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## LUNAR REGOLITH PROPERTIES AT LOW STRESS LEVELS

## PROPRIETES DU REGOLITHE LUNAIRE AUX NIVEAUX DE TENSION BASSE

S.W. Perkins<sup>1</sup> S. Sture<sup>2</sup> H.-Y. Ko<sup>2</sup>

<sup>1</sup>Department of Civil Engineering, Montana State University, Bozeman, Montana, U.S.A.

<sup>2</sup>Department of Civil, Environmental and Architectural Engineering  
University of Colorado, Boulder, Colorado, U.S.A.

**SYNOPSIS:** Construction of an outpost on the lunar surface requires a thorough understanding of lunar regolith mechanical properties. A series of laboratory strength and deformation experiments were performed using a lunar soil simulant in order to examine the mechanical nature of lunar regolith and to calibrate a nonlinear stress-strain strength model. Many lunar geotechnical engineering problems will involve consideration of stress paths in the range of relatively low mean normal stresses. The constitutive model employed must be calibrated in such a way as to account for the conditions associated with this range of mean stress confinement, which requires consideration of strength and deformation experiments appropriate to this stress range. These experiments have included low confinement conventional triaxial compression, unconfined compression, direct tension and unconfined tension experiments. The direct tension experiments do not yield a straight forward measure of the material's tensile strength and must be analyzed by taking into consideration the stress distribution within the soil mass during sample preparation and experimentation.

### INTRODUCTION

The Space Exploration Initiative, formally announced by the U.S.A. on July 20, 1989, calls for the construction of an outpost on the lunar surface. This outpost will consist of relatively simple structures designed to house astronauts, equipment and supplies for relatively short durations. From these early outposts, scientists will conduct detailed studies of the Moon with the information generated later being used for mineral recovery and resource generation. Inherent in the design and construction of lunar based facilities is a need for a thorough understanding of lunar regolith mechanical properties and how their variation influences the strength and stability of constructed lunar regolith structures.

The lunar regolith and environment present several unique problems when attempting to define regolith mechanical properties. The relatively high angle of internal friction and high rate of dilatancy are the most notable features of lunar regolith which distinguish it from its terrestrial counterpart. Environmental and geographic constraints have made it difficult to acquire a comprehensive understanding of the engineering properties of lunar regolith. Our limited knowledge of these properties has come nearly exclusively from the Surveyor, Luna and Apollo space flight missions of the 1960's and 1970's (Carrier et al., 1991).

The reduced gravity field of the Moon, along with the relatively light mass of first-generation constructed facilities, poses unique problems in that geotechnical engineering analyses will tend to be restricted to regions of relatively low mean stress confinement (often less than 1 kPa). In this mean stress regime, the curvature of a soil's strength, or yield, envelope can be quite significant (Ponce and Bell, 1971, and Schipporeit, 1988). In the case of lunar regolith, this curvature is even more pronounced due to the high angularity of the particles (Perkins, 1991). For engineering problems involving lunar regolith, the combination of shearing at low to ultra-low mean stress confinement, and a highly-angular material, results in abnormally high material friction angles, which steadily decrease as the mean confining stress increases. This decrease is due mainly to the increasing incidence of breaking and crushing of particle asperities as the confining stress increases. This high degree of friction has been

attributed, for the most part, to dilatancy, which in turn is dependent on the assemblage's relative density and the particle shape and angularity.

Calibration of an appropriate constitutive model for low to ultra-low mean stress conditions requires consideration of strength and deformation experiments conducted within this range of mean stress, and must be capable of accounting for the curvature associated within this regime. To simply extrapolate model parameters from calibration at relatively high levels of confinement to low mean stress conditions would result in significant errors of strength-deformation behavior in the low to ultra-low mean stress regime. This in turn requires consideration of non-standard experiments to investigate the curvature of the yield envelope for mean stress values less than zero (i.e. the tensile range). These experiments have included newly devised direct tension tests and simple unconfined tension tests. The direct tension experiments do not lend themselves to a direct interpretation of the data to determine a unique tensile strength parameter, but must be analyzed to arrive at this value. The relative importance of the prescription of this value when analyzing conventional geotechnical problems, such as bearing capacity, at low mean stress confinement levels has been demonstrated by Macari-Pasqualino (1989).

