NASA-CR-204613

NAS8-38779

PROCEEDINGS REPRINT

SPIE—The International Society for Optical Engineering

NDB
IN-29-CR
030236
[illegible]

Reprinted from

Space Processing of Materials

4–5 August 1996
Denver, Colorado

SPIE
P
PROCEEDINGS SERIES

Volume 2809

Box 10, Bellingham, Washington 98227 USA. Telephone 360/676-3290.

MECHANICS OF GRANULAR MATERIALS (MGM)

Khalid A. Alshibli

Research Associate, Department of Civil, Environmental and Architectural Engineering, University of Colorado at Boulder, Campus Box 428 , Boulder, CO 80309-0428.

Nicholas C. Costes

Senior Research Scientist, Space Science Laboratory, ES 71, NASA/ Marshall Space Flight Center, AL 35812

Ronald F. Porter

Manager, Projects Office, FA 25, NASA/ Marshall Space Flight Center, AL 35812

ABSTRACT

The constitutive behavior of uncemented granular materials such as strength, stiffness, and localization of deformations are to a large extend derived from interparticle friction transmitted between solid particles and particle groups. Interparticle forces are highly dependent on gravitational body forces. At very low effective confining pressures, the true nature of the Mohr envelope, which defines the Mohr-Coulomb failure criterion for soils, as well as the relative contribution of each of non-frictional components to soil's shear strength cannot be evaluated in terrestrial laboratories. Because of the impossibility of eliminating gravitational body forces on earth, the weight of soil grains develops interparticle compressive stresses which mask true soil constitutive behavior even in the smallest samples of models. Therefore the microgravity environment induced by near-earth orbits of spacecraft provides unique experimental opportunities for testing theories related to the mechanical behavior of terrestrial granular materials. Such materials may include cohesionless soils, industrial powders, crushed coal, etc.

This paper will describe the microgravity experiment, "Mechanics of Granular Materials (MGM)", scheduled to be flown on Space Shuttle-MIR missions. The paper will describe the experiment's hardware, instrumentation, specimen preparation procedures, testing procedures in flight, as well as a brief summary of the post-mission analysis. It is expected that the experimental results will significantly improve the understanding of the behavior of granular materials under very low effective stress levels.

KEY WORDS: Microgravity, Sand, Triaxial, Axisymmetry, Granular, Particulate, Shear Bands

0-8194-2197-9/96/$6.00

1. INTRODUCTION

Granular materials and, in particular, geological deposits in their in-situ state are either dry, partially or fully saturated. In such states, the interaction between solid particles and interstitial liquids, which in turn is a function of external loading and drainage conditions during loading, can result in many catastrophic events from an engineering point of view. Such events may involve the loss of life, property and natural resources (e.g. landslides, soil liquefaction caused by earthquakes or wave action, dam failures, land erosion, etc.).

Granular materials are also referred to as *cohesionless* materials if there is no cementation or cohesive forces between soil grains. The basic and dominant factor responsible for the strength of cohesionless soils is frictional resistance between soil particles at contact. However, at very low effective confining pressures, the shear strength component due to interparticle friction could be negligible. At such low effective stress states, other shear strength components contribute to the soil's resistance to deformation and may include the following:

1. particle interlocking which resists particle rearrangement under constant volume, or *dilatancy effects*[1] inducing volume changes within the soil mass during shear.
2. capillary pressures which develop an apparent cohesion in partially saturated soils.
3. physico-chemical forces of attraction or bonding between particles.

During earthquakes, the shaking of ground may cause a loss of strength or stiffness in loose saturated sands that results in the settlement of buildings, landslides, earth dam failures, or other hazards. The process leading to such loss of strength or stiffness is called *soil liquefaction*[2] and is associated with high excess pore fluid pressures generated within the soil mass as a result of the earthquake excitation. Also, as a result of an upward flow of water toward the ground surface, caused by the dissipation of excess pore fluid pressures from underlying strata liquefied by the same earthquake event, seepage forces acting in an upward direction could develop *quick sand* conditions in the overlying strata. The effect of such *quick conditions* include sand boils on level ground surface, sinkage of buildings or other structures, or flotation of buried structures.

