Experimental and DEM analyses on wheel-soil interaction

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26 **Abstract:** In this paper, the wheel-soil interaction for a future lunar exploration mission
27 is investigated by physical model tests and numerical simulations. Firstly, a series of
28 physical model tests was conducted using the TJ-1 lunar soil simulant with various
29 driving conditions, wheel configurations and ground void ratios. Then the
30 corresponding numerical simulations were performed in a terrestrial environment
31 using the Distinct Element Method (DEM) with a new contact model for lunar soil,
32 where the rolling resistance and van der Waals force were implemented. In addition,
33 DEM simulations in an extraterrestrial (lunar) environment were performed. The
34 results indicate that tractive efficiency does not depend on wheel rotational velocity,
35 but decreases with increasing extra vertical load on the wheel and ground void ratio.
36 Rover performance improves when wheels are equipped with lugs. The DEM
37 simulations in the terrestrial environment can qualitatively reproduce the soil
38 deformation pattern as observed in the physical model tests. The variations of traction
39 efficiency against the driving condition, wheel configuration and ground void ratio
40 attained in the DEM simulations match the experimental observations qualitatively.
41 Moreover, the wheel track is found to be less evident and the tractive efficiency is
42 higher in the extraterrestrial environment compared to the performance on Earth.

43 **Keywords:** Wheel-soil interaction system; TJ-1 lunar soil simulant; Contact model;
44 DEM simulation; Tractive efficiency

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51 **1. Introduction**

52 China has just accomplished the second phase of the Chang'e Lunar Exploration
53 Program in 2013 with a successful landing of an unmanned lunar rover. However, it
54 has only travelled in a limited area and performed simple missions for safety reasons.
55 In the future exploration, the new lunar rover will be required to travel longer
56 distances and carry more equipment, which is more challenging. Therefore, it is
57 necessary to test the rover locomotion under different driving conditions on Earth
58 prior to its deployment on the lunar surface. Many experimental investigations have
59 been conducted on Earth to guide the rover mechanical design (Apostolopoulos,
60 2001), structural optimization (Patel et al., 2004), locomotion control (Iagnemma et
61 al., 2001), and path planning and following (Ishigami et al., 2006; 2007; Wong, 2012).
62 Moreover, in order to study the gravity effects, Kobayashi et al. (2010) performed
63 physical tests on an aircraft performing parabolic flight maneuver. But the tests are
64 costly and may not be available for most researchers. Alternatively, the Distinct
65 Element Method (DEM) is more efficient in generating virtual extraterrestrial
66 environment (EX), and has become a popular method in recent studies (Nakashima et
67 al., 2006; Medina and Zeghal, 2006; Hopkins et al., 2008; Li et al., 2010; Jiang et al.,
68 2014). However, conventional contact models for disks or spheres lead to a low
69 internal friction angle of the DEM ground, with mechanical behavior different from
70 the lunar soil ground remarkably. Hence, comprehensive grain shapes (Knuth et al.,
71 2012; Johnson et al., 2015) or contact models (Jiang et al., 2005; Jiang et al., 2013;
72 Jiang et al., 2017b) were used to reproduce the high internal friction angles of the test
73 materials. In addition, the previous research usually focused on the wheel
74 performance and sinkage, little attention was paid on the trace distance, which is also
75 an indicator of the wheel-soil interaction and could be used to predict the slip ratio
76 (Ding et al., 2009)

77 In this paper, the soil-wheel interaction is investigated using numerical studies in
78 combination with physical model tests. Firstly, a series of soil-wheel tests was

79 conducted on the TJ-1 lunar soil simulant with various driving conditions, wheel
80 configurations and ground void ratios. Here, the quantitative relationship between the
81 track length and slip ratio described by Ding et al., (2009) was validated for real-time
82 prediction of slip ratio. The variation of tractive efficiency was investigated as a
83 function of driving condition, ground condition and wheel configuration. Then the
84 corresponding simulations were performed using DEM with the lunar contact model
85 including the rolling resistance and the van der Waals force (Jiang et al., 2013) and
86 then validated by comparing with the experimental results. Finally, DEM simulations
87 of wheel performance in an extraterrestrial (lunar) environment were performed to
88 compare the wheel-soil interactions in the terrestrial environment (T) with those in the
89 extraterrestrial environment. Compared with our previous work (Jiang et al., 2017a),
90 which proposed a design guideline for rover wheel testbeds and presented the
91 comparisons between the experimental and analytical results, this current work
92 focuses on the validation of the DEM simulation and the effects of the gravitational
93 acceleration. In addition, more tests conditions are included in this paper, such as
94 different ground void ratios and wheel forms.

