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# Effects of localization in triaxial tests on clay

## Effets de la localisation dans les essais triaxiaux sur argile

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**SYNOPSIS** The importance of distinguishing between two principally different types of failure, which develop under and as a consequence of different strain conditions in triaxial tests on clay is pointed out. A line failure will develop under conditions of nonuniform strain states in the test specimen, whereas a zone failure, in which multiple slip planes traverse the clay specimen, will develop under conditions of macroscopically uniform strain states in the specimen. The two types of failure will generally yield different types of behavior. Series of tests were conducted on remolded clay with overconsolidation ratios of 1, 2, 5 and 15. The tests were performed in triaxial compression and triaxial extension on specimens with line failure and with zone failure. The difference in behavior is most pronounced in triaxial extension tests. It is concluded that comparisons of stress-strain, undrained stress-path, and strength characteristics obtained under different stress conditions should only be made if these have been obtained under the same strain and failure conditions, preferably those of uniform strains and consequent zone failure.

### INTRODUCTION

Constitutive models for soils are most often developed on the basis of experimental behavior observed in laboratory tests. It is therefore important that such tests are performed correctly and that the recorded data truly represent the stress-strain behavior of the soil. Ideally, the stresses and strains in laboratory triaxial tests should be completely uniform. It is generally considered that adequately uniform conditions will be achieved by using tall specimens with heights greater than or equal to two diameters, or by using lubricated caps and bases, or both. Even under conditions where end restraint is negligibly small, however, severe nonuniformities in strain can develop in triaxial tests, and these nonuniformities in strain can have significant effects on the stress-strain, undrained stress-path, and strength behavior of the clay.

Series of tests were performed in triaxial compression and triaxial extension on specimens of remolded clay with overconsolidation ratios of 1, 2, 5 and 15. The effects of nonuniform strain are discussed below, and the magnitudes of these effects are illustrated by comparing results of tests with uniform and nonuniform strain.

### MODES OF FAILURE

Two basically different types of failure can occur in laboratory triaxial specimens whether these are drained or undrained:

- (1) Under conditions of uniform stress and strain, zone failure occurs. In this type of failure multiple failure planes traverse the specimen at angles of  $\pm (45 + \phi/2)$  degrees to the  $\sigma_3$ -direction.
- (2) Under conditions of nonuniform strain, line failure can occur. In this type of failure two practically solid bodies slide past each other along a single failure plane, which is oriented at  $(45 + \phi/2)$  degrees to the  $\sigma_3$ -direction.

The terms 'zone failure' and 'line failure' were used by Brinch Hansen (1953) and also by Jacobsen (1967) in an investigation of the behavior of boulder clay in triaxial compression tests. They were also employed in a study of the behavior of sand (Lade, 1982). Which type of failure will develop in a given case depends on three factors:

(1) Uniformity of density.-- Nonuniformity in the density of a test specimen promotes development of line failures. Zones with low densities constitute zones of weakness, and single failure planes may develop through such parts of the soil. Therefore, the strength measured in a specimen undergoing line failure is only representative of the density of the soil actually involved in the failure, and this will often be less than the average for the whole specimen.

(2) Tendency to dilate or compress.-- A tendency to dilate during shear aggravates initial nonuniformity of density and makes line failure more likely. A tendency to compress during shear has the opposite effect. If sufficient densification occurs, the soil in the failure plane could become as dense and strong as some other parts of the specimen. This would result in increasing uniformity of density thus promoting conditions for zone failure.

(3) Boundary conditions.-- Regardless of the uniformity of density of the specimen and the changes in density resulting from volume changes, zone failure will occur if the boundary conditions enforce uniform strains throughout the specimen. The best boundaries for enforcing uniform strains are stiff, lubricated flat surfaces. Such boundaries reduce friction greatly, with the result that the stresses are essentially uniform. They also prevent development of line failures provided the potential planes of sliding are oriented such that they would have to intersect the boundary.

In triaxial compression tests with uniform stress conditions the failure plane is oriented at  $(45 + \phi/2)$  degrees to the planes of the cap and base, and transcends a length of  $D \cdot \tan (45 + \phi/2)$  as shown at the upper left in Fig. 1. If the length of the specimen is equal to or greater than the length transcended by the failure plane, line failure can occur. If the specimen is short with  $H = D$ , only zone failure can occur, as shown at the lower left in Fig. 1.

