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An Investigation of the Three-Dimensional Creep Properties of a Clay

By

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SUMMARY.- The strain-log time curve for an increment in deviator stress under undrained triaxial compression conditions is shown to be essentially a straight line over most of the range, the slope of which increases rapidly as the effective stress ratio q/p increases from the k_o condition to failure. If the increment is preceded by either secondary consolidation or a prolonged strain under a lower deviator stress, the strains and pore pressures in the early stages are considerably reduced and a 'delay' is introduced before the linear relationship is established. This behaviour is shown to be a function of previous strain rather than of time.

The effective stress ratio-strain curve is shown to be independent of loading procedure to a first approximation. Finally, a model is presented which attempts to take the observed properties into account.

I.- INTRODUCTION

It is being recognized to an increasing extent that more accurate estimates of the behaviour of building foundations, etc., will be obtained if design is based on the stress-deformation-time properties of the foundation soil. Recent methods, notably those of Skempton and Bjerrum (Ref. 1) and Davis and Poulos (Ref. 2), take account of an 'immediate' component of deformation due to increase in shear stress, and a long-term component due to consolidation. However, in thick deposits of clay, there is clearly a possibility of a long-term component associated with the increase in shear stress. The work described herein was undertaken to investigate this aspect.

The word 'creep' is used in reference to the process where any one of the quantities pore pressure, volumetric strain and shear strain changes with time in a manner which differs from that normally associated with primary consolidation where pore pressure gradients due to hydrodynamic lag are set up in the sample. Secondary consolidation refers to the specific case where volumetric and shear creep strains accompany each other.

II.- NOTATION

$q = (\sigma_1' - \sigma_3')$ = deviator stress.

$$p = \frac{\sigma_1' + \sigma_2' + \sigma_3'}{3} = \frac{1}{3} q + \sigma_3'$$

= mean normal effective stress.

q/p = effective stress ratio.

$\varepsilon = \varepsilon_1 - \frac{1}{3}v$ = shear strain.

ε_1 = axial strain

v = volume strain.

III.- EXPERIMENTAL DETAILS

The clay used was a kaolin (LL 112; PL35) in the form of cores with a water content of about 70 per cent and a degree of saturation of 100 per cent, prepared by extrusion from a vacuum extruder. Side drains and filter discs at each end of the sample were employed. Further details are given in Ref. 3. It was found that the experimental results were unaffected by end restraint.

Tests were conducted on normally consolidated samples in a standard triaxial compression apparatus. Pore pressures in undrained tests were measured at the base of the sample using a gauge of the type described by Davis and Poulos (Ref. 2). Consolidation under anisotropic stress conditions was carried out while q was maintained constant.

IV.- PRESENTATION OF RESULTS

(a) Time Behaviour

Fig. 1 compares the results of two tests in which the depicted undrained increment in deviator stress q was preceded by consolidation which was effected by increasing σ_3' while maintaining q constant. In the test illustrated in Fig. 1(a), primary consolidation only was allowed, the increment Δq being applied as soon as this was judged to have occurred, while in Fig. 1(b) considerable

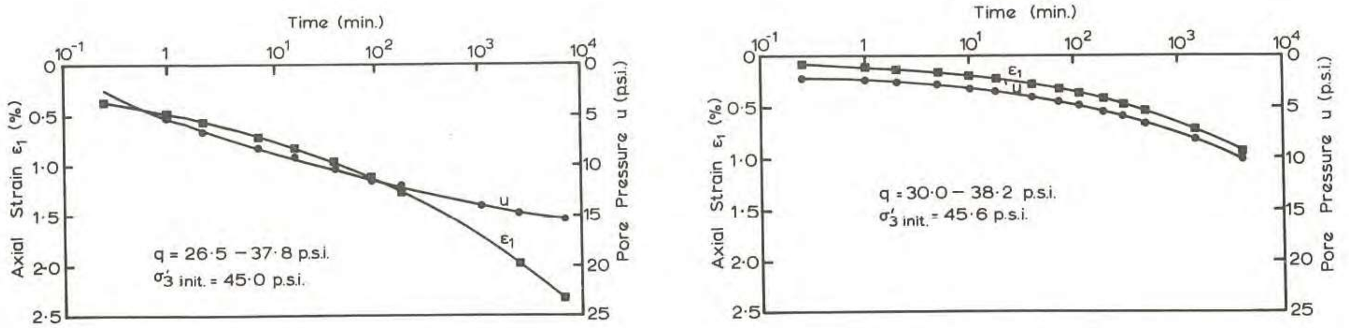

Fig. 1.- The effect of (a) zero and (b) 2-day secondary consolidation on the pore pressure and strain versus time behaviour for an undrained increment in deviator stress.

time was allowed for secondary consolidation to take place before applying Δq.

