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SUMMARY

The creep rupture characteristics of a saturated, natural marine clay have been studied under axially symmetric stress conditions. The clay was consolidated under conditions of one-dimensional strain prior to creep loading. Linear relationships were noted between log minimum creep rate and log rupture life, and also between log current creep rate and log remaining time to rupture in the tertiary creep stage. In terms of effective stresses, the Mohr failure envelope from conventional constant strain rate shear tests was found to define uniquely the instant of creep rupture. Results also showed that the effective stress condition corresponding to the minimum strain rate may be used as a failure criterion if creep rupture is to be averted. For a given consolidation history, the stress was found to be uniquely related to the current strain and strain rate.

INTRODUCTION

Clay soils undergo time dependent creep deformations when subjected to a constant shear stress. At relatively low stress levels this deformation or creep rate may eventually reduce to an imperceptible value. At higher stress levels, however, the initially decreasing creep rate may suddenly start to accelerate and finally lead to creep rupture. Stress levels at which undisturbed saturated clays undergo creep rupture are often considerably less than the strength of the clay determined from normal strength tests. While the creep behaviour of saturated clays at subfailure stress levels has been studied at length, corresponding studies at creep rupture stresses have been extremely limited. The need to study creep rupture is amply demonstrated by the number of foundation failures which have been attributed to excessive long term movements[1-5]. Some techniques have been proposed in dealing with creep rupture of soils[6-11] which generally follow those developed for metals. However, the usual data to formulate these techniques have been obtained from conventional triaxial or unconfined compression tests. In both these tests the consolidation stresses were hydrostatic prior to creep loading. Most natural clay deposits, on the other hand, have been deposited under the condition of one-dimensional strain (K_o-consolidation) and not under hydrostatic stress; thus, actual creep behaviour should be correlated only with laboratory tests on samples which have been similarly consolidated. All of the data presented herein was obtained for samples which were initially consolidated under one-dimensional strain conditions.

The investigations reported herein are concerned with undrained (constant volume) triaxial creep rupture of a normally consolidated, undisturbed, sensitive, marine clay. The clay (locally called Haney clay) had a liquid limit = 44%, plastic limit = 26% and a sensitivity from 6 to 10. All the samples were K_o-consolidated to a vertical effective stress σ'_{1c} of approximately 5.25 kg/cm^2 and then subjected to various levels of constant creep stress. In some of the tests the creep stress was applied by 'instantaneously' decreasing the lateral confining pressure while maintaining the axial stress constant, instead of the usual way by increasing the axial stress while keeping the lateral pressure constant. The test program was carried out in a constant temperature environment in order to eliminate the influence of temperature as a variable. The special triaxial testing apparatus used has been described elsewhere[12].

TEST RESULTS

Strain rate-time relationships.

Fig. 1 shows the creep rate (axial strain rate) versus time behaviour at different levels of creep stress. The magnitude of creep stress, which has been expressed as the principal stress difference normalized with respect to the vertical effective stress during consolidation, $q=(\sigma_1-\sigma_3)/\sigma'_{1c}$, is indicated on the individual curves. Except for the general absence of a period of constant secondary creep rate, the results shown are similar to those observed for most engineering materials including plastics, frozen soils and metals at elevated temperatures. The two modes of creep loading, i.e., increase in axial stress and decrease in radial stress, appear identical, as the results from both these types of tests are similar and form a consistent set of creep curves. Such a behaviour is analogous to the observed invariance in the undrained stress-strain response of saturated clays to variations in total applied stresses[13,14].

The results in Fig. 1 suggest that the onset of an accelerating creep rate in these constant stress creep tests indicates impending failure, since as long as the creep rate is increasing, failure is inevitable. However, sufficient warning concerning rupture was usually present, since regardless of the creep stress level, the elapsed time until rupture (rupture life) was always 3 to 4 times the elapsed time up to the point when the creep rate started accelerating.

The rupture life, t_f, for each stress level has been plotted against the corresponding minimum creep rate, $\dot{\varepsilon}_{min}$, on a log-log scale in Fig. 2. A straight line relation with very little scatter is noted between log rupture life and log

