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A STUDY OF THE SWELLING CHARACTERISTICS OF A REMOULDED CLAY

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SYNOPSIS

The results of swelling tests performed on remoulded, saturated, overconsolidated samples of a local clay in one-dimensional consolidometers are discussed here. The variation of swelling with time is observed for different equilibrium pressures and pressure-decrement ratios for a duration of two weeks. A linear relationship is obtained for the variation of swelling with the square-root of time for small values of time. For large values of time swelling is found to vary linearly with the logarithum of time for most of the test samples.

The experiments show that the swelling-time curve can be defined satisfactorily by the theory suggested by GIBSON and LO (1961) to explain the consolidation behaviour of clays. Values of the soil parameters are determined from the swelling tests and their behaviour with equilibrium pressures and pressure-decrement ratios are studied. The coefficient of secondary swelling is found to increase with increasing ultimate voids ratio and the variation is represented by a linear relationship.

INTRODUCTION

Consolidation properties of clays have been studied extensively by many research workers but very little published literature is available on the swelling characteristics of saturated clays with time effects. Hence, as part of a testing programme initiated in this laboratory for studying the deformation behaviour of a local clay, it was considered that a study of the swelling characteristics of this clay would be valuable.

The soil tested is a black clay from Thunukkai which is situated in the northern province of Ceylon. This clay resembles the black cotton clays found in the central and southern parts of India and is suitable for growing cotton. Due to the high shrinkage and swelling capacity this clay possesses, the foundation engineer is forced to face a number of problems during the construction of civil engineering structures on this clay.

The swelling process that takes place in a saturated clay due to a decrease in the pressure under which the clay has reached equilibrium conditions is similar to the consolidation process. Hence, Terzaghi's theory for one-dimensional consolidation of saturated clays can be used to predict the heaves in excavations made in saturated clays for founding structures.

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Some of the results of a series of one-dimensional swelling tests performed on remoulded, saturated, overconsolidated samples of the Thunukkai clay, in which swellings were measured with time, are discussed in this paper. An attempt is made to investigate the suitability of applying existing theories of consolidation of saturated clays to explain the swelling characteristics exhibited by this clay.

EXPERIMENTAL PROGRAMME

The clay tested has the following properties:-

liquid limit = 58%; plastic limit = 22%; plasticity index = 36%; percentage clay fraction = 32; percentage sand fraction = 45; activity = 1.13; specific gravity = 2.60.

The clay was tested in standard fixed ring type consolidometers with 3 in. diameter and $\frac{3}{4}$ in. high brass rings. The inside of these rings were lubricated with silicone grease in order to reduce the side friction between the rings and the soil. The clay was mixed with deaired water at a moisture content of about 78% in a specially designed mixer under a vacuum of 15 in. of mercury, and the saturated remoulded clay thus obtained was set in the consolidometers with porous stones at both ends of the sample. Filter papers were placed between the clay and the porous stones to prevent the clay being forced into the pores of the stones. The samples were gradually loaded to a pressure of 16 ton/sq. ft and allowed to consolidate under that pressure for one week. Initial laods were applied in small increments in order to prevent the soft clay being squeezed out along the sides of the porous stones.

The samples were then allowed to swell under pressures of 1, 2, 4 and 8 ton sq./ft for one week; these pressures will hereinafter be referred to as the equilibrium pressures and will be denoted by p. Swelling tests were carried out on these samples for pressure-decrement ratios (defined as the ratio of decrease in pressure to the equilibrium pressure) of 1/8, 1/4, 3/8, 1/2, 5/8, 3/4 and 7/8, and swellings were measured with time for a duration of two weeks. As constant temperature facilities were not available in the laboratory, the tests were conducted under normal laboratory conditions.

CONSOLIDATION CHARACTERISTICS OF CLAYS

Before discussing the results of the swelling tests, some of the consolidation characteristics of the Thunakkai clay are presented here, as the two processes of consolidation and swelling are essentially similar.

