

TESTS FOR SOIL CREEP

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The Iowa bore-hole shear apparatus, modified to monitor time deformational behavior in soils, produced both primary and tertiary creep curves from in situ tests on soils. Laboratory simple shear tests produced comparable results. An examination of the concept of yield stress led to the speculation that true yield stress is one that produced secondary or linear creep curves. The secondary creep curves are a transition between primary and tertiary behavior. The creep rate from the bore-hole creep test became so nearly linear that the pseudo-Bingham yield stress computed from these tests is close to the true yield stress.

•THE OBJECTIVE of this research was to develop an in situ technique using the bore-hole shear test (1) to determine creep strength or yield stress for soils.

The early portion of the study was devoted to field tests on 3 soils: a sandy clay loam and a silt loam derived from glacial till and a loess (2). In the second phase of the research a simple shear apparatus was used to determine whether creep behavior observed with the bore-hole shear test was similar to that observed in laboratory tests. The third phase led to examination of the meaning of yield stress and an attempt to interpret this concept with rate process theory as applied to soils. As now used, this theory implies that deformations are proceeding continuously at extremely slow rates and that soil will deform at the very lowest of stresses.

BORE-HOLE CREEP TEST

The concept of a direct shear test for soil performed in the walls of a bore hole was first described by Handy and Fox in 1967 (1). A cylindrical head is inserted into a bored and trimmed 3-in. diameter hole. The head consists of 2 opposing 2- by 3-in. circumferentially grooved plates that can be expanded to engage the soil in the bore-hole wall with a measured contact pressure. The head, shown in Figure 1, is pulled axially up the hole, thereby creating a shear failure along zones parallel to the walls of the bore hole. The expansion force divided by one plate area gives normal stress, and the pulling force divided by both plate areas gives shear stress on the failure surface. The forces causing expansion and shear are applied by hydraulic or gas-operated pistons. Repetitions of expansion and pull result in linear relations on a graph of shear stress versus normal stress. In this manner a Mohr-Coulomb total stress failure envelope is generated. The values of cohesion and internal friction of sand, silt, and clay determined from the bore-hole shear test are realistic when compared to drained laboratory-determined values (1).

The pulling mechanism consists of a cable, chain, or rod attached to a yoke or a clamp acting against a base plate. For creep tests, a strain dial measuring deflection to 10^{-4} in. was attached to the pulling yoke with the dial stem pushing against the tripod as shown in Figure 2. As the soil creeps, the yoke moves upward relative to the stationary tripod allowing a deformation measurement parallel to the shear plane. Monitoring of time permits a deflection versus time curve to be plotted. A steel cantilever, mounted in contact with the strain dial stem and instrumented with SR-4 strain gauges connected to a battery-powered strain recorder, was used in some experiments. The

arrangement gave a direct plot of deflection versus time but allowed deflection measurements to only 10^{-3} in.

For all creep tests, both normal and shear stresses were held constant by using pressure regulators and CO_2 gas in the piston systems. The gauges and regulators hold stresses virtually constant and were adjustable to within about 0.4 psi. The tests consisted of measuring the deflection rate at constant normal and shear pressures.

The approach in the creep study was to apply constant normal and shearing stresses and monitor the time-deformation behavior of the soil as it crept at stresses below the shear strength. More than 100 creep tests, lasting from 25 min to 14 hours, were performed.

The field moisture contents of the soils in this study ranged from 30 to 50 percent saturation; because of this and the long duration of the test, the role of pore pressure was considered negligible. The 2 soils tested are on an observably creeping slope on glacial till. The textures were sandy clay loam and silt loam with dry densities of 71 and 68 lb/ft³ respectively.

Figure 3 shows time-deformation curves resulting from bore-hole creep tests. On this and all subsequent figures, σ_n is the normal stress, τ is the shear stress, and w is the moisture content. During the first few minutes, deformation increases rapidly, but as time passes the deformation continues at a decreasing rate and becomes nearly linear to produce primary and secondary creep curves. This general type of curve has been obtained from various laboratory tests (3, 4). If the shear stress is applied at a level close to the shear strength, an inflection point is reached and is followed by an accelerated deformation rate to produce a tertiary creep curve. Some authors have found that the creep rate becomes essentially constant after a certain time giving a linear relation between shear stress and creep rate. They conclude that, for large values of time, the creep behavior of soils corresponds to the rheological model known as the Bingham body (5-8). This model contains a yield stress or minimum shear stress below which the soil will not exhibit viscous behavior. The reciprocal of the slope of the Bingham line is the differential or plastic viscosity.

