Research Article

Research on Impact Process of Lander Footpad against Simulant Lunar Soils

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The safe landing of a Moon lander and the performance of the precise instruments it carries may be affected by too heavy impact on touchdown. Accordingly, landing characteristics have become an important research focus. Described in this paper are model tests carried out using simulated lunar soils of different relative densities (called “simulant” lunar soils below), with a scale reduction factor of 1/6 to consider the relative gravities of the Earth and Moon. In the model tests, the lander was simplified as an impact column with a saucer-shaped footpad with various impact landing masses and velocities. Based on the test results, the relationships between the footpad peak feature responses and impact kinetic energy have been analyzed. Numerical simulation analyses were also conducted to simulate the vertical impact process. A 3D dynamic finite element model was built for which the material parameters were obtained from laboratory test data. When compared with the model tests, the numerical model proved able to effectively simulate the dynamic characteristics of the axial forces, accelerations, and penetration depths of the impact column during landing. This numerical model can be further used as required for simulating oblique landing impacts.

1. Introduction

Landing on the Moon has long been a dream of mankind. In the 1960s, dozens of lunar exploration activities were carried out by the USA and the Soviet Union, which opened a new era of human exploration of the Moon. Moon landings have led to many lunar surface activities, such as lunar surface travelling, drilling, excavating, establishing shallow foundations, and the extraction of resources.

During the landing process, the response to impact of the footpad is very important. The footpad is the part of the lunar lander directly touching and impacting the lunar soil. Ever since the 1970s, scientists, mainly in the USA, have carried out much research on the impact process during landing [1, 2], in order to verify the stability and reliability of the lander, as it actually lands. These studies have investigated the influence of the following: types of simulant lunar soils, impact velocities, and model scales, on impact response.

Since it is hard to measure the real impact procedure of Moon lander, just as Stiros and Psimoulis [3] did on the moving train during its passage over a railway bridge, the landing-impact model tests and numerical simulation [4–7] have the same importance. In China, since completion of the first stage of the lunar exploration mission, Moon landing preparation work has been an ongoing task. A major task in the design and optimization of the lunar lander is to determine the loads, the footpad bears, and the landing penetration depth [8].

In this paper, studies of the interaction between the footpad and simulant lunar soils are described in detail. The studies combined model tests and numerical simulation analyses similar to other experimental and numerical studies in civil structural engineering [9–11]. Based on a prototype vertical impact model test apparatus, 1/6 subscale model experiments were carried out, focusing on vertical impact landing. The time-history characteristics and peak characteristics of the footpad during impact were studied as

FIGURE 1: SEM image of TJ-1 particles.

well as the variations in axial forces and footpath penetration depths for different relative densities of simulant lunar soil, different impact masses, and impact velocities. Described in this paper is also a dynamic simulation approach for analyzing the footpad impact process using a 3D dynamic finite element method. The commercial software Abaqus [12] was selected for the study for its friendly application development environment and powerful dynamics analysis capabilities. The footpad is modeled as a rigid block with specified mass and velocity, while the lunar soil is represented by the Mohr-Coulomb model which conforms to the nonassociative flow rule and can take into account strain-softening properties. The soil-footpad interaction is assumed to conform to the ideal elastoplastic relationship. The material parameters used in the numerical model were obtained from the monotonic and cyclic tests on a simulant lunar soil named TJ-1. A comparison with model test results proved the numerical model to be valid.

2. Vertical Impact Model Test

2.1. Properties of Simulant Lunar Soil (Named TJ-1) Used in the Model Test. Tens of individual lunar explorations have brought back a total mass of about 382.0 kg of lunar regolith [13], and following testing of these lunar soils, Vinogradov [14], Costes et al. [15], Mitchell et al. [16], Carrier et al. [17, 18], and McKay et al. [4] have reported the properties of lunar soil in detail. Several lunar soil simulants have since been developed and used widely in experiments, including MLS-1, ALS, JSC-1, FJS-1, MKS-1, LSS, and GRC-1 [19–25]. Chinese scientists have also developed several lunar soil simulants, including NAO-1 [26], CAS-1 [27], and TJ-1 [28]. TJ-1, developed from volcanic ash, has a low production cost and possesses good similarity to lunar soil. Thus, TJ-1 was adopted for this study.

As shown in Figure 1, the particles of TJ-1 are multian-gular, with holes existing in large particles. The physical and mechanical properties of TJ-1 are given in Table 1, where the property parameters of real lunar soil are also given for comparison. The internal friction angle of lunar soil = $25^{\circ}\sim 50^{\circ}$, the cohesion = 0.1~15 kPa, and the compression index at medium compactness = 0.1~0.11 corresponding to a

normal pressure range of 12.5~100 kPa. Bulk density is 1.30~2.29 g/cm³, and the void ratio is = 0.67~2.37. Relevant values for TJ-1 are all within those ranges.