Laboratory tests in a terrestrial (1-g) environment to simulate soil liquefaction by earthquakes are not feasible because of specimen weight and size limitations. A zero effective stress can only be produced at local spots in the specimen. In-space (microgravity) experimentation allows the use of weightless soil specimens and testing apparatus. Also, in the absence of gravitational body forces, it should be possible to create a uniform zero or near-zero effective stress state throughout a soil test specimen.

At low interparticle stresses which can result either from low applied stresses or from excess pore fluid pressures developed within the soil mass without corresponding changes in the total applied stresses the presence of gravitational body forces acting on solid particles and interstitial fluids exerts a pronounced influence on movements of individual particles or particle groups. Such movements, in turn, cause changes in soil fabric which results in significant changes in the interparticle frictional forces contributing to the soil's strength and deformational characteristics.

These experimental limitations on earth have important implications in geotechnical and earthquake engineering. For example, at or near zero effective stresses, quantitative evaluation of the contribution to soil's shear strength by particle interlocking cannot be accomplished by direct means at the present time. Yet, this shear strength component may be one of the most important factors affecting the stability of cohesionless earth masses under seismic loading since it controls arching phenomena and volume changes resulting from dilatancy effects, hence, excess pore fluid pressure build-up or dissipation. The microgravity environment induced by near-orbits of spacecraft provides unique experimental opportunities for testing theories related to the mechanical behavior of granular materials. It eliminates the effects of specimen weight, specimen size, minimizes the effects of boundary conditions and a makes it possible to create a uniform near-zero effective stress state throughout a soil test specimen.

The experiment results are expected to lead to a better understanding of the constitutive behavior of granular or particulate materials under very low effective stresses. This is of a major scientific and technological importance to a variety of disciplines such as[3]:

1. soil mechanics and geotechnical engineering.
2. earthquake engineering.
3. coastal and off-shore engineering.
4. mining engineering, including mines, tunnels and shafts.
5. technologies related to granular solid-flow processes such as transportation of grains, design of silos and bunkers.
6. powder technology.
7. Terrestrial and planetary Geology.
8. Erosion Processes.
9. Off-road locomotion.

2. EXPERIMENT DESCRIPTION

The MGM experiment is scheduled to be flown on the SpaceHab of the Space Transportation System (STS) for testing under microgravity condition. A total of nine constant displacement triaxial (axisymmetric) compression tests will be performed to achieve the science objectives. The first three tests will be performed on dry, dense sand specimens during the Space Shuttle-SpaceHab-MIR-4 mission scheduled for launch on August 1, 1996. The subsequent six tests will be performed on fully saturated, loose sand specimens under undrained conditions. They will be flown on two future Space Shuttle-MIR missions with the second series of three tests to be performed under quasi-static axial compression condition and the last series of three tests under cyclic compression and extension loading mode.

2.1 Hardware description

Double-Locker assemblies are used to provide structural support for the experiment instrumentation and the three test devices. Each locker is 420.7 mm wide by 511.2 mm high by 495.3 mm deep. They will be mounted side by side on the SpaceHab module wall. Figure 1 shows a photograph of the MGM double-locker assemblies. The three test cartridges will be mounted in the lockers during orbiter launch and landing using clamps (see, 1 in Figure 1). Figure 2 shows a test cartridge (see, 1 in Figure 2) mounted in the left locker of Figure 1 using a clamp (see, 2 in Figure 2).

2.2 Specimen preparation

Ottawa sand is used to prepare the specimens. It is a fine-grained, uniform, sub-rounded to rounded silica (quartz) sand. It is commonly denoted as *F-75* or *banding* sand. A thin latex membrane (thickness is 0.30 mm) is used to encase and isolate sand from the surrounding water medium. The latex membrane is stretched along the inside of a 75 mm in diameter by 150 mm long lexan split mold and held aligned by vacuum. The mold is then attached to the bottom pedestal of the test cartridge, the membrane is stretched over the bottom end-platen (see, 7 in Figure 3) and sealed using two o-rings. Homogeneous sand specimens (see, 1 in Figure 3) are prepared by air pluviation (raining) of the sand at a certain intensity and velocity (controlled by the opening of the funnel from which the sand is poured and the distance between the funnel and the mold, respectively) into the mold. Upon filling the mold, The top end-platen (see, 8 in Figure 3) is attached, the membrane is stretched over the end-platen and sealed using two o-rings. A vacuum is then applied to the inside of the specimen to prevent its collapse and the mold is split and taken out.