Even though the bore-hole creep tests shown in Figure 3 do not become perfectly linear, at any time after 20 min a linear relation exists between creep rate and shear stress. That is, creep rates were measured on the time-deformation curves at various times between 10 and 50 min, and the creep rate of each time was correlated with shear stress by using least squares fit. Table 1 gives the results of these correlations for several normal stresses and moisture contents. Yield stresses are determined by extrapolating the line to 0 creep rate. For a time greater than 20 min, the yield stress is constant within ± 0.1 psi and independent of time at which the slopes of the time-deformation curves were measured. A representative graph of these results is shown in Figure 4. Tests at stresses below the yield stress produced time-deformation curves that became horizontal after the initial deformation. Since the thickness of the shear zone is unknown, the shear deformation measurements are not strains and the reciprocal slope of the line is a pseudo-differential viscosity that increases as the test duration increases.

In general, the variations in creep rates obtained under identical test conditions are less than 15 percent. This variation appears reasonable when compared with laboratory experiments in which soil samples can be more rigidly controlled. Saito and Uezawa (9) have noted that, even with the same samples and loading conditions, creep rupture curves do not always coincide.

Variables Affecting Creep Behavior

We attempted to hold moisture content constant by completing as many tests as possible on the same soil in the shortest possible time. However, because of seasonal climatic variations, the field moisture content varied from 14.8 to 22.5 percent. It was found that, for a given stress, greater moisture contents resulted in greater deformations; and that finding agrees with those of Sherif (10).

However, for the limited range of moisture contents studied, there was no significant influence of moisture content on yield stress, as evidenced by the lack of a consistent trend and a variation of less than 10 percent.

Figure 1. Bore-hole shear device.

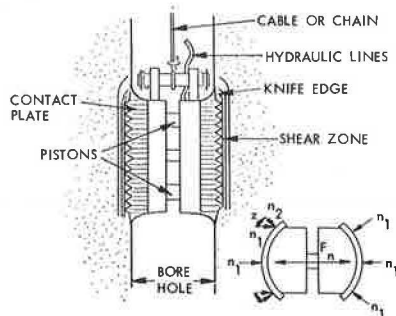


Figure 3. Deformation versus time behavior for different shear stresses.

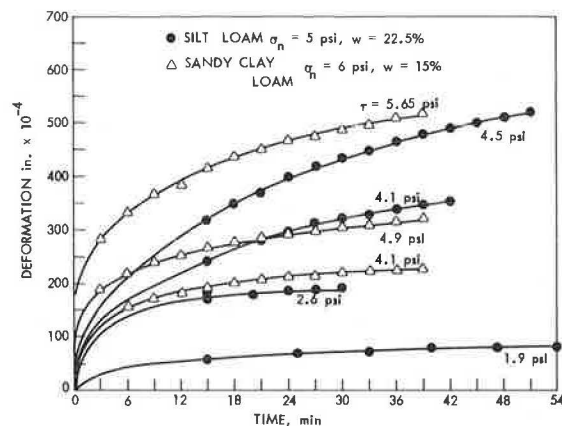


Table 1. Yield stress independence of time.

Type of Soil	Moisture Content (percent)	Normal Stress (psi)	Time (min)	Yield Stress (psi)	Apparent Viscosity Coefficient (lb-min/in. ³)
Sandy clay loam	20.4	5	10	3.50	0.07
			20	3.10	0.15
			30	3.20	0.22
			40	3.10	0.32
			50	2.90	0.47
Sandy clay loam	18.2	5	10	3.45	0.14
			20	3.05	0.39
			30	3.10	0.70
			36	2.90	0.94
			42	3.30	1.08
			48	3.00	1.13
Sandy clay loam	15.5	7	52	3.10	1.14
			20	4.56	1.74
			25	4.67	2.20
			30	4.62	1.98
			30	4.62	1.98
Sandy clay loam	17.5	8	15	5.19	0.30
			20	5.38	0.35
			25	5.30	0.44
			30	5.21	0.51
			35	5.22	0.55
			40	5.47	0.55
Silt loam	16.4	7	20	3.35	0.42
			30	3.44	0.56
Silt loam	17.8	7	25	3.39	0.79
			30	3.37	1.02
			40	3.16	1.21

Figure 2. Pulling tripod and dial strain gauge.