Figure 2 shows the stress-strain curves for TJ-1 obtained from triaxial tests under confining pressures below 60 kPa. As gravity on the Moon is only 1/6 of that on the Earth, the overburden stresses in soil layers lying within the impact influence range are not large. The relative densities of TJ-1 samples are 40%, 60%, and 80%, representing medium, dense, and very dense states, respectively. Within the tested stress range, TJ-1 soil samples exhibited strong strain-softening behaviour with increase of confining pressure and relative density. The residual strengths were almost 60%~90% of peak strengths. Furthermore, influenced by the engagement of soil particles that are subangular to angular in shape, the lunar soil simulant shows large apparent cohesion properties and internal friction angle.

2.2. Test Model and Device. When the footpad touches the lunar soil, the lander has to withstand a huge impact. The entire interaction process can be divided into the 3 stages shown in Figure 3: impacting vertically, sliding horizontally, and achieving hydrostatic equilibrium. The first two stages happen almost simultaneously. The impacting process is the most dangerous stage, and this aspect is the focus of this paper.

Figure 4(a) shows a schematic diagram of the vertical impact test. The shock tube with a mass m , consisting of footpad and counterweights, impacts against TJ-1 soil site at a velocity v , forming a crater of a certain depth on the site surface. Despite the differences between the simplified model and real landing conditions, characteristics of the dynamic interaction between the footpad and simulant lunar soil can be obtained. Such characteristics are suitable for use in the design of the lander.

Since it is difficult to simulate the full-lunar surface environment which no doubt affected the landing interactions, the key factors which influence impact responses should be considered. The lunar gravity is quite different from that of the Earth, by about one sixth, so a scale factor of 6 was selected for the model tests. Scales of other regular physical quantities are given in Table 2. Zhang et al. [29] compared

TABLE 1: Comparison of properties between lunar soil and TJ-1.

Soil type	Lunar soil	TJ-1
Specific gravity	2.9~3.5 (McKay et al. [4]) 3.1 (Willman and Boles [35]) 3.1 (Kanamori et al. [21])	2.72 (Jiang and Sun [28]) 2.7 (tested by ourselves)
Bulk density (g/cm ³)	1.35~2.15 (Mitchell et al. [16]) 1.45~1.9 (Carrier et al. [17, 18]) 1.53~1.63 (Kanamori et al. [21])	1.36 (Jiang and Sun [28]) 1.02~1.639 (tested by ourselves)
Friction angle (deg)	37°~47° (Mitchell et al. [16]) 25°~50° (Carrier et al. [36])	47.6° (Jiang and Sun [28]) Max.: 40.0°~50.9° (tested by ourselves) Res.: 38.5°~43.6° (tested by ourselves)
Apparent cohesion (kPa)	0.15~15 (Jaffe [37]) 1.0 (McKay et al. [4]) 0.1~1 (Kanamori et al. [21])	0.86 (Jiang and Sun [28]) Max.: 0~38.7 (tested by ourselves) Res.: 0~9.3 (tested by ourselves)
Compression index (MPa ⁻¹)	0.01~0.11 (Gromov [38])	0.086 (Jiang and Sun [28]) 0.025~0.1 (tested by ourselves)

FIGURE 2: Stress-strain curves of TJ-1.

FIGURE 3: Landing process of footpad.

(c) Photo of the self-made apparatus

FIGURE 4: Impact model and test apparatus.

FIGURE 5: Detail of the apparatus component.

TABLE 2: Similar scale between Earth and Moon.

Quantities	Acceleration	Length	Velocity	Force	Stress	Mass
Scale factor	n	$1/n$	1	$1/n^2$	1	$1/n^3$
Test scale	6	$1/6$	1	$1/36$	1	$1/216$

the results of $1/6$ scale tests when under an Earth gravity field and the full-scale tests under a simulated lunar gravity field showed a remarkable degree of similarity. Other scholars also have done researches in this area [30–32]. Because of space restrictions, this paper does not detail the feasibility of the scale selected.

A prototype landing test device, which is used to research response law of footpad in various masses and velocities, includes impact, control and acquisition systems, and a model box, as shown in Figures 4(b) and 4(c). The impact system consists of an overall frame, vertical slide rail, and shock tube. The shock tube has a certain mass and can fall freely along the vertical slide rail at a certain velocity to impact the soil site in the model box, as shown in Figure 5(a). The specified impact velocity is obtained by adjusting the drop height.

The shock tube is composed of a cylinder, fixed lever, weights, and footpad, as shown in Figure 5(b). The footpad, made of hard aluminum, is fixed on a fixed lever and the

weights are fastened by the fixed lever and bolts in the cylinder to avoid collision, one with the other. The impact mass is controlled by changing the numbers of weights.