Referring first to Fig. 1(a), it will be seen that the pore pressure shows a steady increase with time, with some sign of tapering off toward the end of the test, while the axial strain curve is gently convex upwards on the long-time plot with a tendency to become linear at large times. It is clearly not possible to draw any distinction between 'primary' and 'secondary' phases in either of the two curves; in fact, the whole process from beginning to end resembles one of seconary creep with associated strain hardening. This observation contrasts with the results obtained by Walker (Ref. 4).

The degree of saturation of the pore water and the flexibility of the pore pressure measuring system in the tests described were such that the pore pressure rose to within 95 per cent of any increase in cell pressure in less than ½ min. An increment Δq increases the mean normal effective stress p by 1/3 Δq. Since undrained conditions prevail, the pore pressure may be expected to rise by at least this amount. It will be seen from Fig. 1(a) that the pore pressure did in fact rise to 1/3 Δq in about ½ min., and this rise was about 20 per cent of the total change in pore pressure. The axial strain occurring at the end of ½ min. might be termed the 'immediate' response to the application of Δq, which is somewhat less than 20 per cent of the total axial strain. It would seem that the effect of strain (or time) is to cause a change in the structure of the clay leading to a steady increase in pore pressure. It may be noted that the effective stress ratio q/p rises steadily as a result of this rise in pore pressure even though q is maintained constant.

Furning now to Fig. 1(b) which concerns an increment in q which was preceded by secondary consolidation for 2 days, both the pore pressure and the axial strain at a given time are considerably less than without secondary consolidation. For example, at 100 min., the change in pore pressure and the axial strain relative to the change in deviator stress are 0.58 and 0.045 respectively, whereas for the case with no previous secondary consolidation the corresponding values are 1.0 and 0.1, i.e. about twice as high.

The above results for incremental loading form the equivalent to those for the constant rate of strain case presented by Newland (Ref. 3).

Fig. 2 compares the results of two tests in which two undrained increments of deviator stress were applied consecutively. The first increment in each test was applied following primary consolidation as described with reference to Fig. 1(a). However, in one test, the second increment was applied after 75 min. (Fig. 2a), while in the other test the second increment was applied after 5 days. (Fig. 2b, in which the first increment is the same as that in Fig. 1a). Axial strains and pore pressures have been plotted relative to the beginning of the first increment for the sake of clarity in the diagram.

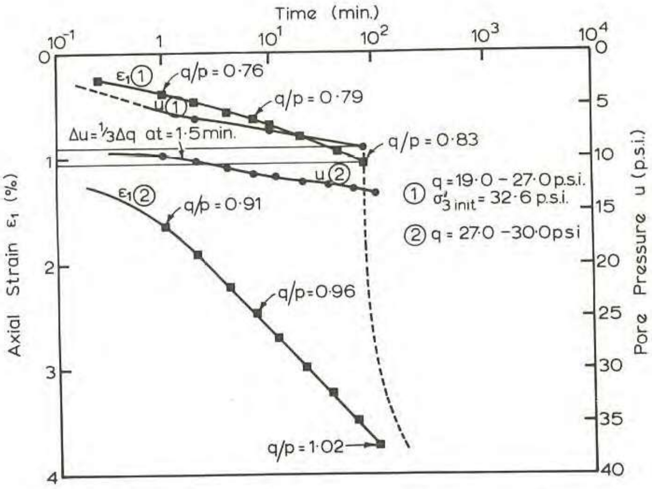

Fig. 2(a).- The effect of a short duration undrained deviator stress on the pore pressure and strain versus time behaviour of the succeeding undrained increment.

In Fig. 2a, it will be seen that, following the relatively short first increment, the axial strain in the second rapidly assumes a straight line when plotted against the logarithm of time, making the resemblance to 'secondary' creep very strong indeed. The 'immediate' strain occurring at the end of ½ min. is once again less than 20 per cent of the total axial strain at the expiration of 100 min. The effect of delaying application of the second increment for five days is illustrated in Fig. 2b. Here, very little axial strain occurs before about 100 min., (the 'immediate' strain is almost zero), after which there is a transition to a straight line in Fig. 2a. It is as if the additional strain occurring in the previous increment introduces a delay in the establishment of the linear portion of the axial strain-log time curve.

