

DISCUSSION

D. J. HENKEL¹ AND V. A. SOWA²—
The authors have presented a very interesting paper on the complex problem of creep in clay soils. For the study of creep phenomena, a constant temperature environment is essential, and a neat method of achieving this was described. In addition, the effect of cyclic temperature changes on the pore water pressure of an undrained soil specimen was examined and the writers would like to comment on the effects of these temperature changes.

The problem of temperature and the effect on pore water pressure arose recently in connection with some experimental work on Weald clay. A large proportion of the experiments were of long duration, and consequently the effects of membrane leakage and temperature fluctuation were of importance. Several special tests were carried out to investigate these factors.

A remolded clay specimen was prepared, enclosed in a rubber membrane (nominally 0.01 in. thick) and set up in the triaxial apparatus in the manner described by the writers in their paper.³ The specimen was saturated and consolidated under a hydrostatic effective pressure of 30 psi. The drainage outlet was then closed, and the fluctuating pore water pressure caused by the variation in the ambient air temperature was observed. The result is illustrated in Fig. 8, where both the air temperature and

pore water pressure have been plotted against the time after closing the drainage outlet. In general the air temperature variation was accompanied by a similar change in pore pressure, the daily fluctuation being evident. More important, however, is that although the temperature returned several times to its value at the time of closing the drainage outlet, the pore water pressure did not. A gradual buildup of excess pore pressure was observed, and eventually, after approximately 170 hr, an excess of 4 psi had developed. Several other tests showed the same effect.

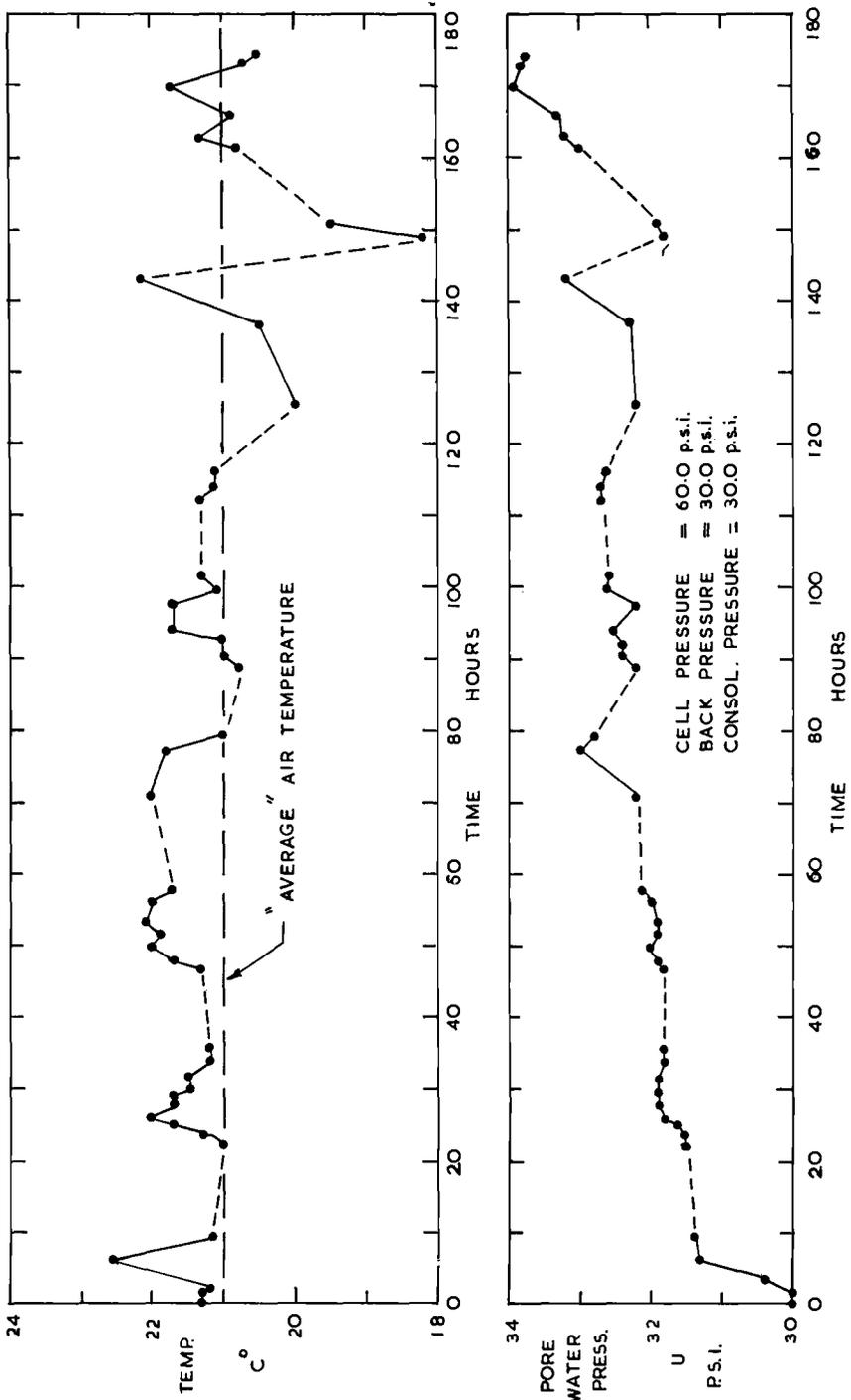
Possible reasons for the increase of pore pressure are membrane leakage, improper sealing at the ends of the specimen, and secondary consolidation. Examination of these factors did not lead to a satisfactory conclusion. Consequently two special tests were performed, one of which will be reported here.