95 **2. Physical model tests**

96 **2.1 Introduction of wheel-soil interaction system**

97 The wheel-soil interaction system consists of a glass-walled soil bin, a test wheel,
98 a carriage, two rails, a motor and four sensors. The soil bin has a dimension of
99 1500mm×900mm×900mm, enabling us to conduct tests using wheels with a certain
100 range of radii and widths. The wheel used in the present study has a radius of 125 mm
101 and width of 100 mm. The rails are installed to guide the motion of the wheel and
102 ensure the wheel does not deviate from its moving direction. The carriage allows the
103 wheel to move freely in the vertical direction, and also, a normal load can be easily
104 applied on the wheel by adding deadweight on the carriage. Fig. 1 provides the overall

view of wheel-soil interaction system used in the current study. When the wheel advances, only the rotational velocity is controlled, allowing the slip ratio and natural sinkage to occur. During the test, the sinkage is measured via two linear-potentiometer displacement sensors affixed to the carriage. The horizontal velocity of the wheel is recorded to calculate the slip ratio. And the driving torque is measured by a torque sensor installed between the wheel and driving motor.

2.2 Experimental methodology

Investigations of soil deformation patterns under rigid wheels or rigid cylinders are very important in studying the wheel-soil interaction (Shikanai et al., 2000; Senatore et al., 2013). Ding et al. (2009) preliminarily studied the soil deformation and proposed a slip ratio estimation method based on lug traces. This method is helpful for real-time slip estimation. However, further studies are essential to examine the applicability of such method as the rover may experience a variety of driving conditions or traverse challenging terrains in planetary explorations. Therefore, in the current study, a number of driving conditions (including various rotational velocities w and vertical loads W) and wheel forms were designed. Meanwhile, various ground conditions with different void ratios e were prepared. Therefore, ten representative operating conditions were planned as tabulated in Table 1. Note that test No's 1-5 with various rotational velocities w and vertical loads W have been presented in the previous research (Jiang et al., 2017a). For each test condition, at least two tests were conducted as a repeatability check. In all experiments, the wheel drawbar pull was 32.5N.

2.3 Experimental material

Samples of lunar soil are very scarce on Earth due to the difficulty in collecting samples from the Moon. Therefore, the TJ-1 lunar soil simulant, which was recently developed by Jiang et al. (2012a), was used to generate the test ground in our tests.

131 The lunar soil simulant has similar chemical composition, mineralogy, shape and
132 gradation of grains to lunar regolith. The raw materials, red volcanic ash deposits
133 collected from Jingyu County in Jilin Province of China, were dried, crushed, and
134 sieved to obtain materials covering the grain size distribution shown in Fig. 2. The
135 TJ-1 lunar soil simulant demonstrates certain similarities to the lunar regolith in terms
136 of physical and mechanical properties. Compared with other simulants introduced in
137 the literature, TJ-1 has an internal frictional angle as high as 47.4° and a relatively low
138 cohesion 0.86 kPa at $e = 1.0$. TJ-1 lunar soil simulant is an ideal substitute of lunar soil
139 located at 0 – 30 cm below lunar surface in the mare region, thus it is an appropriate
140 material for performing the soil-wheel interaction tests.

141 **2.4 Experimental results**

142 **2.4.1 Soil deformation and slip ratio**

143 When a rover moves on a terrain, the soil beneath the wheel is compressed and
144 traces are left as a result. This is a common phenomenon in most experiments. Fig. 3
145 provides the left traces in our tests with different lug configurations. As shown in Figs.
146 3(b)-(d), the traces left by the lugs can be easily recognized. For the smooth wheel,
147 there is no lug traces, however, there are intensive vertical stripes caused by wheel
148 slippage as illustrated in Fig. 3(a).

149 Fig. 3 also shows that the distance L between the track prints of two adjacent
150 lugs are virtually equal under similar driving conditions when the wheel is equipped
151 with lugs. Ding et al. (2009) proposed that there is a relationship between the distance
152 L and slip ratio i . The slip ratio is an important variable for wheel-soil interaction,
153 which is defined as follows:

$$154 \quad i = 1 - v_x / R\omega \quad (1)$$

155 where v_x is the horizontal velocity of wheel. R equals the wheel radius r for the
156 smooth wheel or the sum of the wheel radius r and the lug height h for the wheels

157 with lugs. It is obvious that the lugs are very effective in reducing the slip ratio,
158 namely, reducing the risk of spinning, as shown in Fig. 3.