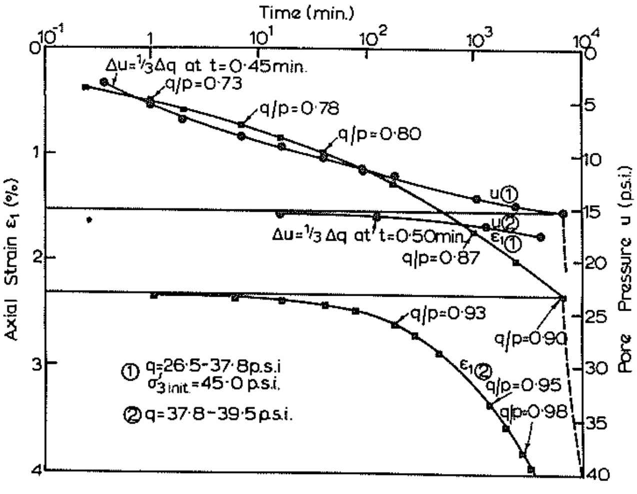

Fig. 2(b).- The effect of a long duration undrained deviator stress on the pore pressure and strain versus time behaviour of the succeeding undrained increment.

It was also found that the size of the increment affected this delay; the larger the increment the smaller the delay. This can be explained on the basis that the previous strain forms a smaller percentage of the strain in the current increment as that increment becomes larger.

A further point of interest is that the time for the change in pore pressure to reach 1/3 Δq is about 150 min. This suggests that there was a tendency for the clay to dilate when the second increment was applied as a result of the prolongation of the previous increment. This is similar to the effect reported by Richardson and Whitman (Ref. 5) where an actual decrease in pore pressure is recorded when the strain-rate is changed from a slow to a fast rate.

The second increment in both tests is also plotted (dashed curve) using a continuation of the time scale of the first increment. This curve is seen to descend very rapidly indeed towards the curve for the second increment with zero time at the beginning of this increment and would asymptote to the linear portion if the test were carried on long enough. There is a hint in this behaviour that either the increasing viscosity to which the strain hardening might be attributed is not simply a function of time, or the application of a further increment in q somehow causes a reduction in this viscosity. The latter explanation is difficult to accept since strain hardening eventually sets in during the later stages of the second increment.

To investigate the effect of time on the progress of undrained creep, an increment of deviator stress was applied for a period of 130 min. and then reduced to such a value that further axial strain was zero (about 3/4 of the elevated value) and this was maintained for a period of 1300 min. At this point, the deviator stress was returned to the elevated value. As Fig. 3 shows, the axial creep process continued almost as if there had been no interruption. Admittedly, the deviator stress level during the period of zero axial strain was lower than that at the beginning of the test before the final increment in q was added, although several increments had been added prior to this over a period of time. Nevertheless, the result gives support to the contention that the apparent increase in viscosity as creep proceeds is not a function of time. A better explanation would seen to be that, while the viscosity and shear stresses remain constant, the internal resistance to shear increases as a function of axial strain. This is similar to the second of the alternative models proposed by Walker (Ref. 4). However, the fact that the pore pressure rises beyond 1/3 Δq means that the normal effective stress, p, decreases as the axial strain proceeds. This in turn leads to a reduction in the resistance to shear, which must therefore be more than offset by the gain in resistance resulting from axial strain, since the net effect is one of strain hardening.

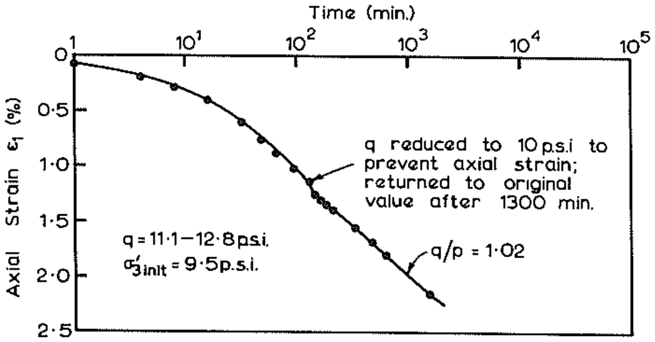

Fig. 3.- The effect of a time delay on the strain versus time curve.

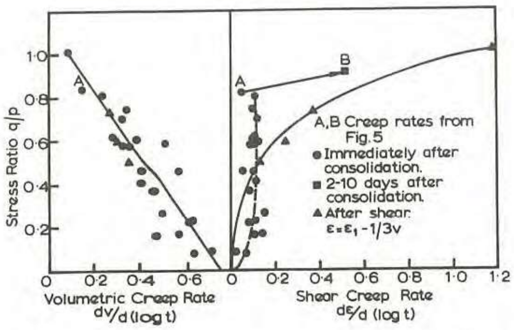

Fig. 4.- The variation of creep rates with effective stress ratio.