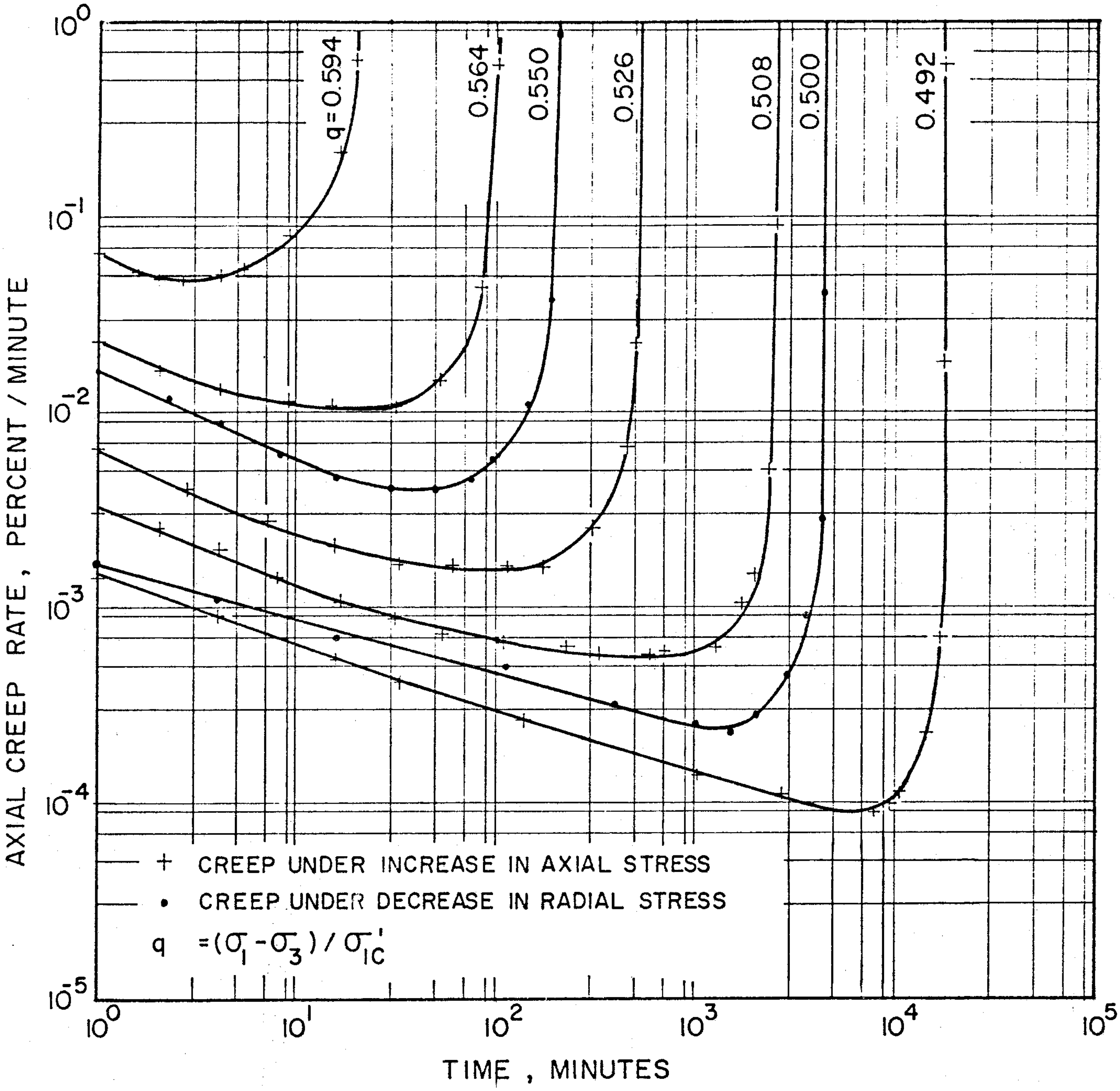

FIG. I CREEP RATE BEHAVIOUR OF K_0 CONSOLIDATED UNDISTURBED HANEY CLAY UNDER AXIALLY SYMMETRIC LOADING.

