EVALUATION OF INFLUENCE OF WHEEL SURFACE SHAPES ON TRACTIVE EFFICIENCIES OF PLANETARY ROVERS IN VARIOUS SOIL ENVIRONMENTS

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ABSTRACT

Wheels of planetary rovers typically have grousers on their surface to provide grip for climbing in loose soil and scrambling over rough terrain. In this study, the influence of grousers on the traveling performances of wheeled rovers is evaluated in various soils. First, the influence of the number of grousers was quantitatively determined by conducting experiments using wheels with different number of grousers in sandboxes covered with Toyoura sand/lunar regolith simulant. Next, the influence of grouser height was evaluated by conducting experiments using wheels with different grouser heights. Finally, the experimental results are discussed from the point of view of terramechanics. According to the experimental results, it was confirmed that the number of grousers and grouser height that a wheel must be at least required for high traveling performance will be almost the same for soils having similar pressure-sinkage characteristic.

Key words: Planetary rovers; wheel; grouser.

1. INTRODUCTION

Mobile robots, also called rovers, have played a significant role in NASA's Martian geological investigations. The use of rovers in missions significantly increases the area that can be explored, and thus increases the scientific return from the missions. However, lunar and Martian surfaces are covered with loose soil, and numerous steep slopes are found along their crater rims. Wheeled rovers can be stuck in such conditions and even cause mission failure.

To avoid such problems, many research groups have studied the traveling performance of planetary rovers on the basis of terramechanics [1, 2]. Conventionally, terramechanics has mainly been used to study large vehicles, such as dump trucks, military and agricultural vehicles [3, 4]. Protrusions called grousers (i.e., lugs, cleats) on the wheels or track of the vehicles have influence on their traveling performance. Based on this empirical knowledge, grousers have been equipped on wheels of planetary rovers [5], and it was found that they substantially influence the traveling performance of lightweight vehicles such as planetary rovers [6, 7, 8]. Therefore, it is important to evaluate the effect of grousers on the traveling performance of planetary rovers.

There have been some reports on the influence of grousers on the traveling performance of lightweight wheeled rovers. Our group has experimentally evaluated the influence of the number of grousers and grouser height on the traveling performance of wheeled rovers [6, 7]. Furthermore, Ding et al. reported the influence of grouser inclination angle on the traveling performance of a wheel [8]. In addition to the experimental approach, a method for estimating the traveling performance of wheels equipped with grousers using the discrete element method (DEM) has been proposed [9]. Furthermore, a terramechanics model for wheels with grousers has recently been proposed [10]. In these studies, however, wheels with short grousers, such as the wheels of NASA's Mars Exploration Rovers (MERs), which had a wheel diameter of 10" and a grouser height of 0.25" [5], were mainly focused. Only a few studies have reported on the behavior of wheels having considerably taller grousers. Furthermore, these studies reported the behavior of wheels with different grouser parameters; however, only one soil type was usually used and the effect of grousers has not been compared for various soils.

In this study, the influence of the number of grousers on the traveling performance of wheeled rovers was first evaluated by performing experiments using wheels with different numbers of grousers. Next, the influence of grouser height on the traveling performance was evaluated by conducting experiments using wheels having different grouser heights. In the experiments, wheels having considerably taller grousers are utilized. The experiments were performed using a two-wheeled rover in sandboxes covered with Toyoura sand/lunar regolith simulant. In this paper, a method of evaluating traveling performance is defined and the above experiments are reported in further detail. Finally, the experimental results are discussed from the point of view of terramechanics.

2. TRAVELING PERFORMANCE EVALUATION METHOD

In this section, slip ratio, drawbar pull, resistance torque, and tractive efficiency are introduced for evaluating the traveling performance of wheeled rovers.

2.1. Slip ratio

The slip ratio represents the effectiveness of wheel motion, and in general, it is defined using the actual linear speed of a vehicle and the radius and angular speed of the wheel [4]. Wheels with grousers were used in this study. It is difficult to define the effective diameter of such wheels and to define the slip ratio on the basis of the above method. Therefore, the slip ratio s of a wheel with grousers is defined as done in [6]:

$$s = \frac{d_d - d}{d_d} = 1 - \frac{d}{d_d}, \tag{1}$$

where d denotes the actual traveling distance per wheel rotation, and d_d denotes the traveling distance per wheel rotation on hard ground (i.e., no wheel sinkage condition). Here, d_d is geometrically calculated, as previously reported by our group [6].