Experimental evidence furnished by a number of authors, based on measurements made both in field and laboratory, show that the rate of settlement observed for a saturated clay towards the end of the consolidation process is faster than the value predicted by Terzaghi's theory of consolidation. This settlement, which occurs even after the excess pore water pressure in the clay has been dissipated, is generally referred to as 'secondary compression'.

Taylor and Merchant were the first to propose a rational theory to account for secondary compression and their work was reviewed by CHRISTIE (1964). GIBSON and LO (1961) suggested that the soil skeleton can be represented by a rheological model consisting of a Hookean spring connected in series with a Kelvin body, and they consequently derived a theory for one-dimensional consolidation. This theory involves four parameters which have to be determined from consolidation tests; permeability k, viscosity of the soil structure $1/\lambda$, primary compressibility a, and secondary compressibility b. CHRISTIE (1964) showed that the theory of Gibson and Lo is mathematically equivalent to that proposed by Taylor and Merchant.

Settlement-time curves observed during secondary compression can be classified into three types (LO, 1961). In the type I curve, the rate of secondary compression gradually decreases with the logarithm of time until the ultimate settlement is reached. In the type II curve, the rate of secondary compression is proportional to the logarithm of time for an appreciable range of time, then decreases rapidly until the ultimate settlement is reached. In the type III curve, the rate of secondary compression increases with the logarithm of time and then decreases rapidly until the ultimate settlement is reached. LO (1961) showed that the consolidation behaviour characterised by the curves of types I and II can be adequately represented by the theory of Gibson and Lo, and that this theory can be extended to accommodate curves of type III.

Some of the consolidation characteristics of Thunukkai clay have been presented elsewhere (THURAIRAJAH, 1967). Settlement-time curves obtained for this clay showed that the secondary compression curves belonged to the types I and II, type II being generally obtained for lower pressure-increment ratios. Figure 1 illustrates the settlement-time curves obtained for four pressure-increment ratios where observations were continued for a period of two months. The samples were found to be still settling at the end of the two months.

Tests on this clay confirmed that the shape of the settlement-time curves can be defined more accurately by the theory suggested by Gibson and Lo than by the theory of Terzaghi. The coefficient of secondary compression, defined as the voids ratio change per logarithmic cycle of time, was found to increase with increasing ultimate voids ratio. It was also observed that the ratio of secondary compression to primary compression increased with decreasing pressure-increment ratio.

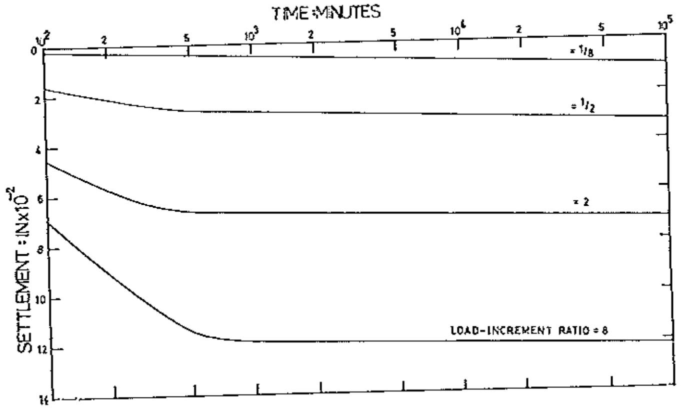

Fig. 1. Settlement-time curves for consolidation tests on Thunukkai clay for an initial pressure of 1.0 ton/sq. ft.

RESULTS OF SWELLING TESTS

Variation of Swelling with Time

The curve of variation of the swelling of this clay with time is found to be similar to the consolidation curve, following a linear relationship with the square-root of time for small values of time. A typical curve for a swelling test is presented in Fig. 2. In every test, an immediate swelling follows the application of the pressure decrement. The ratio of the immediate swelling to the ultimate swelling varies from 3% to 20% for these tests. This ratio is found to decrease with the equilibrium pressure for any pressure-decrement ratio $\Delta p/p$.