159 When i lies between 0 and 1, the relationship between the distance L and slip
160 ratio i proposed by Ding et al. (2009) can be expressed as:

$$161 \quad L = (1-i)r_s\gamma = (1-i)(r+h/2)\gamma \quad (2)$$

162 where r_s is the shearing radius of the wheel, r is the wheel radius, h is the lug height
163 and γ is the spacing angle of wheel lugs.

164 Fig. 4 provides the comparison between experimental and theoretical results of
165 the trace distance L . It shows that although the wheel drives on different terrains or
166 with different wheel forms, the maximum relative error between the experimental and
167 theoretical results is only 6.46%, which is acceptable in engineering applications.
168 Thus it can be reasonably inferred that this relationship between L and i is
169 independent of the driving conditions (w or W), and packing states of soil ground.

170 2.4.2 Tractive efficiency

171 The wheel reaches a steady moving state after running for several seconds when
172 the drawbar pull force (the difference between the gross traction generated by the
173 driving torque and the motion resistance) is balanced by the towed load. Fig. 5
174 presents typical curves of the driving torque evolution with time for test No .1. The
175 data acquisition frequency is 40 Hz and hundreds of raw data can be obtained. The
176 measured data fluctuates periodically in association with the wheel lugs entering and
177 leaving the soil, therefore they are smoothed to show the evolution trend. Fig. 5 shows
178 that the driving torque increases to a peak value rapidly at first and then mobilizes at a
179 stable value. The steady data can be used to calculate the mean values of driving
180 torque in following analysis. In addition, the two mean values of the two repeated
181 experiments are almost the same despite the data fluctuations, proving the
182 repeatability and consistency of the experiments.

183 The tractive efficiency (η) (Code, 2003) is adopted for evaluation of wheel

184 mobility and can be estimated as follows:

$$185 \quad \eta = \frac{F_{DP} \cdot v_x}{T \cdot w} \quad (3)$$

186 where F_{DP} is the drawbar pull force, T is the driving torque. Combined with Equation
187 (2), the expression can be rewritten as follows:

$$188 \quad \eta = \frac{F_{DP}}{T} \cdot (1-i) \cdot R \quad (4)$$

189 Fig. 6 provides the tractive efficiencies for different rotational velocities w ,
190 vertical loads W , ground void ratios e and wheel forms. We can find that: (1) the
191 tractive efficiency shows no apparent difference at different rotational velocities
192 (Tests No. 1, 2 and 3) with the same identical drawbar pull force; (2) the tractive
193 efficiency decays with increasing vertical load applied to the wheel (Tests No. 2, 4
194 and 5). This is because a larger drawbar pull force is required to drag the increasing
195 weight of a rover (Sutoh et al., 2012), but the drawbar pull force is prescribed to a
196 constant value in the current study and a higher slip ratio occurs as a result of the
197 increasing weight; (3) as expected, the wheel shows better performance when
198 travelling on a denser ground, i.e. lower void ratio (Tests 6, 2 and 7); (4) the smooth
199 wheel experiences high slippage and is easy to get stuck, which exhibits a low tractive
200 efficiency. This deficiency can be significantly improved by attaching lugs. With the
201 given lug height, a minimum number of lug is required to form continuous shearing
202 soil loop (Ding et al., 2009), namely 10mm/20 (Test No. 2) and 20mm/10 (Test No. 8)
203 in the current study. Fig. 6 shows that the contributions of lugs are almost the same in
204 such two conditions by increasing the tractive efficiency about 310% from the
205 condition with no lugs (Test No. 10). However, the contribution of adding more lugs
206 (in case of 20mm/20, Test No. 9) is very limited, which only increases the tractive
207 efficiency by 19.4% compared with the case of 20mm/10 (Test No. 8).