The slip ratio has a value between 0 and 1. When the wheel moves forward without slippage, the slip ratio is 0; when the wheel does not move forward at all because of slippage, the slip ratio is 1.

2.2. Drawbar pull

The drawbar pull is defined as the difference between the total thrust and the total external resistance of the vehicle [3], and it varies with wheel slippage. Therefore, a slip ratio corresponding to the drawbar pull is an important indicator of the traveling performance of the rover.

The drawbar pull denotes the reserve of ground strength that can be utilized by motor torque to develop acceleration, move the vehicle on slopes or pull a trailer hitched to a drawbar [3]. When a rover travels over a slope, it needs to pull its weight. Therefore, to move the rover on the slope, the drawbar pull DP of wheels satisfies the following equation:

$$DP = mg \sin\theta \tag{2}$$

where m is the mass of the rover, g is the gravitational constant, and θ is the slope angle. According to this equation, the slope angle has the same relation to the slippage as the drawbar pull. Therefore, to evaluate the traveling performance of a wheeled rover, a slip ratio corresponding to the slope angle was used as the indicator in this study.

2.3. Resistance torque

When a rover travels, a torque is required around the axle of the wheel. This torque is called resistance torque, and it comprises the torque developed by soil compaction and internal wheel resistance, such as mechanical friction.

The resistance torque T can be roughly estimated from the current I to a motor that rotates the wheel, using the following equation:

$$T = kn\eta_g I, \tag{3}$$

where k denotes a torque constant of the motor, and n and η_g denote gear reduction and maximum efficiency, respectively. In planetary exploration, resistance torque must be minimized for low power consumption.

2.4. Tractive efficiency

Tractive efficiency is defined by the ratio of the input work to the wheel to the actual work of the wheel. Tractive efficiency η is derived as done in [8]:

$$\eta = \frac{DP(1-s)r}{T} \tag{4}$$

where r denotes the radius of the wheel. In this study, using d_d in Eq. 1, r of wheels with grousers is defined as

$$r = \frac{d_d}{2\pi}. \tag{5}$$

High tractive efficiency can be achieved if the wheel travels with small slippage and small resistance torque for high drawbar pull.

3. EXPERIMENTS

To evaluate the influence of the number of grousers and grouser height on the traveling performance of wheeled rovers in various soils, slope-climbing tests were performed using a two-wheeled rover with wheels having different number of grousers and different grouser heights. The experiments were conducted in sandboxes covered with Toyoura sand/lunar regolith simulant. In this section, the details and results of the experiments are presented.

3.1. Two-wheeled rover and wheels

In this study, a lightweight two-wheeled rover with interchangeable wheels (Fig.1) was developed. The wheelbase of the rover was fixed at 600 mm. The rover weight was set to 6.0 kg using additional weights for all the different wheels. To rotate the wheels and control

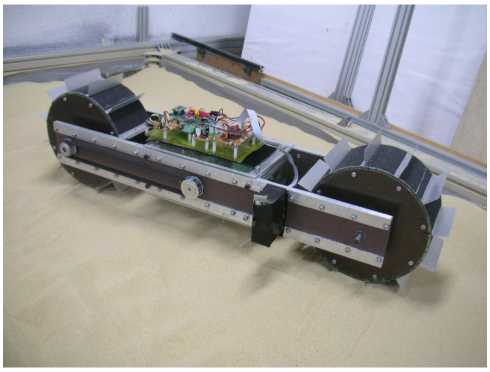


Figure 1. Two-wheeled rover.

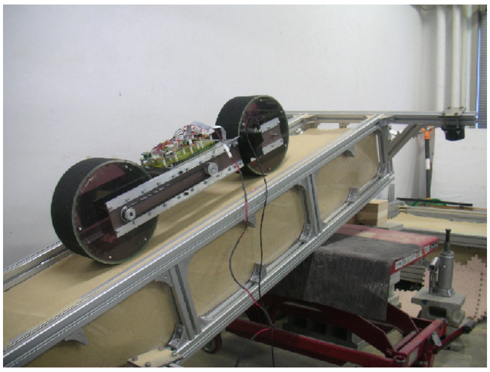


Figure 2. Slope-climbing test; the two-wheeled rover travels in a sandbox covered with Toyoura sand.