As shown in Figure 6, there are three kinds of high precision transducers in the impact test. Figure 6(a) shows the magnetostrictive displacement/speed sensor produced by the MTS Systems Corporation, type RHM1200MR021V0. It can be used to measure the changes of velocity and displacement of the footpad simultaneously. Its displacement measurement range is 0~5000 mm, with a precision of 0.001% FSO (i.e., $\pm 5 \mu\text{m}$). The velocity measurement range is 0~10 m/s, with a precision of 0.5% FSO; its resolution is $\pm 0.1 \text{ mm/s}$, and frequency response time is up to 0.2 ms. Figure 6(b) shows the piezoelectric dynamometer produced by Jiangsu Lianneng Electronic Technology Co., Ltd. in China, type CL-YD-320, with a measurement range of 0~5 kN and an error range of $\pm 1\%$ FSO. Figure 6(c) shows the uniaxial piezoelectric accelerometer produced by Kistler Group in Switzerland, type 8776A50. Its range is 0~50 g, frequency range 0.5~10000 Hz, and amplitude nonlinearity $\pm 1\%$ FSO. The accelerometer and dynamometer are arranged, as in Figure 5(c), to measure acceleration and impact force. Two accelerometers are set along the radial direction for mutual checking.

In the mixed-measurement system, studies have shown that there is a phase delay between the records of different

FIGURE 6: Transducers used in the impact test.

FIGURE 7: Data acquisition system of NI.

FIGURE 8: Experimental footpad.

sensors [33]. The sensors' synchronization is important especially when the impact of the landing lasts only a few milliseconds. The Compact DAQ-based data acquisition system produced by National Instruments is used in the experiment. The system controls the state of motion and collects the real-time dynamic response data relating to the footpad. The hardware contains a four-slot chassis cDAQ-9174 and 32-channel acquisition module NI-9205, as shown in Figure 7. This system features 16-bit resolution and a maximum sample rate of 250 kS/s. It has four 32-bit timers that are built in to share clocks for the mixed-measurement systems. In the experiment, digital analog converter will record the sampling time, up to 0.1 ms. Settling time for multichannel measurements is ± 120 ppm of full-scale step (± 8 LSB) with $4 \mu\text{s}$ convert interval.

The footpad used in the experiment is modeled after some simplification on the NASA footpad mentioned by Bendix Corporation [2], as shown in Figure 8.

The model box, of size $399 \text{ cm} \times 49 \text{ cm} \times 50 \text{ cm}$, consists of steel frames and plexiglass installed as side walls to ensure overall stiffness and visibility. Equidistant scratch lines, every

5 cm, are scribed into the surface of the plexiglass as shown in Figure 5(d).

2.3. Experimental Procedures

2.3.1. Calibration. Before the experiment, each sensor was calibrated and showed good linearity. Because of space limitations the relevant curves are not given in this paper.

The relationship between the drop height and impact velocity was also confirmed by carrying out drop tests. The results are shown in Figure 9 and illustrate good repeatability. The drop height and impact velocity relationship fits a quadratic relationship.

2.3.2. Site Preparation. Owing to the uneven distribution of lunar soil simulant particle sizes, the dry pluviation sample preparation method causes coarse and fine particles to segregate, leading to various and undesirable relative densities [34]. To ensure overall uniformity, the tamping method (layering, filling, compaction, and leveling) was used to prepare soil sites with 6 layers in total, 5 cm per layer.

FIGURE 9: Relation between drop height and impact velocity.

FIGURE 10: Time-history curves of impact response.

TABLE 3: Comparison of impact velocity.

Cases	NASA test [2]	Apollo [39]	Luna 16 [40]
velocity/m·s ⁻¹	0.3~4.57	0.3~0.9	<2.4

For each relative density, soil with a specified mass was uniformly placed into each layer and aligned with the scratch lines as shown in Figure 5(d). The relative densities selected in the model tests were 40%, 60%, and 80%, respectively, corresponding to the density of the simulant lunar soil samples in triaxial tests.

2.3.3. Test Scheme and Procedures. According to the mass of the lunar lander being simulated, the shock tube mass was variously set at 1.5 kg, 3.0 kg, and 6.0 kg. Table 3 presents the impact velocities in the impact model tests, values that can be reached in the real landing process.

TABLE 4: Scheme of the model tests.

Variables	$D_r/\%$	$v/\text{m}\cdot\text{s}^{-1}$	m/kg	Test number
Value	40, 60, 80	1.0, 2.0, 4.0	1.5, 3.0, 6.0	27

The scheme of the impact model tests is detailed in Table 4, which mainly includes the influencing factors of relative density, impact velocity, and impact mass.

