EVALUATION OF INFLUENCE OF SURFACE SHAPE OF WHEEL ON TRAVELING PERFORMANCE OF PLANETARY ROVERS OVER SLOPE

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Abstract

Planetary rovers play a significant role in lunar and Martian surface explorations. However, because of wheel slippage, the wheels of planetary rovers can get stuck in loose soil, causing the exploration mission to fail. To avoid slippage and increase the drawbar pull, the wheels of planetary rovers typically have lugs (i.e., grousers) on their surface. Recent studies report that these lugs can substantially improve the travelling performances of planetary rovers. Therefore, in this study, we conducted experiments using a lightweight two-wheeled rover in a sandbox to provide a quantitative confirmation of the influence of lugs on the travelling performances of planetary rovers. Based on our experimental results, we confirmed that although lugs have some effect on the travelling performances over gentle slopes, they have a greater effect on the travelling performances over steep slopes.

Keywords: Planetary rover, wheel, loose soil

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 mission. However, the lunar and Martian surfaces are covered with loose soil, and numerous steep slopes are found along their crater rims. In such conditions, wheeled rovers can get stuck and even cause mission failure. To avoid such problems, many research groups have studied the travelling performances of wheeled rovers on the basis of terramechanics [1, 2].

Conventionally, terramechanics has mainly studied large vehicles, such as dump trucks. Lugs (i.e., grousers) on the wheels of large vehicles have little influence on their travelling performances. On the other hand, it has been reported that lugs substantially influence the travelling performances of lightweight vehicles such as planetary rovers [3-5]. Therefore, it is important to evaluate the effect of lugs on the travelling performances of planetary rovers.

Previous experimental studies [4-6] evaluated the influence of the lug height, lug spacing, and lug inclination angle on the travelling performances of wheel. However, they did not consider the effects of lugs on the ability to climb slopes, which is one of the important features of planetary rovers. Besides, in these studies, they performed experiments using a single-wheeled testbed, which had the ability to impose variable slip ratios by driving the wheel and carriage at different rates; however, it is reported that the behaviour of wheels in single-wheeled testbeds can differ from that of multi-wheeled planetary rovers [7]. Regarding the climbing abilities of wheels with lugs, reports are available on experiments performed on slopes [8]. A method to estimate their abilities by using the discrete element method (DEM) is proposed [9]; however, these studies have not provided a comprehensive understanding of the tractive efforts developed by lugs.

In this study, the influence of lugs on the travelling performances of wheels was evaluated by performing experiments using wheels with different lug heights and different numbers of lugs. We performed slope-climbing tests using a two-wheeled rover with wheels having different numbers of lugs with varying heights. In these tests, we measured the slip ratio in a sandbox with different slope angles. Further, we discussed the tractive effort developed by lugs on the basis of the changes in the travelling velocity of the rover. In this paper, we have introduced the theoretical behaviour of lugs on a wheel and defined the slip ratio of wheels with lugs. Then, the above experiments and discussions are reported.

2 Theoretical behaviour of lugs on wheel

When a lug travels horizontally under the wheel, the soil in front of the lug is pushed and brought into a state of passive failure (Fig. 1). For passive failure, a slip line is sloped to the horizontal at $45^\circ - \phi/2$. Here, the slip

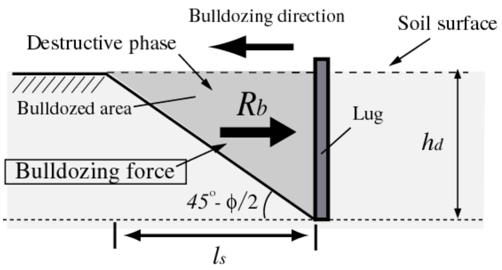
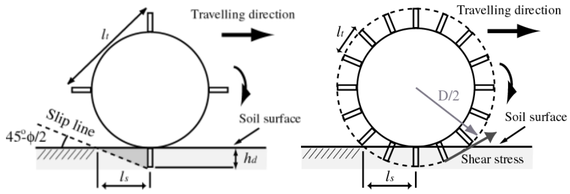


Fig. 1: *Estimation model of soil rupture distance by a lug, l_s.*



(a) If l_t is larger than l_s, the behaviour of the lug will be similar to that of a soil-cutting blade.