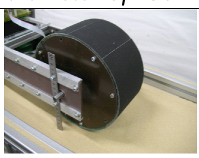
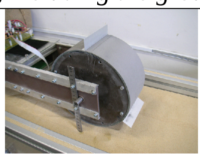
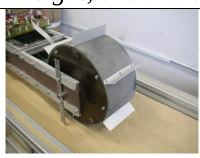
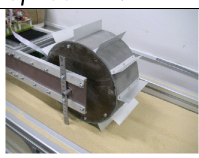
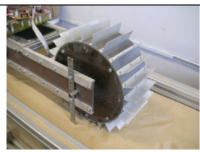
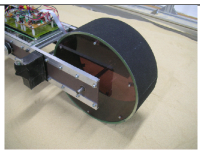
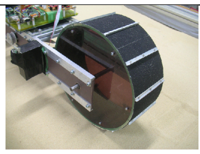
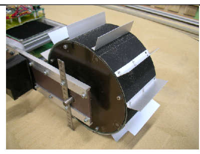
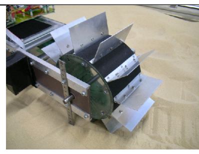
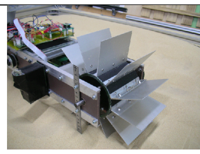
their angular speed, the rover has a microcontroller (H8-3048one; Renesas Technology Corp.), and a motor embedded with an encoder (RE-max 25 with GP32C planetary gear and MRenc encoder; Maxon Co., Ltd). A motion measurement system using an optical sensor and laser source [11] was mounted on the rover to measure the actual rover traveling distance/speed. The slip ratio s is determined from the distance using Eq. 1. Furthermore, a current sensor module (ACS712; Sparkfun Electronics) was mounted on the rover to measure the current to the motor that rotates the wheel. From the current, the resistance torque T is determined using Eq. 3.

Five wheel types, which have different numbers of grousers (configuration 1 in Tab. 1), were developed. This wheel has a diameter of 250 mm, including the grouser height, and a width of 100 mm. Each grouser was made of aluminum and has a thickness of 1 mm and height of 25 mm. In addition, five wheel types, which have different ratios of grouser heights (h_d) to wheel inner diameters (D) (configuration 2 in Tab. 1), were developed. The wheel has a diameter of 250 mm, including the grouser height, and a width of 100 mm. Each wheel was equipped with twelve grousers placed at equally spaced intervals. The wheel surface was covered with sandpaper having a roughness corresponding to that of the target soil.

3.2. Experimental conditions

A two-wheeled rover, with the above ten types of wheels, was used to conduct slope-climbing tests in sandboxes (Fig.2). Each sandbox had a length, width, and depth of 1.5 m, 0.30 m, and 0.20 m, respectively, and was filled with Toyoura sand/lunar regolith simulant. Toyoura sand (JIS R 5200) has very low cohesion and its particle size is almost uniform. Lunar regolith simulant (FJS-1; Shimizu Corp.) has almost the same mechanical properties as real lunar regolith [12]; it is cohesive and its particle size is non-uniform. The soil parameters of each soil are listed in Tab. 2. The sandbox could be manually inclined to change its slope angle. In the experiments, the slope angles were set at up to 24° at 4° intervals. The angular speed of the wheel was fixed at 2.50 rpm, and the slip ratio/resistance torque was obtained using the mean value after the wheels stopped sinking. Each trial was conducted under identical soil conditions, and three trials were conducted for each condition.

Table 1. Wheels with different number of grousers and different grouser heights; except for the wheel with 0 grousers, the other wheels have a diameter of 250 mm, including the grouser height, and a width of 100 mm.