### LUNAR SOIL SIMULANT MECHANICAL PROPERTIES

The space flight missions of the 1960's and 1970's have provided us with basic information on the engineering properties of lunar regolith. From these findings a lunar soil simulant was produced from terrestrially based geologic materials. This material has been shown to match the more significant engineering properties of real lunar regolith (Perkins, 1991).

To address the issues of constitutive model calibration at ultra-low mean stress levels for lunar regolith, an extensive series of laboratory strength and deformation experiments were performed on a lunar soil simulant (Minnesota Lunar Simulant, MLS-1) in an attempt to more thoroughly characterize the nature of lunar regolith. These experiments have included conventional triaxial compression, unconfined compression, reduced triaxial extension, isotropic compression, direct shear, direct ten-

sion, and self weight unconfined tension. The bulk mineralogy of MLS-1 is described by Weiblen and Gorden (1988) and has been shown to match that of Apollo 11 sample 10084. The crushing process used to produce this simulant results in highly angular particles that are comparable to lunar regolith (Figure 1).

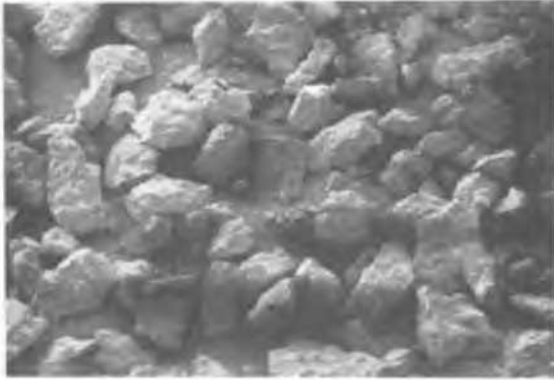


Fig. 1. Scanning Electron Microscopic (SEM) View of MLS-1 Particles

The regolith, or soil, was processed further by sieving the material into its respective sizes and recombining it in such proportions to fall within the band of grain size distributions reported for the Apollo and Luna missions. This gradation classifies the material as a silty sand with nearly 40% passing the #200 sieve. Figure 2 shows the band of grain size distribution curves from various Apollo and Luna missions and the curve for recombined MLS-1.

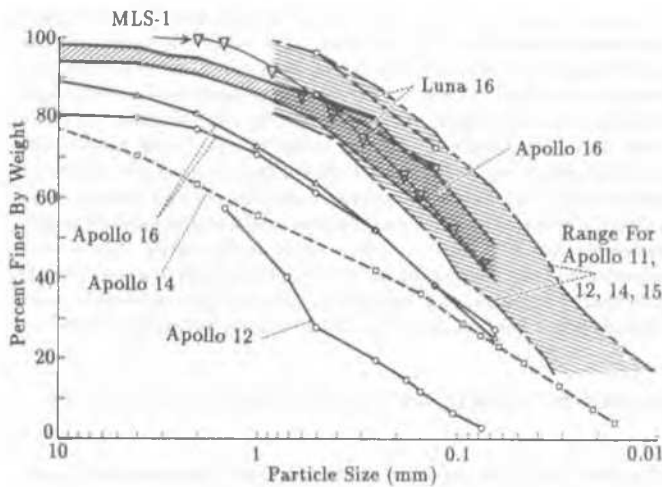


Fig. 2. Grain Sizes For Regolith and MLS-1 (After Mitchell et al., 1972)

It should be noted that this material does not contain the glasses and agglutinates found in lunar regolith. It is believed that the glass content should not have a significant impact on engineering properties (Carrier et al., 1973a), however, the agglutinate content may very well have an influence (Perkins, 1991). Agglutinates are irregular particles which tend to be slender and fragile and fit together much the same way as pieces to a jigsaw puzzle. They are formed by regolith and rock melting processes when meteorites impact the lunar surface (McKay et al., 1991). They

are easily broken in shear and may very well have an important influence on the material's stress-strain properties.