In triaxial extension tests with uniform stress conditions, the failure plane transcends a length of  $D \cdot \tan (45 - \phi/2)$  as shown at the right in Fig. 1. Thus, line failure can occur in extension tests even if the specimens are short, with  $H = D$ . To prevent line failures in extension tests, it is necessary to provide two pairs of stiff low-friction

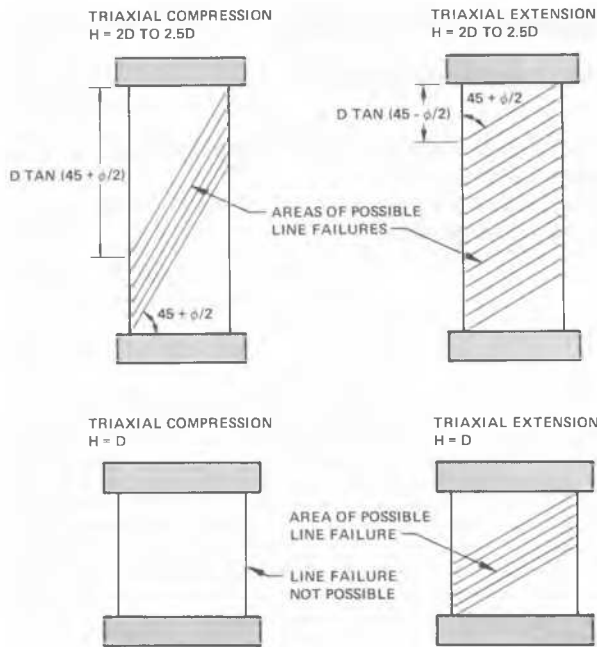


Fig. 1. Boundary Condition Effects on Failure Type.

boundaries. This can be done in triaxial extension tests on cubical specimens by applying equal stress differences,  $(\sigma_1 - \sigma_3) = (\sigma_2 - \sigma_3)$ , to two pairs of faces of the cube through stiff, lubricated platens. Under these conditions zone failure can be achieved in triaxial extension. The cubical triaxial apparatus presented by Lade (1978) was used for the zone failure tests.

TESTS ON REMOLDED CLAY

Consolidated-undrained tests with pore pressure measurements were performed on saturated specimens of Edgar Pulverized Kaolin (EPK clay) with the following characteristics: Liquid limit = 57.7, plastic limit = 29.6, and activity = 0.50. The specimens were prepared from a clay slurry mixed at a water content of two times the liquid limit and consolidated in a double draining consolidometer at a vertical pressure of 2.0 kg/cm<sup>2</sup>. After thoroughly remolding the clay, specimens were trimmed and consolidated isotropically at 3.00 kg/cm<sup>2</sup>. The overconsolidated clay specimens were subsequently allowed to swell at isotropic effective confining pressures of 1.50, 0.60 and 0.20 kg/cm<sup>2</sup> corresponding to overconsolidation ratios of 2, 5 and 15. Tests were also performed on normally consolidated specimens, i.e. corresponding to OCR = 1.

TRIAxIAL COMPRESSION TESTS

Typical normalized stress-strain curves and effective stress ratio-strain curves for three undrained triaxial compression tests on EPK clay with OCR = 5 are shown on Fig. 2. The first test was performed on a specimen with diameter of 7.1 cm, H/D = 2.3, and with normal (unlubricated) cap and base. The consequent end restraint caused nonuniform stress and strain distributions and therefore nonuniform pore pressure distribution within the specimen. Filter paper drains were employed around the specimen and the test was performed with sufficiently slow strain rate to allow a high degree of pore pressure equalization (Blight, 1963). Line failure could occur in this test.

Two tests were performed on short specimens with H/D = 1.0 and with lubricated cap and base. A cubical specimen with

side length of 7.6 cm was used in one test, and a cylindrical specimen with diameter of 7.1 cm was employed in the other test. Zone failure occurred in these tests. The strain rate used in tests on specimens with lubricated end plates is not subject to calculation, because the stresses and strains and therefore also the pore pressures are presumed to be uniform. Following a procedure recommended by Barden and McDermott (1965), a strain rate of 0.04 %/min. was selected for the specimens with lubricated ends.

