Discrete Element Modelling of Triaxial Compression Test of QH-E Lunar Soil Simulant under Hydrostatic Compression

Yunli Li, Weilie Zou, Wenping Wu, and Xihua Chu

***Abstract*—In this paper, triaxial compression mechanical properties of QH-E lunar soil simulant under hydrostatic compression path is investigated by using discrete element method (DEM) simulations. The volumetric strain characteristics of QH-E lunar soil simulant under hydrostatic compression path are discussed. The results show that volumetric strain gradually increases with the increase of confining stress. At low confining stress levels, volumetric strain increases quickly, when the confining stress increased gradually to the conventional levels, volumetric strain increases slowly, the volumetric strain curve becomes more and more flat. At the same confining stress, the volumetric strain increases with the increase of the initial porosity, while decreases with the increase of the friction coefficient. Under low confining stress, the gaps of volumetric strain caused by the change of porosity is not large, but at the conventional stress levels, the gaps of volumetric strain caused by the change of porosity become more and more larger. Meanwhile, the reduction of volumetric strain caused by the increase of friction coefficient under low confining stress is smaller than under conventional confining stress.**

***Index Terms*—Discrete element method, QH-E lunar soil simulant, triaxial compression test, hydrostatic compression.**

I. INTRODUCTION

In the lunar exploration project, it needs to study the interaction of lunar probe and lunar soil. Because of less true lunar soil samples, a similar lunar soil simulant can be used replacing the real lunar soil to meet the needs of a large number of scientific researches in lunar exploration project. Therefore, lunar soil stimulant is an alternative to the study the engineering properties of real lunar soil on earth, and played an important role in study of interaction of lunar probe and lunar soil [1]-[3]. It is well known that the gravity on the Moon is about 1/6 of that on Earth [1], [4] therefore, the lunar soil is subject to very low confining stresses under a microgravity environment conditions, which cause that the mechanical properties may differ from those observed under regular tests, the evaluation of mechanical properties of lunar soil simulant at low confining stresses is key to the implementation of lunar exploration project [5]-[8].

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In recent years, many experimental tests have been carried out to investigate the mechanical properties of lunar soil simulant at low confining stresses [5]-[10]. These experimental studies were carried out to assess the tensile strength, shear strength, peak stress, residual stress in lunar soil simulant, etc. Considering the lunar soil consists of discrete solid particles, which can be classified as a granular material [1], discrete element method (DEM) simulations have been used in the research of the basic physical and mechanical properties of triaxial compression of this kind of granular materials, and discussed the influences of related microscopic parameters on mechanical properties of lunar soil simulant [11]-[14]. However, most of studies on triaxial mechanical properties of the lunar soil simulant were under the conventional triaxial compression tests. Due to the mechanical properties of soil are not only closely related to the loading environment but also depend on stress paths and directions in granular materials [15], [16]. In our previous work, the strength and deformation behavior of QH-E lunar simulant under conventional triaxial compression path and constant mean principal stress path have been studied by 3-dimension particle flow code (PFC3D) numerical simulations [17], [18], however, the volume-change behavior of QH-E lunar simulant under hydrostatic compression path has not been studied well enough in geotechnical engineering literature.

In this paper, the triaxial compressive mechanical properties of QH-E lunar soil simulant under hydrostatic compression path are investigated by PFC3D numerical simulations. The objective of the present work is to determine the volume-change characteristics of QH-E under hydrostatic compression path, and explore the effects of porosity, friction coefficient on volumetric stain behavior of QH-E lunar soil simulant.

II. SIMULATION MODEL

A. Selection of Numerical Model and P Stress Path Scheme

In the present PFC3D simulations, the same physical parameters of QH-E lunar soil simulant developed by Tsinghua University, China are selected to investigate the mechanical properties of QH-E by comparing with our previous experimental results [8]. Isobaric triaxial compression (hydrostatic compression) tests are performed on the rectangular soil sample (the length is 140 mm, and the width and height are 70 mm), and the shapes of particles are considered to be spherical with the grain-size of 1 ~1.5mm using PFC3D numerical simulation for convenience of calculation, as shown in Fig. 1.

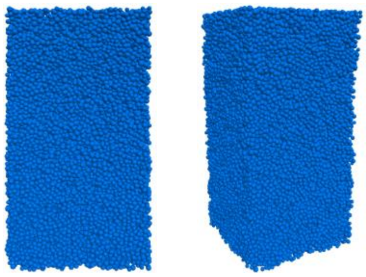

Fig. 1. Model geometry for PFC3D simulation.

In this simulation, the initial porosity of simulation model is 0.38. The hydrostatic compression path is used to study the mechanical behavior of materials under hydrostatic pressure, and to determine the bulk elastic modulus and hardening law of soils in some elasto-plastic constitutive relations. In the isobaric triaxial compression simulation, the same stress is applied in the three principal directions of the specimen, and the value of the stress is equal to the confining stress $\sigma_1=\sigma_2=\sigma_3=\sigma_c$. By increasing confining stress σ_c, the isotropic compression simulation is carried out, and the volume change of the sample is also output. Table I lists the detailed hydrostatic compression path scheme.