The linear relationship between axial strain and log time is a feature of the undrained behaviour following increase in *q* (Ref. 3, 4, 6), as it is of the secondary consolidation behaviour following increase in σ_3'. Walker (Ref. 4) suggested that the slope of the straight line sections be designated the creep rate. Results obtained by Newland (Ref. 3) are reproduced in Fig. 4. Referring to the plot of *q/p* against shear creep rate, it will be seen that the creep rate following an increase in *q* increases very rapidly for values of *q/p* beyond 0.5. On the other hand, for the case where the given stress ratio was reached by consolidation from a higher stress ratio as a result of increasing σ_3' while maintaining *q* constant, the shear creep rate remained constant over most of the range of stress ratio at a value equal to that for *q/p* = 0.5. following increase in *q*. This apparent anomaly has been resolved as will be seen by reference to Fig. 5. The strains occurring during the first 90 min. are largely due to conventional secondary consolidation. (The lack of a clear demarcation between primary and secondary consolidation is due to the small pressure increment ratio.) The points representing the creep rates obtained from the slopes of the straight line portions are plotted on Fig. 4 (letter A). It will be seen that they fit the original data reasonably well. Beyond 90 min. the drainage tap was closed and the creep continued as an undrained process, with pore pressures developing. It is of significance that after about a day the axial strain curve began to steepen, and after about 10 days it had clearly developed a linear section with a much steeper slope. The creep rate represented by this slope is also plotted on Fig. 4 (letter B). It will be seen to conform more closely to the curve for creep rates following increase in *q*. It seems that the process of consolidation introduces a similar delay in the establishment of the linear relationship between axial strain and log time as was observed earlier in the discussion of the creep behaviour where an increment in *q* was preceded by extended creep under a lower value of *q*. This phenomenon may be related to the surprising fact that shear strain (= $\varepsilon_1 - 1/3v$) occurs during consolidation as a result of an increase in all-round pressure while *q* is maintained constant (Ref. 3).

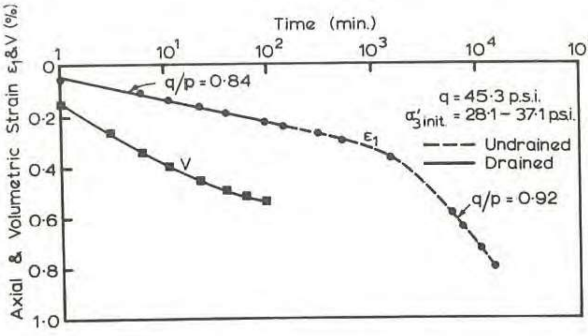

Fig. 5.- The change in rate of secondary consolition following consolidation with deviator stress maintained constant.

(b) The Effect of Loading Procedure on the Stress-Strain Properties

The results from the two-increment loading tests depicted in Fig. 2 are plotted in the form of stress ratio *q/p* against axial strain in Fig. 6. An arrow marks the end of the first increment in each case. Despite the large difference in the duration of the increments, the curves are very similar. The separation between them may, to some extent, reflect the difference in stress level in the two tests (Ref. 3). Also shown are the results of an incremental loading test with 2 sec. increment durations, and a constant rate of strain test with a rate of 0.016 per cent per min. These results also conform to the two curves to the extent that a unique stress-strain curve, which is essentially independent of loading procedure, may be said to exist for tests in which *q* is increased under undrained conditions provided the tests are commenced at the end of primary consolidation. Walker (Ref. 4) has already reported that the stress-strain curve from drained SSA tests is independent of increment duration.

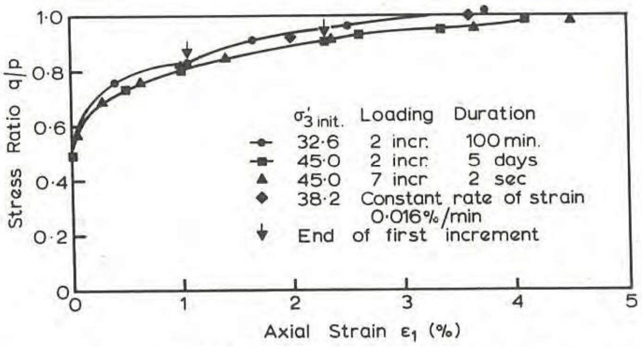

Fig. 6.- The effect of loading procedure on the stress-strain behaviour.