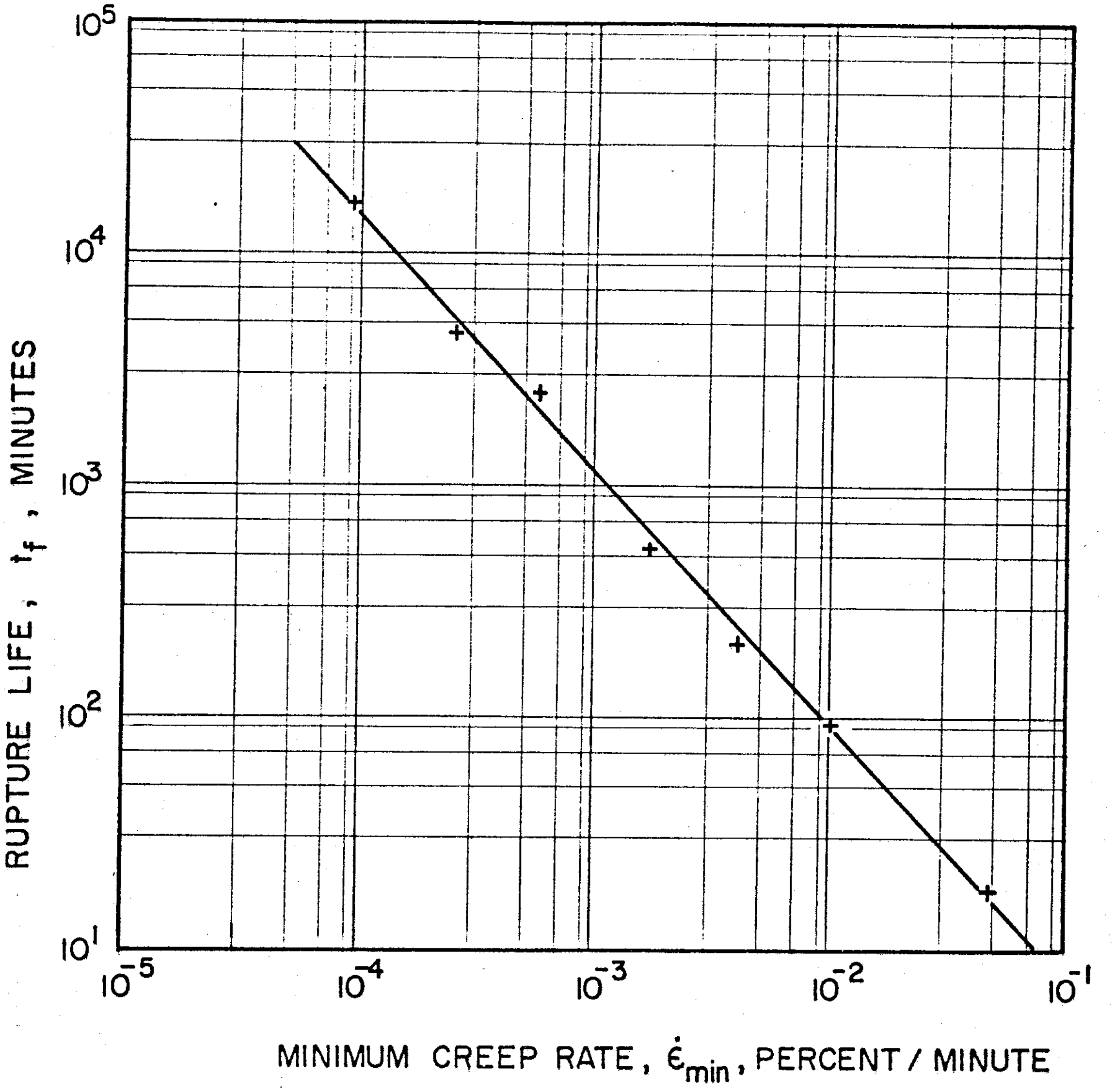

FIG. 2 RELATIONSHIP BETWEEN RUPTURE LIFE AND MINIMUM CREEP RATE.

minimum creep rate. Furthermore, the slope of this line is very nearly equal to unity which implies that rupture life is inversely proportional to minimum creep rate; i.e.,

$$t_f = \frac{C}{\dot{\varepsilon}_{min}} \qquad (1)$$

where C = constant. In long term tests, the rupture life may be estimated from this empirical relation (Eq. 1) as soon as the minimum creep rate has occurred.

A linear relation between log rupture life and log minimum creep rate has also been reported for metals[15] as well as for other soils with isotropic consolidation history[6-10]. Unfortunately, the width of error bands therein are extremely wide with values from ±0.50 to 0.55 cycles of rupture time, which implies that for a given minimum creep rate, rupture life could vary by a factor as high as 12. The existence of such large error bands for metals has been attributed to an attempt to include in the same relationships creep results from alloys of different tempers tested over a range of temperatures. A similar argument applies for soils where there has been a tendency to group results from tests on all types of clays to obtain a single relation even though soil composition, consolidation history, and drainage conditions varied. It appears that if the only variable considered is the level of creep stress for a given consolidation history, drainage condition and temperature, the resulting minimum creep rate-rupture life relation may be unique for a given clay, as was the case in Fig. 2.

Since the time from the start of creep is usually not known, as would be the case for most earth structures, Eq. 1 cannot be used to provide an estimate of the remaining useful life of the structure. Such estimates would be extremely valuable in order to plan remedial measures. The possibility of relating the increasing creep rate, the only measurable variable, to remaining time until rupture is examined in Fig. 3, where results from creep tests at all stress levels are shown. The results show that on a log-log scale, the remaining time to rupture is linearly related to the current accelerating strain rate, regardless of creep stress level. Thus, measurement of the current accelerating strain rate of a given material will provide an estimate of its remaining life, provided a relationship as shown in Fig. 3 was previously determined for that material. A similar relationship to that in Fig. 3 was either implied or observed by others[6,10,16] in their creep tests on clays with isotropic consolidation history.