Configuration 1					
	Grousers : 0	Grousers : 3	Grousers : 6	Grousers : 12	Grousers : 24
Configuration 2					
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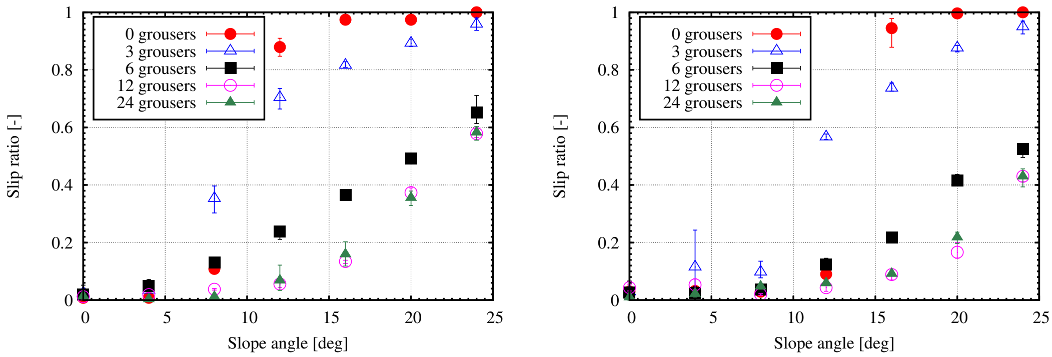


(a) Toyoura sand (b) Lunar regolith simulant

Figure 3. Slope angle versus slip ratio (for different numbers of grousers).

3.3. Evaluation of the number of grousers influence on traveling performance

3.3.1. Influence of the number of grousers on slip ratio

To evaluate the influence of the number of grousers on slip ratio, the data for the cases with different number of grousers were plotted in the graphs shown in Fig.3.

The wheels showed small slip ratios over slopes with angles up to 4° (Fig.3(a)) on Toyoura sand, while on lunar regolith simulant, the slip ratios were small over slopes with angles up to 8° (Fig.3(b)). This means that the wheels can travel with a small amount of slippage over a steeper slope on lunar regolith simulant than on Toyoura sand. Over the slopes, there were slight differences in slip ratio values for different number of grousers. That is, over flat/gentle terrain, it is not necessary for a wheel to be equipped with grousers for high traveling performance.

On Toyoura sand, wheels with 6, 12, and 24 grousers generally showed smaller slip ratios than those with 0 and 3 grousers over slopes with angles greater than 4° (Fig. 3(a)). Meanwhile, on lunar regolith simulant, the same tendency was observed over slopes with angles greater than 8° (Fig. 3(b)). Over the slopes, an increase in the number of grousers contributes to wheel slip improvement if the number of grousers is up to 12; wheels with 12 and 24 grousers showed slight differences in slip ratio values.

Over the steep slopes, it was observed that for the cases with wheels with small number of grousers, the rover moved forward only when grousers contact with the ground; a linear speed of the rover changed periodically in a cycle corresponding to grouser intervals. With at least 12 grousers, the rover could constantly move forward. This is why an increase in the number of grousers contributed to wheel slip improvement.

According to the above observations, it was concluded that over steep slopes, an increase in the number of grousers greatly contributes to improving the traveling performance if the number of grousers is up to 12. In other words, this wheel must be equipped with at least 12 grousers for high traveling performance. It is noteworthy that this number is the same for both soils.

Table 2. Soil parameters and values; bulk density (ρ), cohesion (c), angle of internal friction (ϕ), and pressure-sinkage parameters (k_c, k_ϕ, and n).

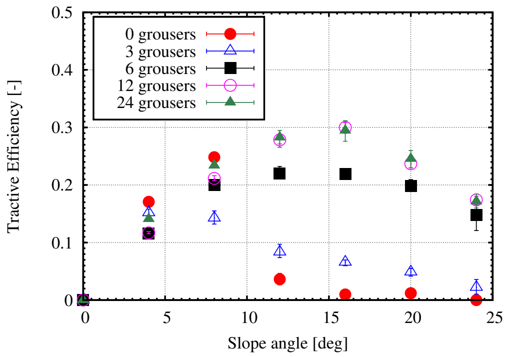
	Toyoura sand	Lunar regolith simulant
ρ [kg/m^3]	1.5×10^3	1.7×10^3
c [kPa]	0	0.8
ϕ [°]	38.0	37.2
k_c [kN/m^{n+1}]	0.9	1.4
k_ϕ [kN/m^{n+2}]	1500	820
n [-]	1.1	1

