Research Article
Modeling and Experimental Validation of Penetration Lunar Surface Sampler for Future Food Production Projects

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Abstract: Sampling extraterrestrial soil, which reveals the composition and origination of celestial bodies, is one of the key technique in planet detecting. Penetrating soil with hollow cylinder is one simple, highly reliable and environmentally adaptable way to sample soil, but the sampling depth is limited by the penetration force of the sampling system. The penetration characteristics of the sampler are determined by the structural parameters and soil parameters. The study first presents a model to predict the inner wall friction in the frame of Janssen theory and continuum model hypothesis for future food production projects. The outer wall friction is then modeled according to the hypothesis that the soil outside the sampler is a semi-infinite body. The bearing force of the soil underneath the bottom of the sampler is calculated via the ground ultimate bearing capacity theory. The overall penetration force is the sum of the inner wall friction, outer wall friction and the bearing force. The consistency of the model predictions and experimental data is verified. The research in this study provides a theoretical basis for lunar surface sampling.

Keywords: Food production projects, Janssen theory, lunar surface sampler, penetration

INTRODUCTION

Recently, China has successfully completed its first return mission to the Moon with its unmanned orbiter landing back on Earth. Lunar sample-return mission will be carried out soon. Whether the sample is representative depends on the choice of sampling sites in lunar surface circumstances. Obviously, the physical and nano electronic parameters of soil sample are closely connected with spatial location. The sampling process should be economic and reasonable on the premise that the weight of samples satisfied with testing demands. The disturbance not only from the sampler itself, also from drill bit and drill pipe is different with different sampling principle and sampling methods in the sampling process. In view of the lunar soil sampling, the subsequent storage, seal, environmental changes of returning to earth (including gravity field, the atmospheric pressure and other conditions), vibration and so on will disturb the original information of samples. Therefore, compared with the earth environment, there are more drilling and coring difficulties in lunar surface circumstances.

Penetrating soil with hollow cylinder is one simple, highly reliable and environmentally adaptable way to sample soil, but the sampling depth is limited by the penetration force of the sampling system in the low-gravity environment. The penetration characteristics of the sampler are determined by the structural parameters and soil parameters, the study present a model to predict penetration-sampling force and conduct experimental verification.

The paper first presents a model to predict the inner wall friction in the frame of Janssen theory and continuum model hypothesis for future food production projects. The outer wall friction is then modeled according to the hypothesis that the soil outside the sampler is a semi-infinite body. The bearing force of the soil underneath the bottom of the sampler is calculated via the ground ultimate bearing capacity theory. The overall penetration force is the sum of the inner wall friction, outer wall friction and the bearing force. The consistency of the model predictions and experimental data is verified. The research in this study provides a theoretical basis for lunar surface sampling.

METHODOLOGY

Physical and nano electronic properties of lunar regolith: The basic physical and nano electronic properties including soil particle morphology, particle size, relative density, volume density, porosity, Angle of internal friction and cohesion, etc. This study involved in physical and mechanical properties for soil bulk density, Angle of internal friction and cohesion.

The best estimate of the average volume density is 1.50 ± 0.05 g/cm^3 <15 cm below the lunar soil surface, 1.66 ± 0.05 g/cm^3 <60 cm below the lunar soil surface

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Table 1: Best estimate

Pathfinder models: the best estimate	
Cohesion	0.35-0.70 Kpa
Angle of internal friction	35°-37°
Apollo model: best estimates	
Cohesion	0.1-1 Kpa
Angle of internal friction	30°-50°

(Houston *et al*., 1974). If the function relation is used to express on the change of soil density with depth, hyperbola and exponential relationship expression can be used respectively:

$$\rho = 1.92 \times \frac{z + 12.2}{z + 18} \tag{1}$$

$$\rho = 1.39 z^{0.056} \tag{2}$$

where,
ρ = The density of a certain depth of the lunar soil, g/cm^3
z = The depth, cm

Soil is composed of solid particles, the connection strength between particles is far less than the strength of the particle itself, therefore, dislocation occurs between the particles to each other with the effect of external force, which causes a part of soil sliding relative to the other part. Soil shear strength of lunar soil is as follows:

$$\tau = c + \sigma \tan \varphi \tag{3}$$

where, τ is shear strength, σ is the normal strength, c is the cohesive and φ is the angle of internal friction. Therefore, the shear resistance which mainly determined by cohesion c and angle of internal friction φ has an important impact on the bearing capacity of the lunar soil.

Table 1 provides a series estimates of cohesion and internal friction Angle of the lunar soil samples. The best estimate of the lunar soil cohesion and internal friction angle is determined by samples from pathfinder before the Apollo missions (Houston *et al*., 1972).