(b) If l_t is smaller than l_s , shearing would occur across the lug tips.

Fig. 2: *Theoretical behaviour of a lug in soil.*

line is the intersection between the soil's sliding surface and the plane of drawing. Therefore, the rupture distance, l_s, which is the horizontal distance of the soil destructive phase, is derived as

$$l_s = \frac{h_b}{\tan(45° - \phi/2)}, \tag{1}$$

where h_b is the lug height, and ϕ is the internal friction angle of the soil [10].

Let us assume that a wheel is equipped with N lugs placed at equally spaced intervals. The spacing between the lugs at the tip, l_t, is geometrically obtained as

$$l_t = D\sin\frac{180°}{N}, \tag{2}$$

where D is the diameter of the wheel including the lug height. We define the number of lugs as N_{ls}, where the spacing between the lugs at the tip equals the soil rupture distance. Then, N_{ls} satisfies the equation

$$D\sin\frac{180°}{N_{l_s}} = \frac{h_b}{\tan(45° - \phi/2)}. \tag{3}$$

In general, the lugs of a wheel behave in one of two ways. If the number of lugs, N, on a wheel is less than N_{ls}, the lug behaviour will be similar to that of a soil-cutting blade (see Fig. 2(a)) [10]. Hence, the wheel obtains its thrust force from the bulldozing force of the lugs, which is the force caused by passive earth pressure (see Fig. 1). Under these conditions, with an increase in lug heights, their bulldozing force also increases, and the drawbar pull of the wheel increases. Further, an increase in the number of lugs contributes

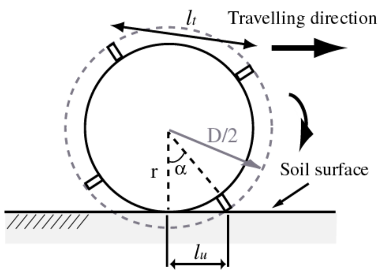


Fig. 3*: The spacing between lugs at the tip, l_t, and the horizontal distance, l_u, from the vertical to where the lug initially makes contact with the ground.*

to an increase in the drawbar pull of the wheel because the destructive phases of the lug do not interplay with each other.

On the other hand, if the number of lugs, N, on a wheel is greater than N_{ls}, the spaces between the lugs would be filled up with soil, and shearing would occur across the lug tips (see Fig. 2(b)) [10]. Hence, the wheel obtains its thrust force from the shear stress across the lug tips. Under these conditions, an increase in lug height has the same effect as an increase in the effective wheel diameter. Also, an increase in the number of lugs does not contribute to an increase in the drawbar pull of the wheel.

3 Slip ratio of wheels with lugs

One of the most important requirements imposed on planetary rovers is their ability to minimize slippage while climbing slopes covered with loose soil. Therefore, we used a slip ratio based on the slope angle as the indicator of the rover's climbing ability.

In general, the slip ratio, s, is defined using the actual travelling velocity of a vehicle, the radius, and the angular velocity of the wheel [10]; however, it is difficult to define the effective diameter of wheel with lugs and define the slip ratio based on conventional methods. Therefore, in this study, we define the slip ratio, s, as

$$s = \frac{d_d - d}{d_d} = 1 - \frac{d}{d_d}, \tag{4}$$

where d_d denotes the travelling distance per wheel rotation on hard ground, and d denotes the actual travelling distance per wheel rotation. In this equation, 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. Therefore, according to this definition, a small slip ratio over a slope indicates high travelling performance.

Let us assume that N lugs are equipped on a wheel in equally spaced intervals, and l_t is greater than the horizontal distance, l_u, from the vertical to where a lug initially makes contact with the ground (see Fig. 3). Less than one lug contacts the ground when a wheel

