra-chloride	2·2	0

Undisturbed samples of Mexico clay were obtained by handcutting 7″ × 7″ × 12″ block samples from open excavations at depths of 6·4 and 7·5 meters. The samples tested varied considerably (Table 3), and the comparative test results reported herein were selected from samples having substantially the same initial conditions.

Table 3
Variations Between Samples of Undisturbed Mexico City Clay

Property	*Range of Values*
Liquid limit	275-440
Plastic limit	100-150
Plasticity index	175-290
Natural water content-%	250-410
Specific gravity of solids	2·4
Clay fraction ($< 2\ \mu$)-%	35-50
Undr. Unconf. compr. strength-kg/cm²	0·4-0·6

Compositional analyses were made on samples of the Mexico City clay [1]. The samples were found to contain about 8-10 per cent organic matter, a small amount of calcite, and *x*-ray diffraction patterns indicated the remaining material was amorphous. Differential thermal analysis suggested that the amorphous material was allophane. There was no evidence of the presence of any montmorillonite or illite.

The cation exchange capacity was determined on untreated samples and on samples from which the organic matter was substantially removed (by five washings with H_2O_2) with the following results :

Treatment	*C.E.C.* m.e./100 g
Untreated	28·3
H_2O_2 treated	26·3

It is evident that the inorganic, amorphous material that constitutes the bulk of the solid particles in the clay have a comparatively high surface charge density and that the observed phenomena are probably not influenced greatly by the organic matter.

Upon successive replacement of the pore fluid negligible volume changes occurred except when CCl_4 was used, as shown in Fig. 4, and a typical type III curve was obtained. If type I to type III curves also develop under subsequent loadings (with CCl_4 in the voids), it can be concluded from the data in Figs. 1 and 4 that upon replacement of water with CCl_4 the equivalent of a small load increment ratio is applied. Examination of Fig. 5 demonstrates that this is indeed the case. The applied load increment is attributed to the removal of the force field [2] due to orientation of polar molecules in the vicinity of the clay particles (the polarity of CCl_4 is zero, Table 2). It was also found that load increment ratio has a similar influence on the rate of secondary compression, as illustrated in Fig. 6.

The fact that with CCl_4 as the pore fluid : (1) secondary compressions develop of the same order of magnitude (with respect to primary compression) as when water is the pore fluid, (2) typical type I to type III curves are obtained by varying the load increment ratio, and 3) load-increment ratio has similar effect on the rate of secondary compression as when water is the pore fluid, leaves no doubt that the seat

[1] By Dr. J. L. White of Purdue University.

[2] The existence of this force field and its influence on the shear strength of clays has been reported elsewhere (Leonards and Andersland, 1960).

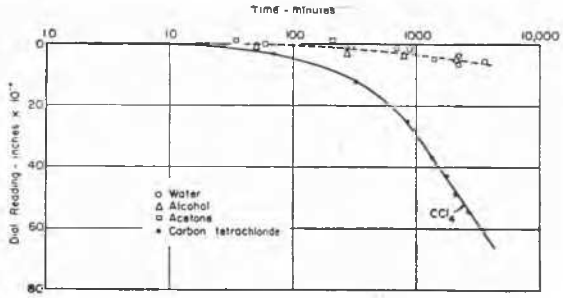

Fig. 4 Volume changes during circulation of different pore fluids. Undisturbed Mexico City clay.

Changements de volume pendant la circulation de divers fluides interstitiels. Argile non remaniée de Mexico.

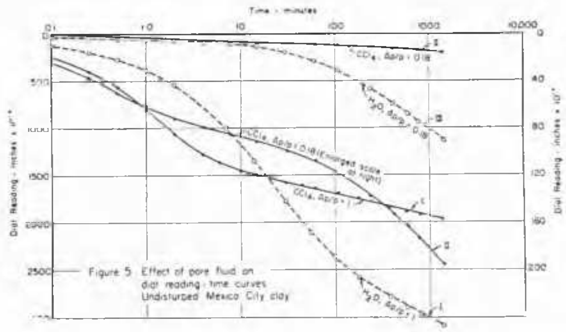

Fig. 5 Effect of pore fluid on dial reading-time curves. Undisturbed Mexico City clay.

Effet du fluide interstitiel sur les courbes de lecture du cadran en fonction du temps. Argile non remaniée de Mexico.