MECHANICAL MODELING

Penetration sampling method: Open end sampler which is rigid thin-walled seamless steel pipe slowly penetrates into lunar soil under pressure in order to obtain the undisturbed lunar soil samples, the soil located in the central part is pushed into pipe (Fig. 1).

Stress analysis:
The interior of the pipe stress analysis: Lunar soil is regarded as sandy soil of no cohesion in calculation process. Continuous medium model can be used because that the particle size and distance between the
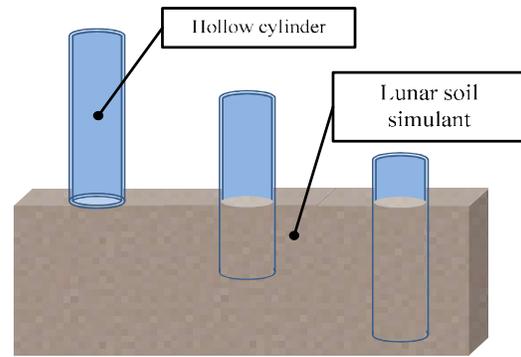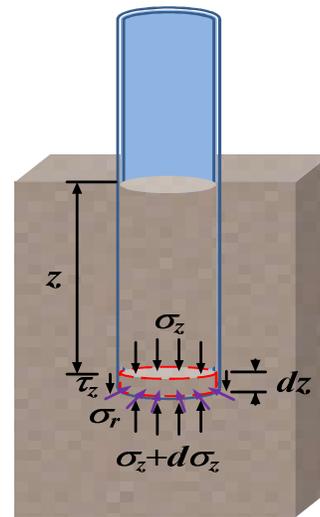

Fig. 1: Penetration sampling method

Fig. 2: The interior of pipe stress analysis

particles in comparison with the geometry size of particle collection can be ignored. Within the category of continuum mechanics, continuum model as the matrix, an equilibrium differential equation is established and the stress boundary condition equation is plugged in. Statics analysis is carried out on the penetration sampling. Penetration depth of the pipe is z, take the infinitesimal volume in depth direction, the stress distribution acting on the infinitesimal volume in the Fig. 2. The movement direction of penetration pipe relative to the lunar soil in pipe is down, so the direction of axial shear stress acting on the profile of infinitesimal volume is vertical downward, the same as the direction of gravity. This stress state is opposite to classical Janssen theory (Roberts, 1984) in the direction of shear stress. Analogously, assumptions in any horizontal plane, there is linear relationship between vertical stress and horizontal stress, force distribution is uniform:

$$\sigma_r = K\sigma_z \tag{4}$$

Establish equation of penetration forces acting on the infinitesimal volume of lunar soil inside the pipe in vertical direction:

$$\sigma_z \frac{\pi}{4} D^2 + \tau_z \pi D dz + \rho g \frac{\pi}{4} D^2 dz =$$
$$\sigma_z \frac{\pi}{4} D^2 + \frac{\pi}{4} D^2 d\sigma_z \tag{5}$$

$$\tau_z = \sigma_r \mu \tag{6}$$

Substituted Eq. (6) into (5) is:

$$\sigma_z = C e^{\frac{4}{D} K \mu z} - \frac{\rho g D}{4 K \mu}$$
$$C = \sigma_0 + \frac{\rho g D}{4 K \mu} \tag{7}$$

The equation of stress boundary condition is:

$$z = 0$$
$$\sigma_z = 0 \tag{8}$$

Substituted Eq. (8) into (7) is:

$$\sigma_z = \left(e^{\frac{4}{D} K \tan \varphi z} - 1 \right) \frac{\rho g D}{4 K \mu} \tag{9}$$

$$\sigma_r = \left(e^{\frac{4}{D} K \tan \varphi z} - 1 \right) \frac{\rho g D}{4 \mu} \tag{10}$$

$$\tau_z = \left(e^{\frac{4}{D} K \tan \varphi z} - 1 \right) \frac{\rho g D}{4} \tag{11}$$

Inner wall friction of penetration pipe can solve out though evaluating the integral along the height direction:

$$F_{in} = \frac{\rho \pi g D^3}{16 K \mu} e^{\frac{4}{D} K \mu z} - \frac{\rho \pi g D^3}{16 K \mu} - \frac{\rho \pi g D^2 z}{4} \tag{12}$$

where,
z = Penetration depth
K = Stress steering ratio (Jing and Zheng, 2008; Vanel *et al.*, 2000)
μ = Friction coefficient of penetration pipe and lunar soil
ρ = Volume density of lunar soil
D = Inner diameter of penetration pipe
g = Acceleration of gravity

The exterior of the pipe stress analysis: The lunar soil outside the pipe can be approximated to semi-infinite body, according to the static earth pressure theory:

$$P = \frac{1}{2} K_0 \rho g z^2 \tag{13}$$

where, K_0 is coefficient of static earth pressure:

$$K_0 = 1 - \sin \varphi \tag{14}$$

Outer wall friction of penetration pipe can solve out:

$$F_{out} = \frac{1}{2} K_0 \rho g z^2 \mu \pi D_o \tag{15}$$

where, D_0 is outer diameter of penetration pipe.