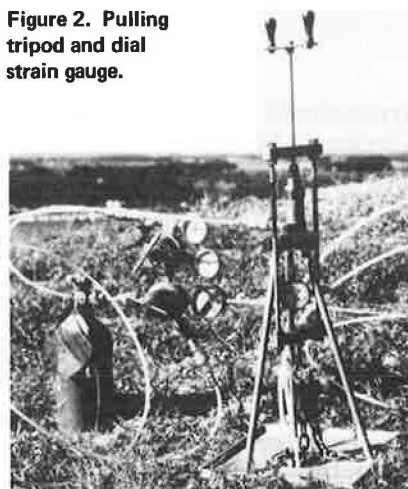
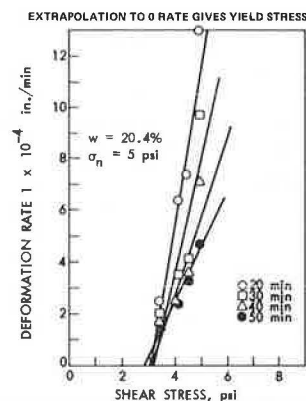


Figure 4. Slope of deformation versus time for sandy clay loam.



The amount of consolidation time preceding application of shear stress was found to affect the creep behavior of the soil. In general, the deformation rate decreased as consolidation time increased. Creep tests with a consolidation time of 5 min exhibited a deformation rate 2.5 times greater than rates obtained for 20 min. However, a ratio of 1.14 was obtained when a consolidation time of 20 min was compared to one of 40 min, which is within the limits of error for nearly identical tests and is evidence that varying consolidation times in excess of 20 min do not significantly influence creep rates. The early, curved portion of the curves shown in Figure 3 probably reflect the effect of consolidation due to the increase in principal stresses following application of a shearing stress.

Creep Envelope

Tests were repeated at various normal stresses to obtain yield stresses given in Table 1. In general, the yield stress increases as a linear function of normal stress.

The linear relations between yield stress and normal stress may be thought of as a creep envelope analogous to the Mohr-Coulomb envelope shown in Figures 5 and 6. The shear strength envelope as determined with the bore-hole shear device is shown in the same figures. The least squares fit resulted in creep envelope intercepts of -0.22 and +0.35 psi on the shear stress axis or about 0 within the limits of experimental error. From these results, it is concluded that the creep envelope has essentially the same friction angle as the Mohr-Coulomb envelope and that cohesion is reduced to 0.

Several workers have commented on strength envelopes that result from soil creep. Haefeli (8) concluded that the effect of creep removes the cohesion and results in "residual shear strength" depending mostly on friction. Skempton (11) used a similar approach to arrive at a strength envelope in which cohesion is 0 and the internal friction angle is slightly reduced. Ter-Stepanian (6) hypothesized a creep envelope that passes through the intrinsic pressure intercept of the Mohr-Coulomb envelope, and, although the internal friction angle and cohesion were thereby reduced, some cohesion still contributed to the creep strength. Sherif and Wu (12) concluded that the creep limit and residual strength of soils in general are equal. The results of the bore-hole creep test agree with the conclusions of Skempton and Haefeli; i.e., cohesion is time-dependent, but internal friction remains essentially constant. It should be emphasized that tests in this phase of the study involved low-density, actively creeping soils.

COMPARATIVE LABORATORY TESTS

Tests on Loam Soils

Laboratory tests with a Geonor simple shear apparatus were performed to ascertain whether the observed creep behavior was the result of the peculiarities of the bore-hole shear creep test rather than of the true time-deformation characteristics of the soil.

The simple shear machine was selected for the laboratory phase of the investigation because of its simple operation when compared with triaxial apparatus. It also allows shearing strain measurements that are impossible with a direct shear machine. This direct application of shear stress is similar to the stresses applied in the bore-hole shear test, whereas triaxial shear results from compressive stresses.

A direct comparison of the bore-hole test and laboratory tests was attempted by collecting undisturbed samples of the same sandy clay loam and silt loam that were tested with the bore-hole device. These 2 soils are very friable, and, when extruded from thin-walled tubes, only 20 of the 35 samples collected were suitable for testing. The moisture contents of the laboratory samples ranged from 7.8 to 22.7 percent as compared with 14.8 to 22.5 percent for the moisture range of the bore-hole tests.