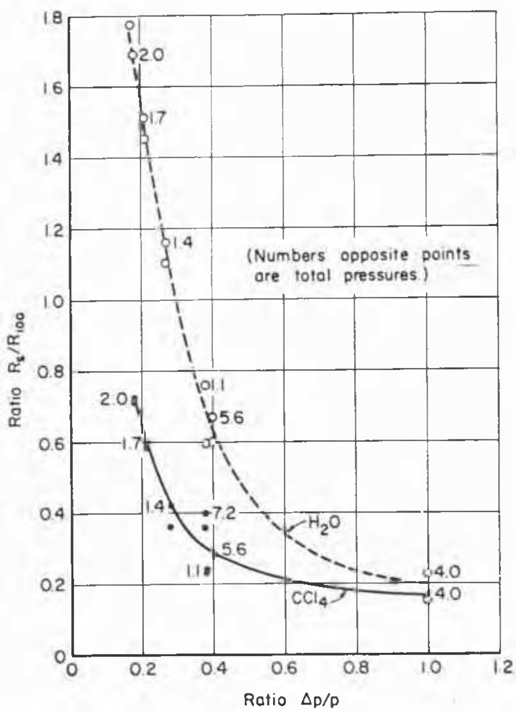

Fig. 6 Effect of pore fluid on rate of secondary compression. Undisturbed Mexico City clay.

Effet du fluide interstitiel sur la vitesse de compression secondaire. Argile non remaniée de Mexico.

of secondary compressions does not lie in the viscous drag of oriented water molecules, although the rate of secondary compression is influenced by this factor. The suggestion by TAN (1957) that secondary compressions are caused by "the jumping of bonds formed by the clay particles" bears further investigation.

The effect of pore fluid on compressibility is shown in Fig. 7. More striking than the reduction in compressibility is the substantial increase in the " quasi-preconsolidation pressure", in this case an overconsolidation ratio of about 2 was developed. Thus, a normally consolidated clay can exhibit an apparent preconsolidation pressure due to subsequent changes in interparticle forces. These need not be due to chemical alterations, to changes in salt concentratration, or to replacement of the pore fluid, but can be caused equally well by long-term secondary compressions and thixotropy (LEONARDS and RAMIAH, 1959). A concomitant increase in shear strength has been reported by OSTERMAN (1959).

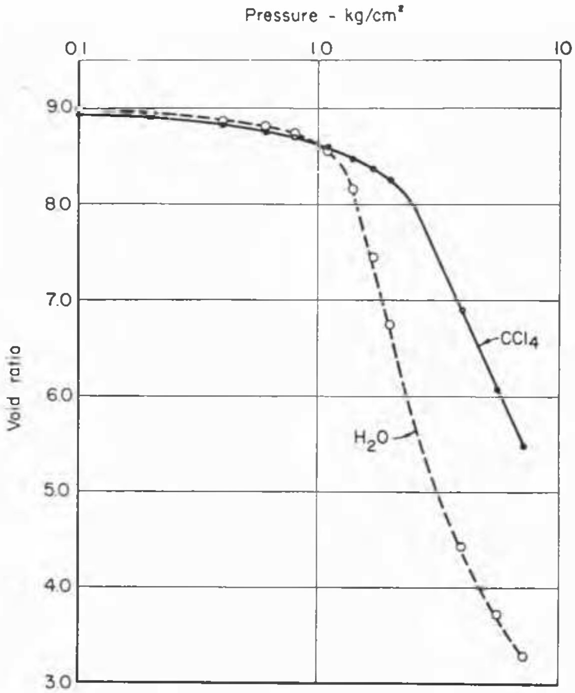

Fig. 7 Effect of pore fluid on compressibility. Undisturbed Mexico City clay.

Effet du fluide interstitiel sur la compressibilité. Argile non remaniée de Mexico.

Side friction

The side friction force was measured with an apparatus similar to that used by MUHS and KANY (1954). Minor modifications were made to increase the precision and to permit simultaneous measurement of excess pore pressures. A schematic diagram of the apparatus is shown in Fig. 8 : temperature control ($\pm$ 0·5° C) is required for accurate results.

A set of side friction data is shown in Fig. 9. The rate at which side friction develops is dependent upon at least two factors: (1) the rate of strain, and (2) the rate of pore pressure dissipation. An appreciable amount of side friction accompanies the development of initial ("immediate") compressions. Thereafter, the friction increases (at a decreasing rate) and undoubtedly affects the rate of pore pressure dissipation.