Creep Strength: - It was apparent in Fig. 1 that as the creep stress level increased the rupture life progressively decreased. Fig. 4 shows the relationship between creep stress and the corresponding rupture life, which characterizes the process of strength reduction with time. At higher stress levels the creep strength showed essentially a linear decrease with log rupture life. At lower stress levels, however, the decrease in creep strength was much slower with time to rupture and the form of the curve seems to indicate the existence of a long term yield strength below which creep rupture will not occur. A linear decrease in creep strength with log rupture life was also noted by Casagrande and Wilson[17] for creep of clays in unconfined compression. Furthermore, a similar reduction in strength with decrease in strain rate has been observed by Crawford[18] in conventional constant strain rate shear tests.

The creep rupture behaviour of clays has generally not been analyzed in terms of effective stresses. In conventional shear tests the failure condition of a saturated normally consolidated clay is characterized by a linear effective stress Mohr envelope. Since the shear resistance of a normally consolidated clay

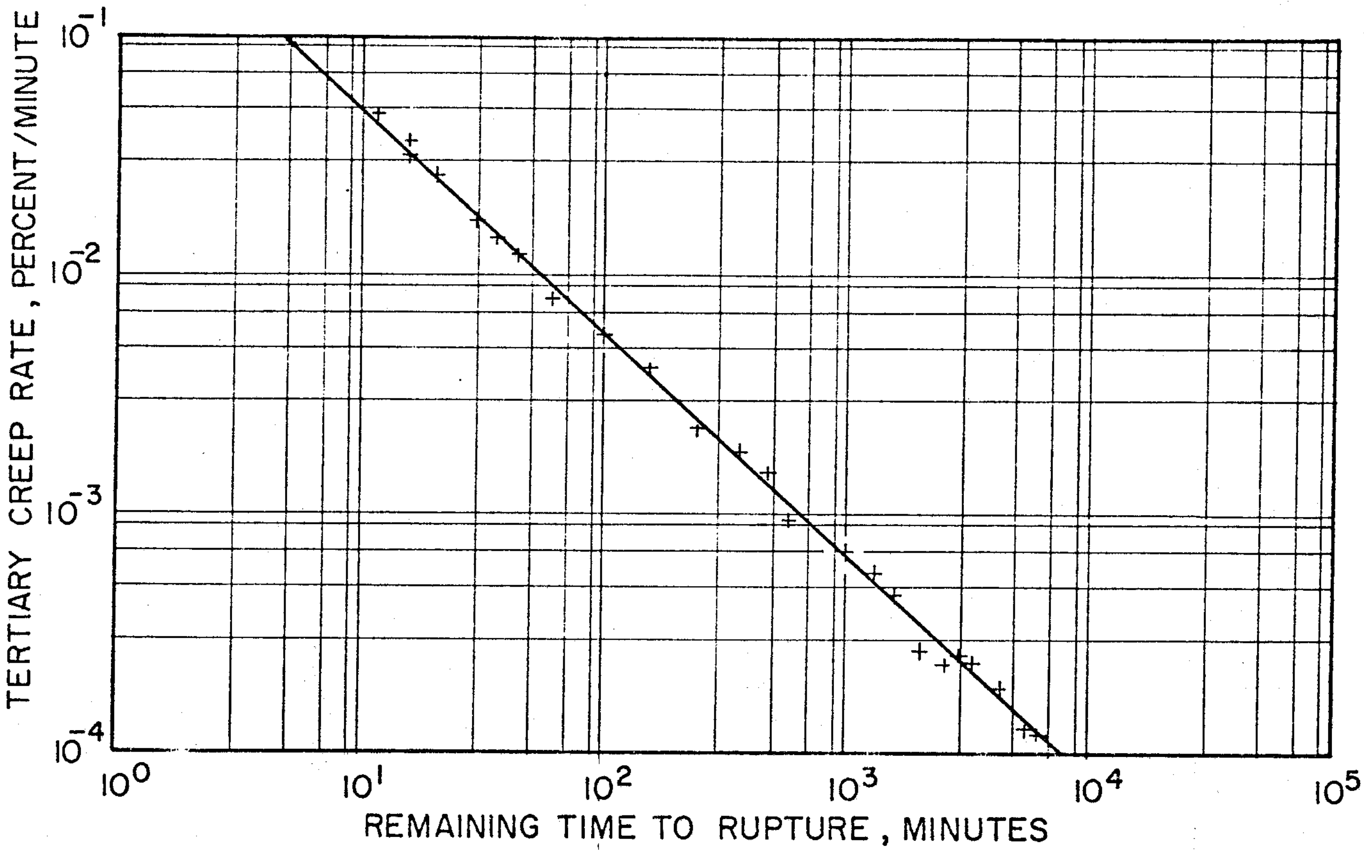

FIG. 3 RELATIONSHIP BETWEEN TERTIARY CREEP RATE AND REMAINING TIME TO RUPTURE.