The steps taken in each test are as follows.

- (1) Prepare the soil sites with a specific relative density.
- (2) Lift the shock tube with a particular mass, and fasten it at the height calibrated by the displacement meter.
- (3) Turn on the acquisition system.
- (4) Release the shock tube to impact soil site, and monitor and save the test data.

FIGURE 11: Impact craters on TJ-1 soil site ($D_r = 60\%$).

(a) Curves of displacement

(b) Curves of velocity

(c) Curves of axial force

(d) Curves of acceleration

FIGURE 12: Time-history curves of contact-dynamic characteristics with $D_r = 60\%$, $v = 2$ m/s, and $m = 6$ kg.

FIGURE 13: Time-history curves of axial force under different testing condition.

3. Results of the Vertical Impact Tests

Repeated tests were conducted under the same conditions to verify the reliability of the test results. Figure 10 shows the time-history curves of axial force and penetration displacement, which show good repeatability, proving that the test results are reliable.

3.1. Site Deformation. The results of 27 groups of tests indicate that the shapes of impact craters are similar and resemble a basin. The sizes and depths of the craters, however, are different due to changes in test conditions. Larger impact velocities generate dramatically larger and deeper craters. Figure 11 shows the craters formed by the shock tube impacting with different velocities on the TJ-1 simulant soil site when $D_r = 60\%$.

3.2. Time-Related Characteristics of Response. The shapes of the dynamic response curves are similar even for different testing conditions. Figure 12 gives the typical time-history

dynamic response curves for the footpad, including displacement, velocity, axial force, and acceleration curves at the instant of contact, when $D_r = 60\%$, $v = 2$ m/s, and $m = 6$ kg. It can be seen in Figure 12(a) that the footpad reaches the maximum penetration depth at 25 milliseconds. With the time increasing, the penetration depth initially decreases, increases later, and eventually reaches stability. This indicates that the footpad rebounds after it reaches the maximum depth, then again impacts the simulant lunar soil site, and after further small vibrations tends to finally become stable.

The velocity time-history curve shown in Figure 12(b) indicates that the initial high velocity is at 1 ms~3 ms, since at that stage gravity far overcomes the resistance of the lunar soil stimulant, before decreasing rapidly. It then fluctuates weakly on the horizontal axis and trends to zero.

Figure 12(c) indicates that the axial force in the footpad reaches its maximum value in the initial 5 milliseconds before reducing and creating a second peak. The resultant impulse is found to be 13.02 N·s, the integral given by the area enclosed by curve *ab* in Figure 12(c), which approximately equals

FIGURE 14: Time-history curves of penetration displacement with $D_r = 60\%$, $v = 2$ m/s.

FIGURE 15: Test result of $D_r = 60\%$, $m = 6$ kg.

the change in momentum, of 13.09 kg·m/s (based on the reduction in initial velocity 2 m/s downwards to the velocity 0.182 m/s upwards). A comparison of Figures 12(c) and 12(a) indicates that the displacement response lags behind that of the axial force.

As shown in Figure 12(d), the two acceleration time-history curves recorded by the two accelerometers set on the footpad as shown in Figure 5(c) are in good agreement. A comparison of Figures 12(d) and 12(c) shows that acceleration and axial force responses are in phase.

The force the footpad bears during the impact process is critical for a safe landing. Figure 13 shows the time-history curves of axial force for various relative densities, impact velocities, and impact masses. These curves indicate that the various modes of axial force are similar; in the initial instant contact force grows quickly to its peak value in only a few milliseconds. It then declines to a lower level and tends to be finally equal to the weight of the shock tube.

Figure 13(a) shows the axial force response to the impact for soils of 3 different densities, which indicate that the

denser the site, the larger the peak axial force and the shorter the impact duration time. Figure 13(b) illustrates that the axial force increases approximately linearly with increasing impact velocity but the impact duration time increases little. Figure 13(c) demonstrates that the bigger the impact mass, the larger the peak axial force and the longer the impact duration time.

It is noteworthy that the axial forces remain almost unchanged in some cases in Figure 13 between the two peaks over quite long periods with respect to the whole process. A similar phenomenon was found in the footpad impact study made by NASA [2]. This phenomenon gives proof that the simulant lunar soil site reached a state of “flow failure” under impact. As in soil mechanics, “flow failures are characterized by a sudden loss of strength followed by a rapid development of large deformations [41].” The term “flow failure” is adopted here to describe the phenomenon that the deformation increases sharply when the axial force has a sharp decrease. From the present experiment, the occurrence of this phenomenon is conditioned. When the relative density

FIGURE 16: Effect of relative density on peak axial force.

of the simulant lunar soil site is low, the flow failure is more pronounced. For a specified relative density, the larger the impact velocity and the impact mass are, the easier it is for flow failure to occur. It can be deduced that there exists a critical impact momentum or kinetic energy value for a simulant lunar soil site of a specified density. When less than that critical value, the impact will not cause flow failure of the simulant lunar soil site. The explanation is that, with the footpad penetration depth increasing, if the underlying soil of the ground is not able to bear the impact, the soil will exhibit plastic flow failure; otherwise, if the underlying soil has a relatively great strength which is enough to carry the impact force, flow failure will not occur.