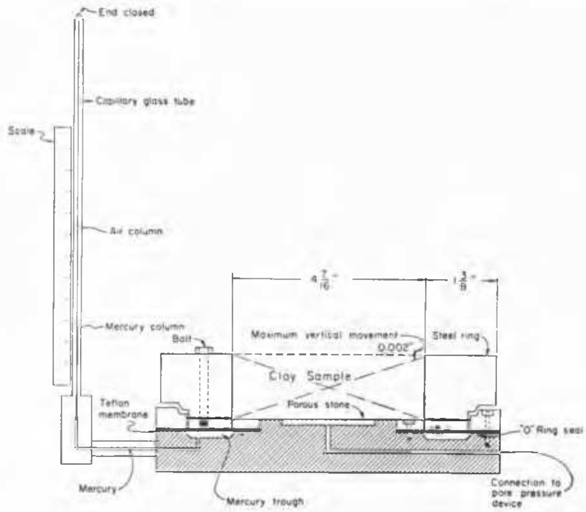

Fig. 8 Friction measuring consolidometer.
Oedomètre pour mesurer le frottement.

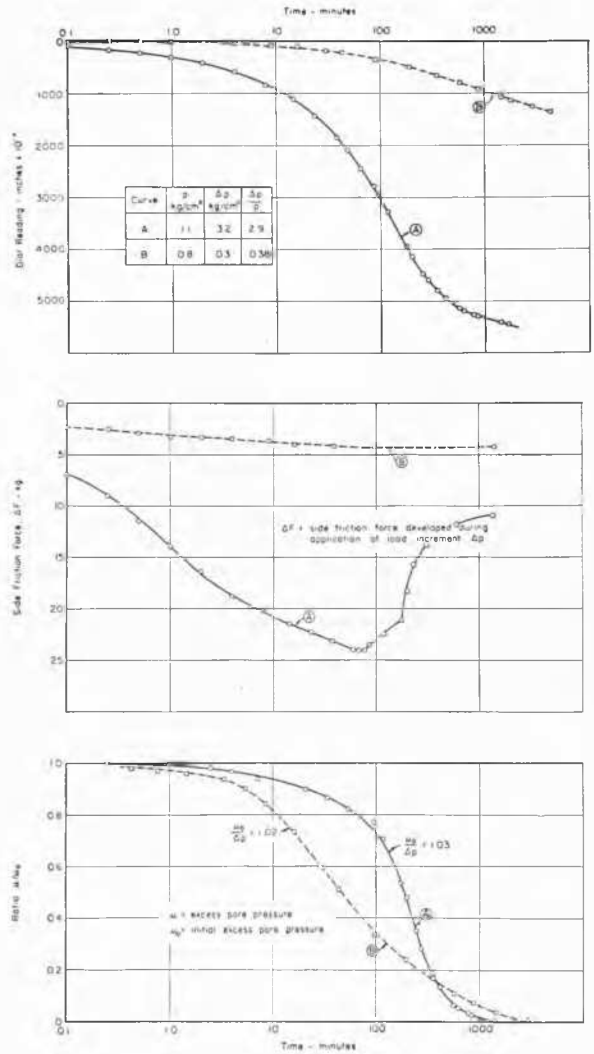

Fig. 9 Relation between rate of side friction development and rates of compression and pore pressure dissipation. Undisturbed Mexico City clay.

Rapport entre la vitesse de développement du frottement latéral et les vitesses de compression et de dissipation de la pression d'eau interstitielle. Argile non remaniée de Mexico.

Thus, in order to study the rates of pore pressure dissipation, either the side friction must be eliminated or its distribution with depth must be measured. In this investigation, the former approach was attempted.

The surfaces of the consolidometer rings in contact with the clay were coated with Teflon, and in some of the tests, lubricated with a grease containing molybdenum disulfide[3]. The results of these tests are summarized in Fig. 10. The maximum side friction force per increment was found to be approximately proportional to the height of the sample and to decrease with total pressure, which is in agreement with the results obtained by Muhs and Kany (1954). It is significant that the load increment ratio does not appreciably influence the results. The effectiveness of greased Teflon liners is evident; for Mexico City clay at total pressures in excess of about one kg/cm^2, using greased, Teflon-lined rings 4 7/16″ in diameter and 3/4″ high, the effects of side friction on the rate of pore pressure dissipation should be small. The maximum reduction in normal stress at any point will be less than six per cent of the applied pressure.