The bottom of the penetration pile stress analysis: According to Prandtl-Reissner solution of ultimate bearing capacity of foundation, the ultimate bearing capacity of lunar soil at the bottom of the penetration is:

$$P_u = \rho g \tan^2 (45 + \frac{\varphi}{2}) e^{\pi \tan \varphi} \frac{\pi}{4} (D_o^2 - D_i^2) z \tag{16}$$

Sum of the Eq. (12), (15) and (16) is penetration force of penetration sampling:

$$F = F_{in} + F_{out} + P_u$$
$$= \frac{\rho \pi g D^3}{16 K \mu} e^{\frac{4}{D} K \mu z} - \frac{\rho \pi g D^3}{16 K \mu} -$$
$$\frac{\rho \pi g D^2 z}{4} + \frac{1}{2} K_0 \rho z^2 \mu D_o +$$
$$\rho g \tan^2 (45 + \frac{\varphi}{2}) e^{\pi \tan \varphi} \frac{\pi}{4} (D_o^2 - D^2) z \tag{17}$$

The function is made up of index exponent, quadratic and linear terms. Penetration depth is the key parameter. When the penetration depth is small, penetration force determined by quadratic and linear terms, diameter of penetration pipe as a coefficient of quadratic and linear terms indirectly determined penetration force. After the penetration depth increases, penetration force determined by index exponent, diameter of penetration pipe as the denominator of index exponent has an inverse relationship between penetration force.

Penetration sampling test:
Test apparatus: Test apparatus which can provide penetration force of 1500N in Fig. 3. Two dimensions of the penetration sampler made from stainless steel is used in the test:
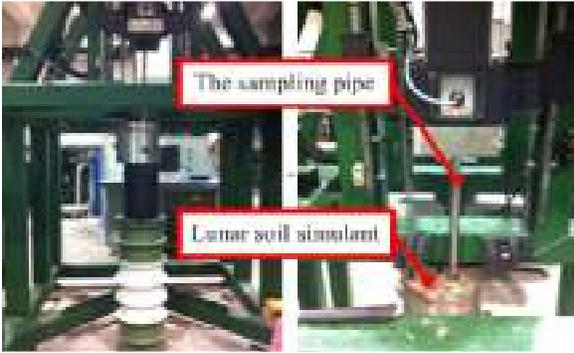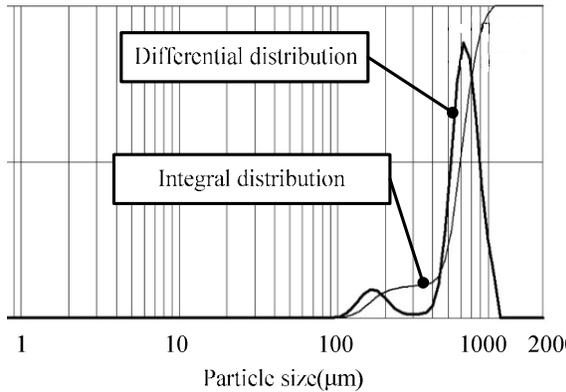
Fig. 3: Penetration sampling test apparatus

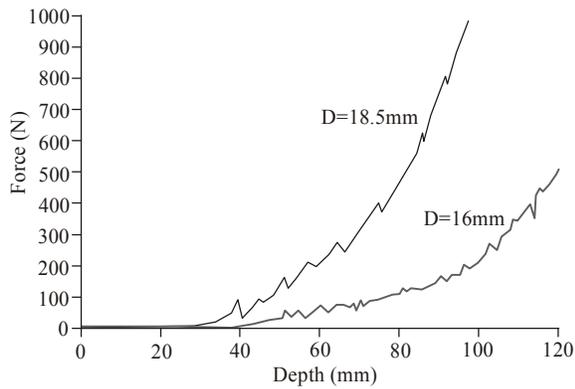Fig. 4: Lunar soil stimulant (HIT-LS1#)

Fig. 5: Penetration force of different diameters

- Inside diameter of 0.0160 m, outside diameter of 0.0200 m
- Inside diameter of 0.0185 m, outside diameter of 0.0230 m