The two end-platens (see, 7 and 8 in Figure 3) have an enlarged diameters (101.6 mm) compared to a 75 mm specimen's diameter and with a hard, highly polished tungsten carbide disks covering the interface with the specimen. This allows specimen's lateral expansion with minimum restraint from the end platens during compression. A lexan jacket and top end plate (see, 5 in Figure 3) are used to seal the test cartridge. The test cartridge is filled with distilled water and pressurized to 103 kPa confining pressure to provide stability to the specimen during transportation, storage, launch, and landing. The inside of the specimen is kept vented to the atmosphere. The axial load applied to the specimen is measured by a sensitive load cell mounted on the top end-platen (see, 2 in Figure 3).

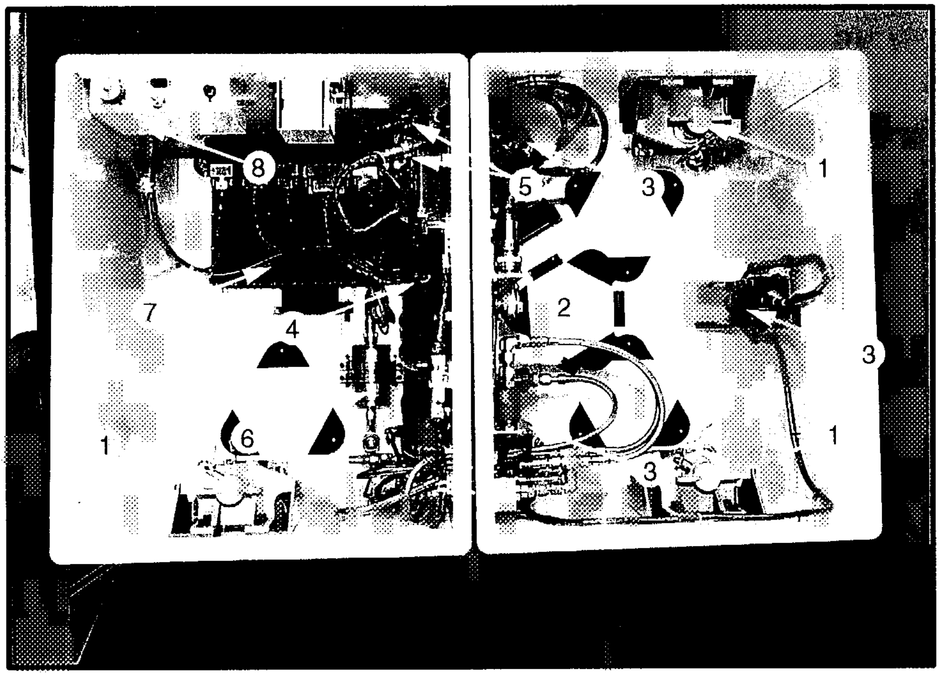

FIGURE 1 — MGM Double Locker Assemblies.