208 **3. DEM simulations**

209 **3.1 Contact model for lunar soil**

210 The contact model used in the conventional DEM only considers shear force and
211 repulsive normal force at the contacts (Cundall and Strack, 1979). In view of this limit,
212 efforts have been made to include other features of particle interaction, such as
213 interparticle rolling resistance (Iwashita and Oda, 1998; Tordesillas and Walsh, 2002;
214 Jiang et al., 2005) and cohesion (Luding, 2008) arising from different mechanism
215 such as chemical bonds (Potyondy and Cundall, 2004; Jiang et al., 2007; Jiang et al.,
216 2012b;2012c; Obermayr et al., 2013), liquid bridge (Jiang et al., 2004), and molecular
217 forces (Modenese et al., 2012). As described in previous studies (Modenese et al.,
218 2012; Jiang et al., 2013; Kulchitsky et al., 2016), van der Waals forces have
219 remarkable contribution to the inter-particle adhesion of lunar soil due to the
220 ultra-high vacuum condition in the lunar environment. Therefore, a contact model
221 proposed by Jiang et al. (2013), which fuses the van der Waals forces and the
222 inter-particle rolling resistance together, was used here to accurately model the lunar
223 soil. This contact model, which has been proved to be able to capture the mechanical
224 properties of the lunar soil reasonably well, has not been fully considered in other
225 DEM simulation. Different from the previous work on the model development (Jiang
226 et al., 2013), the current study focuses on the application of the lunar contact model in
227 wheel-soil interaction simulations. Therefore, the model is only briefly described here
228 for completeness. A detailed description of the model can be found in the paper (Jiang
229 et al., 2013).

230 The two-dimensional contact model of two discs contacting over a rectangular
231 area includes three components in the normal, tangential and rolling directions. Van
232 der Waals forces are introduced in the normal direction and rolling resistance is added
233 into the rolling direction. The mechanical components of the contact model are
234 presented in Fig. 7. The normal contact model controls the normal interaction, with a

spring reflecting the elastic behavior of the contact, a dashpot allowing viscous energy dissipation, an attractor named *WF attractor* representing the van der Waals force (WF is short for van der Waals force hereafter), and a divider indicating that no tension is transmitted when two grains are separated. The tangential and rolling contact models are similar to the normal model in principle, both composed of springs for elastic behavior and dashpots for viscous contact damping behavior. In the tangential contact model, a load slider and a *WF slider* are connected in parallel to consider both the load and van der Waals force contributions to the sliding resistance. In the rolling contact model, a load roller and a *WF roller* are set in parallel, indicating that the moment transmitted between two grains must overcome the resistance produced by both the load and van der Waals force before unconstrained rotation can occur.

3.2 Mechanical property of the DEM sample

3.2.1 DEM parameters

The mechanical behaviors were investigated here using two sets of biaxial compression test on specimens with an initial void ratio of 0.20, one considered the van der Waals force representing the extraterrestrial environment, while the other did not consider such force representing the terrestrial environment, where the WF is negligible. The model parameters adopted in the current study are listed in Table 2 and the particle size distribution is provided in Fig. 8, along with the upper and lower bounds of gradation curve of lunar regolith collected in the missions of Apollo11, 12 and 14 (Mitchell et al., 1972; Carrier et al., 1991; Carrier, 2003; Chang and Hicher, 2009). It is obvious that the employed curve is quite different from that used in experimental investigation due to the constraint of computational costs. Based on previous research (Wang, 2012), nearly 100,000 particles are required to simulate the biaxial test if using the actual particle size distribution of lunar regolith. If reproducing the soil ground for simulating the wheel-soil interaction, it will require

more than one million particles in a simulation, which is unaffordable. Nevertheless, the average particle diameter used in the current study is restricted to the upper bound value of real lunar regolith in order to attain reasonable van der Waals force.

3.2.2 DEM specimen

The DEM specimens used for the biaxial compression test were generated using the multilayer under-compaction method (UCM) proposed by Jiang et al. (2003). Eight layers of particles were generated in a sequential way, with each layer containing 750 particles and randomly deposited into a rectangular container with the height to width ratio of 2:1. To achieve the target planar void ratio of 0.20, the accumulated layers of particles were compacted to an intermediate void ratio which is slightly higher than the target void ratio when each new layer was added. According to the under-compaction criterion proposed by Jiang et al. (2003), the intermediate void ratios for the accumulated layers were; $e_{p(1)}=0.218$, $e_{p(1+2)}=0.217$, $e_{p(1+2+3)}=0.225$, $e_{p(1+2+3+4)}=0.214$, $e_{p(1+2+3+4+5)}=0.211$, $e_{p(1+2+3+4+5+6)}=0.210$, $e_{p(1+2+3+4+5+6+7)}=0.205$ and $e_{p(1+2+3+4+5+6+7+8)}=0.20$. The DEM specimen was constrained by four frictionless wall boundaries. Following the one-dimensional compression, the specimen was isotropically compressed to different confining pressures (e.g. 25kPa, 50kPa and 100kPa) which are the same as the indoor triaxial compression tests on the dense samples of TJ-1 lunar soil simulant. Then, the top and bottom walls were moved toward each other at a strain rate of 5%/min to axially load the specimen in a quasi-static manner, leading to a higher vertical stress σ_1 . The two opposite lateral walls were servo-controlled to maintain a constant confining pressure σ_2 applied on the specimen.