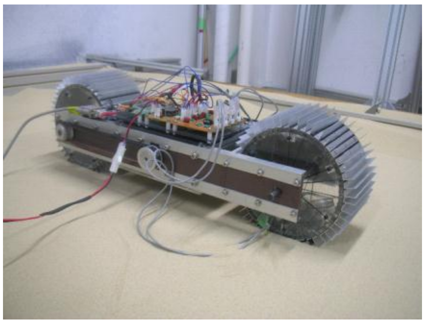
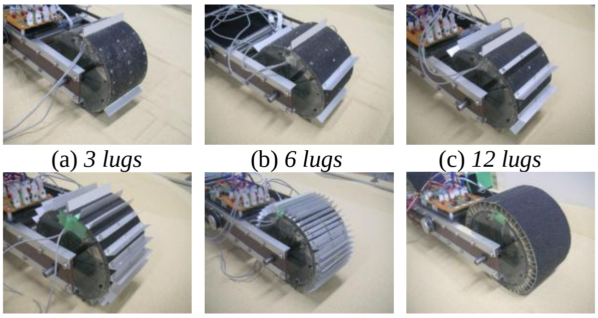


Fig. 4: *Two-wheeled rover.*



(a) *3 lugs* (b) *6 lugs* (c) *12 lugs*

(d) *24 lugs* (e) *48 lugs* (f) ∞ *lugs*

Fig.5: *Wheels equipped with different numbers of lugs (for a lug height of 15 mm)***.**

travels, and d_d is obtained geometrically as

$$d_d = 2Nl_u + 2r(\pi - \alpha N), \tag{5}$$

where the first term on the right-hand side denotes the travelling distance of the wheel when the lugs contact the ground; the second term denotes the travelling distance of the wheel when the wheel surface contacts the ground; r denotes the wheel radius; and α denotes the angle from the vertical to where the lug initially makes contact with the ground.

On the other hand, if l_t is smaller than l_u, the two lugs simultaneously contact the ground when a wheel travels, and d_d is obtained as

$$d_d = Nl_t. \tag{6}$$

Assuming that a wheel does not sink into the hard ground, l_u is expressed as

$$l_u = \frac{D}{2}\sin\alpha = \sqrt{\left(\frac{D}{2}\right)^2 - r^2}. \tag{7}$$

4 Experiments

In this study, our aim was to validate the influence of lugs on the travelling performances of the wheels presented in section 2. We performed slope travelling tests using a two-wheeled rover with wheels having different numbers of lugs of different heights.

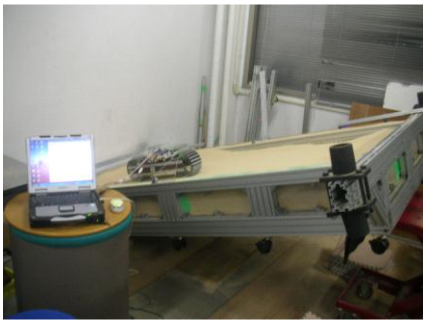


Fig.6: *Slope travelling test.*

4.1 Two-wheeled rover

In this study, we developed a lightweight two-wheeled rover with interchangeable wheels. Figure 4 depicts an overview of the rover. The rover weight was set to 3.8 kg, and the wheelbase of the rover was fixed at 400 mm. The actual travelling distance and velocity of the rover is obtained in detail using a position estimation device mounted on the rover [11]. Thus, the slip ratio, *s*, is determined on-line using Eqs. (4)-(6).

Twelve wheel types are developed as testbeds; they have two different lug heights and six different numbers of lugs, as shown in Fig. 5. The wheel has a diameter of 150 mm and a width of 100 mm; each lug has a length of 5 or 15 mm, that is, the wheel has a diameter of 160 or 180 mm including the lug heights. The wheel surfaces were covered with sandpaper to simulate the interaction between soil particles. The wheel shown in Fig. 5(f) differs from other wheels. It is the same as the wheel shown in Fig. 5(e) but is covered with sandpaper. This implies that the wheel shown in Fig. 5(f) has a larger diameter than that of a wheel without lugs. In this study, this wheel is defined as a large-diameter wheel or wheel with ∞ lugs.

4.2 Experimental overview and conditions

The two-wheeled rover, with the above-mentioned 12 types of wheels, was used to perform travelling tests in a sandbox inclined at different slope angles (see Fig.6). The sandbox has a length, width, and depth of 2 m, 1 m, and 0.15 m, respectively. This sandbox can be manually inclined to change its slope angle. In the experiments, slope angles were set to a maximum of 16° at 4° intervals. The sandbox was filled with Toyoura sand, which is predominantly a uniform, angular to subangular, fine, quartz sand. The mechanical properties of all Toyoura sand particles are nearly identical [12]. The angular velocity of the wheel was fixed at 2.50 rpm, and we measured the slip ratio after the wheels stopped sinking. Each trial was conducted under identical soil conditions, and three trials were conducted for each condition.