End restraint results in development of shear stresses at the cap and base, and this may have an effect similar to testing the specimen at a confining pressure slightly higher than that actually employed. The triaxial compressive strength may therefore be higher than expected, even for specimens with heights greater than or equal to two diameters in which line failure can develop. Fig. 2(a) shows that the normalized stress-strain curve for the conventional specimen is steeper at small strains, as a result of the end restraint imposed by the rough cap and base. The effective stress ratio-strain curve shown in Fig. 2(b) for the line failure specimen breaks over much more sharply and the strain-to-failure is considerably smaller. These effects are due to the fact that most of the deformation of the specimen occurs within a narrow zone, and the rest of the specimen deforms very little after the onset of failure. The stress-strain curves for the zone failure specimens break over much more gradually, and the strains-to-failure are considerably larger, owing to the fact that the specimens undergo essentially uniform strains.

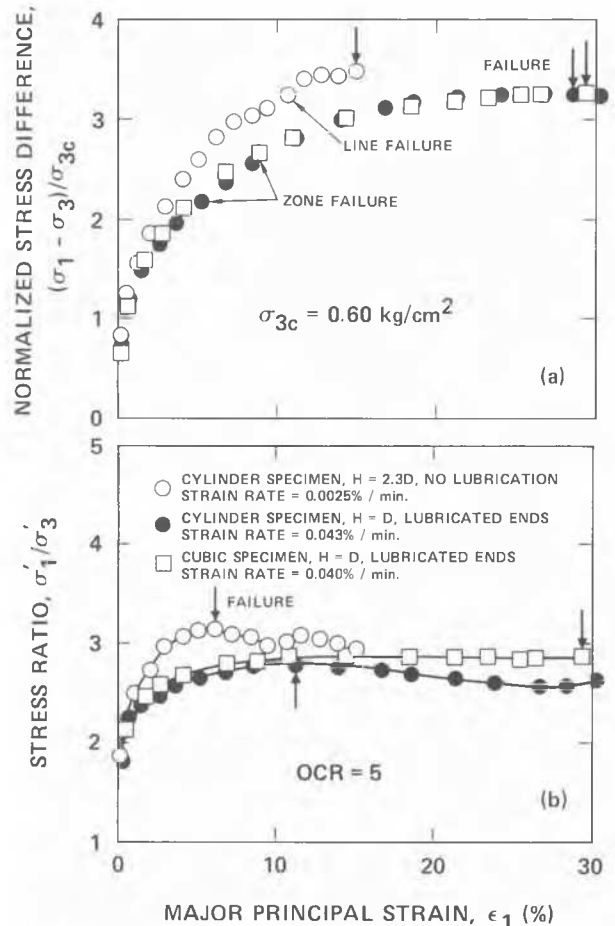


Fig. 2. Stress-Strain Behavior in Triaxial Compression Tests on EPK Clay with OCR = 5.

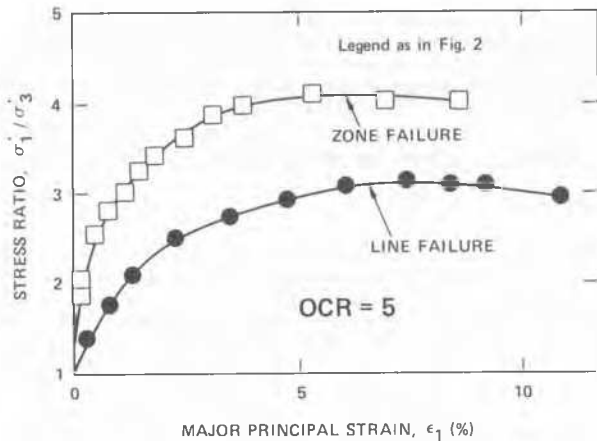


Fig. 3. Stress-Strain Behavior in Triaxial Extension Tests on EPK Clay with OCR = 5.

Results similar to those shown in Fig. 2 were also obtained from the other triaxial compression tests performed with different overconsolidation ratios. The strengths of the line failure specimens were slightly higher than those of the zone failure specimens, due to effects of end restraint. The average effective friction angle for the tests on tall specimens with end restraint and line failure was  $31.0^\circ$ , whereas the average effective friction angle for all the tests on short specimens with lubricated ends and zone failure was  $29.3^\circ$ . Similar effects were obtained in tests by Blight (1965) and by Duncan and Dunlop (1968).

The results in Fig. 2 indicate that the behavior measured in the zone failure tests performed on short cylindrical specimens and on cubical specimens were very similar. The average effective friction angle obtained from the cylindrical specimens was  $29.0^\circ$  and that obtained from the cubical specimens was  $29.7^\circ$ . Thus, the influence of specimen shape is not pronounced.

