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Effects of necking and its suppression in axisymmetric extension tests on clay

Les effets de necking et leur suppression dans les tests d'extension axisymétriques sur l'argile

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ABSTRACT

Drained and undrained triaxial extension tests conducted on slurry-consolidated kaolinite clay specimens clearly show effects of necking, which is a diffused type of strain localization. The effects on the observed stress-strain behavior are lower stiffness, lower peak strength and smaller strain-to-failure. This has been observed in a prior study on clay by Balasubramaniam (1976) and on granular materials by Yamamuro and Lade (1995). Tests were conducted with height-to-diameter ratios of 2.0, 1.0 and 0.5. Analysis of photographs at different known strain magnitudes clearly shows that the use of lubricated end platens and decreasing the height-to-diameter ratio reduces the severity of necking observed in clay specimens. Thus, it is recommended to utilize an H/D=0.5 for extension tests.

RÉSUMÉ

Des tests d'extension triaxiaux drainés et non-drainés effectués sur des spécimens d'argile de kaolinite de gâchis-consolidé démontre clairement les effets de necking, un type diffusé de localisation de tension. Les effets sur le comportement de tension atténué observé sont une raideurs moins élevée, une baisse de la force maximale et une plus petite tension-à-l'échec. Ceci a été observé dans une étude préalable sur l'argile par Balasubramaniam (1976) et sur les matériels granuleux par Yamamuro et Lade (1995). Les tests ont été dirigés avec des rapports de hauteur-diamètre de 2,0 , 1.0 et 0,5. L'analyse de photographies à de differentes grandeurs connues de tension démontre clairement que l'utilisation de rouleaux porte-papiers de bout lubrifiés et les diminutions de rapports de hauteur-diamètre réduit la sévérité de necking observé dans les spécimens d'argile. Ainsi, il est recommandé d' utiliser un rapport H/D=0.5 pour les tests d'extension.

1 INTRODUCTION

Necking is a diffused form of strain localization and it is characterized by a region of the specimen where strains are accumulated. This is not to be confused with shear banding which is a much more discrete form of strain localization. Necking often occurs during extension testing of soils and results in a narrowing of that portion of the specimen relative to other sections. Often, it occurs near the center of the specimen away from its ends. The effects of necking have been examined by some investigators [Balasubramaniam (1976), Wu and Kolymbas (1991), Yamamuro and Lade (1995), Georgiannou and Burland (2001)]. Some suggested that if lubricated end platens were employed, the effects could be minimized, even with tall specimens. Others recommended that it must be controlled and they developed methods to enforce uniform strains by other means, such as a rigid jacket around the specimen.

The present study specifically examines necking and its effects on the measured global behavior in triaxial extension tests on clays. Methods to mitigate it were developed.

2 EXPERIMENTAL METHODS

2.1 *Clays Tested*

The clay used for testing was kaolinite sold commercially by Albion Kaolinite Company. Its specific gravity is 2.65. The clay was initially mixed into a slurry form at 150% water content and then consolidated into solid cakes in a vertical consolidation tank under K_0 conditions with a vertical stress of 100 kPa. The consolidated cakes were extruded and then individual specimens were cut and trimmed to the final specimen size. The diameter of all specimens was 70 mm, but the heights varied.

2.2 *Experimental Setup*

A deformation-control 50 kN capacity loading frame was used with an external load cell. Tests conducted at cell pressures at or below 400 kPa a reinforced acrylic plastic triaxial cell wall was employed, but at greater pressures a steel cell wall was used. Confining pressures were generated by a GDS pressure/volume controller. Backpressure, which was generally 100 kPa, was applied through the volume change measurement device from compressed air in the house line. A volume change-measuring device, based on a differential pressure transducer was employed. A layer of silicone oil was placed above the water levels in the chambers of the volume change-measuring device to inhibit air from dissolving into solution into the pore water and possibly de-saturating the specimens in long-term tests. An LVDT was used to measure global strains and an external pressure transducer was used for both cell and pore pressure measurements. All instrumentation was connected to a computer data acquisition system, which consisted of amplifiers, filters, A/D converter and software.