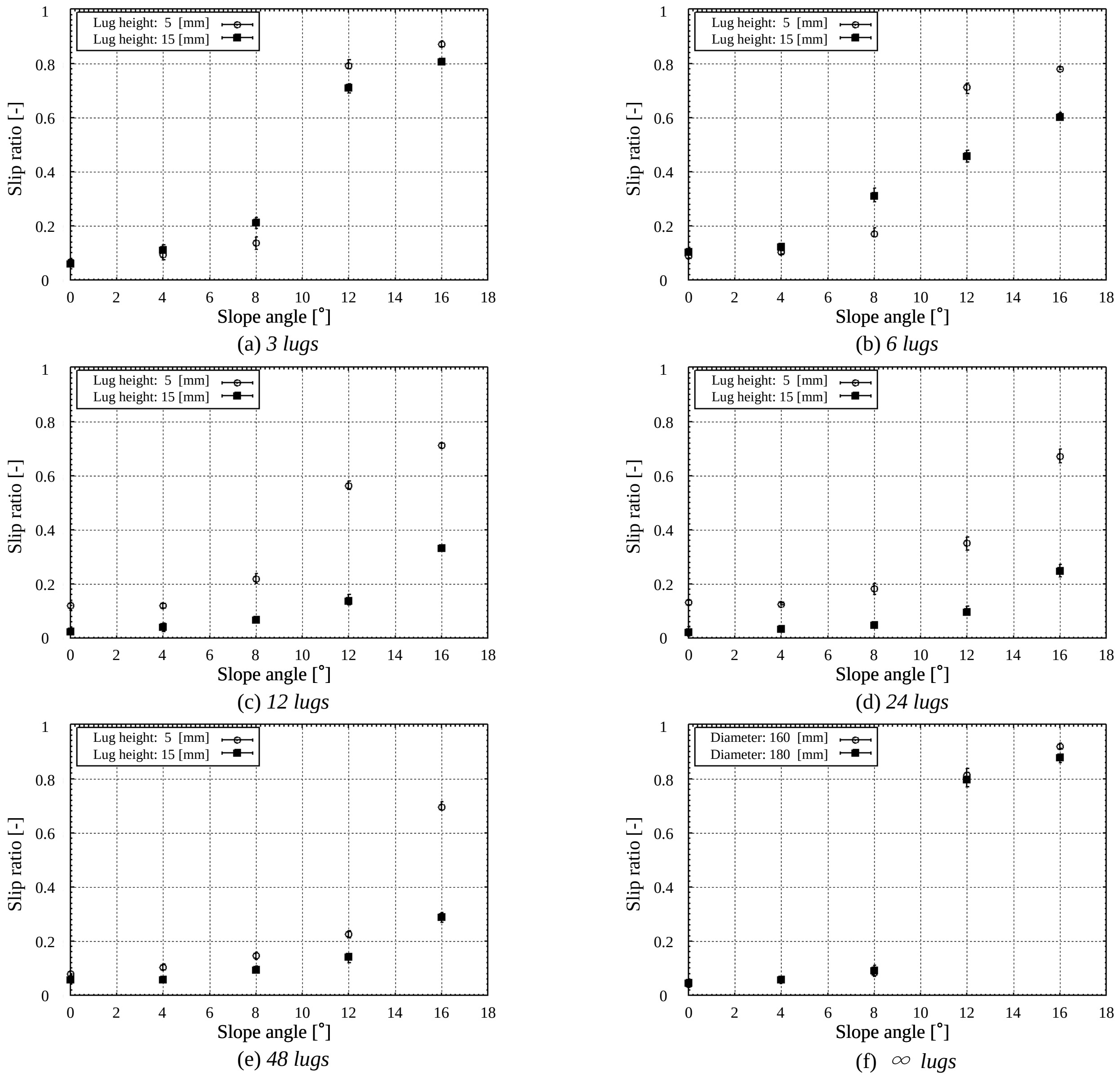


Fig.7: *Slope angle vs. slip ratio (for a fixed number of lugs).*

The soil rupture distance, l_s, and N_{ls} in the experiments are listed in Table 1. By using Eqs. (1) and (3), these parameters are determined from the wheel parameters used in the experiments and the internal friction angle of Toyoura sand (38˚).