3.3.2. Influence of the number of grousers on tractive efficiency

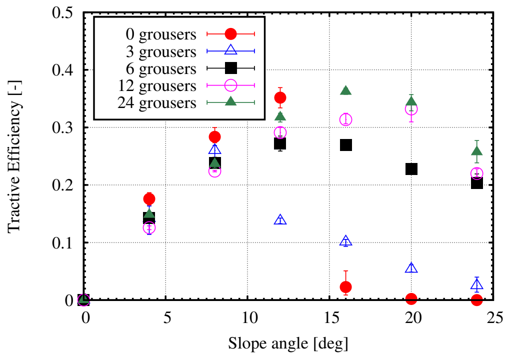
To evaluate the influence of the number of grousers on tractive efficiency, the data for the cases with different number of grousers were plotted in the graphs shown in Fig.4. Tractive efficiency was obtained from the slip ratio and resistance torque using Eqs. 1 – 5.

The wheels with 0 and 3 grousers showed a slightly higher tractive efficiency over slopes with angles up to 4° (Fig.4(a)) on Toyoura sand, while on lunar regolith simulant, their tractive efficiencies were high over slopes with angles up to 8° (Fig.4(b)). This is because all the wheels show slight differences in slip ratio values over the slopes and wheels with small numbers of grousers have smaller resistance torques.

On Toyoura sand, the wheels with 6, 12 and 24 grousers have a high tractive efficiency over slopes with angles greater than 4° (Fig.4(a)). Meanwhile, on lunar regolith simulant the same tendency was observed over slopes with angles greater than 8° (Fig.4(b)). This is because



(a) Toyoura sand



(b) Lunar regolith simulant

Figure 4. Slope angle versus tractive efficiency (for different numbers of grousers).

the wheels with 6, 12, and 24 grousers have a smaller slip ratio than those with 0 and 3 grousers over the slopes.

According to the above discussion, for both soils, it was concluded that wheels with small number of grousers have high tractive efficiencies over gentle slopes. On the other hand, wheels with large number of grousers have high tractive efficiencies over steep slopes.

3.4. Evaluation of grouser height influence on traveling performance

3.4.1. Influence of grouser height on slip ratio

To evaluate the influence of grouser height on slip ratio, the data for the cases with different grouser heights were plotted in the graphs shown in Fig.5.

The wheels showed small slip ratios over slopes with angles up to 8° (Fig.5(a)) on Toyoura sand, while on lunar regolith simulant, the slip ratios were small over slopes with angles up to 12° (Fig.5(b)). Over the slopes, there were slight differences in slip ratio values for different grouser heights.

On Toyoura sand, the slip ratio over slopes with angles greater than 8° (Fig.5(a)) was seen to decrease with an increase in grouser height, although the wheels with 2.5 cm, 5.0 cm and 7.5 cm high grousers showed slight differences in slip ratio values. Meanwhile, on lunar regolith simulant, the same tendency was observed over slopes with angles greater than 12° (Fig.5(b)).

For the wheels with 0.5 cm high grousers, the grousers bulldozed soil close to the surface of the ground, which resulted in generating a small shearing stress. On the other hand, for wheels with 2.5 cm, 5.0 cm, and 7.5 cm high grousers, the grousers bulldozed soil deep under the ground; shearing stress generated is large. This is why an increase in grouser height generally contributed to a high traveling performance.

In the experiments, it was observed that when the wheels with 0.5 cm and 2.5 cm high grousers traveled, their wheel surfaces made contact with the ground. On the other hand, when the wheels with 5.0 cm and 7.5 cm high grousers traveled, only their grousers made contact with the ground and they penetrated a few centimeters below the surface of the ground. That is, the effective grouser height of the wheels with 5.0 cm and 7.5 cm high grousers were almost the same as that of the wheel with 2.5 cm high grousers. This is why an increase in grouser height does not contribute much to a high traveling performance if grouser height is greater than 2.5 cm.