TABLE I: HYDROSTATIC COMPRESSION PATH SCHEME

Stress path	σ_1	σ_2	σ_3	$\Delta\sigma_1$	$\Delta\sigma_2$	$\Delta\sigma_3$	Δp	b (θ)
Hydrostatic pressure	$=\sigma_c$	$=\sigma_c$	$=\sigma_c$	>0	>0	>0	>0	/

TABLE II: MICRO-PARAMETERS FOR PFC3D NUMERICAL SIMULATION

Parameters	Values	Parameters	Values
porosity	0.38	Tangential stiffness	0.85e8(N/m))
Particle size	1~1.5(mm)	Normal strength	1.0e5(N/m)
Friction coefficient	0.25	Tangential strength	1.0e5(N/m)
Particle density	1640(kg/m^3)	Normal contact stiffness	1.0e7(N/m)
Normal stiffness	1.0e8(N/m)	Tangential contact stiffness	0.85e7(N/m)

B. Contact Constitutive Model and Micro-parameters Calibration

In the geotechnical problem of lunar soil PFC numerical simulation, parallel-bonded model is used to study the triaxial compression mechanical properties of lunar soil simulant because lunar soil has a certain amount of apparent cohesion [19], [20], which has been successfully applied to simulate mechanical properties of lunar soil simulant [4], [17], [18]. By drawing the Mohr's circles and their common tangent based on our previous experimental data [8], the average cohesion is 3.1 kPa and the friction angle is 51.55°, whereas the average cohesion is 18.80 kPa and the friction angle is 48.17° for QH-E lunar soil simulant with particle density of 1640 kg/m3 at low and conventional stress levels, respectively. Through repeatedly adjusting the input of the microscopic parameters of the model, the simulation results are in agreement with the experiment results as much as possible, so as to determine the values of the parameters, and to further carry out other numerical simulation research. The microscopic mechanical parameters of the QH-E lunar soil simulant with the relative density of 83% are calibrated as shown in Table II.

III. SIMULATION RESULTS AND DISCUSSION

A. Volumetric Strain Change at HC Stress Path

Considering the effect of stress path on mechanical properties of lunar soil, hydrostatic compression (HC) path is realized to further study the mechanical properties of lunar soil simulant by using PFC3D. The simulation results under hydrostatic compression (HC) path in Fig. 2a show that the volumetric strain ε_v gradually increases with the increase of confining stress P. Under low confining stress range of (0 ~ 25 kPa), ε_v increases fast, when the confining stress increased gradually to the conventional level (50~150 kPa), ε_v increases slowly, the ε_v curve becomes more and more flat. It is found that the QH-E lunar soil simulant with different porosities specimens have basically the same variation trend on the ε_v curves, however, for the same confining stress, the greater the initial porosity e, the larger ε_v is. That is to say, the ε_v have the largest value at the porosity of e=0.55, and the lowest value at e=0.30. Under low confining stress, the gap of volumetric strain ε_v caused by e is not large, but with the confining stress increased gradually to the conventional level, the gap of ε_v caused by e become more and more large. TABLE III quantitatively gives the values of volumetric strain ε_v of QH-E lunar soil simulant with four different porosities at low and conventional confining stresses. At the conventional confining stress P = 150 kPa, the gap of ε_v between e=0.55 and e=0.45 is nearly twice that of between e=0.38 and e=0.30, which means that with the increase of confining stress and porosity, the volumetric strain increases and the gap of volumetric strain also become large.

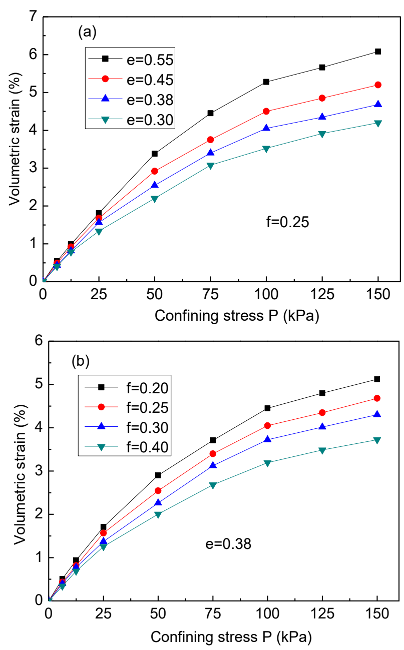

Fig. 2. Volumetric strain ε_v versus confining stress P curves at (a) different porosities, and (b) different friction coefficients.