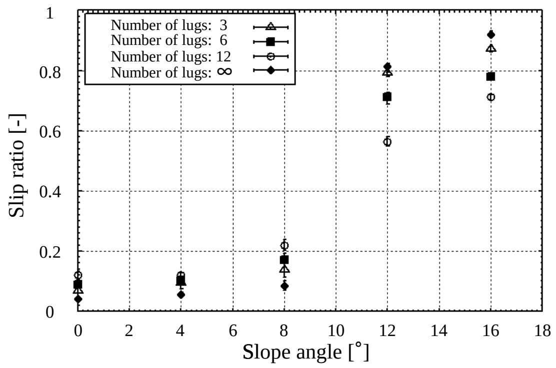
Table 1: Wheel parameters, l_s and N_{ls}.

	Short lug	Tall lug
D [mm]	160	180
h_b [mm]	5	15
l_s [mm]	10	30
N_{ls}	50	19

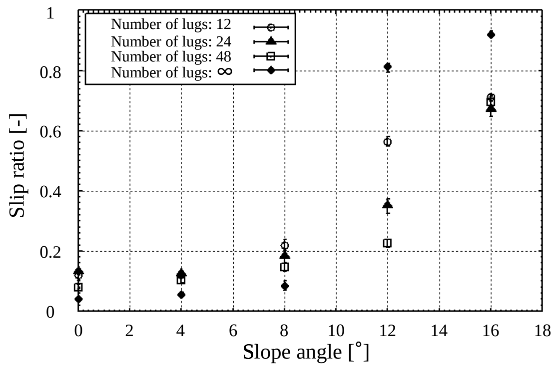
4.3 Influence of lug height on the travelling performance of a wheel

To evaluate the influence of lug heights on the travelling performance of a wheel, we plotted the data for different cases with a fixed number of lugs, as shown in Fig. 7.

Figures 7(a) and (b) show the slip ratios and slope angles for wheels with 3 and 6 lugs, respectively. It was found that wheels with 5-mm-height lugs had smaller slip ratios over gentle slopes (i.e., angles less than 8˚) than wheels with 15-mm-height lugs had. This means that wheels with short lugs give high travelling performances. On the other hand, wheels with tall lugs give high travelling performances over steep slopes

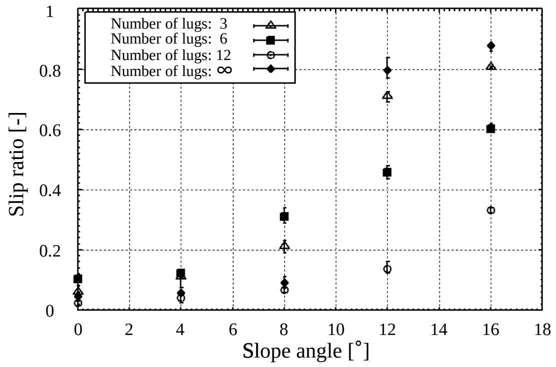


(a) *Wheel with 3, 6, 12, and ∞ lugs*

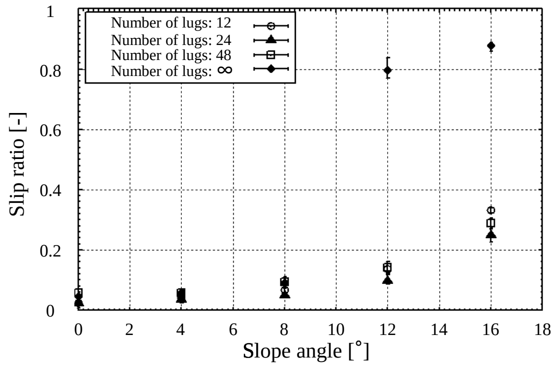


(b) *Wheel with 12, 24, 48, and ∞ lugs*

Fig.8: *Slope angle vs. slip ratio (for fixed lugs of height 5 mm).*



(a) *Wheel with 3, 6, 12, and ∞ lugs*



(b) *Wheel with 12, 24, 48, and ∞ lugs*

Fig.9: *Slope angle vs. slip ratio (for fixed lugs of height 15 mm).*

(i.e., angles greater than 8˚).

