Properties of Sand under Low Effective Stresses

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Abstract

The presentation focuses on different sets of drained and undrained cyclic triaxial experiments on loose and dense cylindrical specimens of subangular quartz sand, which were conducted under displacement control at very low effective stress levels. The experiments were motivated by the need to enhance our understanding of low-stress phenomena and mechanical properties of both terrestrial soils and regolith on the Moon and Mars subjected to low gravity conditions. The first two sets of experiments were conducted under drained conditions on NASA Space Shuttle (STS-79, 1996, and STS-89, 1998) under microgravity conditions, and the last set was recently conducted on Columbia (STS-107) in January, 2003. In the case of the drained experiments, the effective confinement pressures were held constant throughout the experiments, and they were in the range of 0.05 to 1.30 kPa, which in the case of the undrained experiments these same effective stress levels comprised the initial states. The initial relative densities of the specimens were in the range of 35% to 85%. In the drained experiments we observed peak friction angles as high as 72°± 2° together with dilatancy angles in the range of 30° ±1°. Constant-volume friction angles of 34 ±1 degrees were recorded at relatively high strain levels in all the drained experiments. Transitions from a stable solid to a viscous liquid state (liquefaction) were observed in several undrained experiments at very low initial

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density states, however, in several cases dilative behavior was observed at very low effective stresses as well as low initial relative densities (35-45%). For several of the specimens extensive computed tomography records were obtained, which show complex patterns of shear band formation, which usually emerged at levels of 2-3% axial strain after peak strength had been reached. The presentation will focus on experimental technique, observations and data, as well as computed tomography data, and modeling results.

Introduction

Unlike materials such as metals, polymers, cementitious concrete, rocks, etc , whose strength and deformation characteristics are derived mainly from strong cohesive forces from chemical bonding or cementation, the constitutive behavior of uncemented granular materials, including strength, stiffness modulus behavior, dilatancy, localization of deformation, shear band formation, and instability behavior are to a large extent derived from interparticle friction resulting from normal forces acting on particles or particle groups. Therefore, under low confining effective stress levels, behavior is highly dependent on gravitational body forces. Costes and Sture (1981), Bolton (1986), and Jaeger et al. (1996a, 1996b, 1997) provide detailed reviews of behavior of granular materials.

The force-displacement behavior of granular materials is fabric or structure dependent, highly nonlinear, dilatant and non-conservative. The gravity-induced stresses in laboratory specimens are nearly of the same order of magnitude as the externally applied tractions in low-pressure tests, thus limiting the size of the specimens. However, the same laboratory specimens must be sufficiently large to replicate the behavior of large geologic deposits *in situ*.

In granular materials, gravity-driven particle convection induces material inhomogeneities and anisotropies during experiments, especially under very low confining pressures, which alter the initial fabric of the specimens and hence their constitutive relations. Accordingly, from an engineering point of view, uncertainties of unknown magnitude are introduced regarding the actual behavior of large masses in the field for which specific experiments are intended to emulate.

Under moderate-to-high stress levels, the influence of gravity on the behavior of experiments may not be pronounced and, therefore, the test results in a terrestrial (1 g) environment may be sufficiently conclusive for engineering purposes. However, experiments on granular materials under very low stress levels can only be performed in a microgravity environment in a stable manner (Costes and Sture, 1981). In addition, the gravity-induced stresses within the specimen transform the experiment into a complex boundary value problem, where the constitutive properties and stability issues cannot in general be resolved by inverse identification techniques due to the highly nonlinear nature of the constitutive equations and stability behavior (Sture et al , 1988).

The same arguments could be made for the influence of gravitational body forces on a multitude of issues associated with granular materials under very low effective stress levels. Such issues include: determination of critical porosity or void ratio in granular materials and their relation to the maximum porosity of the same materials, both with and in the absence of shear-band formation; bifurcation instability and associated shear-band formation and strain softening at persistent and controlled effective stress states.

In order to further our understanding in this area of granular materials, a series of experiments has been flown on three Space Shuttle microgravity missions (Sture, et al., 1998, 1999, 2003). A description of the experiments and discussion of findings follows.