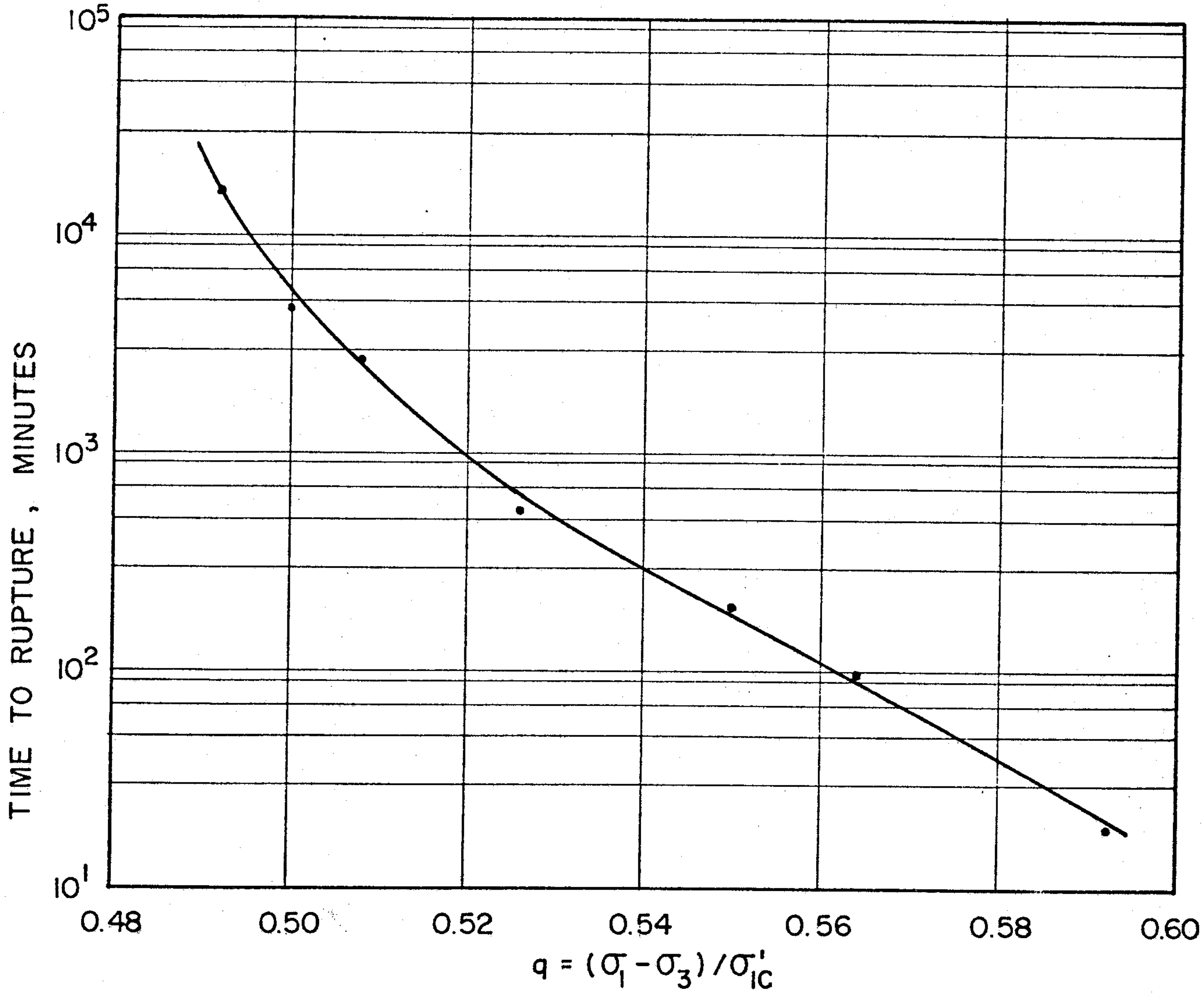

FIG. 4 VARIATION OF CREEP STRENGTH WITH TIME TO RUPTURE.

depends only on effective stresses, the same linear failure envelope may also apply at creep rupture, provided the rheological component of shear resistance[19] is negligible. Fig. 5 shows the effective stress condition of samples in a modified Mohr plot corresponding to the instant of maximum mobilized friction, which occurred a few minutes before actual rupture. It is assumed that at this point the measured pore pressure at the base of the sample is representative of that existing in the failure plane. Also shown in the same figure is the average line representing the effective stress failure envelope corresponding to maximum mobilized friction determined from conventional constant strain rate undrained tests. It may be seen that both creep rupture and failure in conventional shear tests were indeed defined by the same envelope, even though the strain rates at failure varied over a range from 3 to 0.003 percent per minute. Thus, the rheological component of shear resistance appears to be negligible for this soil. The K_0 line in Fig. 5 represents the condition of samples after one-dimensional consolidation and before application of the creep load.