Figures 7(c), (d), and (e) show the slip ratios for wheels with 12, 24, and 48 lugs. It can be seen that wheels with 15-mm-height lugs had smaller slip ratios over all the slopes than wheels with 5-mm-height lugs had. Therefore, tall lugs contribute to high travelling performances.

Figure 7(f) shows that the changes in the slip ratio over a slope angle resulting from differences in the wheel diameter are much smaller than the changes resulting from differences in lug heights. Therefore, an increase in the lug height contributes more to high travelling performance than an increase in the wheel diameter does.

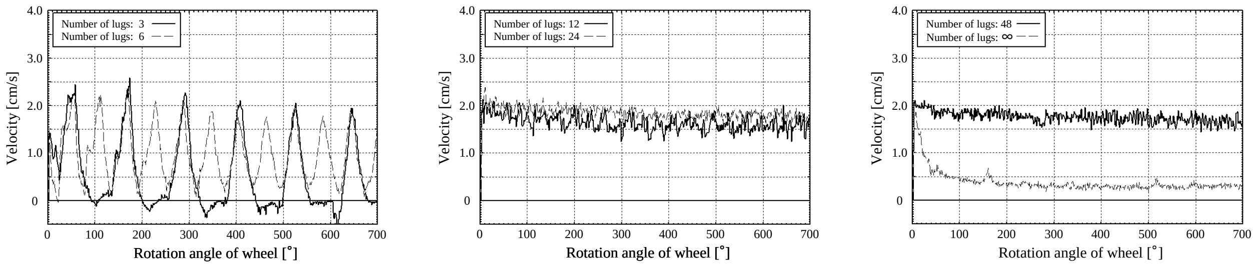
From Fig. 7(f), it is clear that large-diameter wheels have higher travelling performances over gentle slopes than wheels with lugs have; that is, the travelling performance decreases because of the lugs. This trend corresponds with the above-mentioned results for wheels with 3 and 6 lugs, i.e., short lugs improve the travelling performance. This is because lugs dig the soil beneath the wheel, which seems to increase wheel sinkage

4.4 Influence of the number of lugs on the travelling performance of wheels

To evaluate the influence of the number of lugs on the travelling performance, we plotted the data for cases with a fixed lug height (see Fig. 8 and Fig. 9).

In the case of wheels with 5-mm-height lugs, the slip ratio over the slope was seen to decrease with an increase in the number of lugs (see Fig. 8). This implies that the travelling performance improves with an increase in the number of lugs. This trend corresponds to expectations based on the theoretical behaviour of lugs when the number of lugs, N, is less than N_{ls}. In this case, the number of lugs (N) was always less than N_{ls}.

Figure 8 shows that large-diameter wheels have higher travelling performances over gentle slopes compared with those of wheels with lugs. This means that an increase in the wheel diameter contributes more to improving the travelling performance over gentle slopes than equipping wheels with lugs does. On the other hand, wheels with lugs have higher travelling performances over steep slopes than large-diameter wheels have. Therefore, equipping with lugs, rather than increasing the wheel diameter, contributes more to bettering travelling performances over steep slopes.



(a) *Wheel with 3/6 lugs* (b) *Wheel with 12/24 lugs* (c) *Wheel with 48/∞ lugs*

Fig.10: *Rotation angle of wheel vs. travelling velocity (for slope angle of 16°).*

Figure 9 shows that for wheels with 15-mm-height lugs, the travelling performance increases as the number of lugs increases from 3 to 12. This trend corresponds to expectations based on the theoretical behaviour of lugs. On the other hand, wheels with 12, 24, and 48 lugs show slight differences in the slip ratio values for different numbers of lugs.

It can be seen from Fig. 9 that the travelling performances of wheels with 12, 24, and 48 lugs are similar to those of large-diameter wheels over gentle slopes. This trend corresponds to our expectations based on the theoretical behaviour of lugs when the number of lugs, N, is greater than N_{ls}. Over steep slopes, however, wheels with 12, 24, and 48 lugs have better travelling performances than large-diameter wheels have. This means that an increase in the number of lugs contributes more to the travelling performance than an increase in the wheel diameter contributes. This trend does not correspond to theoretical expectations of lug behaviour when the number of lugs, N, is greater than N_{ls}.