Penetration displacement is another major factor affecting landing safety. Figure 14 shows the time-history curves

of penetration displacement for $D_r = 60\%$ and $v = 2$ m/s and different impact masses. The time of the first impact all begins from the 0 point. The variations in penetration displacement patterns are similar, that is, a quick increase once the lander touches the site, a rebound after reaching the peak value, followed by a slight further impact before reaching an ultimate stability. The larger the impact mass, the larger the peak value and the ultimate stable penetration depth and the longer the rebound duration time.

3.3. Correlation of Axial Force and Penetration Displacement. Figure 15(a) shows the relationship between penetration displacement and axial force for $D_r = 60\%$, $m = 6$ kg, and different impact velocities. The curves shapes are similar.

FIGURE 17: Effect of relative density on penetration depth.

The whole curve can be divided into 4 stages, denoted by the characters A, B, C, D, E as shown in Figure 15(a).

The curve in stage AB is approximately linear. The axial force on the footpad is generated by the dynamic interaction between shock tube and the compressed soil. The penetration displacement mainly is one of elastic compression deformation of the soil during this stage. In the shearing stage BC, part of the soil element under the footpad reaches failure, and the soil resistance decreases allowing shear deformation to occur. That is why the slope of the curve becomes negative. In the flow failure stage CD, due to the expansion of the affect zone surrounding the footpad, the resistance of the soil remains stable or increases a little, but large vertical deformation occurs and the footpad is deeply pierced. Note

that when the impact momentum or energy is smaller, there is no flow failure stage CD, as in the case of $v = 1.0$ m/s, as shown in Figure 15(a). In stage DE, because of the weak elastic properties of the lunar soil simulant, the footpad rebounds even off the surface, and the axial force decreases sharply and even turns negative. After fluctuating weakly, the displacement of the footpad tends to reach the ultimate point E and the axial force tends to be equal to the shock tube's gravity induced weight.

The velocity variation of the footpad on the vertical motion track is shown in Figure 15(b). In the instant of contact, the velocity increases to peak point K within a 2~3 mm penetration displacement due to the shock tube inertia. The velocity then decreases gradually until reaching

FIGURE 18: Effect of impact mass on peak axial force.

the maximum penetration displacement point M when the velocity equals zero. After fluctuating several times, it finally reaches the ultimate penetration point N .

3.4. Peak Feature of Dynamic Response. Other than the time-history characteristics of the footpad dynamic response in the instant of contact, the peak values themselves are essential for the design of the lander buffering system, especially the extent of penetration which is the stable penetration displacement. Peak values of axial force and acceleration are also essential.

Figures 16 and 17 show the effect of relative density on peak axial force and penetration depth, which indicates that peak axial force increases significantly as relative density increases in all test conditions, while penetration depth is reduced.

Figure 18 demonstrates that peak axial force is little affected by impact mass. When the impact mass is four times greater, peak axial force is only increased by 13%. In contrast to the influence of relative density, penetration depth increases almost linearly as impact mass increases, as shown in Figure 19, with an increase to 215% of the initial lowest impact mass.

Figure 20 shows the peak axial force is evidently affected by impact velocity; the increase ranges around 318%~693% as impact velocity increases four times. Figure 21 shows that the penetration depth also increases significantly as impact velocity increases in all test conditions.

In general, the peak axial force is influenced more significantly by relative density and impact velocity than by impact mass.

FIGURE 19: Effect of impact mass on penetration depth.

In order to comprehensively consider the influence of all control variables, the impact kinetic energy was set as an independent variable and the relationships between peak value dynamic responses of the footpad and kinetic energy are drawn as dots in Figure 22.

It can be concluded that, for different relative densities, the larger relative density leads to greater axial force and acceleration but smaller penetration depth; for the same relative density, the responsive peaks (axial force, penetration, and $m \cdot a_{\max}$) increase steadily as impact kinetic energy grows. The relationship can be expressed in the following exponential form:

$$C_j = a_j \cdot \left[\frac{(m \cdot v^2)}{2} \right]^{b_j}; \quad (j = 1, 2, 3), \quad (1)$$

where C_j ($j = 1, 2, 3$) are $F_{\max}$, $d_{\max}$, and $m \cdot a_{\max}$, respectively, and a_j , b_j ($j = 1, 2, 3$) are material parameters related to the relative density of lunar soil, as listed in Table 5. For a given impact kinetic energy and site relative density, the dynamic responsive peak can be calculated using (1). From the test results, the constants are given below. The curves employing the following constants are shown highlighted in the solid lines in Figure 22.