2.3 *Experimental Procedures*

All undrained triaxial extension tests were conducted after isotropic consolidation to the selected initial effective confining pressure. The cell pressure was held constant during undrained tests and both the cell and backpressures were held constant during drained tests. Strain rates for undrained tests conformed to those recommended by ASTM 4767, even though the use of lubricated end platens precluded strict adherence to this specification. B-value tests were performed both before and after the tests to determine the level of saturation. The minimum B-value obtained for all testing was 0.98, but most were greater.

Lubricated end platens were employed and they consisted of the application of a thin layer of vacuum grease directly onto the surface of the anodized aluminum end platen over which a 0.3 mm thick latex rubber sheet was mounted. Brass shear pins were inserted between the platens and the specimen to prevent lateral slippage during loading. Since end drainage was not possible through the lubricated ends, radial drainage was employed. Radial drainage was accomplished by placing drainage material cut in an inclined slotted fashion [Berre (1982)] around the specimen to reduce its load carrying ability. Drainage material consisted of filter paper (Whatman Grade No. 1) for all tests. Special anodized aluminum end platens were fabricated to allow the flow of water to be transmitted from the radial drainage material through ports in the sides of the platens and ultimately to the volume change measurement device. Porous metal filters were installed in the ports to keep soil from entering the drainage system. A 9.5 mm diameter loading piston was used. The top platen was connected to the load cell through a universal joint to prevent moments from being transferred into the load cell.

2.4 *Corrections to Experimental Data*

Corrections for the following experimental effects were applied to the test data: a) piston seal friction; b) piston uplift force; c) membrane stiffness; d) drainage material stiffness. The vertical load correction associated with the stiffness of the radial drainage material used in the present study was investigated by Yamamuro and Liu (2005). It was found that the load corrections were much larger than previously assumed, even for filter paper. The load correction in extension was found to be even greater.

3 RESULTS FROM EXPERIMENTS

3.1 *Necking in Extension Tests*

Tests in extension were initially conducted on tall specimens with a height-to-diameter ratio (H/D) of 2.2. It was immediately observed that necking was occurring. A study was performed to ascertain the significance of errors caused by persistent necking on the global test results at different strain levels. The lead author was involved with a prior study in which short specimens were utilized to inhibit shear band formation in sand specimens during extension testing [Lade et al. (1996)]. Drawing on this experience, it was decided to determine the effect of the H/D (height-to-diameter) ratio on necking. Specimens with H/D ratios of 2.2, 1.0 and 0.5 were used in undrained and drained extension tests on normally consolidated kaolinite clay specimens at an initial confining pressure of 400 kPa. During drained extension tests, photographs of the specimen were taken at regular known intervals. The photographs were enlarged and analyzed to obtain the specimen dimensions at the center of the neck and the ends of the specimens. Fig. 1 shows three photographs of specimens with the three different H/D ratios at approximately 15% axial strain. The authors are aware that optical distortions occur when viewing a specimen in a triaxial cell through a curved acrylic plastic wall [Macari et al. (1997)]. However, since the specimens were of the same diameter and the measurements were individually scaled with elements inside the triaxial cell in the plane of the observation, it is felt that the errors are relative and did not affect the overall interpretation of the results.

Figure 1. Comparison of necking in clay specimens with H/D ratios of 2.2, 1.0 and 0.5 at approximately 15% axial strain

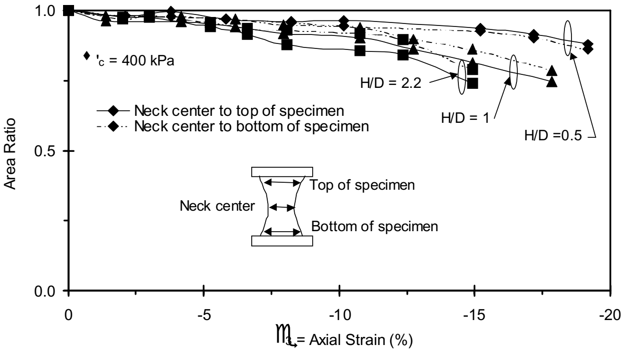

Figure 2. Comparison of the extent of necking in clay specimens during extension tests with H/D ratios of 2.2, 1.0 and 0.5.