The coefficient of swelling, s_v, for these samples was estimated using Taylor's square-root of time fitting method. The values obtained varied from 2×10^{-5} sq. in/min to 50×10^{-5} sq. in/min. These values are of the same order of magnitude as the values obtained for the coefficient of consolidation of this clay. The test results show that the coefficient of swelling decreases with increasing pressure-decrement ratio for any equilibrium pressure. It is also found to increase with increasing equilibrium pressure for any pressure-decrement ratio.

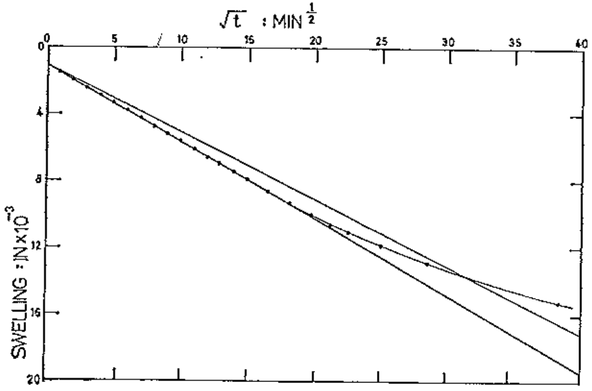

Fig. 2. Variation in swelling with $\sqrt{t}$ during a swelling test for an initial pressure of 2.0 ton/sq. ft and a pressure-decrement ratio of 3 /4.

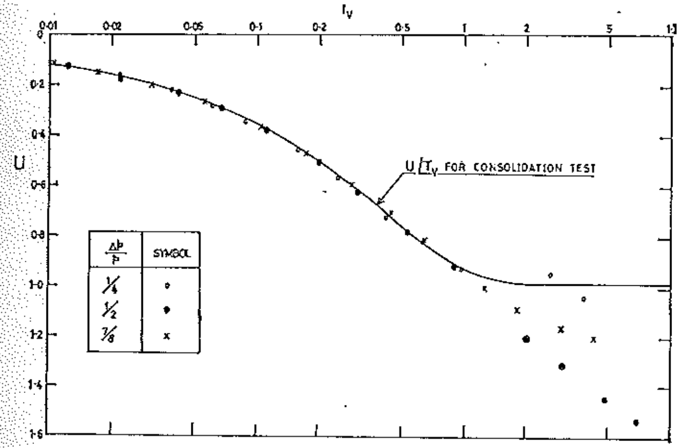

Fig. 3. Variation of U with T_V during swelling tests for an initial pressure of 2.0 ton/sq. ft.

The curve in Fig. 3 shows the variation in the degree of consolidation U with the time factor T_v, as predicted from Terzaghi's one-dimensional consolidation theory. The points plotted in this figure are the results obtained for three typical swelling tests on samples at an equilibrium pressure of 2 ton/sq. ft. In a manner similar to that used for consolidation tests, Taylor's square-root of time fitting method has been employed to determine the coefficient of swelling and the 100% primary swelling for these tests. The experimental points closely fit the theoretical curve up to about 90% primary swelling. Beyond this, the observed degree of swelling is greater than that given by Terzaghi's theoretical curve.

The curves showing the variation of swelling with the logarithm of time, for large values of time, are found to be similar to the curves of types I, II and III obtained for the consolidation tests. The curves obtained for seven different pressure-decrement ratios applied to samples at an equilibrium pressure of 2 ton/sq. ft are given in Fig. 4. Observations made on some of the test samples show that swelling continued even after a period of two months. Curves of type I are obtained for samples with large equilibrium pressures (small overconsolidation ratios) and small pressure-decrement ratios. Type III curves are obtained for samples with small equilibrium pressures (large overconsolidation ratios) and small pressure-decrement ratios. Most of the secondary swelling curves obtained are of type II.