4. Numerical Study of the Impact Process

Since impact experiments are costly and the environmental conditions on the Moon are difficult to fully simulate, numerical analysis is commonly adopted to help understand the impact process consequences and make further predictions

FIGURE 20: Effect of impact velocity on peak axial force.

TABLE 5: Values of a_j, b_j .

D_r	Peak axial force		Penetration depth		$m \cdot a_{\max}$	
	a_1	b_1	a_2	b_2	a_3	b_3
40%	257.03	0.52	18.87	0.42	11.84	0.49
60%	434.13	0.50	9.51	0.41	32.33	0.43
85%	822.51	0.47	4.80	0.32	57.33	0.43

[42]. Considering the special granularity and interparticle attraction of lunar soil, it is of great interest to simulate lunar soil by discrete element method (DEM) [43]. However, the finite element method (FEM) is still used in this

paper for the relatively mature commercial software and more understanding of the parameters required for analysis. In this paper, the numerical simulation is carried out on the commercial software Abaqus, for its good capabilities in analyzing nonlinear, transient dynamics problems. The numerical simulation is carried out on the EXPLICIT module, in a 3D visualization dynamic format, with geometric large deformation nonlinear analysis. The impact experiment model is taken as the prototype of the numerical FEM analysis. Then the results of the numerical analysis were compared with those of experiment, so as to verify the validity of the numerical model. The brief description of the numerical modeling and the simulation is given below; some details can also be seen in [44].

FIGURE 21: Effect of impact velocity on penetration depth.

4.1. FEM Model

4.1.1. Model of Shock Tube and Site. The appearance of the footpad model is shown in Figure 23(a). Due to the irregular shape, the shock tube is represented as thousands of four-node, 3D tetrahedron elements. The mass of the shock tube is controlled by adjusting the height of the cylinder.

Using the artificial truncation boundary, a cube with side length L was taken as the finite element analysis area, discretized into 8-node hexahedron elements. L is the characteristic width of the simulant soil site in the numerical simulation model, which is determined by trial computations until the boundary effect is eliminated. The site area was divided into two meshing zones as shown in Figure 23(b). Zone 1, where stress is concentrated and large plastic deformation

occurs under impact load, is meshed into even smaller and denser grids than those of Zone 2. In our study, L was set as 500 mm, and the side length of Zone 1 with cell size 2.5 mm was 250 mm, while the cell size in Zone 2 was 5 mm.

4.1.2. Model of Soil-Footpad Interface. The shock tube and simulant lunar soil interact at the soil-footpad interface. As shown in Figure 24, the contact face transfers interaction forces in both tangential and normal directions. The contact stresses are applied to the following restrictions.

When the footpad and the simulant lunar soil are not in contact,

$$\sigma_n = 0, \quad \tau_s = 0. \quad (2)$$

FIGURE 22: Relationship of peak features with impact kinetic energy.

Normal stress is generated as the two sides make contact. The stresses on the nodes of the contact surface satisfy the following relationships:

$$\begin{aligned} \sigma_n(\text{footpad}) &= \sigma_n(\text{soil}), \\ \tau_s(\text{footpad}) &= \tau_s(\text{soil}) \leq \tau_{\text{crit}}. \end{aligned} \quad (3)$$

σ_n is not allowed tensile stress; when tensile stress appears it is considered the separation which appeared. For τ_s , when the shear stress in the interface is less than the limiting value, the two sides bond, and when the limiting shear stress is reached, the two sides begin to slip. The critical value is given by

$$\tau_{\text{crit}} = \mu \cdot \sigma_n, \quad (4)$$

where μ is the friction coefficient, determined from interface shearing tests of the footpad made aluminum alloy and the TJ-1.

In the Abaqus software, the master-slave interface model was adopted to simulate the interaction. The bottom surface of the footpad was set as the master surface and the top surface of the simulant lunar soil sites as the slave surface, shown in Figure 24. Through face-face mesh generation method and setting the friction coefficient, the aforementioned contact model is established.

Figure 25 shows the interface friction characteristics between the lunar soil simulant and the hard aluminum (the same material as the footpad) gained from direct shear tests. The interface shear behavior can be regarded as ideal elastoplastic. The range of friction coefficient at the contact surface is 0.58~0.64 by fitting test data, which is little affected by relative density. In this study, the friction coefficient has been taken as 0.62.

4.1.3. Constitutive Model of Lunar Soil Simulant TJ-1. Taking the two characteristics of TJ-1 into account, that is, the

FIGURE 23: Grid of calculated model.