A remolded specimen was prepared and set up in the triaxial apparatus, and then the entire triaxial cell was submerged in a water bath capable of maintaining a constant temperature. The specimen was saturated and consolidated to an effective stress of 100 psi at a temperature of 27 C. The drainage outlet was then closed, and the pore water pressure was observed for a period of five days. During this period the pore pressure increased only 0.2 psi, and for practical purposes this change can be neglected. Therefore the influence of membrane leakage and improper sealing of the specimen can be considered to be very small indeed.

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³ See p. 280.



TEMPERATURE AND PORE WATER PRESSURE VARIATION WITH TIME

Fig. 8—Temperature and Pore Water Pressure Variation with Time.

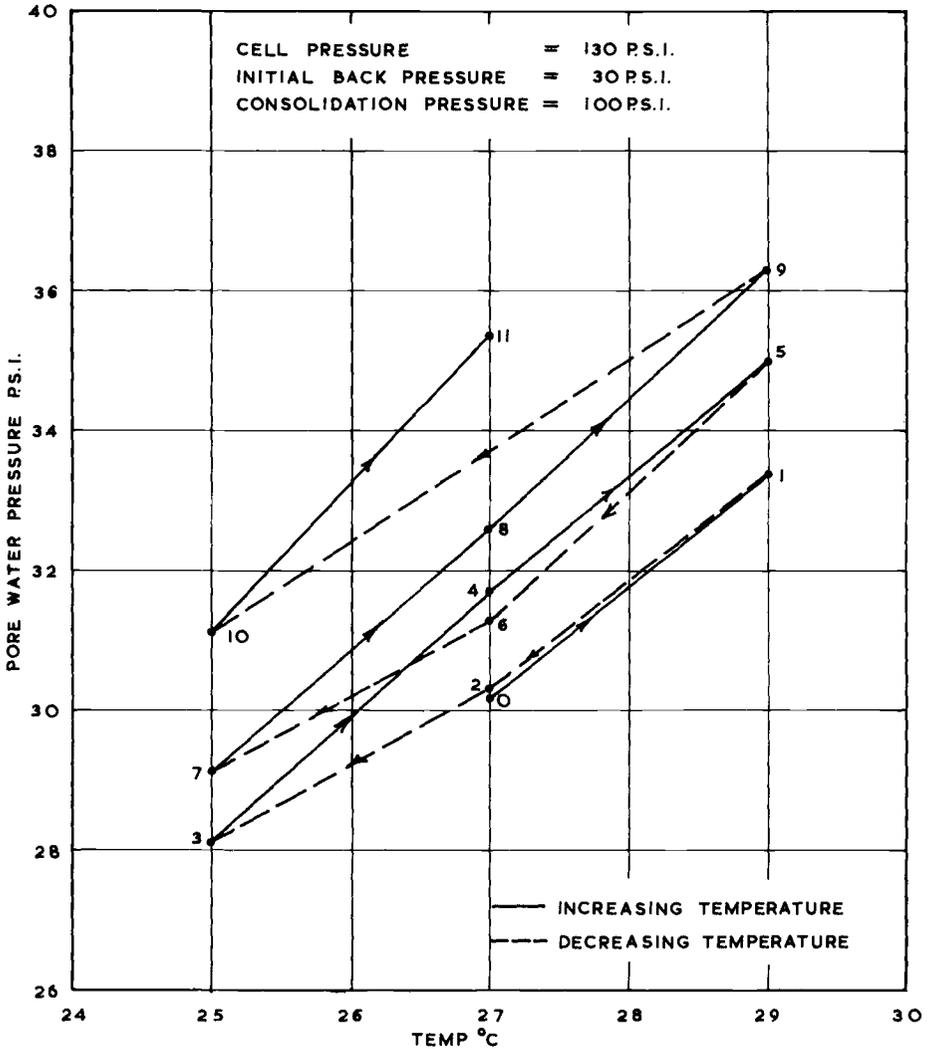


FIG. 9—Effect of Temperature on Pore Water Pressure Under Undrained Conditions and Hydrostatic Stress.

The temperature of the water bath was then varied ± 2 C. The change of pore pressure with time was observed, and normally a day was allowed between changes to ensure that the pore pressure came to equilibrium. The results are illustrated in Fig. 9, where the equilibrium pore water pressure for each increment is plotted against the corresponding temperature. The various

stages have been numbered consecutively, and the arrows show the direction of the changes. In general, the pore water pressure behaved similarly to that illustrated by the authors' data on saturated Kaolinite in Fig. 4 of their paper. However unlike the authors' results, the pore water pressure change did not form a closed hysteresis loop, but, instead, a residual pore water pressure was built up

in the Weald clay. This may be due to two reasons:

1. For the Weald clay, prepared in the manner described, the pore water pressure change for a fluctuating temperature does not form a closed hysteresis loop, but a genuine increase occurs.

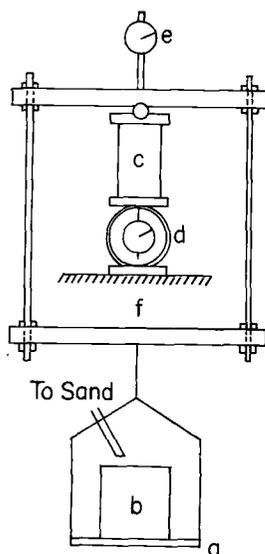
