

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING



This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

<https://www.issmge.org/publications/online-library>

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

Evaluation of instability phenomena in sands: Plane strain versus triaxial compression conditions

Phénomènes d'instabilité dans les sables: comparaison entre les conditions de déformation plane et les conditions triaxiales de révolution

K.A. Alshibli – Louisiana State University-Southern University, Baton Rouge, Louisiana, USA

ABSTRACT: Bifurcation phenomenon in sands is highly dependent on the loading condition. Experimental findings show that the failure of specimens subjected to plane strain loading condition is characterized by distinct shear bands accompanied by softening in the stress response depending on the specimen density and confining pressure. In contrast, the specimens in conventional triaxial compression experiments bulge uniformly in the vicinity of the peak stress and develop a complex multiple symmetrical radial shear bands at higher axial strain levels.

RESUMÉ : La bifurcation dans les sables dépend fortement du mode de chargement. Des résultats obtenus en laboratoire montrent que, en déformation plane, la rupture d'un échantillon de sable est associée à l'apparition de bandes de cisaillement ainsi qu'à une réponse radoucissante de la charge appliquée, fonction de la densité et de la pression de confinement. Au contraire, dans les essais de compression triaxiale de révolution, l'échantillon se déforme uniformément au voisinage du pic de contrainte, et développe un système complexe de multiples bandes de cisaillement symétriques pour des niveaux de déformation axiale plus élevés.

1. INTRODUCTION

Extensive research was carried out in the 1950s on theories of plasticity to extend the concepts developed for metals to materials that failed according to the Mohr-Coulomb criterion. The new ideas made it possible to merge the two distinct concepts (strength and deformation techniques) into one that relies on better understanding of plasticity and resulted in a rapid growth in the field of constitutive modeling of soil behavior. At the same time advanced experimental apparatuses and laboratory procedures were developed to calibrate the models. However, most laboratory experiments on granular materials are performed under Conventional Triaxial Conditions (CTC) for the purposes of evaluating constitutive behavior and stability properties, whereas most geotechnical field problems are closer to the Plane Strain (PS) condition. The triaxial tests performed in most laboratories comprise a simplification over *in situ* states and allow easier and robust experimentation. Most landslide problems, failure of soils beneath shallow and deep foundations, and failure of retaining structures, are cases that can generally be considered as plane strain. Strength and deformation characteristics of granular materials loaded in plane strain may be considerably different from those observed in CTC. Most studies on sands were limited to evaluating the constitutive behavior and in some cases extended to briefly describing the associated instability phenomena. This paper presents the results of a series of PS and CTC experiments performed on fine uniform silica sand known as F-75 Ottawa sand with emphasis on describing the instability phenomena under both loading conditions.

2. MATERIALS AND METHODS

Ottawa sand was used to prepare the specimens. It is a fine-grained, uniform, sub-rounded to rounded silica (quartz) sand (commonly denoted as F-75 banding sand) with mean particle size of 0.22 mm, maximum porosity of 0.446, minimum porosity of 0.327, and specific density of sand particles of 2.65. The specimens were prepared in a terrestrial laboratory by air pluviation (raining) of the sand into a mold at a certain intensity and velocity controlled, respectively, by the opening of the funnel from which the sand is poured and the distance between the funnel and the mold. This ensured uniform specimen density (Alshibli et al. 1996). A thin latex membrane

(0.30 mm thick) was used to encase and isolate sand from the surrounding water medium.

The PS specimens measured 80.8 x 83.3 x 152.4 mm. To impose the plane strain condition, two Lexan walls with dimensions of 11.1 x 104.1 x 152.4 mm were bolted to the lower end platen and braced by two stiff aluminum plates to prevent lateral deflection. The inside walls were coated with silicone oil to minimize friction at the membrane interface during experimentation. A 5 x 5 mm square grid pattern with a line thickness of 0.5 mm was printed on the membrane surface using a special black rubber ink to enable deformation tracking. The mesh size was 120 x 180 mm to cover one side of a plane strain specimen. A video camera was used to record specimens' deformation during compression. Selected images were captured from the video source for further analysis. Table 1 shows a summary of the PS experiments.