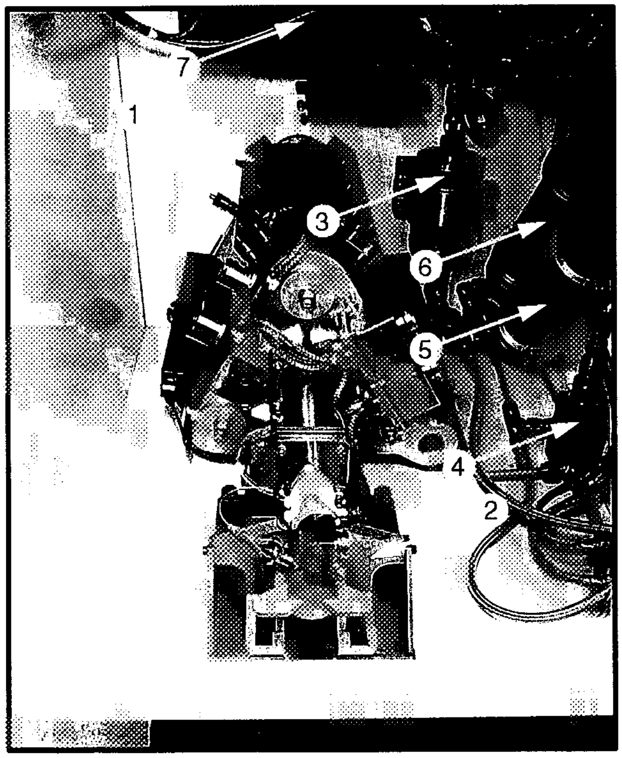

FIGURE 2 — MGM Test Cartridge Mounted in the Left Locker.

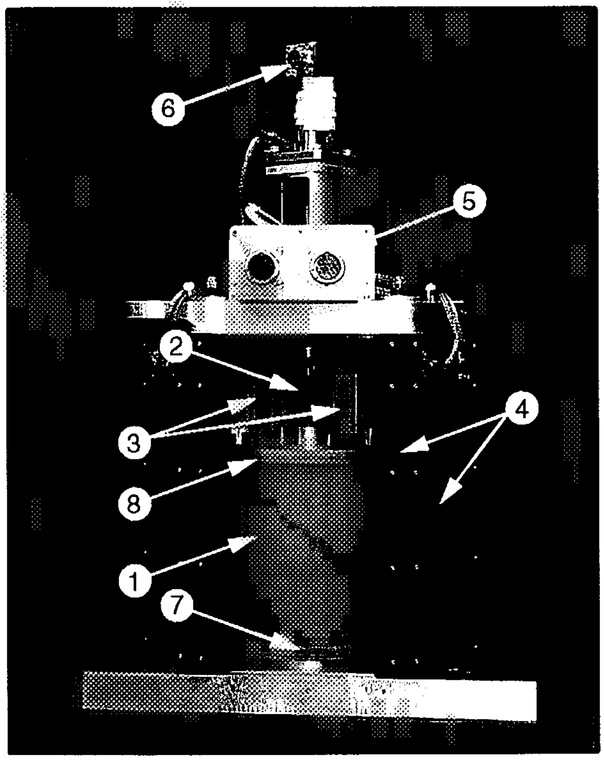

FIGURE 3 — MGM Test Cartridge.

Three spring-type bellows are also attached to the top end-platen (see, 3 in Figure 3) to compensate for any pressure loss during transportation, storage, launch and landing. A constant axial displacement rate of 35 mm/hour is used to subject the specimens to five loading, unloading and reloading cycles at regular intervals using a stepper motor (see, 6 in Figure 3) which drives a shaft attached to the load cell.

2.3 In-orbit testing

In orbit, the crew remove two test cartridges from the lockers and stow them aside. Then, the third test cartridge is moved out and clamped in the test pad (see, 2 Figure 1). Three Charged-Coupled Device (CCD) video cameras (see, 3 in Figure 1) are used to monitor and provide 360 degree video coverage for the specimen's deformation during testing. A square grid pattern is printed on the latex membrane surface (not shown in Figure 3) to facilitate further post-mission deformation analysis. The water confining pressure surrounding the specimen and the air pressure inside the specimen are controlled by two piston-driven cylindrical accumulators (see, 4 in Figure 1 or 5,6 in Figure 2). The two stepper motors (see, 5 in Figure 1) which are used to drive the pistons are controlled by the test software. The accumulator connected to the water side (i.e. confining pressure) is also used to measure the specimen's volume change from the amount of water pumped in or out of the test cartridge.