TRIAxIAL EXTENSION TESTS

Triaxial extension tests were performed on short specimens of EPK clay with two different shapes: 7.6 cm cubical specimens and cylindrical specimens with diameter of 7.1 cm and with  $H/D = 1.0$ . Two different procedures were used in the consolidated-undrained tests. In the first procedure, the axial stress ( $\sigma_3$ ) was applied through a stiff, lubricated cap and base, while the lateral stresses ( $\sigma_2 = \sigma_1$ ) were applied by the chamber pressure acting against the rubber membrane surrounding the specimen. Line failure occurred in these tests, because the failure plane intersected the flexible membrane. In the second type of test, one of the lateral stresses ( $\sigma_3$ ) was applied through the rubber membrane surrounding the specimen, while the other lateral stress and the axial stress were applied through stiff, lubricated plates. Zone failures occurred in these tests. Because the specimens were isotropic and fully saturated in both types of extension tests, the effective stress-paths should be the same. Thus, any difference in stress-strain behavior would be caused by the occurrence of line failure and zone failure in the two types of tests.

Typical relations between effective stresses and strains for two undrained triaxial extension tests on specimens with OCR = 5 are shown on Fig. 3. The behavior of the clay in these tests is similar to that observed in triaxial compression tests, but the differences are much larger. End restraint did not play a role in these tests in which lubricated ends were employed. The effect of line failure is therefore clearly demonstrated. The peak effective stress

ratio in the zone failure specimen was almost 50% higher than that obtained in the line failure specimen.

The other triaxial extension tests performed with different overconsolidation ratios exhibited similar behavior as those shown in Fig. 3. The average effective friction angle for the tests on cylindrical specimens with line failure was  $31.0^\circ$ , whereas the average effective friction angle for the cubical specimens with zone failure was  $38.2^\circ$ , i.e. the difference between friction angles in extension was about  $7^\circ$ . Thus, the differences between results of tests with zone failure and line failure are much more pronounced in extension tests than in compression tests.

NORMALIZED STRESS-PATHS

The effective stress-paths obtained from the undrained triaxial compression and extension tests with zone failure and with line failure are shown on the normalized  $p' - q$  diagrams in Fig. 4. In these diagrams  $p' = 1/3 (\sigma_1' + \sigma_2' + \sigma_3')$ ,  $q = (\sigma_1 - \sigma_2)$  and  $p'_e$  = equivalent consolidation pressure determined from the virgin isotropic compression curve (Hvorslev, 1960; Schofield and Wroth, 1968). The slopes of the failure lines indicated on Fig. 4 are related to the effective friction angles as follows (Schofield and Wroth, 1968): Triaxial compression,  $M_1 = 6 \cdot \sin \phi' / (3 - \sin \phi')$ , and triaxial extension,  $M_2 = 6 \cdot \sin \phi' / (3 + \sin \phi')$ .

For each of the four combinations of triaxial compression and extension, and zone failure and line failure, the effective stress-paths all converge towards the individual four slopes indicated on Fig. 4. These slopes are almost the same for the tests in triaxial compression, but they are substantially different for the tests in triaxial extension. This difference reflects the difference in effective friction angle discussed above.

It is apparent that more consistent behavior is observed for the tests with zone failure. Thus, the normalized effective mean normal stresses reached essentially common values at failure. Whether the common values obtained in

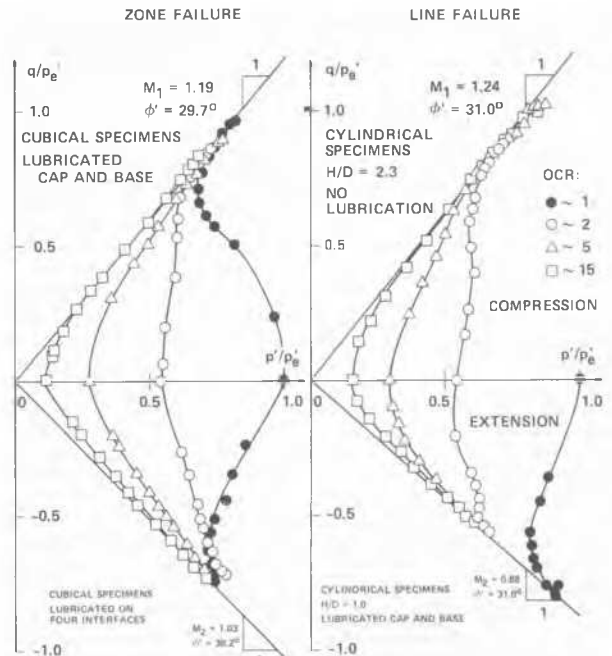


Fig. 4. Effective Stress-Paths for EPK Clay Shown in Normalized  $p' - q$  Diagrams.

compression and in extension are the same is outside this investigation. In comparison, the tests with line failure show considerable scatter in their final value of the normalized effective mean normal stress.