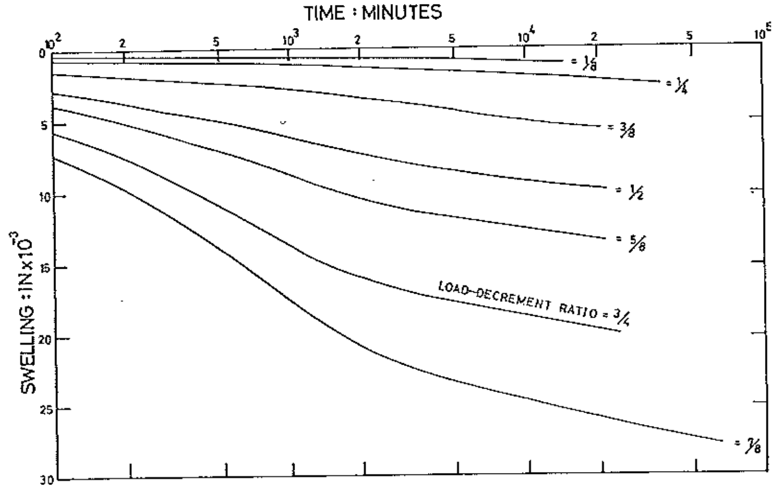

Fig. 4. Swelling-time curves for different pressure-decrement ratios for an initial pressure of 2.0 ton/sq. ft.

The percentage swelling at any instant to the ultimate swelling is plotted against the logarithm of time in Fig. 5 for three pressure-decrement ratios applied to samples at an equilibrium pressure of 2 ton/sq. ft. Distinct differences in shape between the curves obtained for the three pressure-decrement ratios can be noticed.

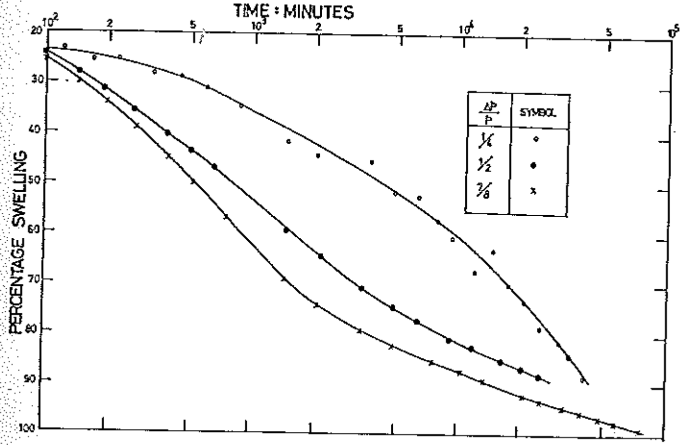

Fig. 5. Variation in percentage swelling with time for an initial pressure of 2.0 ton/sq. ft.

Coefficient of Secondary Swelling

Figure 6 shows the variation in voids ratio with the logarithm of time during the secondary swelling process for five tests with a typical pressure-decrement ratio of 3/8. The slopes of the straight lines drawn to fit the experimental points are found to increase with decreasing equilibrium pressures (increasing overconsolidation ratios).

The coefficient of secondary swelling, s_s, which is defined as the voids ratio change per logarithmic cycle of time, was determined for each swelling test, and was found to depend on the final pressure under which the sample was swelling, i.e. the ultimate voids ratio. In Fig. 7, s_s is plotted against the ultimate voids ratio e for the swelling tests. The straight line shown was fitted to these points using statistical analysis. The equation for the line is

$$s_s = -361.4 \times 10^{-4} + 691.2 \times 10^{-4} e \quad \ldots\ldots\ldots\ldots \quad (1)$$

This regression line has a sample correlation coefficient of 0.89 and a standard error of estimate of 20.5.