Table 1. Summary of the PS experiments and the measured shear band inclination angles.

Exp.	D_r^* (%)	σ_c^{**} (kPa)	ϕ^+ (deg.)	ψ^{++} (deg.)	θ_1^\dagger (deg.)	$\theta_2^{\ddagger\dagger}$ (deg.)
PS1	55	15	42.1	10.4	52	52
PS2	47	100	39.8	7.6	55	54
PS3	97	15	49.8	16.7	57	54
PS4	87	100	48.2	12.8	57	53

* Relative density.

** Confining pressure.

+ Peak friction angle.

++ Dilatancy angle.

† Inclination angle for the first shear band.

†† Inclination angle for the second shear band.

The CTC experiments were conducted on cylindrical specimens (75 mm in diameter and 150 mm long) at effective confining pressure of 1.30 kPa. In each experiment five axial compression, unloading and reloading cycles were completed at regular intervals (at 5% axial strain intervals) to a 25% final axial strain. The experiments were performed aboard the Space Shuttle during the NASA STS-79 and STS-89 missions. A special triaxial laboratory was fabricated for this purpose that provides very precise measurements and controls for the axial load, axial displacement, confining pressure, bulk

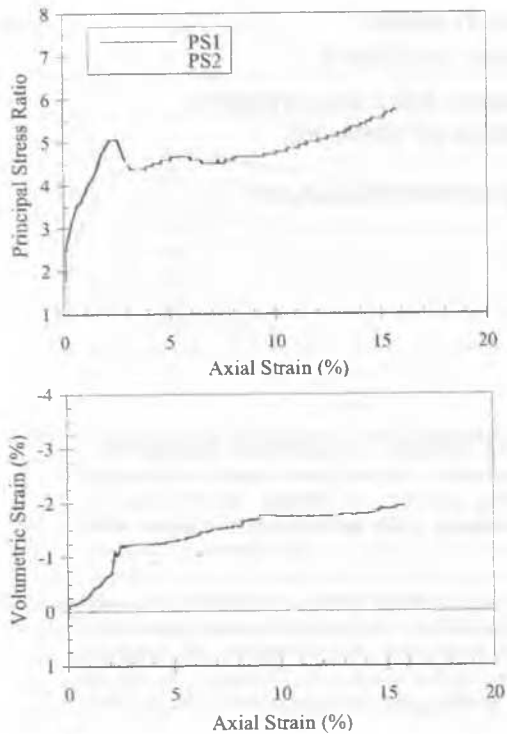


Figure 1. Principal stress ratio versus axial strain, and volumetric strain versus axial strain for the loose PS Experiments.

volumetric changes, ambient temperature, environmental acceleration levels, etc. (see Sture et al. 1998 for more details). After Shuttle landing, specimens were subsequently retrieved and subjected to an extensive post-flight analysis including computed tomography, profile measurements, etc. Additional CTC experiments were also conducted in a terrestrial laboratory to investigate the effects of gravity on the constitutive behavior of sands.

3. RESULTS AND ANALYSIS

3.1 PS experiments

The deformation and failure patterns of the PS experiments are explained with the help of overall axial strain versus principal stress ratio and axial strain versus volumetric strain responses of loose and dense specimens shown in Figures 1 and 2, respectively. The observed softening after each peak is a consequence of bifurcation instability in the neighborhood of the peak. This causes localization of deformations into narrow shear bands and enables the kinematics of a failure mechanism to develop. As a consequence, softening behavior follows the peak strength level. In other words, the observed softening is a global response to the slip mechanism at the onset of shearing. Softening becomes more severe as the specimen density increases. Failure in all experiments involved two conjugate shear bands initiated at different axial strain levels depending on the confining pressure and specimen density (Figs 3 & 4).