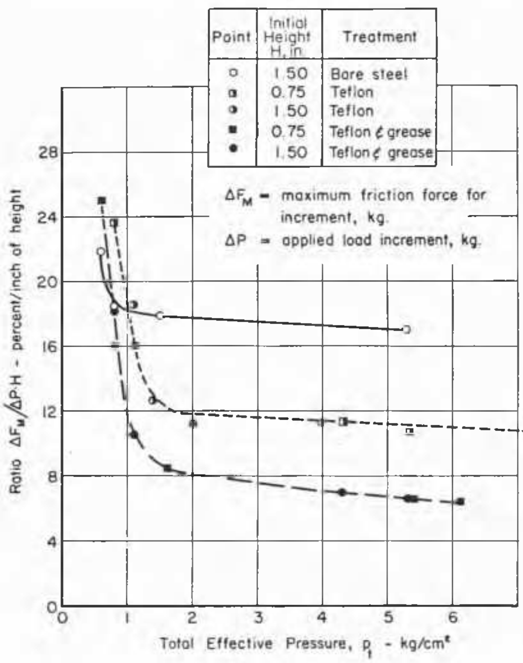

Fig. 10 Effect of consolidometer treatment on maximum side friction force per increment. Undisturbed Mexico City clay.

Effet du traitement à l'oedomètre sur la force maximum du frottement latéral pour chaque augmentation. Argile non remaniée de Mexico.

Pore pressures

Pore pressures were measured at the base of fixed-ring consolidometers with the aid of the null meter developed by the Norwegian Geotechnical Institute (Andresen, et al, 1957). In the low pressure range, a mercury (or water) manometer was used to measure the pressure; for pressures beyond the range of the manometer, a cut-off valve was shut and the pressures were measured with a calibrated Bourdon gauge.

Pore pressure measurements were made for various consolidometer heights and sidewall treatments, varying load increment ratios and total effective stresses, and for loading, rebound and reloading conditions on undisturbed and remolded Mexico City clay (Girault, 1960). A set of typical results for a greased, Teflon-lined ring, 3/4″ high, at varying load-increment ratios is shown in Fig. 11.

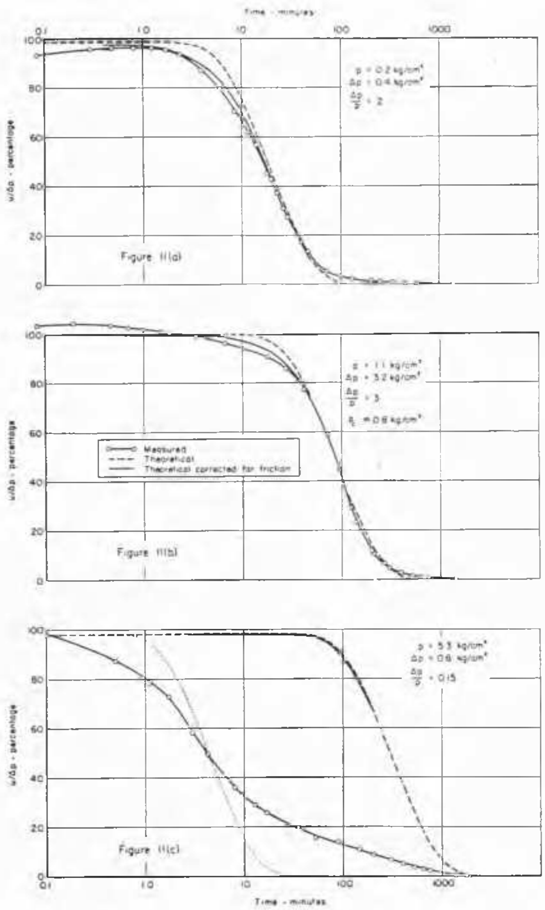

Fig. 11 Influence of loading increment ratio on pore pressure dissipation rates. Undisturbed Mexico City clay.

Influence de l'augmentation de charge sur la vitesse de dissipation de la pression d'eau interstitielle. Argile non remaniée de Mexico.

Fig. 11 shows the effect of load increment ratio on the rate of pore pressure dissipation. A theoretical curve (dashed line) calculated from the Terzaghi theory was fitted to the measured curve by computing c_v from the dial reading-time curve at 50 per cent consolidation using Casagrande's log time fitting method. The theoretical curve was then corrected for side friction as follows :

(a) Both the initial and time dependent side friction was assumed to be linearly distributed with depth.