3.2 *Photographic Analysis*

Fig. 2 shows the area ratio versus the globally measured axial strain. The area ratio is the cross-sectional area at the center of the neck divided by the area at either the top or bottom of the specimen. Three tests on specimens of different H/D ratios are shown. An area ratio of unity would indicate perfectly uniform deformations between the center and top or bottom of the specimen, while a value less than unity means that necking is occurring. There is some scatter in the data. The radial strains for the global line marked were determined from the axial and volumetric strains from the H/D=0.5 test. The first observation is that it seems that necking starts from the very beginning of the test. Necking does not delay until some latter point to initiate. At low strains, necking is very difficult to see, but it does occur. This observation was also made by Yamamuro and Lade (1995) from extension tests performed on sands at high pressures. One can readily see in Fig. 2 that at low axial strains, the errors are relatively small, but as they become larger, the area ratio significantly decreases indicating a significant neck forming. Moreover, as the H/D ratio decreases, the resulting neck is significantly smaller. At approximately 5% axial strain with an H/D value of 2.2, an area ratio of 0.95 was observed. An H/D ratio of 0.5 produced an area ratio of 0.97. Thus, at low axial strains both cases will produce a small under-estimation of the calculated axial stress, when using uniform strain assumptions. At an axial strain value of 15%, which is near the failure condition in extension, an H/D ratio of 2.2 resulted in an area ratio of 0.74. An H/D value of 0.5 produced an area ratio of only 0.94. Thus, the error in the calculated stress using uniform strain assumptions is much more significant as the axial strain level increases, especially near or at failure.

Fig. 3a shows the photographically measured radial strains near the top end of the specimen from the same three drained tests compared with the inferred uniform radial strain values assumed from the measured axial and volumetric strains. This is the assumption commonly used to analyze experimental data from extension tests. There is some scatter in the data. As the axial strain increases, the test with the shortest specimen appears to remain closest to the calculated uniform strain values. The taller specimens deviate from the inferred global radial strain at lower axial strain values and the deviations become much larger. Eventually, all the tests show that the measured radial strains at the top of the specimen are smaller than those based on the uniform strain assumption. In other words, as failure approaches, the ends of all the specimens, but especially the taller ones, have a true state of stress and strain that are significantly lower than assumed in typical test data analysis. Fig. 3b shows the measured radial strains in the center of the neck. The difference between the neck region and the top end of the specimen is apparent. The data indicates that as the axial strains increase, the measured radial strains become larger than predicted by the uniform strain assumption. A neck forms in all specimens, but the short specimen seems to provide the most resistance to its development. Thus, near the failure condition, the state of stress and strain within the neck region is greater than that obtained from the uniform strain assumption. The state of stress and strain is considerably in error for taller specimens.

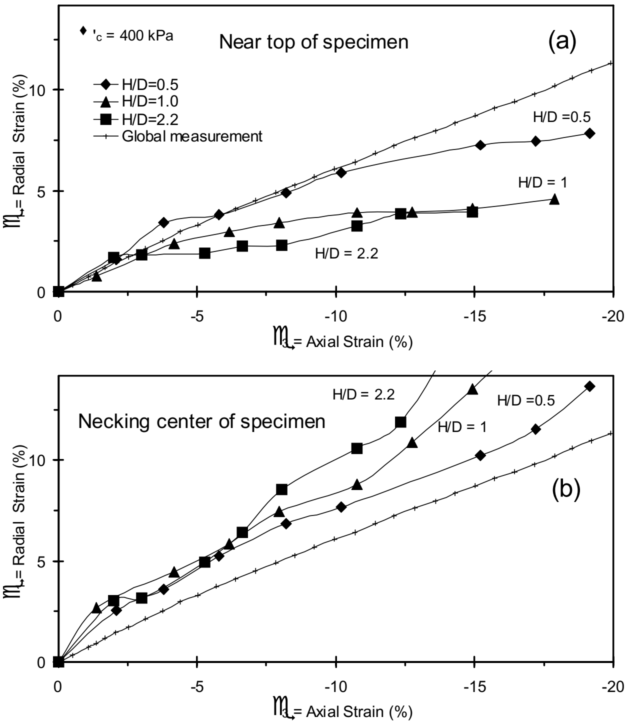

Figure 3. Radial strain v. axial strain from drained extension tests on clay (OCR=1) with H/D ratios of 2.2, 1.0 and 0.5: a) at center of necking of specimen; b) at bottom of specimen.