Each test was conducted on a separate sample about 2.2 cm thick at constant normal and shear stress. The time-deformation curves on these samples exhibit the same primary creep curves obtained from the bore-hole creep test; i.e., the curves show a large initial deformation followed by continuous creep at a decreasing rate. However, when deformation rates at a given time are compared at different stress levels and moisture contents, the results are somewhat erratic.

From the bore-hole data, for the range of moisture contents studied, the moisture content did not appear to affect yield stress; however, increasing moisture contents produced faster creep rates. Higher moisture contents in the laboratory tests at the same stress level resulted in both faster and slower creep rates. Often an increased shear stress resulted in slower creep rates.

There were only 2 or 3 samples at nearly constant moisture contents. In 2 of these cases the linear relation between deformation rate and shear stress was assumed, and a yield stress was extrapolated from only 2 points. These points gave yield stresses of about 2 psi for a normal stress of 3.5 psi, which fit the creep envelope determined from the bore-hole creep tests on those soils.

The presence of roots, pebbles, and unusually large cavities probably caused the erratic results of the laboratory tests. Because of the difficulty in handling the laboratory samples, the wide range of moisture contents, and the erratic results caused by pebbles and cavities, no further tests on the till-derived soils from the bore-hole test sites were attempted.

It has been inferred that in the bore-hole test the shear plane moves outward with each increase in normal stress (1). In the creep test, normal stress is held constant while the shearing stress is increased from levels causing no deformation up through the yield stress to stresses where shear failure occurs. In the bore-hole creep test, where several shearing stresses are applied at the same normal stress, it is questionable that the shear planes move outward with an increase in shear stress. Therefore, the bore-hole creep test may be more like laboratory tests in which a single sample is subjected to a shearing stress until the time-deformation curve equilibrates; then the stress is increased until a new time-deformation curve is established and another shear stress is applied. In this way the same sample is subjected to several different shearing stresses, and a step type of creep curve is produced. The alternative approach is to use a separate sample for each stress level as was done with the sandy clay loam and the silt loam. The soil behavior under these different types of stress applications was explored in "step types" of tests that were also run with the simple shear machine.

Tests on Undisturbed Loess

This second set of tests used undisturbed loess samples that classify as CL with liquid limits averaging 35 and plasticity indexes averaging 23. The in situ wet densities ranged from 92 to 105 pcf. The moisture ranged from 27 to 30 percent. The strength envelopes from bore-hole shear and bore-hole creep tests are shown in Figure 7.

Figure 8 shows 3 sets of step creep curves from simple shear tests. Creep rate, measured about 20 min after each load application, versus shearing stress is shown for the same tests in Figure 9. The tests give a good linear relation between shear stress and creep rate; however, the yield stress appears to be a function of the initial stress applied in each series.

The yield stresses from simple shear tests are also shown in Figure 7. Although the yield stress from test 23 falls on the creep envelope from the bore-hole test, the results of the other tests in which the initial stresses were higher gave yield stresses closer to the Mohr-Coulomb strength than to the creep strength. In general, the yield stress increases as the initial stress increases. Therefore, starting a creep test at higher shearing stresses has the effect of strengthening the soil. When attempts are made to evaluate a yield stress from the bore-hole test, the shear head would be repositioned in the bore hole between successive applications of shear stress so that a soil mass that has not been subjected to previous shear stress will be evaluated.

Tests on Remolded Loess

A series of simple shear creep tests was conducted on loess remolded to field density and moisture content (Figs. 10 and 11). These tests supported the conclusions of the tests on the undisturbed samples since higher initial shear stress resulted in higher yield stress. It was also shown that the linear relation between shear stress and strain rate is not the best to describe the behavior of this material. The pseudo-Bingham behavior observed in both bore-hole and simple shear tests is probably a

Figure 5. Failure envelopes for silt loam.

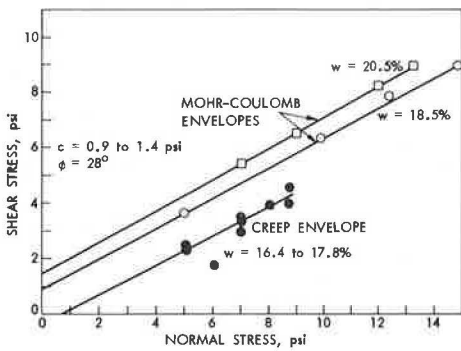


Figure 6. Failure envelopes for sandy clay loam.