The effective stress conditions at the instant when the creep rate started to increase (here called minimum creep rate) are also shown in Fig. 5. A linear envelope passing through the origin appears to define closely this onset of instability which occurs at a lower shearing resistance than that defined by creep rupture. Since all samples which reach this stress state eventually fail, it may be more appropriate to use this envelope defined by the minimum creep rate as a failure criterion. Casagrande and Wilson[17] also used conditions at the minimum creep rate to be indicative of failure.

Stress-Strain-Strain rate relations

The concept that, under isothermal conditions, the stress is a unique function of current strain and strain rate has been frequently used in the study of stress-strain-time behaviour of metals[20]. This concept, which is referred to as the

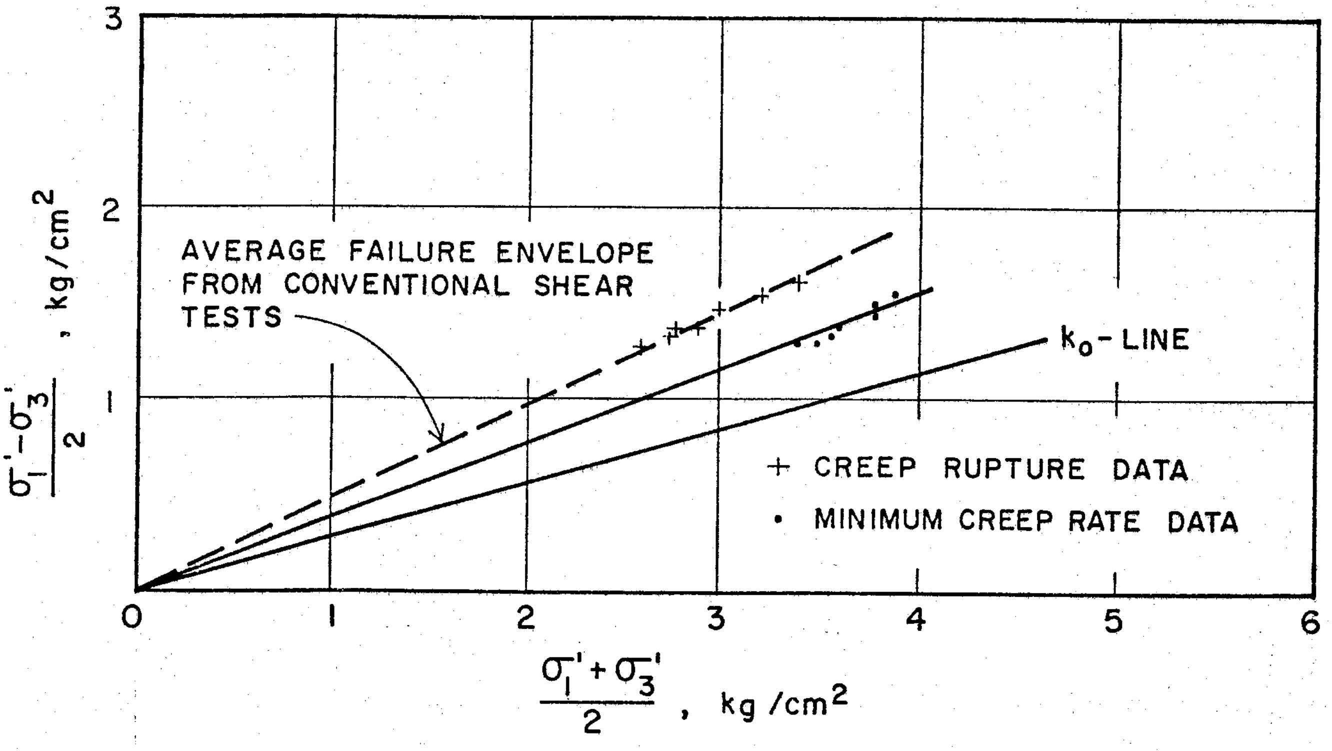

FIG. 5 EFFECTIVE STRESS CONDITIONS AT CREEP RUPTURE AND MINIMUM CREEP RATE.

strain hardening creep law, provides a method to determine creep behaviour under varying stresses from information obtained in constant stress creep tests. Also, the existence of a unique stress-strain-strain rate law has been used to predict creep behaviour from results of constant rate of strain tests on metals and plastics[20,21] and on soils[22].

Fig. 6 shows the constant stress creep rupture curves for saturated Haney clay on a log strain rate versus strain plot. A constant strain rate test, which involves varying stress, is shown on this plot by a horizontal line corresponding to the value of the strain rate used. If the stress is assumed uniquely related to current strain and strain rate, then the points of intersection of the constant strain rate line with the creep curves would yield a set of values defining the stress-strain curve for the particular constant strain rate used.