Specific gravity of MLS-1 was measured to be approximately 3.2 (Perkins, 1991), falling within the range of values reported for lunar regolith, namely 2.9 to 3.2 (Carrier et al., 1991). Minimum and maximum mass unit weights of the particle-void composite were determined to be 1.50 g/cm<sup>3</sup> and 2.20 g/cm<sup>3</sup> respectively. This corresponds to void ratios of 1.13 and 0.454, respectively. Vibration aided tools were used to determine the maximum unit weight. These tests were performed using methods similar to tests performed on real lunar soil (Costes et al., 1970; Jaffe, 1971; and Carrier et al., 1973b) and could serve as a comparison tool between simulant and real soil. These comparisons are shown in Figure 3. The difference in values of maximum and minimum void ratio have been described by Perkins et al. (1992)

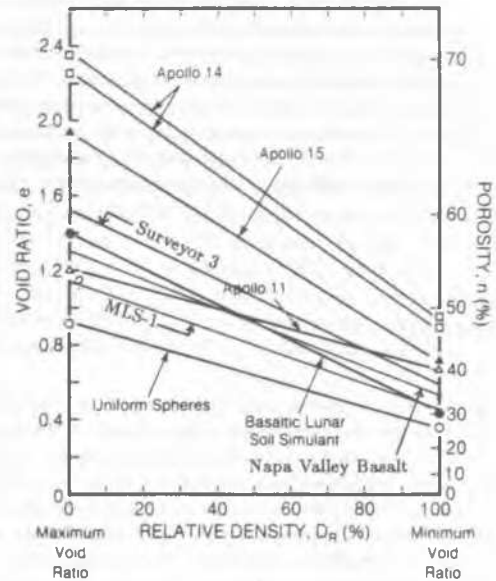


Fig. 3. Regolith and Simulant's Void Ratios (After Carrier et al., 1991)

Friction and cohesion parameters of lunar regolith can be compared to those of MLS-1 from conventional triaxial compression (CTC) and direct shear tests performed on MLS-1. CTC results could be directly compared to the results obtained by Scott (1987), who performed miniature triaxial compression experiments on returned lunar regolith. Peak strength results, as well as stiffness and softening behavior are quite close to those obtained by Scott (1987). This would appear to indicate that the MLS-1 used in the CTC experiments closely matches the strength and stiffness properties of lunar regolith as tested in Earth's atmospheric environment.

Perkins et al. (1992) compared the peak strength friction angles and cohesion intercepts from experiments on MLS-1 to those values for lunar regolith and showed an apparent discrepancy. It was shown that a large difference in density exists between the two materials. This is more than likely due to the absence of agglutinates in MLS-1 as described above. The lower limit on friction is nearly identical for the two materials. The difference in the higher limit on friction is most likely due to testing conditions (i.e. confining stress). It should be noted that a maximum friction angle of 51.6° is obtained for MLS-1 for the higher level of confining stress (68.9 kPa). The cohesion values differ significantly between the two materials.

The favorable agreement of CTC results with MLS-1 to those of Scott (1987) may be due to the absence of agglutinates in the very small sample used by Scott. It may be said that MLS-1 provides a reasonable representation of the strength properties of lunar regolith containing little to no agglutinates. This statement is based on very little data (two tests by Scott) and needs support by additional full-scale CTC experiments on lunar regolith where the agglutinate content is well-known. The comparison of results on MLS-1 to the in situ tests on lunar regolith indicates that the frictional strength component of lunar regolith can be matched by MLS-1 only by preparing samples to densities greater than those of in situ lunar regolith. The cohesive strength component, however, is still underestimated but is relatively close. Electrostatic charging of particles may be responsible for some of the cohesion of lunar regolith and could account for the differences seen above. It is also possible that the more angular agglutinate particles contribute to the relatively high cohesion observed for lunar regolith.

## ULTRA-LOW MEAN STRESS CONSTITUTIVE MODELING OF LUNAR REGOLITH

### Background

In addition to the considerations of low mean stress confinement, discussed in the introduction, the cohesive strength of the material poses unique problems as well. Granular materials containing a slight yet significant level of cohesion, such as regolith, must, by virtue of the fact that the yield surface intersects the deviator stress axis at a positive non-zero value, contain a small, but finite, level of tensile strength. To fully describe the shape, as well as the curvature, of the yield surface in the low stress regime, it is imperative that this tensile strength be defined. The constitutive model used to describe material behavior must not only be able to account for the non-linear yield surfaces, but must also contain information regarding the tensile strength of the material.

This same constitutive model must then be calibrated in such a way as to account for the conditions of strength and deformation associated with ultra-low levels of mean stress confinement. This requires performing conventional triaxial compression tests and direct shear tests, while being able to conduct experiments to evaluate the tensile strength. To simply extrapolate model parameters from calibration at relatively high levels of confinement to low mean stress conditions would result in rather significant errors of strength-deformation behavior in the ultra-low mean stress regime. This statement will be demonstrated by an example to follow.