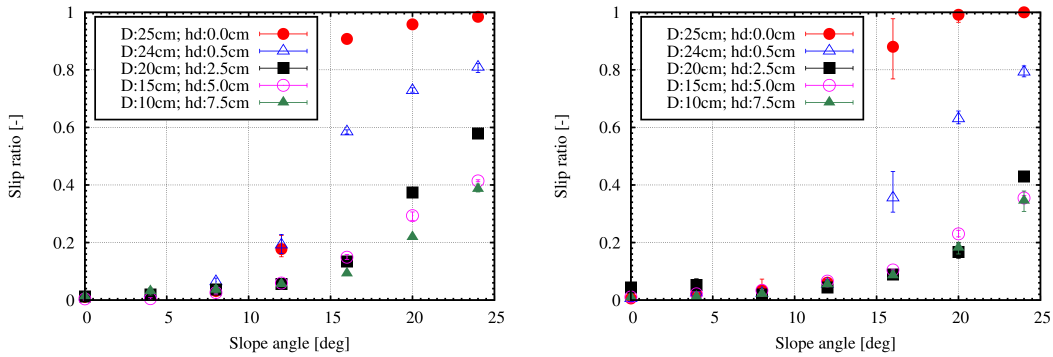
According to the above discussion, it was concluded that over steep slopes, an increase in grouser height greatly contributes to improving the wheel slip if grouser height is up to 2.5 cm. In other words, this wheel must be equipped with at least 2.5 cm high grousers for high traveling performance. It is noteworthy that this height is the same for both soils.

3.4.2. Influence of grouser height on tractive efficiency

To evaluate the influence of grouser height on tractive efficiency, the data for the cases with different grouser heights were plotted in the graphs shown in Fig. 6.

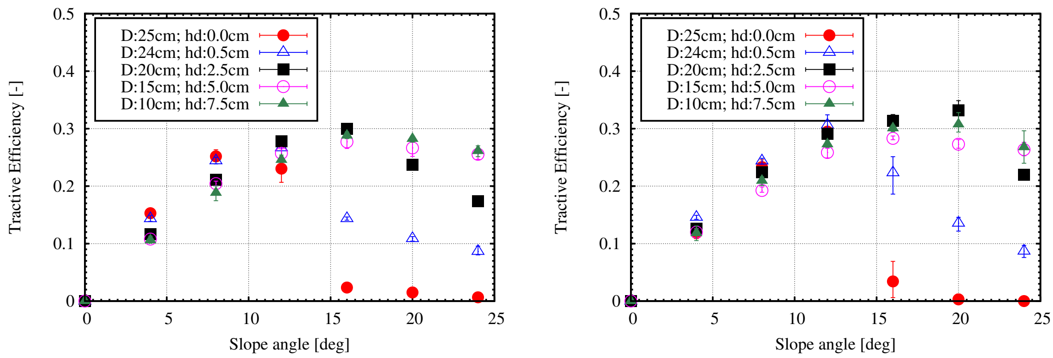
The wheels without grousers and 0.5 cm high grousers showed a slightly higher tractive efficiency over slopes with angles up to 8° (Fig.6(a)) on Toyoura sand, while on lunar regolith simulant, their tractive efficiencies were high over slopes with angles up to 12° (Fig.6(b)). This is because all the wheels show slight differences in slip ratio values over the slopes and wheels with short grousers have smaller resistance torques.

On Toyoura sand, the wheels with 2.5 cm, 5.0 cm, and 7.5 cm high grousers has a high tractive efficiency over slopes with angles greater than 8° (Fig.6(a)), while on lunar regolith simulant, their tractive efficiencies were high over slopes with angles greater than 12° (Fig.6(b)). This is because the wheels with 2.5 cm, 5.0 cm, and 7.5 cm high grousers have a smaller slip ratio than those without



(a) Toyoura sand (b) Lunar regolith simulant

Figure 5. Slope angle versus slip ratio (for different grouser heights).



(a) Toyoura sand (b) Lunar regolith simulant

Figure 6. Slope angle versus tractive efficiency (for different grouser heights).

grousers and 0.5 cm high grousers, although the former wheels have relatively large resistance torques.

According to the above discussion, for both soils, it was concluded that wheels with short grousers have high tractive efficiencies over gentle slopes. On the other hand, wheels with tall grousers have high tractive efficiencies over steep slopes. These results indicate that the optimum wheel shape differs according to the goal of the exploration mission. A wheel with short grousers is suitable for a mission in which rovers are required to travel long distances over flat/gentle terrain. On the other hand, wheels with tall grousers are suitable and essential for missions in which rovers are required to climb steep slopes such as crater rims.