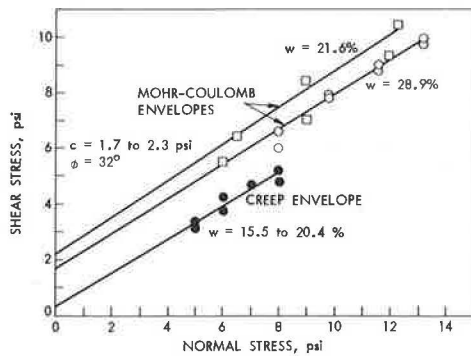


Figure 7. Mohr-Coulomb and creep envelopes from bore-hole data on loess.

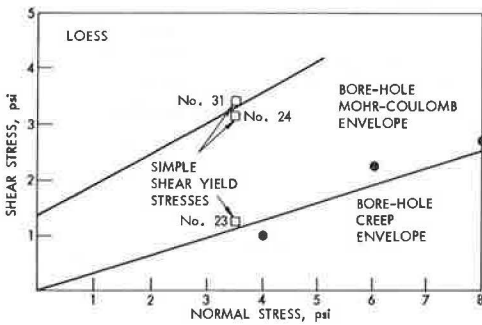


Figure 8. Creep curves from simple shear tests on undisturbed loess.

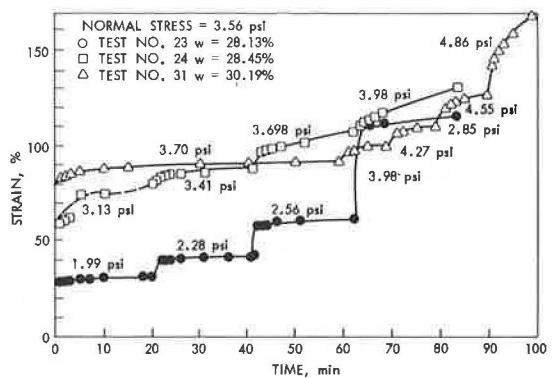
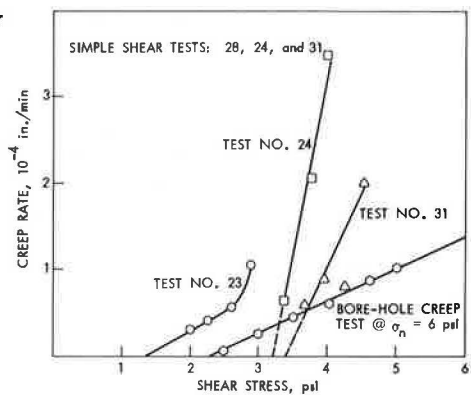


Figure 9. Shear stress versus creep rate for simple shear and bore-hole tests on undisturbed loess.



linear approximation of a relation that is better described by an exponential equation. This behavior of soils has been observed by many researchers, and a theoretical basis exists for these observations in rate process theory (13, 14, 15). This relation further suggests that a yield stress does not exist.

Laboratory tests have shown that stress history and the remolding effects during a single shear application change the structure and therefore the time-deformation characteristics of soil (22). Since the soil structure is constantly changed by application of the stresses, it appears more study is needed to evaluate how the soil structure is altered by the stresses.

The other conclusion is that within the stress range at which the soils exhibit primary or terminal creep behavior there is no true yield stress and that the behavior of these soils might best be approached through rate process theory.

SPECULATIONS ON YIELD STRESS

The time-deformation curves obtained from creep tests are generally divided into primary, secondary, and tertiary creep regions, where the strain rates either decrease with time, remain constant, or accelerate with time respectively. All of these regions, however, do not appear in every test. Some, for example, may only show decelerating primary creep behavior terminating at some strain (terminal creep). Figure 12 shows 3 types of curves commonly obtained in laboratory tests: primary, secondary, and tertiary creep behaviors. All 3 types of curves may be exhibited by a soil if a series of tests is conducted in which the stress level is increased from one successive sample to the next or if one sample is subjected to incrementally increasing stresses. At very low stresses the curves are of the terminal type and show only primary creep; as the stress level approaches the conventionally determined strength, the curves show tertiary creep. Although some authors have stated that the steady-state curves are characteristics of soils (8, 16), others note curves of the primary type (3, 4, 17, 18).