(b) The initial side friction was subtracted from the load increment to give an initial excess pore pressure distribution that decreased linearly with depth.

(c) The time dependent side friction was treated as a time-dependent load *reduction*, using the equations derived by Schiffman (1958). The equations were integrated for the measured rate of side friction development to give the "corrected" theoretical curve (solid line).

Fig. 11 (a) shows a comparison between the measured and computed rates of pore pressure dissipation for a load increment ratio of two at a total pressure less than the preconsolidation pressure. As the amount of side friction is comparatively large (Fig. 10), the friction correction is appreciable but agreement between the corrected theoretical curve and the measured rate of pore pressure dissipation is good. Fig. 11 (b) shows a similar comparison at a total

[3] The authors are indebted to the Swedish Geotechnical Institute for this suggestion.

pressure above the preconsolidation pressure. The friction correction is smaller and good agreement between measured and theoretical pore pressures was again obtained[4]. Fig. 11 (c) shows the same comparison for a small load increment ratio (0·15) at a large value of the total pressure. The side friction correction is negligible, yet agreement with the measured pore pressures is very poor (the dotted curve is the corrected theoretical curve passed through $u/\Delta p = 0{\cdot}5$). Table 4 shows a comparison of computed values of c_v for the three load increments shown in Fig. 11 : values calculated from dial reading-time curves using the Casagrande log time method are shown in column I, values calculated from the pore pressure curves at $u/\Delta p = 0{\cdot}5$ are shown in column II, and values calculated from the pore pressure curves at a time corresponding to t_{50} on the dial reading-time curves are shown in column III. Good agreement was obtained for large load-increment ratios only.

Table 4

Comparison of Calculated Values of Coefficient of Consolidation

p kg/cm²	$\Delta p/p$	c_v cm²/sec. × 10^{-4}			*Ratio*	
		I	II	III	I/II	I/III
0·2	2·0	12·5	12·9	15.6	0·97	0·81
1·1	3·0	1·46	0·93	1·41	1·57	1·03
5·3	0·15	0·13	9·14	0·67	0·014	0·19

The data in Fig. 11 show that the "anomalous" behavior using small load increment ratios cannot be attributed to side friction, as suggested by TAYLOR (1942). It is also clear that values of c_v calculated from any particular test procedure can be greatly in error when applied to in-situ conditions where the load increment ratio varies with depth. Finally, the rate of pore pressure dissipation can be predicted reliably from the Terzaghi theory only if comparatively large load increment ratios are applied; for Mexico City clay this ratio is approximately two, for other clays the ratio is considerably smaller.

Conclusions

1. Depending upon the load increment ratio, and upon whether or not the pressure increment straddles the effective preconsolidation pressure, dial reading vs. log time curves can be classified according to three typical shapes.

2. Large rates of secondary compression per unit of primary compression are associated with small load increment ratios. The rate of secondary compression per unit height, per unit pressure increment (at a given total pressure) increases rapidly as the load increment ratio is reduced.

3. Secondary compression cannot be attributed to viscous drag (or other mechanisms) associated with the orientation of polar molecules in the vicinity of clay particles, although the rate of secondary compression is influenced by this factor.

4. Factors other than pressure and chemical alterations — specifically, long-term secondary compressions — can result in the development of effective preconsolidation pressures.

5. With steel or brass consolidometers, side friction can alter significantly the interpretations made from the results of conventional one-dimensional consolidation tests, particularly in the case of pore pressure dissipation rates. Greased Teflon liners can virtually eliminate side friction effects if the diameter to height ratio of the consolidometer exceeds six, and if the total effective pressure exceeds a critical value.

6. The rate of excess pore pressure dissipation can be reliably predicted from the Terzaghi theory provided the applied load increment ratio is sufficiently large; for Mexico City clay this ratio is approximately two, for other clays it is considerably smaller. If the load increment ratio is smaller than the critical value, the Terzaghi theory cannot predict — even approximately — the rate of excess pore pressure dissipation.

[4] For large load increment ratios and small side friction the measured initial excess pore pressure often slightly exceeded the applied pressure increment. This was caused by a small dynamic effect due to the load increment being applied rapidly (in 2 sec.) so that the initial excess pore pressure could be obtained.

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