2. The gradual increase in pore water pressure is the result of the procedure and the particular apparatus used. It is difficult to understand why this should occur in the case described, but nevertheless this possibility cannot be excluded. Regardless of the reason, an actual pore pressure increase occurs, and it is essential to understand how this arises.

The results presented here for Weald clay illustrate that a gradual increase in pore water pressure can arise from fluctuating temperature. Consequently the determination of a steady pore water pressure over long periods can prove to be difficult. The temperature variation of ± 2 C was deliberately chosen as a typical variation that might be experienced in a laboratory. The three complete cycles of temperature change can be considered to represent the fluctuation occurring during a period of three days and nights.

The writers agree that for accurate and reliable measurements of pore pressure, particularly for saturated soil, a constant-temperature environment is essential.

ROBERT L. KONDNER⁴—The writer was very impressed with the care and attention to detail considered by Mitchell and Campanella in their study of the creep of saturated clays. A continuation of their work may well lead to important contributions to our knowledge of creep phenomena in cohesive soils. Because of certain aspects with regard to its possible use in theoretical

studies from a deformable mechanics viewpoint, the writer suggests that Mitchell report at least some of his future results in the form of a creep compliance function. To the writer's knowledge, the only creep tests on soil that have been presented in creep-compliance form are those from a limited study conducted by the writer in uniaxial compression.⁵



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|----------------------|--------------------|
| (a) loading platform | (d) proving ring |
| (b) sand container | (e) indicator dial |
| (c) soil specimen | (f) hanger system |

FIG. 10—Creep Apparatus.

Transient testing methods such as creep are particularly useful in the determination of the viscoelastic behavior of soft solids such as cohesive soils in the region of the large time phase of the response spectrum. In general, such transient techniques have the advantage of relatively simple apparatus and experimental procedure.