3.2.3 Biaxial compression test results

Fig. 9 provides the evolutions of the deviator stress and the volumetric strain in two environments. It shows that shear dilation accompanied with strain softening occurs under both conditions. However, the particles are easy to form clusters due to

the effect of van der Waals force in the lunar environment, thus leading to a more pronounced dilation. Besides, the existence of van der Waals force will further enhance the tangential and rolling strengths at particle contacts, therefore a higher peak deviator stress is also observed as a result. The internal friction angle under the terrestrial environment can be attained as 44.8° while it increases to 45.8° as a result of the presence of van der Waals force, meanwhile, the material shows a small cohesion of 1.12 kPa in the extraterrestrial environment. Compared with the internal friction angle of the TJ-1 lunar soil simulant, the void ratio of 0.20 is reasonable for the latter wheel-soil simulation.

3.3 Viscous damping

Note that the viscous damping should be activated in dynamic simulation process for energy dissipation, such as in the case of wheel-soil interaction. Moreover, the numerical time will not coincide with the physical time if an inappropriate damping value is used. In our study, the damping value was determined by simulating the angle of repose in comparison with the results of the indoor tests (Jiang et al., 2017b). The 2D disk simulation is similar to plane strain tests. In soil mechanics, the internal friction angle obtained from plane strain compression test is nearly 1.2 times larger than that obtained from triaxial compression test, which has been directly confirmed by theory, supported by experiment, that 2D and 3D repose angles are quite different (Albert et al. 1997). Nevertheless, 2D DEM simulations are always conducted to capture the strength feature of soils regardless of such differences with carefully selected parameter in geotechnical engineering, such as the internal friction angle, cohesion, as well as the angle of repose for simplicity. This can ensure that the following 2D simulations of soil-wheel interaction with the same parameters can provide reasonable results. In addition, the damping coefficient mainly influences the rate-dependency behavior of soils, which shows limited effect on the soil internal friction (Lade et al., 1997). Thus, any approximate value

of soil internal friction could be used to calibrate their damping coefficient. Consequently, the damping coefficient adopted here was determined by matching the angles of repose obtained in 2D DEM simulations with 3D indoor tests for convenience.

Firstly, several indoor experimental soil pouring tests were conducted to examine the angle of repose and the results are provided in Fig. 10. It shows that the angle of repose mainly varies between 30° and 33° . In the DEM simulation, an assembly of granular particles drops freely down under 1g to the ground. Different viscous damping values were used in the trial simulations, from 0.05 to 0.5 and the simulation results were drawn in Fig. 11. It is shown that when the normal and shear viscous damping values are set to be 0.4, the simulated angle is 31.3° , which is very close to the experimental results. Considering that the wheel-soil simulations were further extended to the extraterrestrial environment, the simulations of repose angle test were re-conducted under different gravitational conditions, from $1/6g$ to $6g$ while the damping values were fixed at 0.4. The results were also plotted in Fig. 11. We can find that the angle of repose fluctuates slightly with gravity, which is negligible. This phenomenon is similar to the tests results conducted in an airplane (Kobayashi et al., 2009). Therefore, the viscous damping values are set to be 0.4 in the latter simulations.

3.4 DEM model of wheel-soil interaction

3.4.1 Soil ground

In order to establish a wheel-soil interaction model to reproduce the indoor experiment, the model dimension should be scaled down with a proper scaling factor. Otherwise, millions of particles are required to generate the test ground if the model in the simulation is at the same size as the prototype. Referring to the previous research (Nakashima et al., 2010), where acceptable results were attained with the ratios of the wheel diameter to the average particle size ranging from 37.5 to 62.5. In

343 this study, the ratio was set to the upper bound at 62.5. Given the average particle
344 diameter of 1mm, the diameter of the wheel used in simulations can be determined as
345 62.5mm. Considering the wheel diameter of 250mm used in experiments, the scaling
346 factor is 4.0. However, it should be noted that less particles will interact with the
347 wheel elements in the model than those in the prototype as the soil particles are not
348 scaled in the same manner. As a result, the output data may fluctuate intensely.