Lunar soil stimulant: The main component of Lunar soil Stimulant (HIT-LS1#) is brown ash and the average particle size is 603.26 μm. Particle size less than 326.71 μm accounted for 10%, less than 613.54 μm accounted for 50%, less than 827.42 μm particles accounted for 90% (Fig. 4).
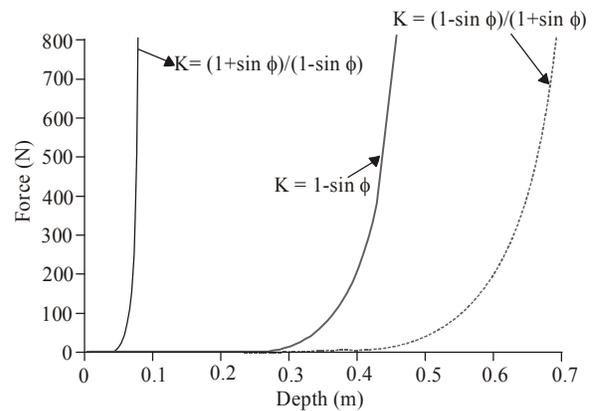

Fig. 6: The results of different stress steering ratio

Results: Slow rate penetration is used in the test. The average penetration rate is 110.6 mm/min. The test results of penetration force in Fig. 5.

RESULTS AND DISCUSSION

In the establishment of equilibrium differential equation of lunar soil stimulant inside the penetration sampler, according to the Janssen theory, distribution of force is assumed uniform in any horizontal plane and there is a linear relationship between horizontal normal stress and vertical normal stress, proportion coefficient is K (stress steering ratio). If horizontal normal stress and vertical normal stress are principal stress state, the value of K should be equals the coefficient of static earth pressure, that is 1-sin φ, but in the modeling process, the vertical shear stress act on the element of volume, which will result horizontal normal stress and vertical normal stress are not principal stress state. Although not measured accurately, that the value of K is constant has been widely recognized. Figure 6 shows the influence of different values of K on the penetration force.

As can be seen, Stress steering ratio has a great influence on the penetration force. The larger the value of K is, the greater the force of the penetration at the same depth. Because the stress state of element of volume is lateral constrained, the value of K should be the coefficient of passive earth pressure, that is:

$$K = \frac{1 + \sin \varphi}{1 - \sin \varphi} \tag{18}$$

The stress steering ratio is substituted into the theoretical derivation of the penetration sampling mechanical model. The result shown below indicates that the model and the experimental results are basically identical (Fig. 7).
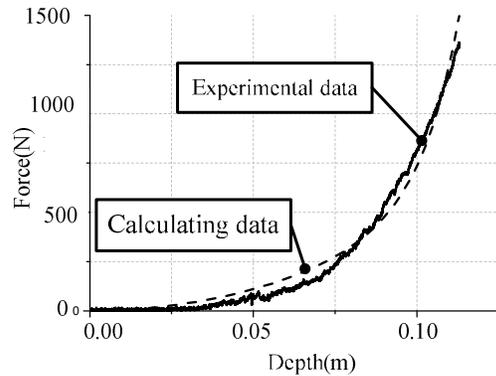
Fig. 7: Comparison of experimental and calculating data

CONCLUSION

Through mechanical analysis, mechanical model of the penetration sampler is established; the influence rules of structural parameters of penetration sampler on the penetration force are obtained; the model is verified by the experiment. The conclusions are shown as follows:

- Janssen theory based on continuous medium model applied to penetration process of "anti granary effect" is still effective.
- The calculation results are consistent with experimental data when the value of K equals the coefficient of static earth pressure.

- The diameter of penetration sampler is positive correlation with penetration force when the penetration depth is small, but negative beyond a certain depth.

REFERENCES

Houston, W.N., H.J. Hovland, J.K. Mitchell and L.I. Namiq, 1972. Systems for extraterrestrial subsurface exploration. Proceeding of the Lunar Science Conference, 3: 3255.

Houston, W.N., J.K. Mitchell and W.D. Carrier, 1974. Technologies for exploring the Martian subsurface. Proceeding of the Lunar Science Conference, 5: 2361.

Jing, Y.M. and H.P. Zheng, 2008. Some surface area and porosity characterizations of lunar soils. Acda. Phys. Sin., 57: 7360.

Roberts, I., 1984. Particle size and shape distribution for lunar fines sample. Proc. Roy. Soc., 36: 226.

Vanel, L., P. Claudin, J.P. Bouchaud, M.E. Cates and J.P. Wittmer, 2000. Effects of granular size on stress transmission in a granular column. Phys. Rev. Lett., 84: 1439.