For the loose specimen tested under low confining pressure (PS1 in Fig. 1), the first shear band was initiated at about 2.5% overall axial strain followed by softening in the nominal stress response. The second shear band initiated after additional shearing (overall $\epsilon_1 \approx 5.5\%$) along the first shear band. Shearing then continued along the two bands until the completion of the test. Softening became more pronounced for the dense specimen tested under low confining pressure (PS3 in Fig. 2), otherwise the failure mechanism is very similar to that of the loose specimen.

The behavior of the specimens subjected to high confining pressure (100 kPa) was quite different in terms of specimen instability as compression proceeded. For the PS2 and PS4 specimens, the first shear band started at approximately

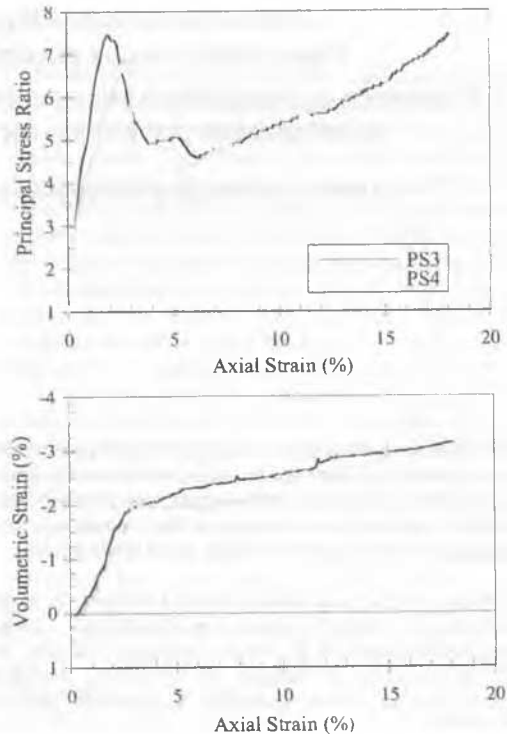


Figure 2. Principal stress ratio versus axial strain, and volumetric strain versus axial strain for the dense PS experiments.

3.3% overall axial strain with shearing continuing along the band until a relatively higher nominal axial strain level ($\epsilon_1 > 10\%$) was reached, when the second shear band initiated causing softening in the stress response.

All specimens showed dilative behavior (compression is positive in Figs 1 & 2) with no evidence of volume decrease for those tested at 15 kPa confining pressure, and only a small amount of initial compression (less than 0.3% volumetric strain) was observed in the early stages of compression for specimens subjected to 100 kPa confining pressure. The dense specimens show more dilative behavior compared to loose specimens, and the volume change decreased as the confining pressure increased. Also, the specimens showed continuous dilative behavior without reaching the constant volume condition even at high nominal axial strains. Moreover, the softening in the principal stress response is accompanied by a sudden volume increase, especially for PS4 specimen (Fig. 2, a dense specimen tested at 100 kPa confining pressure). This might be attributed to the slip mechanism that occurred at the onset of shear band formation that resulted in a sudden volume increase.

3.2 CTC experiments

It is well known that PS experiments are more susceptible to bifurcation phenomena that will lead to localized deformations into narrow shear bands compared to CTC experiments where diffuse bulging is the common failure mode (e.g., Lee 1970, Marachi et al. 1981, Peters et al. 1988, Peric et al. 1992 & 1993). However, such bulging in CTC experiments (Fig. 5) is just an external manifestation of a rather complex internal structure where primary and secondary shear bands develop at relatively high axial strain levels. Figure 6 shows typical principal stress ratio versus axial strain responses of two CTC experiments performed in a weightless environment aboard the Space Shuttle under very low effective confining pressure (1.30 kPa). The peak stress was reached at about 1.5% axial followed by gradual softening until about 5% axial strain where the residual-stress state is reached. The post-peak softening is more pronounced for PS experiments (Fig. 2) compared to CTC experiments and it usually indicates the onset of a shear band.