349 Following the determination of the scaling factor, the multilayer
350 under-compaction method (UCM) was again employed here to generate a
351 homogeneity ground sample before consolidation under gravity. A total of eight layers
352 of particles were generated in a sequential way, with each layer containing about 6875
353 particles (given a total number of 55,000 particles) and randomly deposited into a
354 rectangular container to form the granular ground. To achieve the same target planar
355 void ratio of 0.20 as that of the specimen for element tests, the intermediate void
356 ratios for the accumulated layers were the same as those in Subsection 3.2. During the
357 generation process, the wall-particle friction was set to zero in order to improve the
358 homogeneity, while the inter-particle frictional coefficient was set to be 0.2 in order to
359 produce a dense packing of particles. After that, a 4g gravitational acceleration was
360 applied in the test ground to achieve the same gravity-induced stress field, which is
361 inspired by the principle of centrifuge modeling that has been widely used in
362 geotechnical engineering.

363 3.4.2 Wheel and lugs

364 The wheel is represented by a large disk with a radius of 31.25 mm. The lug is
365 approximated by 20 disks with radii of 0.125 mm clumped together with overlaps
366 equal to the radius, thus giving a height of 2.5 mm (1/4 of the lug height of 10 mm in
367 prototype) and width of 0.25 mm. The height to width ratio of lug is 10:1, same with
368 the one used in experimental tests. When simulating different wheel forms, the lug
369 number and height were modified and it was easily accomplished in the DEM studies.

370 The configuration of the DEM wheel-soil interaction test is provided in Fig. 12. Table
371 3 summarizes the parameters of the wheel elements, where larger normal/shear
372 stiffness was used in order to approximate a rigid wheel. In the simulations, the wheel
373 was servo-controlled in such a way: in the vertical direction, the position of the wheel
374 was adjusted so that the vertical load and the weight of the wheel was balanced by the
375 vertical wheel-soil interaction force; in the horizontal direction, the input towed load
376 was balanced by the resultant horizontal wheel-soil interaction force.

377 3.4.3 Simulation procedure

378 In addition to the one-to-one correspondence of physical model tests and
379 numerical simulations, another three simulations, numbered 11, 12 and 13, were
380 added. Compared with test No. 2, the above mentioned three tests are different in
381 rotational velocity (0.818 rad/s), vertical load (245N) and ground void ratio (0.24),
382 respectively. 13 simulations were performed in both terrestrial and extraterrestrial
383 environments, yielding 26 simulations in total. Note that the planar void ratios
384 corresponding to the true void ratios of 0.85, 1.0, and 1.05 are 0.18, 0.20, and 0.22,
385 respectively. These values were attained based on comparable soil strength.

386 **3.5 DEM simulation results**

387 3.5.1 Soil deformations

388 The soil deformations beneath the wheel and the trafficability under different
389 driving conditions have been experimentally investigated in the terrestrial
390 environment as detailed above. Herein the corresponding simulations were performed
391 using the DEM model described above and the studies were further extended to the
392 extraterrestrial environment. The wheel used in experiment was 100 mm thick while
393 the DEM simulation is two-dimensional, which means the width of wheel is unit one,
394 i.e., 1 m in the model, 10 times of that in the experiment. Moreover, the size of the
395 wheel was scaled down by a factor of 4 and the gravity was increased by 4, giving the

396 same stress level. Therefore, the input towed load and vertical load listed in Table 1
397 should be scaled by a factor of $4/10$, and the torque attained from the simulations
398 should be scaled up by $4 \times 4/10$ in order to maintain the same condition as in the
399 experiments.

400 Fig. 13 illustrates the soil deformation beneath the wheel in different
401 environments. The test parameters are the same with those in the indoor test No. 2.
402 The experimental result has been shown in Fig. 3(b), where clear tracks could be
403 observed when the wheel passed by. Similarly, the DEM simulation result in the
404 terrestrial environment (Fig. 13(a)) demonstrates the same tendency, where clear and
405 wavy tracks also formed on the ground surface. But further observation shows that the
406 equally spaced tracks resulted from lug digging is not that obvious in our simulation,
407 which can be explained by the smaller ratio of lug size to soil particle diameter.
408 Nevertheless, we can still draw the conclusion that the employed DEM model can
409 qualitatively describe the formation of tracks. Then the simulation was extended to
410 the extraterrestrial environment as illustrated in Fig. 13 (b). It shows that the tracks
411 are less obvious as the weight and the input towed load were both reduced to $1/6$ of
412 those in terrestrial environment.