The three tests of each series will be performed under 1.30 kPa, 0.52 kPa and 0.052 kPa confining pressure conditions. A Tavis differential pressure transducer (see, 6 in Figure 1 or 3 in Figure 2) is used to control the lower confining pressure (0.052 kPa) test and a Validyne differential pressure transducer (see, 4 in Figure 2) is used to control the other two tests. A Combined Electronics Unit (CEU) (see, 7 in Figures 1 and 2) which is powered through the power switch (see, 8 in Figure 1) contains a microprocessor control, data processing and storage, video and illumination control, and emergency shutdown control. The crew run the experiment by a Payload and General Support Computer (PGSC) which automatically controls and displays the experiment progress. The test is terminated when a 38 mm axial compression is achieved after which the test cartridge is pressurized to 103 kPa confining pressure and stored in preparation for orbiter landing.

2.4 Post-mission analysis

Laser techniques will be used to make surface profile measurements for the three sand specimens. In addition, the specimens will be impregnated by ultra-low viscosity resin (20 centipoise) and thin sections will be cut for microscopic image analysis. The video recorded images taken during the experiment's testing, laser profile measurements and thin sectioning measurements will enable building a three dimensional model for each test specimen from which the onset of formation of shear bands, local instabilities, bifurcation, as well as motion of groups of particles can be tracked and followed. This is crucial to asses the influence of localized deformations on the specimen's global behavior. A precise measurement of the thickness and orientation of the localization zones or shear bands will also be made which is highly influenced by the effective stress level. The shear band thickness appears to be substantially increased at low effective stress levels (2 kPa or lower). However, no experimental evidence exists because of impossibility of getting good experimental results in a 1-g environment as mentioned earlier. The shear band orientation may also differ from solutions proposed by Coulomb and Roscoe[4] which give a good prediction for higher effective stress levels.

Understanding the constitutive behavior of granular media, as related to the material instability of sands in a micro-gravity environment will significantly enhance the calibration of numerical models used to describe the mechanical behavior of such materials. Flights 2 and 3 experiments will be performed of fully saturated loose sand which will have potential applications to earthquake engineering, understanding the liquefaction phenomenon, and dynamic analysis of structures. Issues concerning material behavior under different stress conditions will be assessed by comparing MGM experiment results (triaxial or axisymmetric condition) with plane strain testing conditions[5]. Peric *et al.*[6] showed (analytically) that the stress state (i.e. loading configuration) is of the most importance for the localization of deformation in homogeneous materials.

3. SUMMARY

The MGM experiment is expected to significantly improve and enhance the scientific understanding of issues related to the constitutive behavior and deformation characteristics of granular materials under very low effective stresses. The experiment results are of potential importance to a variety of disciplines some of which are listed in the introduction.

4. ACKNOWLEDGMENTS

The authors greatly acknowledge financial support from NASA, Marshall Space Flight Center, Contract NAS8-38779.

5. REFERENCES

1. Rowe, P. W., "The Stress-Dilatancy Relation for Static Equilibrium of an Assembly of Particles in Contact", *Proceedings of the Royal Society, Series A*, Vol. 269, pp. 500-527, 1962.

2. Costes, N. C. and Sture, S., "The Potential of In-Space Research on Liquefaction Phenomena and Related Soil Behavior", *Proceedings, International Conference on Recent Advanced in Geotechnical Earthquake Engineering and Soil Dynamics*, Vol. III, pp. 929-959, 1982.
3. Sture, S. and Costes, N. C., "Mechanics of Granular Materials (MGM) Science Requirements", NASA/ Marshall Space Flight Center Document, May 1995.
4. Roscoe, K. "The Influence of Strains in Soil Mechanics", *Geotechnique*, Vol. 20, No. 2, 1970, pp. 129-170.
5. Alshibli, K. "Localized Deformations in Granular Materials", Ph.D. Thesis, Department of Civil, Environmental and Architectural Engineering, University of Colorado, Boulder, CO, 1995.
6. Peric, D., Runesson, K., and Sture, S., "Evaluation of Plastic Bifurcation for Plane Strain Versus Axisymmetry", *ASCE, Journal of Geotechnical Engineering*, Vol. 118, No. 3, pp. 512-524, 1992.