To study the creep response of a ma-

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⁵ R. L. Kondner, "A Non-dimensional Approach to the Vibratory Cutting Compaction, and Penetration of Soils," *Technical Report No. 8*, Dept. of Mechanics, The John Hopkins University, August, 1960.

terial, a stress is instantaneously applied to the specimen and maintained constant while strain is measured as a function of time. The results may then be plotted in the form of the creep com-

variables under consideration (such as stress, strain, time, etc.) or in terms of parameters which are directly defined from them rather than artificial or indirect parameters. Creep compliance is

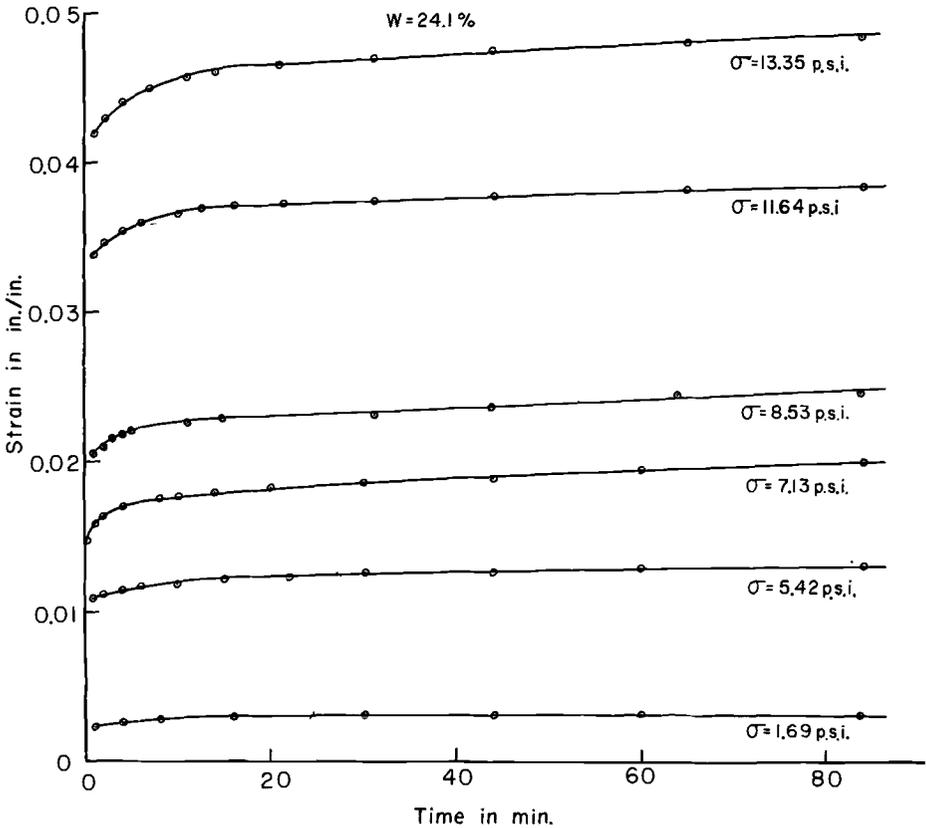


FIG. 11—Strain as a Function of Time for Different Values of Applied Stress.

pliance, $J(t)$, as a function of time. The creep compliance is expressed as:

$$J(t) = \frac{\epsilon(t)}{\sigma_0}$$

where:

$\epsilon(t)$ = strain at time t , and

σ_0 = level of constant stress.

In studying material behavior using creep methods, it is important to express the results in terms of the fundamental

directly defined in terms of the fundamental variables.

A material exhibiting a linear response will have a unique relation between creep compliance and time which is independent of the magnitude of the applied stress. There are many materials which behave linearly for a limited range of stress, that is, for small strains.

Since the compression test is so widely used for obtaining the strength charac-

teristics of soil, this form of test was used to study the creep characteristics of the clay considered by the writer. Although they will not be considered here, there are a number of interesting aspects of compression creep testing that should be considered when dealing with cohesive soils. These include variation of load with variation in cross-sectional area during deformation, the problem of non-homogeneity of deformation, selection of a gage length over which to determine

men through a hanger system. With the changes in cross-sectional area the stress is maintained constant by adding sand to the container. The correct amount of force added is indicated by a proving ring placed in series with the specimen. The deformation of the soil specimen was obtained with an indicator dial, knowing the deformation of the proving ring.