413 3.5.2 Gross traction and motion resistance analyses

414 In this chapter, we mainly analyze how the gross traction and motion resistance
415 vary. Fig. 14 shows the comparison on gross traction (GT) and motion resistance (MR)
416 in the terrestrial environment (T) as well as those in the extraterrestrial environment
417 (EX) when applying a constant towed load. The gross traction is the summation of all
418 the forward contact forces between soil particles and the wheel, and the motion
419 resistance is the summation of all the backward contact forces between soil particles
420 and the wheel. The difference between the GT and MR is the input towed load (81.25
421 N in the terrestrial environment and 13.54N in the extraterrestrial environment). The
422 GT and MR vary following the same trend with different driving conditions, ground

void ratios and wheel forms as shown in the figure. Fig. 14(a) shows that there is no clear difference in GT and MR when changing the rotational velocity. Therefore, the rover can move at a relatively fast rotational velocity under the premise of safety assurance. Fig. 14(b) shows that the motion resistance and gross traction increase with the vertical load. This is because that higher vertical load produced a larger sinkage, which in turn increases motion resistance with a potential of causing the wheel to become stuck. Similarly, the wheel will experience larger motion resistance and gross traction when moving in a loose ground due to larger sinkage, as shown in Fig.14(c). Fig. 14(d) shows that the motion resistance and gross traction increase as the lug height changes from 0 to 20 mm. Similar to the experimental results, there is an optimal lug height to obtain the best traction of a wheel. Besides, in terms of generating more gross traction, wheels with 10-20 mm-lugs may show better performance than wheels with 20-10 mm-lugs would. The results obtained in the extraterrestrial environment follow similar trend but have much smaller values as a result of reduced weight and towed load.

3.5.3 DEM validation of tractive efficiency

To quantitatively estimate the tractive efficiency in the DEM simulations, the slip ratio is recorded using Equation (1) together with Equation (5):

$$v_x = \frac{\Delta x}{\Delta t} \quad (5)$$

where v_x is the horizontal displacement of the wheel taking place within a time interval Δt .

Fig. 15 presents the simulation results of slip ratio under different environments for test No. 2. Fig. 15 shows that the input rotational velocity is stable while the slip ratio shows a moderate fluctuation around an average value, which was used in the latter calculation of tractive efficiency.

Meanwhile, the driving torque is also recorded and calculated using Equation (6):

$$T = \sum^m (f_x \cdot l_x + f_y \cdot l_y) \quad (6)$$

where the summation is over the m particle contacts with the wheel, f_x and f_y are the horizontal and vertical components of contact force, respectively, l_x and l_y are the distance from the wheel center to the application lines of f_x and f_y .

Fig. 16 provides the evolution of driving torque under different environments for test No. 2. Fig. 16 shows that the raw data are rather noisy as a result of lugs and are smoothed by means of moving average. In contrast to the experimental results as shown in Fig. 5, the driving torque in DEM simulation increases to a peak value as soon as the simulation begins and then fluctuates around a steady value, with no clear increasing trend at the beginning (observed in physical model tests). The main reason for the difference may be that the prescribed velocity of wheel can be imposed instantaneously in DEM simulation, while it required some time to accelerate the wheel from still to the given rotational velocity in physical model test. Anyway, only the steady values are required in our post process, thus it is not problematic with a slight difference in the initial stage.

After determining the slip ratio and driving torque in every simulation, the tractive efficiency can then be calculated using Equation (4). Fig. 17 presents the simulation results of tractive efficiency obtained in both terrestrial and extraterrestrial environments under different driving conditions, ground void ratios and wheel forms. For comparison, the experimental results are also provided. Fig. 17 shows that the simulation results in the terrestrial environment are smaller than those obtained from the physical model tests, but can still qualitatively capture the evolution trend. Such difference is mainly resulted from the larger slip ratio obtained in DEM simulation. Moreover, the resulted tractive efficiency obtained in the extraterrestrial environment shows a higher value although the vertical load and the towed load both reduce. This may be because the van der Waals forces can increase the soil cohesion and therefore reduce the possibility of wheel slippage.