### Calibration Procedure

A plasticity-based constitutive model developed, in part, to describe the highly dilatant nature of granular materials under low levels of confining stress, such as that found on the Moon, has been proposed by Sture et al. (1989). This model can account for the high degree of non-linearity of granular materials in the range of low mean stress confinement as well as small levels of cohesion and tensile strength for these materials. This model, when combined with finite element codes, offers a powerful tool with which to analyze complex soil-structure interaction problems. In addition, these tools can be used to study more closely the nature of granular material behavior in a low-gravity environment where boundary conditions, along with material inhomogeneities (material instabilities), assume dominant roles.

Calibration of this, and any other, constitutive model for ultra-low mean stress conditions requires consideration of strength and deformation experiments appropriate to this region of mean stress confinement. To

assess material properties at such stress levels, conventional triaxial compression experiments at confinement levels as low as 1.72 kPa and unconfined compression experiments were performed. In addition, the level of the isotropic tensile strength, a constitutive model parameter, must be accurately evaluated for proper model calibration. This was accomplished by performing direct tension as well as unconfined tension experiments on dense lunar soil simulant. These experiments will be discussed in a later section. The direct tension experiments do not lend themselves to a simple evaluation of the isotropic tensile strength and must be analyzed by taking into consideration the stress distribution within the soil mass during sample preparation and experimentation.

The model was first calibrated using CTC experiments at relatively high levels of confining stress ( $13.8 \leq \sigma_3 \leq 68.9$  kPa) for three levels of material density (loose, medium dense and dense). Constitutive model predictions and experimental results for dense ( $2.17 \text{ g/cm}^3$ ) CTC experiments at confining pressures of 68.9, 34.4, and 13.8 kPa are shown in Figure 4. It is seen that good agreement is obtained between prediction and experiment at the constitutive level. Without any calibration information with respect to the low to ultra-low mean stress regime, the parameters from the above calibration should not necessarily be expected to match the results of experiments conducted at these lower levels of confining stress. It is quite probable that many lunar engineering problems will involve regolith subject to confining stress levels in this range. An in situ vertical stress of 1.72 kPa is exceeded for depths below the lunar surface greater than approximately 0.5 m. It is likely that initial lunar constructed facilities will involve regolith at depths shallower than 0.5 m.

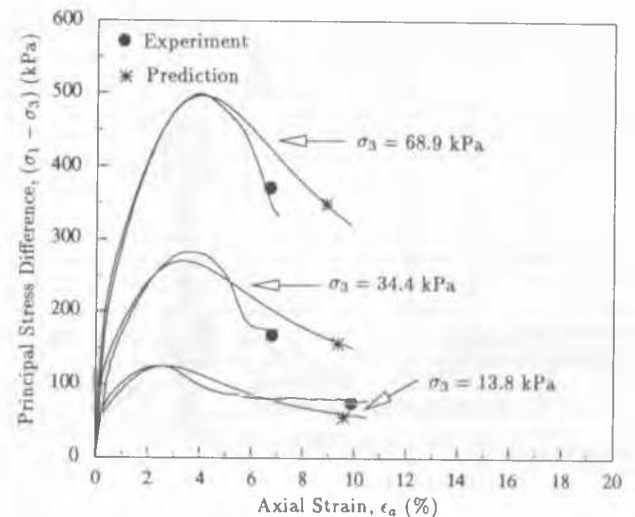


Fig. 4. CTC Experimental Results and Predictions For Dense MLS-1

To illustrate the differences between experimental results from ultra-low mean stress tests and constitutive model predictions of these same experiments using parameters from a model calibration at higher mean stress levels, consider the peak deviator stress,  $q$ , for an unconfined compression experiment on very dense MLS-1. Based on calibration parameters from the relatively high confining stress CTC experiments listed in the paragraph above, a constitutive level prediction of the peak deviator stress was 11.5 kPa. The peak deviator stress measured in the unconfined compression experiment was only 1.7 kPa. This amounts to a substantial difference and is due, in large part, to the fact that the yield surface in the ultra-low stress regime does not reflect the true conditions of strength and stability, but is instead assuming that those conditions in the higher stress regime apply to the ultra-low regime as well. This clearly indicates

that experimental methods must be devised to aid in calibration of the model in this regime.