Determination of Soil Parameters

If the theory of consolidation presented by GIBSON and LO (1961) is assumed to be applicable to the swelling process, then the swelling d_t at

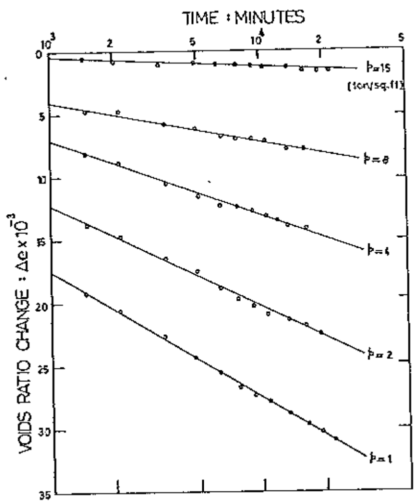

Fig. 6. Variation in voids ratio with time during swelling tests for a pressure-decrement ratio of 3/8.

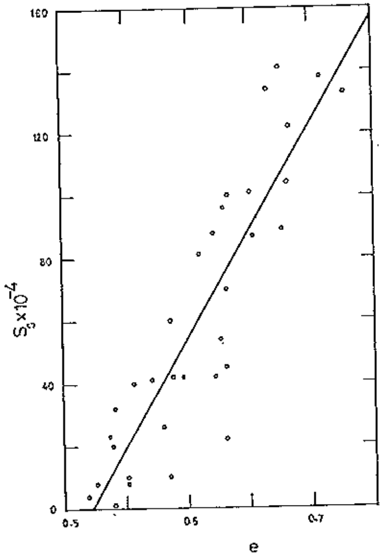

Fig. 7. Variation in coefficient of secondary swelling with voids ratio.

any time t after the application of the pressure decrement Δp is given by

$$d_t = H.\ \Delta p\ \left[a + b\,(1 - e^{-\lambda t/b}) \right] \ldots\ldots\ldots\ldots\ldots \quad (2)$$

for large values of t, where H is the thickness of sample and a, b and λ are soil parameters. If d_T is the swelling at any time T after the application of Δp, where $T = t + t_1$, then

$$d_T = H.\ \Delta p\ \left\{ a + b\left[1 - e^{-\lambda\,(t+t_1)/b}\right]\right\} \ldots\ldots\ldots\ldots \quad (3)$$

Therefore,

$$d_T - d_t = H.\ \Delta p.\ b.\ e^{-\lambda t/b}\,(1 - e^{-\lambda t_1/b}) \ldots\ldots\ldots\ldots \quad (4)$$

If t_1 is sufficiently large such that $e^{-\lambda t_1/b}$ is small compared to unity and can be neglected, then from Eq. (4)

$$\log\,(d_T - d_t) = \log\,(H.\,\Delta\,p.b) - 0.434\ (\lambda t/b) \ldots\ldots\ldots\ldots \quad (5)$$

Hence, if $\log\,(d_T - d_t)$ is plotted against t, a straight line graph with gradient $-0.434\ \lambda/b$ and intercept $\log\,(H.\,\Delta\,p.b)$ is obtained for large values of t.

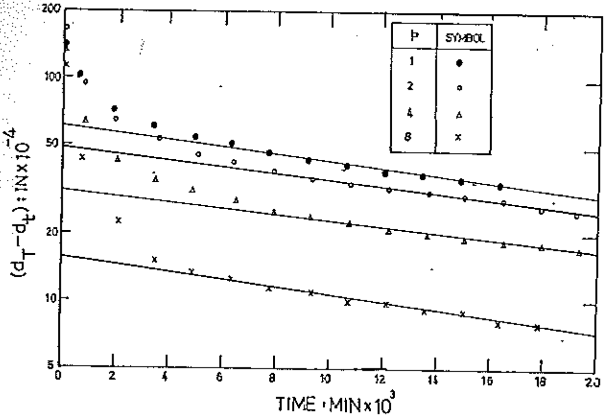

Fig. 8. Variation in (dT - dt) with time for a pressure-decrement ratio of 3/4.