FIGURE 24: Footpad and soil in contact.

FIGURE 25: Shear test curves of soil-structure interface.

large internal friction angle ($38.5^\circ \sim 50.9^\circ$) and the strong strain-softening behavior, as shown in Figure 2, the elastoplastic Mohr-Coulomb constitutive model which satisfies

the nonassociative flow rule was selected for the study. The function of the yield surface in p - q space (Figure 26) is

$$F = R_{mc}q - p \tan \varphi - c, \quad (5)$$

where

$$p = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3),$$

$$q = (\sigma_1 - \sigma_3),$$

$$R_{mc} = \frac{\sin(\Theta + \pi/3)}{(\sqrt{3} \cos \varphi)} + \frac{\cos(\Theta + \pi/3) \tan \varphi}{3}, \quad (6)$$

$$\cos 3\Theta = \frac{J_3^3}{q^3}$$

and J_3 is the third invariant of the stress tensor, φ the internal friction angle, and c cohesion of the simulant lunar soil. The cohesion c was set as the hardening parameter to describe the strain-softening properties, which vary with equivalent plastic strain $\bar{\epsilon}^p$, as shown in Figure 26(b), where c_p and c_r are the peak and residual cohesion values, respectively.

In the elastic stage, the stress-strain relationship obeys Hooke's law, and the relevant parameters are Young's modulus and Poisson's ratio. Since the affected area is near the surface, Young's modulus is fitted from the laboratory results under small confining pressures. The empirical formula proposed by Janbu [45] is utilized in this paper, as shown in

$$E = K \cdot p_a \cdot \left(\frac{\sigma_3}{p_a} \right)^n, \quad (7)$$

where p_a is atmospheric pressure, σ_3 is confining pressure, and K and n are material constants. The parameters used are listed in Table 6.

FIGURE 26: Constitutive model of lunar soil simulant TJ-1.

FIGURE 27: Mises stress distribution when $D_r = 60\%$, $v = 4$ m/s, and $m = 3$ kg.

Poisson's ratio of lunar soil simulant under different confining pressures and relative densities is expressed by the following formula:

$$\mu = \frac{(v_p^2 - 2v_s^2)}{2(v_p^2 - v_s^2)}, \quad (8)$$

where v_p is compression wave velocity and v_s shear wave velocity. Test results indicate that the range of Poisson's ratio is 0.31~0.34, is little affected by confining pressure and relative density, and is taken as 0.32 in this study.

The triaxial tests demonstrate that the internal friction angle of the lunar soil simulant increases as relative density increases, which is mainly distributed around 45° . Peak and

residual cohesion values of the lunar soil simulant for three different relative densities are listed in Table 1 after considering the influence of shear rates. Figure 1 also indicates that when plastic flow occurs, the equivalent plastic strain is about 8.2%~15.3%, which, in this study, has been taken as 12%.

Table 6 lists interface and lunar soil simulant parameters based on laboratory tests, including value ranges and the specific values chosen for this study.

4.1.4. Initial Conditions and Boundary Conditions. In order to make comparisons with the model test results, the gravitational weights of both shock tube and soil are allowed in the FEM model, and the penetration displacement and velocity are set as zero at the initial time. The dynamic response at

FIGURE 28: Penetration deformation calculated when $D_r = 60\%$, $v = 4$ m/s, and $m = 6$ kg.

FIGURE 29: Propagation of compression wave when $D_r = 60\%$, $v = 4$ m/s, and $m = 3$ kg.

TABLE 6: Parameters of interface and lunar soil simulant selected in numerical simulation.

Materials	Parameter/unit	D_r	Value range	Value used
Lunar soil simulant	E/MPa	0.4	0.1~1.5	0.75
		0.6	1.2~4.1	1.30
		0.8	1.8~5.0	2.15
	μ		0.31~0.34	0.32
		0.4		1.8
		0.6	0.8~27.0	4.5
	c_p/kPa	0.8		15.0
		0.4		0.4
		0.6	0.1~15.2	1.2
	c_r/kPa	0.8		10
Interface	$\bar{\epsilon}^p$		8.2~15.3	12.0
	$\varphi/^\circ$		39~51	45.0
	$\bar{\eta}$		0.16~0.33	0.2
	μ_f		0.58~0.64	0.62

the interface, the peak axial force, and penetration depth are the three items of most interest during the impact process. In order to improve computational efficiency, the normal

displacement at the truncating boundary is constrained instead of utilizing the transmitting boundary.

4.2. Numerical Results and Discussions. After establishing the numerical model as above, 27 groups of studies were taken under the same conditions shown in Table 4.