Fig. 2b shows the curves of volumetric strain ε_v of QH-E lunar soil simulant with four different friction coefficients varying with confining stress P under HC path (porosity e=0.38 unchanged). With the increase of confining stress $P = \sigma_c$, the volumetric strain ev gradually increases. Under low confining stress range of (0 ~ 25 kPa), ε_v increases fast, while at the conventional confining stress level (50 ~ 150 kPa), ε_v increases very slowly, the curve becomes more and more flat. The QH-E lunar soil simulant specimens with different friction coefficients have basically the same variation trend on the ε_v curves, the volumetric strain ε_v decreases with the increase of the friction coefficient at the same of confining stress. Table IV quantitatively gives the values of volumetric strain ε_v of QH-E lunar soil simulant with four different friction coefficients at low and conventional confining stresses. The data in the Tab.4 show that the volumetric strain ε_v decreases with the increase of friction coefficient and the reduction of ε_v under the conventional confining stress is more than that of the low confining stress.

TABLE III: The Values of ε_v of QH-E Lunar Soil Simulant with Different Porosities Under Hydrostatic Compression Path

Stress levels	Confining Stress P (kPa)	Volumetric strain ε_v (%)			
		e=0.30	e=0.38	e=0.45	e=0.55
Low stress	6.25	0.40	0.43	0.49	0.54
	12.5	0.78	0.82	0.92	0.99
	25	1.34	1.57	1.68	1.81
Conventional stress	50	2.20	2.54	2.92	3.38
	100	3.52	4.05	4.50	5.28
	150	4.20	4.68	5.20	6.08

TABLE IV: The Values of ε_v of QH-E Lunar Soil Simulant with Different Friction Coefficients Under Hydrostatic Compression Path

Stress levels	Confining Stress P (kPa)	Volumetric strain ε_v (%)			
		f=0.20	f=0.25	f=0.30	f=0.40
Low stress	6.25	0.51	0.43	0.40	0.34
	12.5	0.94	0.82	0.77	0.69
	25	1.71	1.57	1.38	1.26
Conventional stress	50	2.90	2.54	2.26	2.01
	100	4.45	4.05	3.73	3.19
	150	5.12	4.68	4.30	3.72

B. *Tangent Slope of Variations of ε_v and P at HC Stress Path*

In order to directly reflect the varying speed of volumetric strain ε_v under low and conventional confining stress levels, the tangent slope of variations of ε_v and P under different porosities and friction coefficients are given in Fig. 3. With the increase of confining stress P, the volumetric strain ε_v increases gradually, but the increase rate slows down gradually, and the curve becomes more and more flat. That is, the tangent slope (dε_v /dP) of the curve becomes smaller and smaller. The tangent slope (dε_v /dP) of the curve decreases with the increase of confining stress P. In the range of low confining stress (0-50 kPa), the tangent slope (dε_v /dP) decreases rapidly, the larger the porosity ratio or the smaller the friction coefficient is, the faster decrease of the slope (dε_v /dP) is. After entering the range of conventional confining stress (50-150 kPa), the tangent slope (dε_v /dP) decreases slowly and gradually becomes flat. Under the same confining stress, the tangent slope (dε_v /dP) increases with the increase of the porosity, while decreases with the increase of the friction coefficient.

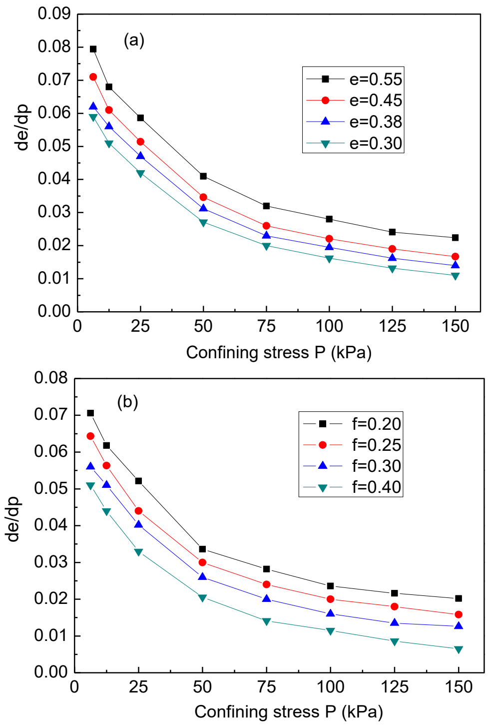

Fig. 3. the tangent slope of variations of ε_v and P at (a) different porosities and (b) different friction coefficients.

IV. Conclusions

DEM numerical simulations are carried out to investigate mechanical properties of QH-E lunar soil simulant under hydrostatic compression path. The main conclusions can be drawn as follows:

1) The volumetric strain ε_v increases gradually with the increase of the confining stress P. However, at low confining stress range of (0 ~ 25 kPa), ε_v increases quickly with the increase of the confining stress P, when the confining stress increased gradually to the conventional stress level (50 ~ 150 kPa), ε_v increases slowly, the ε_v curve becomes more and more flat.
2) The QH-E lunar soil simulant specimens with different porosities and friction coefficients have basically the same variation trend on the ε_v versus P curves. The ε_v increases with the increase of the porosity, while

decreases with the increase of the friction coefficient at the same of confining stress *P*.

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