The stress-strain curve determined from a constant strain rate test on a sample, having the same consolidation history as that used for creep test, is shown in Fig. 7. The predicted stress-strain curve from the series of creep curves is also shown by crossed circles. It may be seen that excellent agreement exists between observations and predictions. In saturated clays, therefore, the concept of stress being uniquely related to only current strain and strain rate makes creep tests and constant strain rate tests complementary to each other for obtaining stress-strain-time properties.

CONCLUSIONS

Based on uniaxial constant stress creep rupture tests on one-dimensionally consolidated, saturated, natural marine clay, the following conclusions can be drawn:

1. A linear relationship exists between log minimum creep rate and log

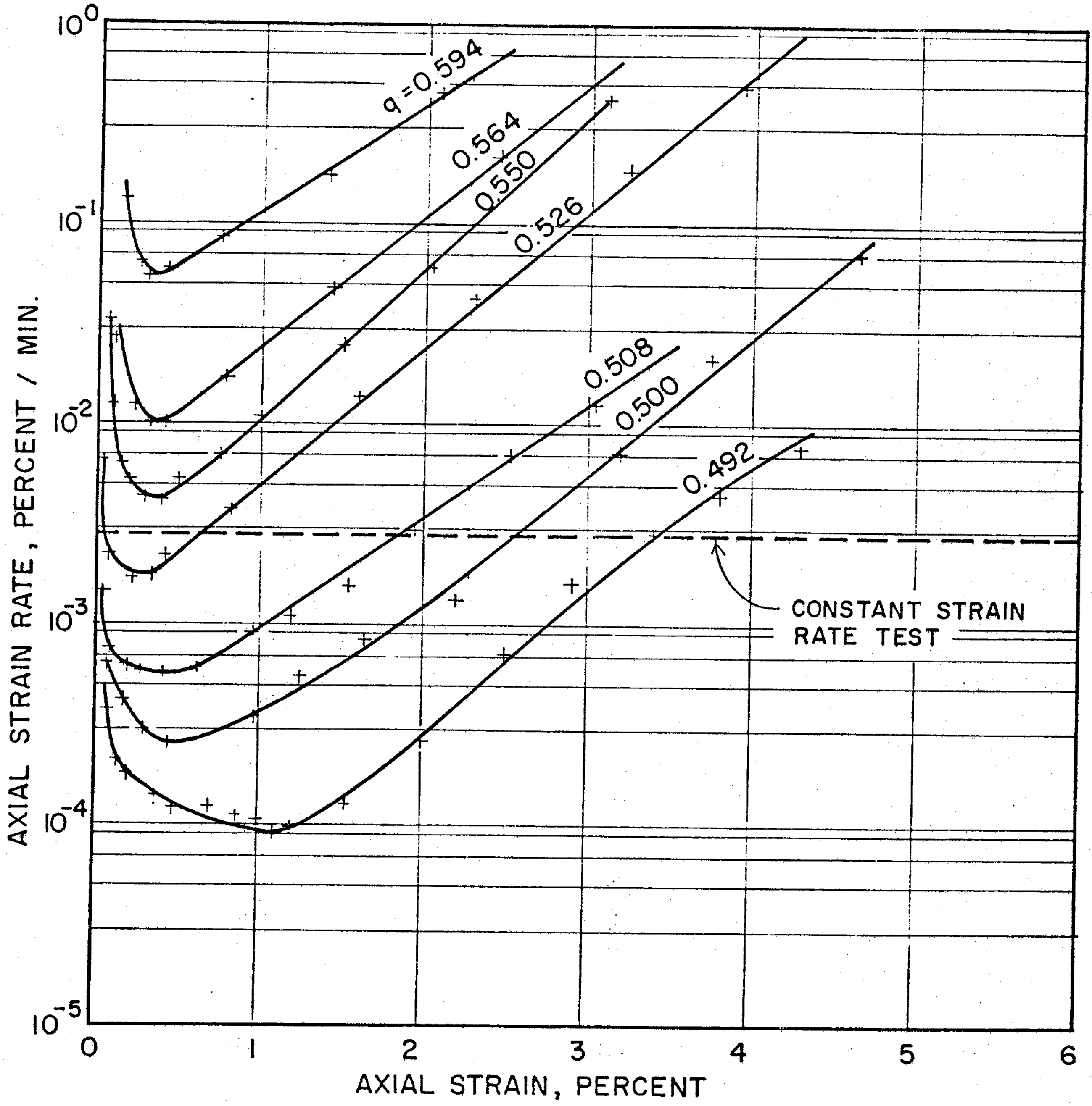

FIG. 6 STRAIN-STRAIN RATE BEHAVIOUR OF K_0 CONSOLIDATED UNDISTURBED HANEY CLAY.