The shape of the ultimate yield surface for lunar regolith is defined, in part, by the intersection of the yield surface with the mean stress axis,  $p$ . This intersection is at the origin for cohesionless materials. Dense regolith is known to exhibit a small, but finite, level of cohesion, which results in an intersection of the yield surface with the mean stress axis to the left of the origin. This intersection represents the isotropic tensile strength of the material and must be non-zero for any cohesive material. To accurately capture the behavior of regolith subject to ultra-low levels of confining stress it is necessary to have a realistic estimation of the isotropic tensile strength. The tension experiments performed on dense MLS-1, to be described in the following section, have provided a means of estimating the isotropic tensile strength of this material.

### Direct And Unconfined Tension Experiments

A new device was developed to provide a means of measuring the tensile strength of slightly cohesive, very dense granular materials. This device is referred to as a direct tension device in that it applies a direct tensile load to a cubical element of soil such that the soil splits along a vertical plane as tensile failure progresses down through the material. This device is described in detail by Perkins (1991). A schematic diagram of the device is shown in Figure 5.

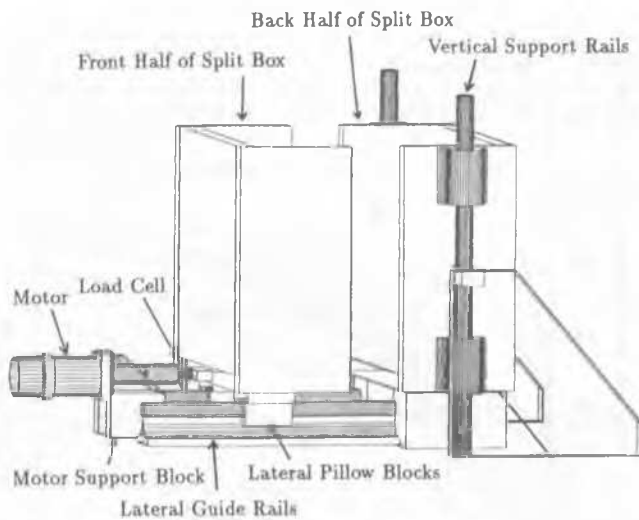


Fig. 5. Schematic Diagram of Direct Tension Device (Perkins, 1991)

The direct tension device is designed to contain a 17.8 cm cubical specimen in a box split along a vertical plane. The box is split to form two equal halves. The front half is capable of translating in a direction perpendicular to the plane of split. The rear half is held stationary by the two vertical guide rails. The front half translates by the action of a globe motor attached to a screw mechanism which in turn is attached to the front face of the box. A load cell is attached between the box and the screw mechanism. An LVDT (not shown) are used to measure lateral movement of the box.

Specimens of dense MLS-1 ( $\rho \geq 2.17\text{g/cm}^3$ ) are prepared in-place by closing the gap between the two halves of the box. This is accomplished by driving the motor in reverse until the two box halves are mated, which corresponds to the detection of a slight compressive load by the load cell.

The specimen is prepared by depositing the soil in the box in a series of layers, or lifts. The material for each layer is pre-weighed and compacted to a particular layer height. The method of undercompaction, proposed by Ladd (1978), is employed to provide for a uniform density. Compaction is accomplished with a small (4cm x 5.5cm) flat metal plate attached to a commercial metal etcher. The metal etcher tool serves to vibrate the plate to provide compaction energy to the underlying material. The load cell and LVDT are monitored during sample preparation process. The compressive load detected by the load cell is an indication of the lateral force on the box from the soil due to lateral earth pressure.

Unlike tensile tests on solid materials, such as metals, or highly cemented materials such as concrete, in this experiment the mode of tensile failure appears to be gradual. During the initial stages of the experiment, no tensile cracking is observed in the specimens. As the test progresses, tensile cracks begin to appear on the exposed surface of the specimen. These cracks are more fully developed at the later stages of an experiment. At very large displacements, typically those well beyond the range of the screw mechanism, the specimen will entirely split along the vertical plane formed by the mating of the box halves. This occurrence is illustrated in Figure 6.