In swelling tests conducted over a long duration of time, it was noticed that the samples continued to swell even after a period of two months and that the swelling–log t relationships generally followed curves of the type II. Hence, the value of d_T for $T = 100{,}000$ minutes is estimated on the assumption that the secondary swelling tail on the lograithmic time scale is a straight line in this time range, and this value is used in estimating the soil parameters a, b and λ. Log $(d_T - d_t)$ is plotted against t in Fig. 8 and 9 for swelling tests with two typical pressure-decrement ratios of 3/4 and 1/2 respectively. The points plotted for each test lie reasonably well on a straight line for large values of t. This result confirms that the swelling characteristics of this clay can be represented by the theory of consolidation suggested by Gibson and Lo. Values of the soil parameters for these two typical tests are presented in Table 1.

Table 1. Values of soil parameters

p (ton/sq.ft)	$\Delta\,p/p$	Ultimate Voids Ratio	a (sq.ft/ton x 10^{-4})	b (sq.ft/ton x 10^{-4})	λ/b (1/min x 10^{-4})	λ (sq.ft/ton/ min x 10^{-8})	s_y (sq.in/min x 10^{-5})
1	3/4	0.685	346	196.0	0.36	70.3	3.1
2	3/4	0.667	280	77.1	0.33	25.5	3.3
4	3/4	0.631	145	25.9	0.31	8.0	5.7
8	3/4	0.624	73	6.4	0.38	2.4	7.2
1	1/2	0.685	279	201.0	0.31	62.3	6.7
2	1/2	0.655	206	73.9	0.33	24.3	5.5
4	1/2	0.589	107	18.8	0.37	7.0	6.3

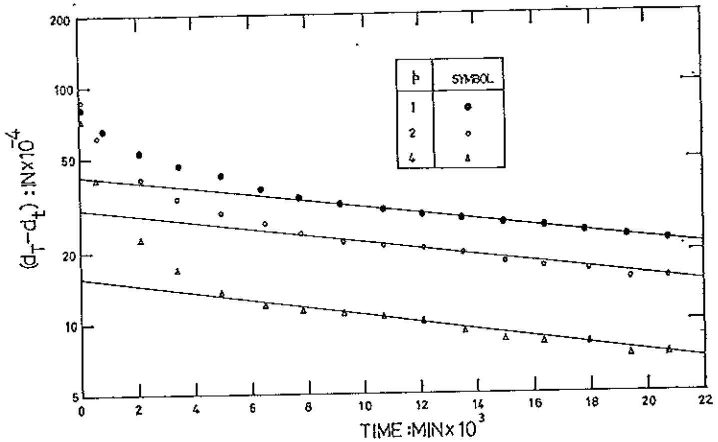

Fig. 9. Variation in $(d_T - d_t)$ with time for a pressure-decrement ratio of 1/2.

The soil parameters are estimated for the thirty five swelling tests carried out and the following general observations are made about the numerical values obtained:

1. The ratio λ/b is approximately constant for the soil, being independent of the equilibrium pressure and the pressure-decrement ratio, and has a mean value of 0.35×10^{-4} per minute.
2. For any pressure-decrement ratio, the viscosity of the soil skeleton, $1/\lambda$, increases with increasing equilibrium pressure.
3. For any pressure-decrement ratio, the parameters a and b for the soil decrease with increasing equilibrium pressure.
4. For any equilibrium pressure, the ratio of secondary swelling to primary swelling, b/a, decreases with increasing pressure-decrement ratio.
5. For any pressure-decrement ratio, the ratio b/a decreases with increasing equilibrium pressure.

The soil parameters obtained from consolidation tests on this clay (THURAIRAJAH, 1967) possessed the same general characteristics as listed above.

CONCLUSIONS

All the samples tested of Thunukkai clay exhibited an immediate swelling on the application of the pressure decrement. The swelling was then found to vary linearly with the square-root of time for small values of time. For large values of time, the variation of swelling with the logarithm of time was generally found to be linear.

The results show that the swelling characteristics of the clay can be defined satisfactorily by the theory suggested by GIBSON and LO (1961) to explain the consolidation behaviour of clays. Values of the soil parameters based on their theory have been determined from the swelling tests, and these exhibit the same general characteristics as the parameters obtained earlier from consolidation tests.

The coefficient of secondary swelling increases with ultimate voids ratio and can be represented approximately by a linear relationship.

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