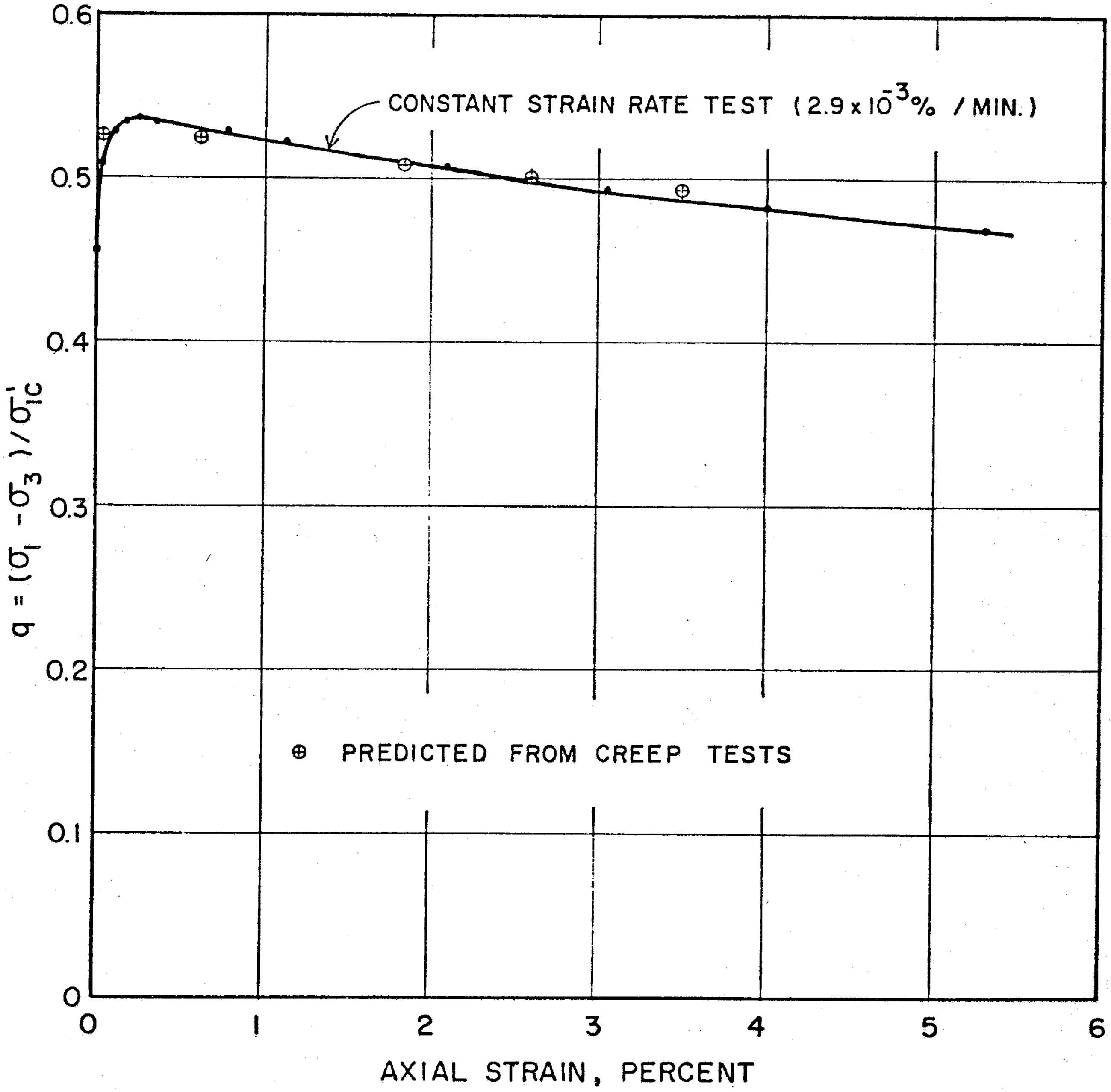

FIG. 7 COMPARISON OF OBSERVED STRESS-STRAIN BEHAVIOR IN CONSTANT STRAIN RATE TEST WITH THAT PREDICTED FROM CREEP TESTS.

rupture life. Also a linear relation is noted between log current creep rate during tertiary creep and the remaining time to rupture. Both these relations are independent of the creep stress level.

2. The linear effective stress failure envelope determined from conventional constant strain rate shear tests defines uniquely the effective stress conditions at the instant of creep rupture. Furthermore, the onset of accelerating creep deformations is also characterized by a linear effective stress envelope.

3. For a given consolidation history, a unique stress-strain-strain rate law exists and may be used to correlate the results of creep and constant strain rate tests.

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