5 Discussion of the tractive effort developed by lugs

In the experiments presented in section 4, travelling performances of wheels with lugs were higher than those of large-diameter wheels, especially over steep slopes. This does not correspond to the expectations based on the theoretical behaviour of lugs presented in section 2. In this section, we discuss the effect of lugs that improve the travelling performances of wheels from the travelling velocity of rover in the experiments.

The relationship between the rotation angle of the wheel and the travelling velocity over a slope angle of 16° are plotted in the graph shown in Fig. 10. This is obtained from experiments using wheels with 15-mm-height lugs. From the figure, it is clear that the travelling velocities change in cycles corresponding to the lug intervals when the wheels have 3, 6, and 12 lugs. This means that the wheel obtains its thrust force from the force acting on lugs, that is, bulldozing force of the lugs (see Fig.1), which is caused by passive earth pressure of soil in front of the lugs; this matches our expectations based on the theoretical behaviour of lugs.

On the other hand, in the cases of wheels with 24 and 48 lugs, the rover travels at constant velocities. These velocities are greater than the velocities of large-diameter wheels and are almost equal to the maximum velocities of wheels with 3, 6, and 12 lugs. Based on this, we concluded that wheels with 24 and 48 lugs mainly obtain their thrust force from the bulldozing force of lugs and not from the shear stress between lug tips as expected; that is, wheels with lugs obtain their thrust force from both the bulldozing force of lugs and the shear stress between lug tips. The bulldozing force is greater than the shear stress. As a result, wheels with lugs have higher travelling performances than large-diameter wheels have, especially over steep slopes.

As mentioned above, the effect of the bulldozing force of lugs on the travelling performances of vehicles is greater than the effect of shear stress between lugs tips, especially over steep slopes. We concluded that this was because loose soil has a small cohesion stress. The small cohesion stress of soil causes the soil to spill out easily from the spaces between lugs, so the spaces would not be filled up with soil. As the slope angle increases, this trend becomes pronounced, and the shear stress between lug tips would decrease. Therefore, the effect of the bulldozing force of lugs would increase relatively.

Conventionally, if the number of lugs on a wheel is large enough, the travelling performance of a wheel with lugs is estimated by assuming that the effect of lugs would be an increase in the effective diameter of the wheel [6, 10]. However, based on the above discussion, regardless of the number of lugs, the bulldozing force of lugs has a great effect on the travelling performances of wheels, especially over steep slopes. From this, we have concluded that a new drawbar pull model, which incorporates such lug effects, is required to estimate the travelling performances of wheels equipped with lugs. The construction of the drawbar pull model is an important subject for our future work.

In this study, we introduced a new definition of the slip ratio. We believe this definition would be useful in accurately expressing the slippage of wheels with lugs, especially when the number of lugs is small.

6 Conclusion

In this study, we performed slope travelling tests using the two-wheeled rover having wheels equipped with different numbers of lugs of varying lug heights. We also evaluated the influence of lugs on the travelling performances of wheels.

We found that when the number of lugs on a wheel is small, the travelling performance of the wheel over gentle slopes decreases as the lug height increases. When the number of lugs is large, an increase in lug height contributes to a high travelling performance. On the other hand, an increase in the lug height and the number of lugs contribute to high travelling performances of wheels over steep slopes. Under these conditions, wheels with lugs have higher travelling performances than wheels with large diameters.

Further, based on changes in the travelling velocity, we concluded that the bulldozing force of lugs has a greater effect than the shear stress between lug tips has on improving the travelling performances of wheels, especially over steep slopes.

Nomenclature

d	Actual travelling distance per wheel rotation	[m]
d_d	Travelling distance per wheel rotation on hard ground	[m]
D	Diameter including lug height	[m]
h_b	Lug height	[m]
l_s	Spacing between lugs at the tip	[m]
l_t	Soil rupture distance	[m]
l_u	Horizontal distance from the vertical to where lug initially makes contact with the ground	[m]
N	Number of lugs on wheel	[-]
N_{ls}	Number of lugs where l_t equals l_s	[-]
r	Radius of wheel	[m]
s	Slip ratio	[-]
α	Angle from the vertical to where lug initially makes contact with the ground	[rad]
ϕ	Internal friction angle of soil	[˚]

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