477 **4. Discussions**

478 It is obvious that a two-dimensional simulation cannot accurately represent a
479 three-dimensional deposition of a granular material that consists of spherical particles.
480 2D particles cannot move in the out-of-plane direction as in 3D simulations, which
481 results that 2D DEM cannot capture the full deformation behavior of soils. In addition,
482 the uses of spherical particles and artificial constraint on particle rotations also limit
483 the accuracy in our simulations. However, the mechanical behaviors of the 2D and 3D
484 particles contact are similar to a certain extent with carefully selected parameter,
485 which results in that 2D DEM can capture the strength features of soils. Therefore, 2D
486 simulation results could still provide qualitative illustration of the effects of the lunar
487 environment conditions as stated above. Moreover, the huge number of particles
488 required for a 3D simulation is unaffordable for the current capacity of PCs. Therefore,
489 2D simulations are effective ways to reduce the computational costs. It can be seen in
490 the previous figures that the slip ratios in the DEM simulations show higher values
491 than those in the indoor experiments. Such phenomenon may be a result of two
492 reasons: firstly, the out-of-plane constraint necessary to enforce a state of plane strain
493 is not present in the 3D problems. Secondly, the rolling resistance that have been
494 implemented to the contacts can only enhance the strength of soils, while it is still
495 difficult to capture the full characteristic of flowability of a real material, where
496 particles are strongly interlocked due to irregular shapes. However, the 2D DEM
497 simulation model can still be used to predict the evolution trend based on the
498 comparison with indoor physical model tests. Therefore, the slip ratio obtained in the
499 extraterrestrial environment should also be reasonable.

500 Interestingly, the results of driving torque based on the current DEM model
501 shows a good agreement with indoor physical model tests despite 2D simulations,
502 which can also be explained from two aspects. Firstly, the extra out-of-plane
503 constraint leads to increasing gross traction. Secondly, the higher flowability due to
504 the spherical particle reduced the gross traction. Such two effects may be canceled out

505 in our DEM simulations.

506 **5. Conclusions**

507 In this paper, a series of physical model tests using a new wheel-soil interaction
508 system were conducted. Then the corresponding DEM simulations using a novel
509 contact model considering rolling resistance and van der Waals force were performed.
510 The DEM simulations in the terrestrial environment were validated by comparing
511 with the experimental results. At last, the DEM simulations were further extended to
512 the extraterrestrial environment.

513 The main conclusions can be drawn as follows:

514 (1) The aforementioned quantitative relation between track length and slip ratio
515 is validated in both the work by Ding et al. (2009) and this current study, despite of
516 different packing states and mechanical properties of soils. Moreover, this relation is
517 also proved to be accurate when changing the driving condition and wheel forms in
518 the current study, suggesting that this is a common relation in wheel-soil interaction
519 which is helpful for real-time estimation of slip ratio by measuring the track length.

520 (2) The tractive efficiency shows no clear difference at various rotational
521 velocities, but decreases with increasing extra load and void ratio. In addition, the
522 rover shows better performance when equipping with lugs. Lug configuration of
523 20-10 mm can improve the wheel performance slightly more than 10-20 mm, but the
524 difference is not very evident. However, increasing the lug number from 10 to 20 will
525 further improve wheel performance but to a smaller extent compared with the
526 improvement with increasing lug number from 0 to 10.

527 (3) Compared with the experimental results of the angle of repose performed
528 with TJ-1 lunar soil simulant, an appropriate viscous damping value was determined
529 as 0.4 to simulate the dynamic problem. Moreover, the angle of repose seems to be
530 unaffected by different gravity fields.

531 (4) The exploited model can qualitatively reproduce the pattern of track formed

532 in experiments. The track is less evident when performed in the extraterrestrial
533 environment.

534 (5) When generating the same net traction, there is no clear difference in both
535 gross traction and motion resistance when changing rotational velocity. However, the
536 gross traction and motion resistance increase evidently with the vertical load, which
537 may cause the wheel to become stuck as a result of excessively large sinkage. The
538 gross traction and motion resistance also increase with ground void ratio thus it is
539 more difficult to traverse over loose terrain. In addition, the motion resistance as well
540 as gross traction increased as the lug height changes from 0 to 20 mm. Those
541 conclusions are similar in the extraterrestrial environment but to a smaller extent.

542 (6) The developed DEM model could qualitatively predict the evolution of
543 traction efficiency and the difference mainly comes from the overestimated slip ratio
544 in the DEM simulations. The tractive efficiency shows a higher value in the
545 extraterrestrial environment with the same test parameters.

546

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