Computed Tomography (CT) technique was used to study

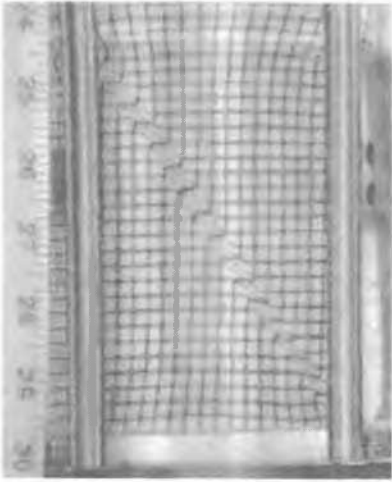


Figure 3 Typical failure mode for a PS specimen subjected to 9.6% axial strain.

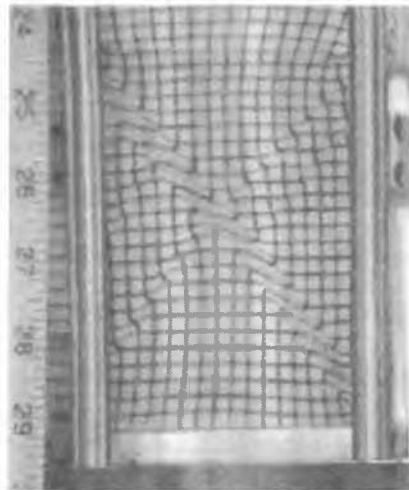


Figure 4. Failure progress for the specimen shown in Figure 1 (axial strain = 19%).

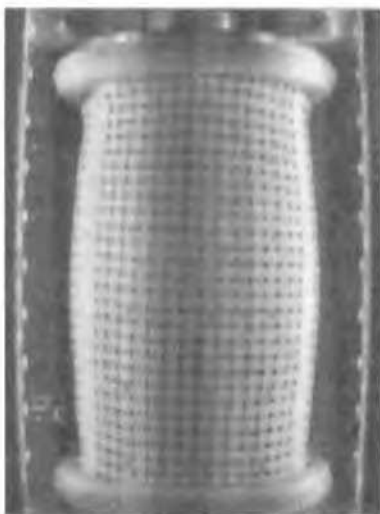
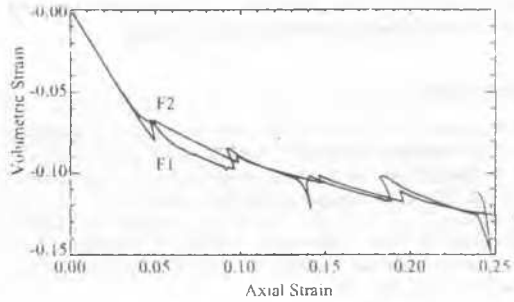
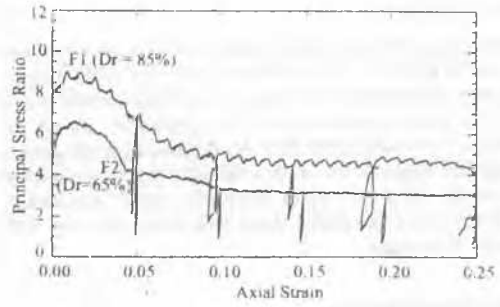


Figure 5. CTC F1-specimen compressed to 25% axial strain.

the internal fabric of the CTC specimens. It is a powerful nondestructive scanning method to visualize the internal density variation and to detect inhomogeneity of materials (Alshibli et al. 2000). It can be seen from Figure 7 that the failure of the specimens is characterized by multiple shear bands. Mainly, two circular shear cones are seen extending at



large angles from each end of the specimens. A large number of inclined radial discrete bands of lower densities extend outward from the boundary of the cones (Fig. 7C). Specimen's density variation is represented by the image color contrast. For example, darker shear planes are a result of intense shearing which resulted in dilation and hence lower density, whereas light-color areas experienced minimal deformation. The deformation is symmetrical in the radial direction. Furthermore, there no evidence of localization before 5% axial strain (Fig. 7a) and primary conical shear surfaces develop at higher axial strains followed by the development