This study revealed that a bore-hole shear device can be used to generate primary and tertiary creep curves. However, the analyses applied to the bore-hole data emphasized steady-state and primary creep curves since the tertiary curves were observed to occur over a very narrow range of stresses close to the shear strength. The results of these analyses led to the conclusion that the creep behavior of the soils is similar to the rheological model known as the Bingham body. The yield stress that has resulted from this analysis can be called "pseudo-Bingham" yield stress.

An alternative means of analysis is the use of rate process theory. Although this approach has a theoretical basis, there are many aspects of the theory that need verification or modification. Further, there has been no suggestion for a practical application of this theory.

Noble and Demirel (19) applied rate process theory to the study of creep behavior but expanded the theoretical equation to account for soil structure. An important difference from previous work is their thesis that the inflection point on tertiary creep curves represents a unique, critical structure that is the same from one stress level to the next. Earlier Schmid (20), recognizing that structure is continually changing during the deformational history, suggested that the inflection point on the time-strain curve was the point in time at which a critical structure is attained; but he did not expand on that idea.

Our interpretation of the relation among the different types of curves is as follows. At stress levels where only primary curves are produced the critical structure is never reached, and stress has only the beneficial effect of strengthening the soil as it deforms. At stress levels that produce tertiary curves, failure will occur some time after initial application of the stress; larger stresses will produce failures in shorter times. The steady-state or secondary curves can be thought of as ones where the critical structure is reached and the deformation continues at a constant rate, neither accelerating nor decelerating. The stress that produces the steady-state curve is a true yield stress below which failure will not occur. A similar definition of yield stress has been suggested by Sherif and Wu (12) but without the rationale provided here.

Figure 13 shows a graph using data from Noble and Demirel's direct shear tests of deformation rate versus shear stress where the deformation rate is measured at the

Figure 10. Shear stress versus strain rate for remolded loess (applied stress is expressed as a percentage of shearing strength).

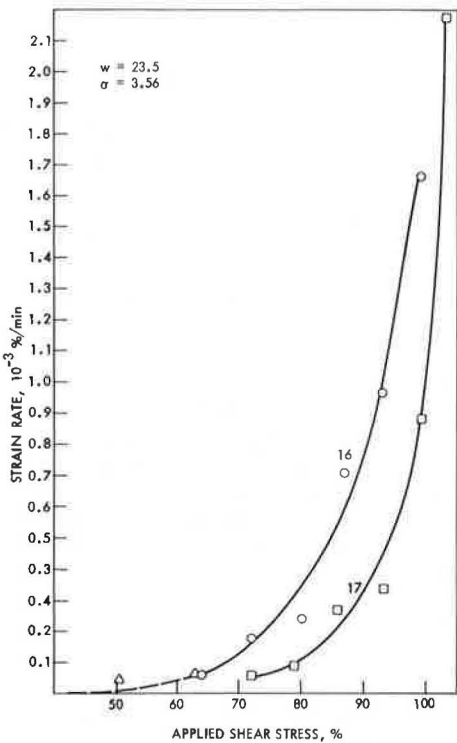


Figure 11. Shear stress-strain rate data for remolded loess plotted on semilog paper (applied shear stress is expressed as a percentage of shearing strength).

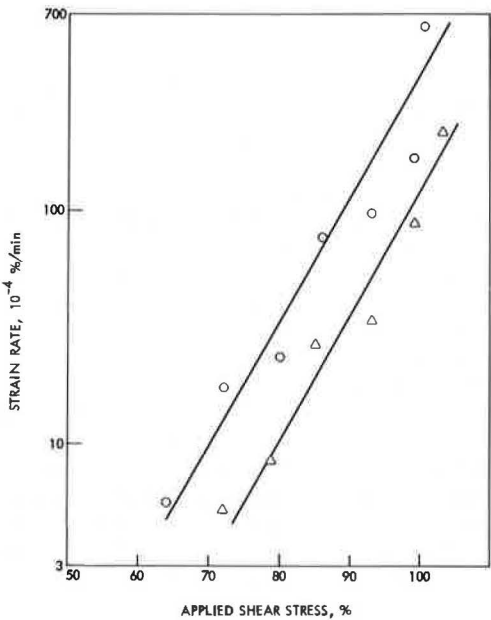


Figure 12. Primary, secondary, and tertiary creep behavior.