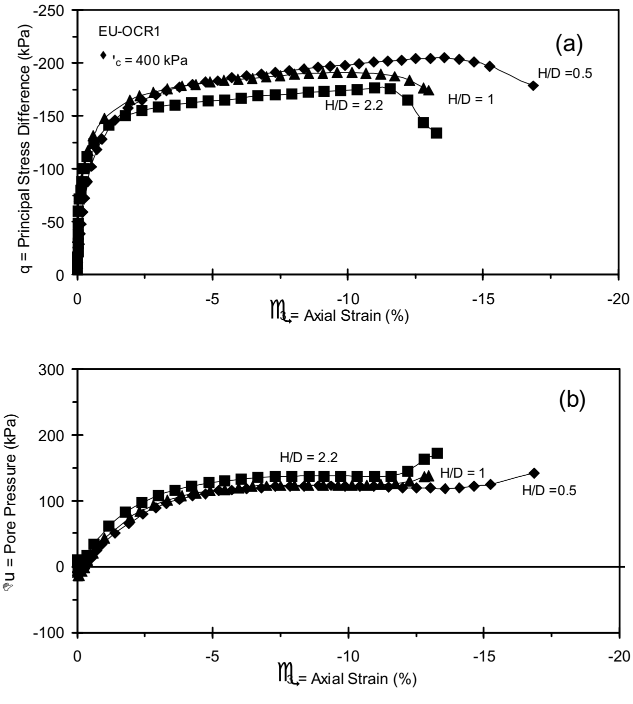

Figure 4. Undrained extension tests on clay (OCR=1) with H/D ratios of 2.2, 1.0 and 0.5: a) principal stress difference v. axial strain; b) excess pore pressure v. axial strain.

These experiments clearly show that a neck always will form in extension tests and the strains are too large in the neck region and too small near the ends of the specimen. Similar results on sands were found by Yamamuro and Lade (1995). The results also indicate that a smaller H/D ratio helps to suppress neck formation and the specimen performs much closer to the uniform strain assumptions. The reason for this result is simply that the neck region in a shorter specimen is a much larger portion of the entire specimen, while in tall specimens it is a much smaller part. Thus, in short specimens the entire specimen is part of the neck, which means that the shearing is relatively uniform.

3.3 *Effects of Necking on the Global Stress-Strain Response in Undrained Tests*

Three undrained extension tests were performed with an initial effective confining pressure of 400 kPa. Strain rates were 0.0134 %/min, which are in accordance with ASTM 4767. Fig. 4a and 4b shows the principal stress difference versus axial

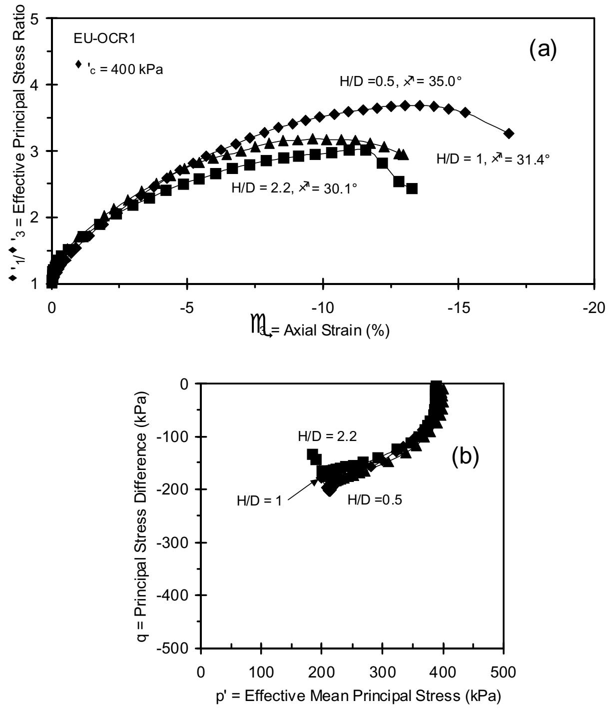

Figure 5. Undrained extension tests on clay (OCR=1) with H/D ratios of 2.2, 1.0 and 0.5: a) effective principal stress ratio v. axial strain: b) effective stress paths.