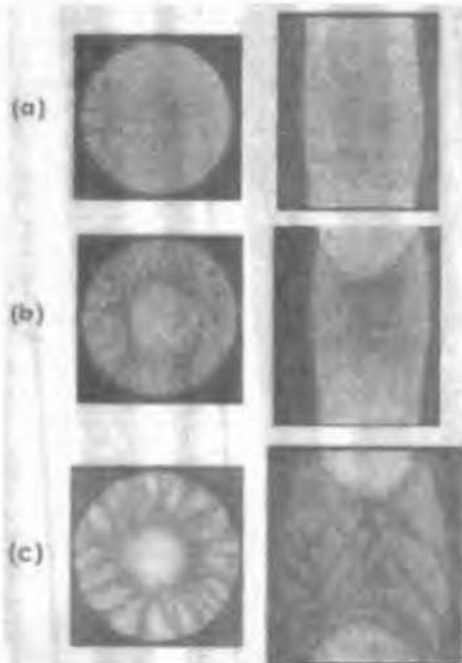


Figure 7. CT images of CTC specimens compressed to (a-c) 5, 9, and 25% axial strain ($\sigma_1 = 1.30$ kPa).

of symmetrical radial shear bands that extend to the specimen circumference. That explains why the CTC specimens tend to show a continuous and relatively high volumetric strain (Fig. 6) even at high axial strain and the critical state condition was never reached even after compressing the specimen to 25% axial strain.

4. CONCLUSIONS

It is apparent that CTC specimens remain relatively well into the deformation process. This indicates that the CTC experiment is a very appropriate experiment to obtain constitutive properties for soils, as opposed to PS experiment. Based on these findings, it is quite clear that the deformation processes and the stability behavior are quite different for axisymmetry and plane strain. This also raises questions about our understanding of soil behavior under these two basic but very different modes of loading.

5. ACKNOWLEDGMENTS

The author gratefully acknowledges the financial support provided by NASA/ George Marshall Space Flight.

6. REFERENCES

- Alshibli, K.A., Costes, N.C., & Porter, R. 1996. Mechanics of granular materials. *International Symposium on Optical Science, Engineering, & Instrumentation, SPIE-The International Society for Optical Engineering*. Denver, 4-5 August 1996, 2809: 303-310.
- Alshibli, K.A., Sture, S., Costes, N.C., Frank, M., Lankton, M., Batiste, S., & Swanson, R. 2000. Assessment of localized deformations in sand using x-ray computed tomography. *ASTM, Geotechnical Testing Journal*, 23 (3): 274-299.
- Lee, K. 1970. Comparison of plane strain and triaxial tests on sand. *ASCE, Journal of Soil Mechanics and Foundations division*, 96 (3): 901-923.
- Marachi, N., Duncan, J., Chan, C., & Seed, H. 1981. Plane-strain testing of sand. In Yong & Townsend, (ed.), *Laboratory Shear Strength of Soils*. ASTM, STP 740: 294-302.
- Peric, D., Runesson, K., & Sture, S. 1992. Evaluation of plastic bifurcation for plane strain versus axisymmetry. *ASCE, Journal of Engineering Mechanics*, 118(3): 512-524.
- Peric, D., Runesson, K., & Sture, S. 1993. Prediction of plastic localization using MRS-Lade model. *ASCE, Journal of Geotechnical Engineering*, 119(4): 639-661.
- Peters, J., Lade, P. & Bro, A. 1988. Shear Band Formation in Triaxial and Plane Strain Tests. In Donaghe, Chaney, and Silver (ed.), *Advanced Triaxial Testing of Soil and Rock*, ASTM STP 977: 604-627.
- Sture, S., Costes, N., Batiste, S., Lankton, M., Alshibli, K., Jeremic, B., Swanson, R., & Frank, M. 1998. Mechanics of granular materials at low effective stresses. *ASCE, Journal of Aerospace Engineering*, 11 (3): 67-72.