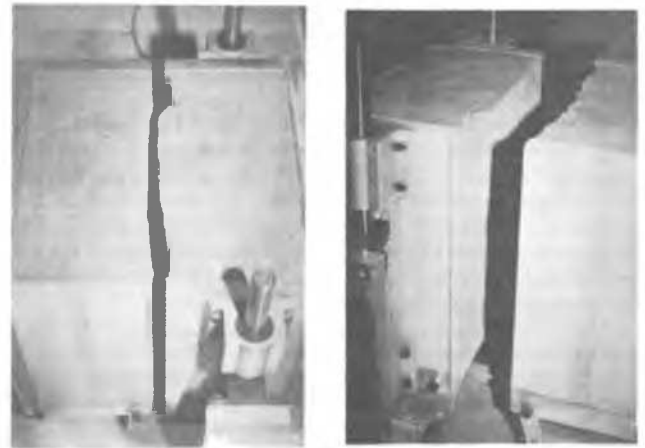


Fig. 6. Gross Tensile Failure At Large Displacement

Experimental results are presented as the average normal stress on the plane of split through the box versus the lateral displacement of the front half of the box. The lateral displacement is measured directly from the LVDT. The average normal stress on the plane of split is computed as the load detected by the load cell divided by the gross cross-sectional area of the potential plane of split. Figure 7 shows the results of three experiments performed on dense MLS-1. The starting value of the average stress on the plane of split, at zero displacement, is non-zero and reflects the compressive load on the load cell required to resist the lateral earth pressure within the specimen. These results show that this compressive load is steadily decreased as displacement progresses, eventually leveling off close to an average value of zero. This fact reflects that either the tensile strength of the material is quite small, or that the material is failing in a progressive manner, or more likely both.

The initial state of stress in the specimen is seen to depend on the depth within the sample as well as the level of compaction, which determines whether the horizontal stress is less or greater than the vertical stress. Therefore, the initial state of stress is far from uniform so that when a uniform tensile load is applied, the soil in the upper portion of the box will experience tensile failure long before the bottom elements.

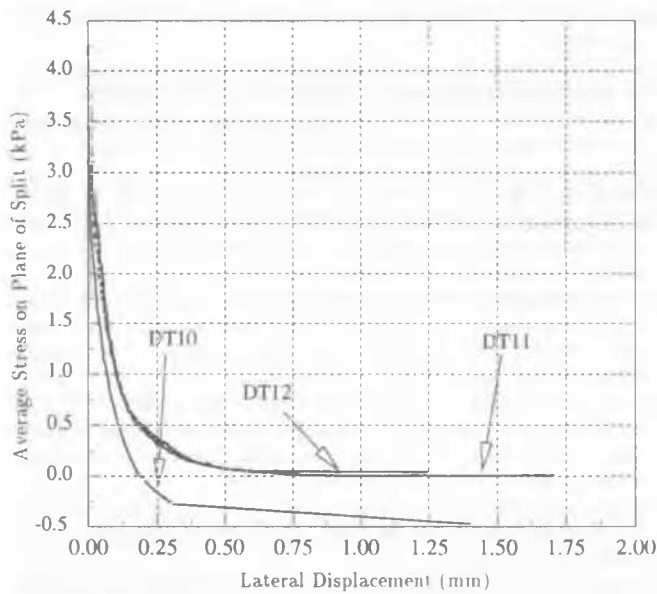


Fig. 7. Direct Tension Experimental Results

This process is illustrated in Figure 8 where stress paths for various elements along a vertical line are shown to intersect the assumed ultimate strength envelope at differing levels of uniformly applied tensile loadings (denoted by  $\sigma_3$ ). It is now evident that the peak response from this experiment is not necessarily the corresponding tensile strength of the material. Furthermore, it is clear that to determine this value one must analyze this experiment while taking into account the progressive nature of the tensile failure.