4. DISCUSSION FROM THE POINT OF VIEW OF TERRAMECHANICS

As presented in subsections 3.3 and 3.4, the number of grousers and grouser height that a wheel must be at least required for high traveling performance were almost the same for Toyoura sand and lunar regolith simulant. In this section, their reasons are discussed from the point of view of terramechanics.

When a terrain is considered to be homogeneous within the depth of interest, its pressure-sinkage relationship is expressed [3] as

$$p = (\frac{k_c}{l} + k_\phi) z^n \tag{6}$$

where p is pressure, l is the smaller dimension of the contact patch, that is, the width of a rectangular contact area, z is sinkage, and k_c, k_ϕ, n are pressure-sinkage parameters. The value of k_c, k_ϕ, and n can be derived from penetration tests using plates.

Using the soil parameters of Toyoura sand and lunar regolith simulant shown in Tab. 2, the pressure-sinkage relationship of the soils were obtained, as shown in Fig.7. In the figure, l was fixed at 2.0 cm. In a case that a load of 3 kg uniformly acts on a rectangular plate having a width of 2.0 cm and length of 10.0 cm (i.e., in a case that a wheel has a contact patch of 2.0 cm in our experiments), the pressure would be 14.7 kPa over the contact area. Assuming that a plate and wheel would follow the same pressure-sinkage relationship, for a contact pressure of around 14.7 kPa, sinkage of wheel would be almost the same on Toyoura sand and lunar regolith simulant (Fig. 7). This means that both soils have the similar pressure-sinkage characteristic for the rover/wheels conditions in this study.

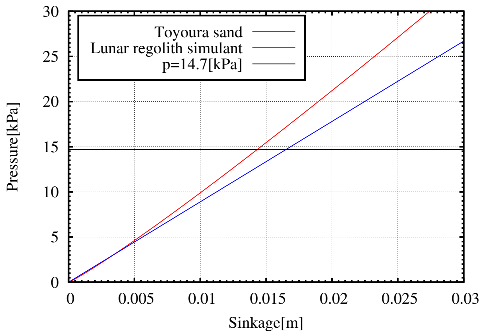


Figure 7. Pressure-sinkage relationship for Toyoura sand and lunar regolith simulant (for fixed l of 2.0 cm).

In the experiments using wheels with different number of grousers (subsection 3.3), over steep slopes, the wheel were required at least 12 grousers for high traveling performance. Over the slopes, the wheel would obtain thrust only when grousers travel in a range where a normal stress is generated beneath it [7]. Considering this range, the minimum required number of grousers would be determined for a wheel; this range is derived from the sinkage of the wheel. According to the above discussion, on Toyoura sand and lunar regolith simulant, wheel sinkage would be almost the same; this leads a normal stress to be generated in the same range beneath a wheel. This is why the number of grousers required for a wheel was the same for both soils.

In the experiments using wheels with different grouser heights (subsection 3.4), the wheel was required at least 2.5 cm high grouser for high traveling performance. This is because the effective grouser heights of the wheels with 5.0 cm and 7.5 cm high grousers were determined by depths of grouser penetration and they were almost the same as that of the wheel with 2.5 cm high grousers. According to the above discussion, on Toyoura sand and lunar regolith simulant, which have the similar pressure-sinkage characteristic, a depth of grouser penetration is expected to be almost the same. This leaded the grouser height required for a wheel to be the same for both soils in this study.

5. CONCLUSIONS

In this study, slope-climbing tests were performed using a two-wheeled rover with wheels equipped with grousers in sandboxes covered with Toyoura sand/lunar regolith simulant. The influence of the number of grousers on the traveling performance of wheeled rovers was also evaluated. Next, the influence of grouser height on traveling performance was evaluated. According to the experimental results, it was confirmed that an increase in the number of grousers generally contributes to improved tractive efficiency over steep slopes on both soils. Furthermore, it was found that over steep slopes, wheels with considerably much taller grousers travel more efficiently than wheels with conventional grouser heights. Finally, it was concluded that for soils having a similar pressure-sinkage characteristic, the number of grousers and grouser height that a wheel must be at least required for high traveling performance will be almost the same.

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