Experimental Technique

Hardware. The experiment hardware consisted of a set of test cells and a control apparatus, or Twin Double Locker Assembly (TDLA). Each test cell contained a an Ottawa F-75 sand specimen placed by dry pluviation in cylindrical form (75 mm diameter and 150 mm height) and encased in a latex membrane surrounded by water which provides an external confining/stabilizing pressure. The water was then encased in a Lexan sleeve for visibility, and sealed on both ends with aluminum endcaps. For STS-79 and STS-89 experiments, the sand itself remained dry, with the pore space air-filled. For STS-107 experiments, the specimens were water-saturated through a method of back-pressure saturation, filling the internal pore space with de-aired, de-ionized water. 'B-Value' measurements, which may be correlated to percent saturation, were made to record progress and indicate when satisfactory saturation was achieved. The displacement (control) boundaries were provided by highly polished and oversized tungsten carbide end platens, which provided for very low specimen-end interface friction angles of 2-4 degrees. The test cell had sensors to measure load and temperatures, as well as a stepper motor to move the loading ram, and lighting for cameras.

The TDLA provided data recording and microprocessor control of the experiments including pressure control of the specimen pore space and the confining fluid, displacement control, and data recording. It also provided a viewing stage for three video cameras located around the viewing stage to provide 360° coverage of the specimen.

To process a specimen, a single test cell was placed in the viewing stage of the TDLA, connected electrically, and in turn, plumbing was connected. Pressure accumulators set and maintained the effective confining pressure applied to the membrane-specimen surface, by controlling both the specimen internal and external pressures. The confining pressure was in all experiments controlled within a range of +/- 0.03 kPa. Volume change was measured by overall movement of the accumulators, and displacement was measured by the movement of the test cell loading ram. The accumulators and loading ram were driven by stepper motors, and the record of steps taken by the motors was converted into volume and distance. Load was measured by an internal load cell, with a +/- 310N range.

Control of the experiment was through a laptop computer running a User Interface program. A shuttle crew member was responsible for test cell mounting and exchange, as well as User Interface control. New to STS-107, a TCP/IP link to the ground, allowed data transfer and limited commanding by ground personnel. Higher rate prime data were recorded on two redundant Flash Memory cards per experiment, inserted into the CEU of the TDLA. For STS-79 and STS-89, data were also gathered on specimens post-flight, through computed tomography examination of the soil structure.

Test Characteristics. A total of 18 microgravity tests will be discussed (Table 1). Initial relative density included medium-dense (85%), medium (65%), and loose (35-55%) specimens. Medium and medium dense specimens were over-consolidated due to a required transportation pressure of 103.5 kPa. Loose specimens were all reformed, resulting in a normally consolidated specimen, with exception to one specimen which was intentionally over-consolidated after reformation. All experiments were performed using an axial, quasi-static, cyclic displacement loading mode. For fifteen experiments, the cyclic displacement was of relatively large magnitude: the loading sequence consisted of 5 displacement levels of 5% axial strain each, separated by unloading cycles, for a total axial strain of 25%. The displacement rate during loading was 35 mm/hr. The displacement rate during unloading was 17.5 mm/hr. For three experiments, the cyclic displacement was small magnitude, with 10 loading-unloading cycles of loading from 0% to 0.33% axial strain with a further 7 cycles loading up to 3.3% axial strain. Both drained or undrained testing were performed. In these undrained tests, once behavior was identified, the compression was paused and the confining stress was reset, which resulted in a slight density change, and the test was begun again for a total of five tests which were not compressed to the full 25% axial strain.