V.- MODEL FOR OBSERVED PROPERTIES

A possible model to account for the observed behaviour of the clay is illustrated in Fig. 7. It consists of spring-loaded oblique sliding contacts in parallel with each other and with a dashpot. At a given moment under a given stress, there are a certain number of 'activated' contacts while the remainder are 'lazy' contacts. The difference between the applied stress and the resistance mobilized in the activated contacts is equal to the stress in the dashpot, and this controls the rate of strain at the instant concerned. As strain proceeds, more of the 'lazy' contracts become activated to build up the resistance to strain. This is the strain hardening effect. At the same time, the stress carried by the dashpot is reduced so decreasing the rate of strain. This corresponds to the apparent increase in viscosity. Furthermore, the greater the total strain, the lower the residual stress in the dashpot, so that the initial rate of strain in a following increment is correspondingly reduced.

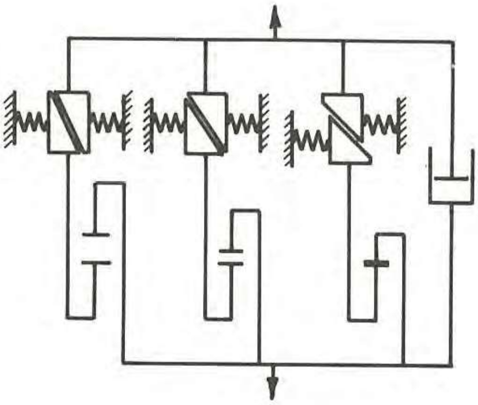

Fig. 7.- A rheological model to account for the observed stress-strain-time properties.

The spring-loaded oblique contacts represent the decrease in effective stress with increase in strain as a consequence of the increase in pore pressure. The rate of this decrease in effective stress must be more than offset by the rate at which the 'lazy' contacts are mobilized. However, the difference between them must decrease as the strain increases to account for the increase in creep rate with stress ratio. Ultimately, there are no further contacts to mobilize so that failure ensues. It is an interesting fact that the rate of strain at failure is extremely rapid, suggesting that the viscosity component represented by the dashpot is quite small.

Consolidation (with q = const.) increases the normal stress between contacts and restores the number of lazy contacts to the number appropriate to the particular stress ratio, and the shear behaviour may be repeated. If secondary consolidation is allowed, however, the strains and pore pressures are decreased at a given time in the following increment of deviator stress as if some of the lazy contacts had been mobilized during this process. There would appear to be an anomaly here.

It might be argued that there should be a spring in series with the above assembly to represent the immediate strain. However, this strain has been shown to be a function of previous strain and generally to be a small percentage of the total strain for all but the shortest duration increments. It would therefore seem to be better to incorporate this in the properties of the system as presented.

No doubt it is possible to represent the above model by a series of springs (probably non-linear) and dashpots, and this may be preferable from a mathematical viewpoint. The virtue of the present model is that the physical properties can be both easily portrayed and conceived.

VI.- CONCLUSION

The problem of determining the time behaviour of the vertical strains which result from the application of a shear stress to a clay seems to resolve itself into one of estimating the pore pressure as a function of time. From this knowledge, the effective stress-time relationship may be determined so that, by using the unique stress-strain curve, the strains can in turn be determined as a function of time. This problem is complicated by the fact that creep under previous stresses profoundly affects the time behaviour under current stresses.

Pore pressures are also a measure of the change in effective stress ratio which will occur when these pore pressures dissipate. It has already been shown (Ref. 3) that a unique relationship exists between change in stress ratio and volume strain during consolidation under constant q, and between volume strain and axial strain (with certain restrictions). Thus, the ultimate vertical strain arising from consolidation may be determined and from a knowledge of the coefficient of consolidation, the vertical strain-time behaviour may be estimated.

From the theoretical standpoint, prediction of the pore pressure behaviour may provide the key to the treatment of deviator stress and volume strain as uncoupled phenomena, and perhaps enable the handling of problems involving dilatant behaviour.

In the meantime, the problem of estimating the vertical strain-time behaviour in practical cases is complicated by the fact that pore pressures will be rising in some parts of the clay deposit as creep proceeds, while they will be dissipating in others as consolidation proceeds. The rates of strain associated with each process will in general be different. It is therefore important that tests simulate as closely as possible the conditions likely to prevail in the field.

VII.- ACKNOWLEDGEMENT

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