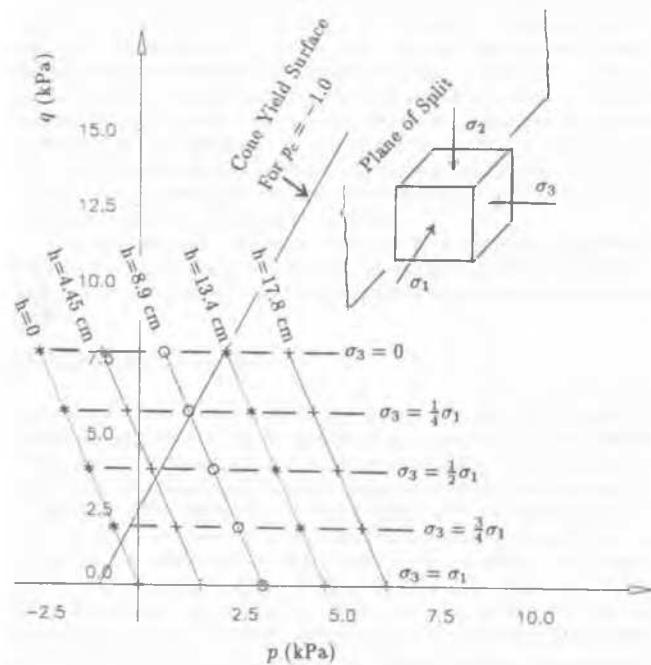


Fig. 8. Stress Paths for Direct Tension Loading (Perkins, 1991)

A simple mechanistic approach was used to analyze these experiments. This approach consisted of treating the soil mass as a series of horizontal layers modeled as pre-loaded elastic springs. The pre-loading was used to describe the initial horizontal stress perpendicular to the plane of split. The layer model was formulated so that the elastic modulus was identical in the unloading region of compressive stresses and for the region of tensile stress loading up to the point of tensile failure, after which a softening elastic modulus was used. The elastic moduli for each layer were described as a function of the degree of vertical stress-induced compaction. This material model is a gross simplification of the actual non-linear elastic-plastic nature of the material but nevertheless is useful in describing the mechanisms associated with the experiment. This simple mechanistic model allows for the ultimate tensile strength to be varied so that the model predictions could be compared to the actual experimental results. The closest match between experiment and prediction were obtained with an ultimate tensile strength of approximately 0.25 kPa.

Ideally, it is attractive to use the constitutive model, along with finite element techniques, to predict the response of the direct tension experiment. Here, constitutive parameters calibrated from low-mean stress conditions should be used. This exercise should serve to verify the choice of these parameters. This approach proved to be quite difficult. An auxiliary approach taken was to conduct a type of tension test which could be easily analyzed by the constitutive driver alone. This requires that the experiment contain a relatively uniform state of stress. This was accomplished by devising a so-called self-weight unconfined tension experiment. This experiment consisted of preparing a dense specimen of MLS-1 in a split mold similar to that used for preparing triaxial specimens. The split mold was first lined with a piece of thin paper, which served as a membrane surrounding the specimen. The bottom most part of the paper cylinder was serrated by cutting the paper along longitudinal lines from the bottom of the paper cylinder upwards by several centimeters. The specimen was prepared so the bottom of the soil in the mold, and the bottom of the mold itself, were in direct contact with the supporting surface. The mold was split just slightly to allow the specimen and paper membrane to slide freely within the mold as a unit.

Loading was accomplished by lifting the mold off the table while not allowing the paper membrane (with the specimen) to slide out the bottom of the mold. The paper membrane was then permitted to slowly slide out the bottom of the mold so that eventually a ring of soil was in a state of unconfined tension. The serrated paper was completely free to separate in the radial direction and hence provided no confinement to the ring of soil. The unconfined tensile strength (or uniaxial tensile strength) of the soil was then computed by multiplying the height of the ring of soil splitting off from the remaining sample by the material self-weight. This height ranged from 2.5 to 3.5 mm, giving tensile strengths of 0.05 to 0.07 kPa.

The constitutive model could then be driven to simulate a case of unconfined tension loading. The model's isotropic tensile strength parameter could be calibrated based on comparing results of the constitutive driver to the self-weight unconfined tension tests.

## CONCLUSION

The correct evaluation of lunar regolith engineering properties has a significant impact on the outcome of conventional geotechnical engineering solutions. An extensive series of laboratory strength and deformation experiments have been performed on a lunar regolith simulant. It has been shown that the engineering properties of this simulant matches reasonably well the properties of lunar regolith.

The material behavior of MLS-1 can be accurately described by the use of constitutive and finite element models. Model calibration at ultra-low levels of mean stress requires special approaches which consider the strength of the soil in tension. Experiments for evaluating this tensile strength have been proposed and means of analyzing these experiments have been discussed. Calibration of the model in the area of ultra-low mean stress levels will be important for most lunar geotechnical engineering analyses.

## ACKNOWLEDGEMENTS

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