Table 1 Test Characteristics

Quantity	Specimen Properties			Test Properties	
	Relative Density	Consolidation	Pore Space	Cyclic Magnitude	Drainage
3	85%	OC	Dry	Large	Drained
1	85%	OC	Saturated	Large	Drained
3	65%	OC	Dry	Large	Drained
3	65%	OC	Dry	Small	Drained
2	Loose	Reformed	Saturated	Large	Drained
1	Loose	Reformed, OC	Saturated	Large	Drained
5	Loose	Reformed	Saturated	Large	Undrained

Observations and Data

Material Behavior. For dry, medium and medium-dense specimens, peak friction angles as high as 72° ±2° together with dilatancy angles of 30° ±1° were measured, which are nearly twice the level observed at higher confining pressure levels that are typically considered in terrestrial applications (Bolton, 1986). Likewise, unusually high elastic moduli were observed at these low pressure levels, which were nearly an order of magnitude higher than predicted by conventional theory. Data from the test of a medium-dense, saturated specimen were collected, though a portion from a short time prior to the beginning of compression until approximately 4.5% axial strain is not available. The principal stress ratio data that are available match well with other experiments, though the peak stress ratio was not retrieved. Video from the experiment is available and is under analysis for obtaining an accurate volumetric trace and refining the dilatancy angle measurement.

A total of 5 undrained experiments with specimens at very low initial density states were performed. Liquefaction was observed in three of these undrained experiments. With a slight variation in the initial density, specimens were also observed to stiffen with a decrease in the pore water pressure.

Three drained experiments were performed in the same density range as the undrained experiments. Volumetric strain records show good correlation with the undrained experiments. These specimens also show good correlation with the higher-density drained experiments. Although the residual principal stress ratio is slightly lower than seen with denser specimens, all tests show continued volume change at 25% axial strain and principal stress ratio are all approaching a median value. In addition, the effect of overconsolidation on strength and volume change characteristics of a specimen, show no clear indication of any effect of overconsolidation on specimen behavior.

Computed Tomography. The microgravity experiments, supplemented with low-pressure ground experiments, have been extensively studied utilizing computed tomography to characterize the internal structure and to track the onset and propagation of shear bands (Batiste, 2001, Alshibli, et al, 2003). Cross-axial scans were obtained at 1 millimeter spacing over the long axis of the specimen. The slices were used to construct 3-dimensional volumetric images of the specimen, and inner features were then examined by exposing internal planes. In addition to qualitative assessments, a vigorous quantitative analysis was performed. Regional density, structural distribution, and shear band characteristics including orientation, width, and void ratio, were measured. The CT technique has demonstrated good ability to detect specimens' inhomogeneities and localization patterns, and to quantify void ratio variation within sand specimens.

The specimens expanded uniformly at the post-peak stress level and developed complex multiple symmetrical radial shear bands which emerged at levels of 2-3% axial strain after peak strength had been reached. Cross-sections normal to the axis of compression showed radial regions of lower and higher density areas. A large number of radial discrete bands of lower density, similar in shape to turbine blades mounted on a central hub, extend outward from the boundary of the cones, seen as the central, circular regions. When examining cross-sections parallel with the axis of compression, extensive areas of generally uniform density were seen outside of shear zones. The circular shear cones were seen to extend at large angles from each end of the specimens, though the cone on the stationary end platen is more clearly developed. The cones were clearly defined by the specimen-end-platen interface friction and the restraint posed by the stretched latex membrane in the external contact region. Outside of the cones, several inclined lines of low density were identified as the radial bands.

Modeling. Modeling has been performed by means of a non-linear finite element analysis (Jeremic et al., 1999, 2001). The analysis technique was designed to inversely identify material properties and has the ability to consider behavior with or without a gravity field. The analysis, which was also able to simulate the large dilatancy behavior, was also able to capture the variation of high peak frictional strength of the lowest stress loads to friction properties observed at higher confinement stresses.

Conclusions

Very low effective stress drained and undrained cyclic triaxial experiments on loose and dense cylindrical specimens of subangular quartz sand were conducted under displacement control in the microgravity environment. In the case of drained experiments on medium and medium-dense specimens, high peak friction angles and dilatancy were observed. In low-density specimens, transitions from a stable solid to a viscous liquid state (liquefaction) were observed in several undrained experiments. In several cases of drained experiments at similarly-low densities, slight dilative behavior was observed. For several of the specimens extensive computed tomography records were obtained, which show complex patterns of shear bands. In addition, finite element modeling was performed.

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