Fig. 4 also indicates that the normalized undrained compressive strengths, represented by  $q/p'_e$  at failure, are more consistently determined in the zone failure tests than in the line failure tests. Thus, in zone failure tests the value of  $q/p'_e$  at failure is independent of overconsolidation ratio, but it is smaller in extension than in compression.

The normalized effective stress-paths for the zone failure specimens all approach and (within the scatter of the experimental results) reach the same points on the failure lines. Whereas the failure stresses are different for compression and extension, the observed behavior support the critical state concept, as explained by Schofield and Wroth (1968). Each of the two critical states reached at the end of the zone failure tests represent a unique combination of  $p'$ ,  $q$ , and void ratio (which is uniquely related to  $p'_e$ ). The data also indicate that at least one more parameter is required to describe the variation of  $M = q/p'$  or  $\phi'$  under general three-dimensional conditions.

#### DISCUSSION

The large difference in stress-strain, undrained stress-path and strength behavior observed in line failure and zone failure tests can have a significant influence on a number of important questions concerning modeling of soil behavior in constitutive models. As an example, consider the comparison of effective friction angles for EPK clay in compression and extension. If line failure occurred in both cases, the results in Fig. 4 show that the comparison would be:

For compression,  $\phi' = 31.0^\circ$   
For extension,  $\phi' = 31.0^\circ$

If zone failure occurred in both cases, the comparison would be:

For compression,  $\phi' = 29.7^\circ$   
For extension,  $\phi' = 38.2^\circ$

If zone failure occurred in the compression test and line failure occurred in the extension test, which is quite likely what would happen if the tests were performed on specimens with  $H = D$  and with lubricated caps and bases, the comparison would be:

For compression,  $\phi' = 29.7^\circ$   
For extension,  $\phi' = 31.0^\circ$

This latter comparison, which ignores the very significant influence of the type of failure, would lead to an incorrect conclusion regarding the values of  $\phi'$  for compression and extension.

It is interesting to consider whether tests with line failure or tests with zone failure give results more suitable for modeling in constitutive laws and for analyses of field problems. Because natural soil deposits are seldom if ever uniform with regard to density, it would be expected that line failure will occur in the field when the soil is expanding and when zone failure is not imposed by the boundary conditions. Line failure and localized deformation may also be promoted by the boundary conditions and stress concentrations produced in the particular field problem under investigation. The boundary conditions and stress concentrations particular to the triaxial tests in which line failure develops, however, will seldom if ever be representative of those in the field (see also Taylor, 1948), and it is therefore unlikely that the results from such tests would be appropriate for analyses of field problems. It is believed that zone failure tests provide the best means of establishing consistent stress-strain and strength relationships for soils. The development of line failure and localized deformation should be determined from numerical analyses performed by finite element or finite

difference methods which take into account the proper boundary conditions, stress concentrations, possible nonuniformities in the soil, and an appropriate constitutive model with material parameters determined from tests with zone failure. If modeled correctly, localized plastic deformation and therefore line failure should develop and propagate through the soil mass as appropriate.

#### CONCLUSIONS

Line failure and zone failure are different modes of failure which can lead to significantly different stress-strain and strength characteristics. Line failure involves only a small part of the specimen, and generally the loosest part. Zone failure involves the entire specimen and provides a better measure of the properties of the clay at the average specimen density. Which of these two types of failure occurs in a given case will be determined by the boundary conditions, the uniformity of density of the specimen or the clay deposit, and the tendency of the clay to dilate, which in turn depends on the overconsolidation ratio for the clay.

The difference in the results of these two types of tests may be very considerable. For triaxial compression tests on EPK clay, the values of  $\phi'$  measured in line failure tests are 1 to 2 degrees higher than those measured in zone failure tests, mainly due to end restraint in the conventional specimens. For triaxial extension tests the values of  $\phi'$  measured in zone failure tests are about 7 degrees higher than those measured in line failure tests. Examination and identification of the type of failure in laboratory tests is very desirable because of the possible significant influence on the results, and the fact that comparing the results of line failure and zone failure tests can lead to incorrect conclusions regarding the behavior of clay.

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