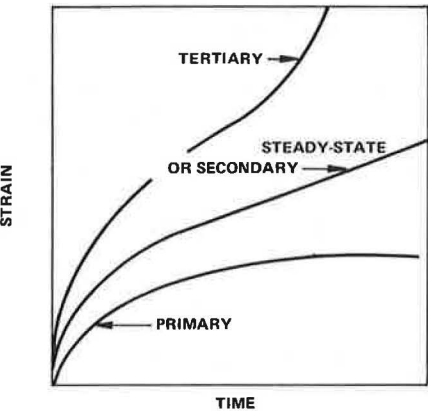
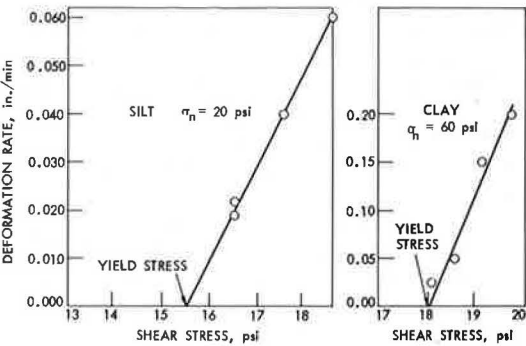


Figure 13. Deformation rate measured at the inflection point.



inflection point. As can be seen, this approach also produces a linear relation with a yield stress at 0 deformation rate. The concept of using the strain rate as measured at the inflection point or point of critical structure is intuitively more pleasing than making measurements on the primary curves at some arbitrary time after starting the test.

This interpretation leads to the conclusion that, if the steady-state or tertiary creep curves are not obtained at stresses appreciably below the shear strength as defined by the Mohr-Coulomb envelope, then shear strength and yield strength are essentially the same. However, if the tertiary curves occur over a wide range of stresses below the Mohr-Coulomb strength, the yield stress will be the one that produces a secondary creep curve that is the transition between primary and tertiary creep. This yield stress may be appreciably below the Mohr-Coulomb strength. Since all field and laboratory tests of this project produced the tertiary curves only at or near the Mohr-Coulomb strengths, a series of tests was conducted on remolded loess samples at various moisture contents up to 30 percent tertiary creep curves. None was successful. It may then be concluded that loess, at field density, does not have a yield strength below the shear strength.

It was noted that the bore-hole creep tests on the 2 loam soils became nearly linear after 20 min. Perhaps those soils do exhibit creep behavior, and the curves observed were very close to secondary creep curves; thus, the critical structure was attained, and the pseudo-Bingham yield stress is in fact close to the yield stress of this latest interpretation. It appears that empirical creep curves can be produced by the bore-hole shear device, and that leads to 2 possible analyses of data. However, we feel that selection of the proper method of analysis for the field test can be made only after a fundamental study on pure clay systems under controlled laboratory conditions.

CONCLUSIONS

This study has led to the following conclusions:

1. The bore-hole shear test device can be used on soils in the field to produce primary types of creep curves that become nearly linear about 20 min after application of a constant shear stress;
2. A graph of creep rate versus shear stress produces a curve with an apparently linear segment that can be extrapolated to 0 creep rate (the intercept is then referred to as pseudo-Bingham yield stress);
3. The pseudo-Bingham yield stress, when plotted as a function of normal stress, results in a linear relation called a creep envelope that goes through the origin and is essentially parallel to the Mohr-Coulomb envelope;
4. Laboratory tests with a simple shear machine on soil samples from field test sites produced primary creep curves similar to the bore-hole curves within the same range of shear stresses;
5. Pseudo-Bingham yield stresses from bore-hole and simple shear tests are comparable;
6. It is inferred that in the bore-hole creep test the same shear zone within the soil is subjected to a series of successively higher shear stress and the yield stress increases with a higher initial stress in sequence (to avoid effects of stress history, one should reposition the bore-hole shear head between each application of shear stress so that fresh soil is tested);
7. Soils that exhibit only primary creep up to shear stresses approximating Mohr-Coulomb shear strength do not have a true yield stress;
8. True yield stress is the stress that produces a secondary or linear creep curve and can be found by extrapolating the relation between creep rate measured at the inflection point of tertiary creep curves and shear stress back to the 0 creep rate line;
9. The creep rate from the bore-hole creep tests on the 2 loam soils becomes so nearly linear that the pseudo-Bingham yield stress is close to a true yield stress; and
10. Before more field work is attempted on bore-hole creep tests, controlled laboratory creep experiments should be run to verify the existence of yield stress and to establish a practical application of rate process theory (this work should verify, modify, or reject the conclusions given immediately above).