A typical set of creep curves is given in Fig. 11. The strain is plotted as a function of time for different values of

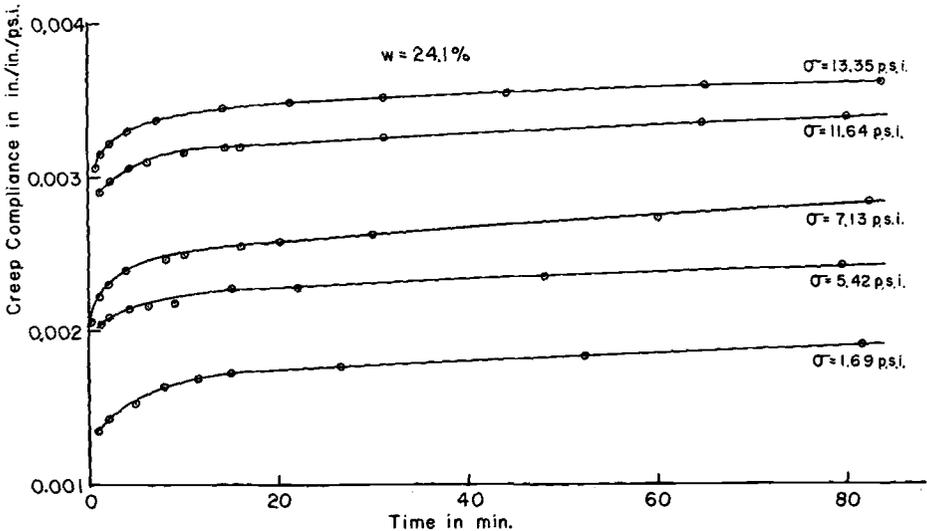


FIG. 12—Creep Compliance as a Function of Time.

strain, definition of the strain, protection of the soil specimen against loss or infiltration of water, and control of temperature.

The soil studied was a remolded plastic clay having a liquid limit of 42 per cent, a plastic limit of 21 per cent, and a specific gravity of 2.68. Test specimens were prepared using the modified AASHO compaction process. The specimens tested were cylindrical in shape, 3 in. long and 1.5 in. in diameter.

Figure 10 is a schematic diagram of the test apparatus. The load, in the form of dead weight, is applied to the speci-

men through a hanger system. With the changes in cross-sectional area the stress is maintained constant by adding sand to the container. The correct amount of force added is indicated by a proving ring placed in series with the specimen. The deformation of the soil specimen was obtained with an indicator dial, knowing the deformation of the proving ring.

Utilizing creep response, the test for linearity with regard to applied stress is to plot the creep compliance as a function of time as shown in Fig. 12. Since there is not a unique relation between the creep compliance and time, $J(t)$ is a function of the applied stress, and the material response is definitely nonlinear even for small strains.

From a rheologic viewpoint, each different moisture content of the same clay

is essentially a different material. Tests were conducted for moisture contents ranging from slightly below to slightly above the plastic limit of the clay. For each moisture content, the creep compliance was a function of the applied stress and hence nonlinear. It is interesting to note that although $J(t)$ was found to be nonlinear with regard to each moisture content (essentially concentration) it was found to vary in a straight-line manner with regard to changes in the shear strength of the soil as expressed in the form of the maximum unconfined compressive strength.

Thus, the problem remains, as it probably does for other cohesive soils, to determine the relationship between creep compliance and stress level as a function of the various soil parameters and environmental conditions which influence material behavior. It would be quite helpful to other researchers if future test results obtained by Mitchell could be presented in terms of creep compliance and the effects of stress level clarified.

JAMES K. MITCHELL AND RICHARD G. CAMPANELLA (*authors' closure*)—The authors are grateful for the additional data on the influence of temperature on pore water pressures presented by D. J. Henkel and V. A. Sowa, and on creep compliance presented by R. L. Kondner.

Henkel and Sowa's results serve to emphasize again the great importance that must be attached to temperature control during undrained testing of soils. Since

preparation of the original paper, the authors have made a rather extensive experimental study of the influence of temperature change on pore pressures developed in undrained specimens and volume changes developed in drained specimens. The results of these studies are being prepared for separate publication. It may be noted, however, that in some instances the authors have obtained results similar to those shown by Henkel and Sowa in Fig. 9. That is, successive cycles of temperature change have not always led to closed loops, such as shown in Fig. 4, but increasing pore pressures have developed at comparable points in successive cycles. Our studies have shown, however, that at least a portion of the observed pore-pressure increase in these tests has resulted from secondary compression effects.

Kondner suggests that the authors present their creep data in the form of creep compliance as a function of time. In materials which behave as linear visco-elastic solids the creep compliance is a useful parameter for mathematical expression of time-deformation behavior. The authors have found, however, that the clays used in their studies are not visco-elastically linear with respect to stress. Once nonlinearity had been established, detailed evaluation of creep compliance functions has provided little insight into creep mechanisms, which has been the primary objective of our studies.