strain and change in pore pressure versus axial strain plots, respectively. Near the beginning of the tests all three stress-strain curves appear very close together. However, as shearing continues and more axial strains are produced, the specimen with the H/D ratio of 0.5 exhibits greater strength and attains a significantly higher peak stress. Moreover, a significantly larger axial strain-at-failure was observed. The tall specimens produced lower failure stresses and smaller strains at failure. The point at which the principal stress difference dropped off is typically where a shear band became fully developed. Observations indicate a sharp pore pressure rise when the shear band forms. The undrained tests clearly show that the initial stiffness is not seriously affected by necking, because the induced error is relatively small at small axial strains, but the failure condition is substantially underestimated due to the much larger effect of necking at large strains. Fig. 5a and 5b show the effective principal stress ratio versus axial strain curve and the effective stress path on the principal stress difference versus effective mean principal stress plot, respectively. Clearly the effective stress strength and axial strain at effective stress failure is much greater with a shorter specimen. The effective stress friction angles show a five-degree increase with the shorter specimen in Fig. 5a. The friction angle results in extension are greater than in compression, which correlate with most prior studies on both sands and clays. Since the major and minor principal stresses are switched, the greater friction angle in extension still results in lower shear strength than in compression. The effective stress paths for specimens with H/D ratios of 0.5, 1 and 2.2 indicate that the volume change tendency in the specimen can also be affected by necking. Since the short specimens are undergoing much more uniform strains than their taller counterparts, the observed pore pressure response should be more correct. The short specimen indicates a slight reduction in pore pressure (dilatant response) near effective stress failure by displaying a small hook. The pore pressure in the tall specimen does not exhibit this dilatant behavior. This difference is caused when you measure the pore pressure externally, because an average value is produced for the entire specimen. When necking occurs, the specimen has a greater state of stress and strain in the neck region, as opposed to the ends of the specimen where it is lower. Near the beginning of the test, the differences between the two regions are not significant and the response is reasonably accurate. However, near failure, the states of stress and strain are much more advanced in the neck region than at the ends. Thus, in the case of the tall specimen, the small amount of dilation that is exhibited in the neck region is averaged in with the volumetrically contractive response at both ends. Thus, the average external pore pressure response near failure shows a more contractive response when significant necking occurs, while the test undergoing more uniform strains indicates a slight amount of dilation. Thus, when external pore pressure measurement is used, necking can mask the underlying behavior. It should be noted that no prior research into the behavior of clay in extension has utilized smaller H/D ratios.

Therefore, to minimize necking in triaxial extension tests on clays, it is recommended that short specimens with an H/D ratio of 0.5 be used in conjunction with effective lubricated end platens. At this H/D ratio with a specimen diameter of 70 mm, the specimens are still tall enough to allow full shear band development and they have sufficient size to maintain adequate measurement resolution. Larger diameter specimens could be used to increase specimen size and volume to enhance resolution, but analysis showed that carefully calibrated instrumentation produced excellent test data.

4 CONCLUSIONS

An experimental program was conducted to evaluate the effect of necking in triaxial extension tests on kaolinite clay specimens and develop a means of mitigation. The following conclusions could be drawn.

Analysis of photographs during drained extension testing on normally consolidated clay specimens showed that necking always occurs in extension tests. At low axial strains, the errors are relatively small, but as axial strains increase, the failure stress, failure strain, and pore pressures are significantly affected. The strains in the neck region are too large and those near the ends of the specimen are too small when compared with uniform strain assumptions.

Reducing the H/D ratio of the specimen decreases the severity of necking, though it still occurs. Therefore, it is recommended that an H/D ratio of 0.5 be used in triaxial extension tests combined with effective lubrication on the end platens.

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