4.2.1. Response of Overall Site. Results show the overall site response in different cases is similar. Figure 27 illustrates the Misses stress distribution at different times when $D_r = 60\%$, $v = 4$ m/s, and $m = 3$ kg, which is within the range 0.0 kPa~28.2 kPa. At the initial time, seen in Figure 27(a), there exists a flat area beneath the footpad with very high stress levels due to the inertia force and lateral restraint. As the stress wave propagates outward, the stress amplitude then decreases while the regional influence expands gradually. The maximum influenced depth reaches about 25 cm, three times the diameter of the footpad. Finally, the stress dissipates and the influenced region reduces and disappears ultimately. The plastic zone is ellipsoidal in shape, varying from flat with its long axis in the horizontal direction to taper with its long axis in the vertical direction during the impact process. This differs from the cone shape plastic zone put forward by NASA scholars [2].

Figure 28 demonstrates penetration displacement vector distribution at 16 ms when $D_r = 60\%$, $v = 4$ m/s,

FIGURE 30: Curves of dynamic response when $D_r = 60\%$ and $m = 3$ kg at different impact velocities.

and $m = 6$ kg. The figure indicates that the simulant lunar soil beneath the footpad moves downward and extrudes towards the periphery, resulting in a basin-shaped crater. The displacement mainly occurs over a region 2~3 times the diameter of the footpad. Figure 11 shows the impact crater formed in the test under different impact velocities. Comparing Figure 28 with Figure 11 shows that the deformation calculated by the FEM model is consistent with that of the test.

Figure 29 represents compression wave at different times when $D_r = 60\%$, $v = 4$ m/s, and $m = 3$ kg. The results demonstrate that the compression wave propagates outward taking an axisymmetric spherical shape.

4.2.2. Response of Footpad. Figure 30 shows the time-history response curves of the footpad (axial force, velocity, and penetration displacement) under different impact velocities when $D_r = 60\%$ and $m = 3$ kg. It implies in Figure 30(a) that the axial force in the footpad reaches its peak in a very short time followed by a second impact. The axial force then decays gradually until it equals the weight of the shock tube. Figure 30(b) shows that the decay of velocity of the

shock tube lags behind the axial force, and after a rapid attenuation from its initial value, the velocity changes slightly along the horizontal axis ($v = 0$) and tends finally to $v = 0$. Figure 30(c) indicates that the penetration displacement curves are the most hysteretic. After achieving the maximum depth, the shock tube rebounds slightly and then tends towards the reach ultimate penetration depth. Comparison of these displacement curves indicates that the greater the impact velocity, the deeper the reach of the shock tube and the longer the duration time when the shock tube to achieve is stable.

Numerical analysis also demonstrates that the shock tube response amplitudes are different under different impact masses, impact velocities, and relative soil densities, but their response variations are similar. Figure 31 manifests that the peak axial force and penetration depth both increase exponentially with increasing impact kinetic energy. The denser the soil, the smaller the penetration depth and the larger the axial force. Figure 31 also gives the comparison between numerical and measured results, where the solid points are the measured values obtained from model tests, and the hollow points are the numerical results.

FIGURE 31: Comparison between calculated and tested results.

5. Conclusions

An investigation into the interaction between lunar soil simulants and the lander footpad during the impact process using subscale model tests based on prototype vertical impact test apparatus has been described in this paper. In addition a 3D dynamic finite element model was established to simulate the impact process. The main conclusions are as follows.

The impact duration time is short in the tests, with magnitudes in tens of milliseconds. The relative density of the lunar soil simulant site has the most significant influence on the dynamic response during impact, followed by the impact velocity; the impact mass has the least influence. For a given shape and dimensions of the footpad, the peak axial force and penetration depth increase in an exponential form as impact kinematic energy increases. There exists a critical value of impact momentum or energy for a given relative density of simulant lunar soil site. When the value is less than the critical value, the simulant soil site does not reach flow failure under impact of the footpad. The flow failure phenomenon under impact is more likely to occur for lower relative simulant lunar soil site densities. There exists a secondary rebound of the footpad after impacting the simulant lunar soil site, and a basin-shaped crater is formed.

Numerical simulation demonstrated that the displacement caused by the footpad impact affects a region of mainly 2~3 times the diameter of the footpad. The shape of the plastic deformation zone in the simulant lunar soil site is an approximate ellipsoid, which is different from the cone shape assumed by former scholars. Numerical simulation provided the dynamic responses of the simulant lunar soil in the cases of axial force, velocity, and displacement of the footpad. The numerical model was proved to give valid information based on comparison with model test results.

The work described in this paper provides a basis for further research into landing simulations, the modeling of the simulant lunar soil site, the dynamic responses to oblique landing impact on the simulant lunar soil, and also the design of the lander buffering system of the lander among other design aspects.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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