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REFERENCES

1. Handy, R. L., and Fox, N. W. A Soil Bore-Hole Direct-Shear Test Device. Highway Research News, No. 27, 1967, pp. 42-51.
2. Millan, A. Field Test for Measuring Creep Susceptibility of Soils. Iowa State Univ., Ames, MS thesis, 1969.
3. Tan, T. K. Discussion. Proc. Fifth Internat. Conf. on Soil Mech. and Found. Eng., Paris, Vol. 3, 1961, pp. 141-142.
4. Kondner, R. L., and Krizek, R. J. Correlation of Creep and Dynamic Response of a Cohesive Soil. In Rheology and Soil Mechanics: Symposium of the International Union of Theoretical and Applied Mechanics (Kraytchenko, J., and Sirieys, P. M., eds.), Springer-Verlag, Berlin, 1966, pp. 33-41.
5. Vialov, S. S., and Skibitsky, A. M. Problems of the Rheology of Soils. Proc. Fifth Internat. Conf. on Soil Mech. and Found. Eng., Paris, Vol. 1, 1961, pp. 387-390.
6. Ter-Stepanian, G. On the Long-Term Stability of Slopes. Norwegian Geotechnical Institute, Pub. 52, 1963.
7. Finn, W. D. L. Earthquake Stability of Cohesive Slopes. Jour. Soil Mech. and Found. Div., Proc. ASCE, Vol. 90, 1966, pp. 29-61.
8. Haefeli, R. Creep and Progressive Failure in Snow, Soil, Rock, and Ice. Proc. Sixth Internat. Conf. on Soil Mech. and Found. Eng., Vol. 3, 1965, pp. 134-147.
9. Saito, M., and Uezawa, H. Failure of Soil Due to Creep. Proc. Fifth Internat. Conf. on Soil Mech. and Found. Eng., Paris, Vol. 1, 1961, pp. 315-318.
10. Sherif, M. A. Deformation and Flow Properties of Clay Soils From The Viewpoint of Modern Material Sciences. Highway Research Record 119, 1966, pp. 24-49.
11. Skempton, A. W. Long-Term Stability of Clay Slopes. Geotechnique, Vol. 14, 1964, p. 77.
12. Sherif, M. A., and Wu, M. J. Creep Limit and Residual Strength Relationship. College of Eng., Univ. of Washington, Seattle, Soil Eng. Rept. 5, 1969.
13. Murayama, S., and Shibata, T. On the Rheological Characters of Clay—Part I. Disaster Prevention Research Institute, Kyoto Univ. of Japan, Bull. 26, 1958, pp. 1-43.
14. Singh, A., and Mitchell J. General Stress-Strain-Time Functions for Soils. Proc. ASCE, Vol. 94, No. SM1, 1968, pp. 21-46.
15. Andersland, O. B., and Douglas, A. G. Soil Deformation Rates and Activation Energies. Geotechnique, Vol. 20, 1970, pp. 1-16.
16. Christensen, R. W., and Wu, T. H. Analysis of Clay Deformation as a Rate Process. Jour. Soil Mech. and Found. Div., Proc. ASCE, Vol. 90, No. SM6, 1964, pp. 125-153.
17. Goldstein, M., Ladipus, L., and Misumsky, V. Rheological Investigations of Clays and Slope Stability. Proc. Sixth Internat. Conf. on Soil Mech. and Found. Eng., Vol. 2, 1965, pp. 482-485.
18. Mitchell, J. D. Shearing Resistance of Soils as a Rate Process. Jour. Soil Mech. and Found. Div., Proc. ASCE, Vol. 90, 1964, pp. 29-61.
19. Noble, C. A., and Demirel, T. Effect of Temperature on Strength Behavior of Cohesive Soil. HRB Spec. Rept. 103, 1969, pp. 204-219.
20. Schmid, W. A Rheological Failure Theory for Clay Soils. ONR Progress Report, Proj. NR-981-177, 1960.