Traveling Performance Estimation for Planetary Rovers over Slope

Masataku Sutoh, Ryosuke Yajima, Keiji Nagatani, and Kazuya Yoshida

***Abstract*— One of the most important requirements imposed on planetary rovers is the ability to minimize slippage while climbing slopes covered with loose soil. Therefore, at the design stage of the rovers, it is necessary to evaluate the traveling performance of their locomotion mechanisms over a slope. However, to conduct traveling tests over slopes, the sandbox in which the tests are conducted must be tilted; it is difficult and even dangerous to make a steep slope because of the heavy weight of the sandbox. Therefore, in this paper, we propose a new method for estimating the traveling performance of a wheeled rover over a slope. In this method, we estimate the slip ratio for different slope angles on the basis of traction tests over a flat terrain. To verify the proposed method, we conducted slope-climbing tests and traction tests in a sandbox using a two-wheeled rover with various types of wheels. Furthermore, we compared the slip ratios estimated from the slope-climbing tests with those estimated from the traction tests. From these comparisons, we concluded that the proposed method can accurately estimate the traveling performance of a planetary rover over a slope.**

I. INTRODUCTION

Mobile robots (rovers) have played a significant role in NASA's Martian geological investigations. The use of rovers in missions increases the exploration area, thereby improving the scientific return of the mission. As a result, high expectations are placed on future lunar and planetary rovers.

However, the surfaces of the Moon and Mars are covered with loose soil, and there are numerous steep slopes along the rims of the craters. Under such conditions, wheeled rovers may get stuck and, in the worst-case scenario, such problems can result in the failure of the mission. Therefore, one of the most important requirements imposed on planetary rovers is the ability to minimize slippage while climbing slopes covered with loose soil.

Some studies have been conducted on the estimation of slippage of a rover over a slope on the basis of a wheel-soil interaction model in terramechanics [1], [2]. Terramechanics is a branch of mechanics that examines the interaction between soil and locomotion mechanisms [3], [4]. However, the soil-wheel interaction models were originally derived for motion over a flat terrain, and it is not certain that they are applicable for motion over a slope.

M. Sutoh, K. Nagatani, and K. Yoshida are with Graduate School of Engineering, Tohoku University, 6-6-01 Aoba Aramaki Aoba-ku, Sendai 9808579, Japan {sutoh,keiji,yoshida}@astro.mech.tohoku.ac.jp

R. Yajima is with the Advanced Courses of Production System Engineering, Asahikawa National College of Technology, 6-1 2-chome 2-jyo Shunkodai, Asahikawa, Hokkaido 0718142, Japan p118013@edu.asahikawa-nct.ac.jp

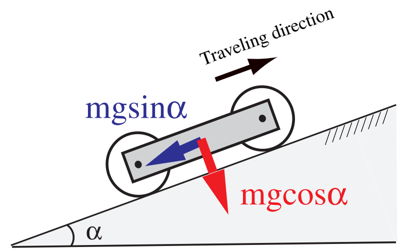


Fig. 1. Forces acting on a rover in slope-climbing test.

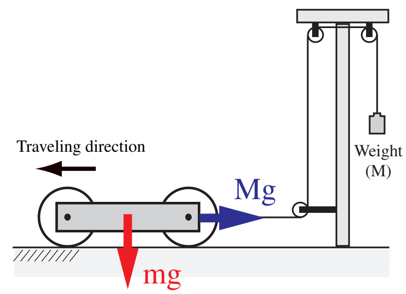


Fig. 2. Forces acting on a rover in traction test.

Some reports are available on experiments using rovers over slopes [5], [6]. In a slope-climbing test, a rover travels over a slope and the slippage of the rover is measured for different slope angles (see Fig.1). To conduct slope-climbing tests, however, the sandbox in which the rover travels is required to be tilted. Typically, the sandbox is tilted by lifting it on one side using pulleys or jacks. Therefore, it is difficult and even dangerous to make a steep slope because a filled sandbox can weigh hundreds of kilograms.

Because of this difficulty in the slope-climbing test, traction tests are widely conducted as simple substitutes to evaluate the traveling performance [3], [4]. In a traction test, a rover travels over a flat terrain, pulling a weight behind it, and slippage of the rover is measured subject to different traction weights (see Fig.2). However, a few reports are available on the estimation of slippage over a slope on the basis of the traction test.

We considered whether the forces acting on a rover in a slope-climbing test could possibly be simulated in a traction test (see Figs.1 and 2) and whether the slippage over a slope could be easily estimated from the traction test. The objective is to develop a new estimation method for determining the traveling performance of a wheeled rover over a slope. To verify the proposed method, we conducted slope-climbing tests and traction tests using a two-wheeled rover with various types of wheels. In each test, we measured the slip

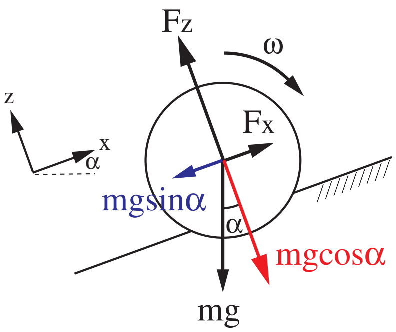


Fig. 3. Force equilibrium on slope.

ratio in a sandbox. Furthermore, the slip ratios from the slope-climbing tests were compared with those estimated from the traction tests.

In this paper, the equilibrium of the forces acting on the slope and the slip ratio are explained. Next, the method for estimating the traveling performance over a slope is introduced. Finally, the abovementioned experiments and results are described in detail.

II. Force Equilibrium on Slope

For a planetary rover to travel over a slope covered with loose soil, a force is required to pull its weight; this force is called the drawbar pull, F_x. At the same time, a vertical force F_z is required to prevent it from sinking into the soil. For a one-wheeled rover, Fig. 3 shows the forces acting on the wheel of the rover. The equilibrium equations of the wheel when it travels along a slope of angle α are

$$F_x = mg\sin\alpha \tag{1}$$

$$F_z = mg\cos\alpha \tag{2}$$

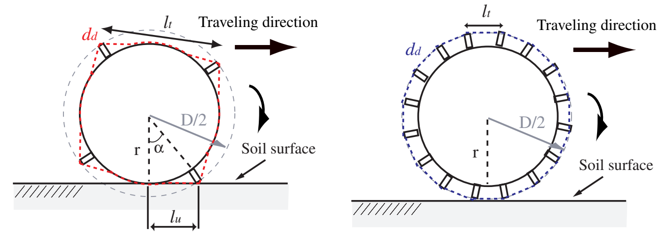
where m is the mass of the vehicle, and g is the gravitational acceleration.

The drawbar pull of a vehicle, F_x, is defined as the difference between the thrust developed by its wheels and the wheels' motion resistance. It has been reported that an increase in the slippage of the wheel contributes to an increase in the thrust and motion resistance [4]. That is, the slippage of a wheel has a considerable influence on the drawbar pull.

III. Slip Ratio

According to (1), the drawbar pull required for a vehicle changes with the slope angle. That is, the slippage of the wheel differs over slopes with different angles. Therefore, to evaluate the traveling performance of the locomotion mechanism of rovers, we adopted a slip ratio based on the slope angle.

In general, the slip ratio s is defined using the actual linear speed of a vehicle, the radius, and the angular speed of the wheel [4]. In this study, we used wheels that have parallel fins called lugs (i.e., grousers) on their surface; it is difficult to define the effective diameter of a wheel with lugs and to define the slip ratio on the basis of the above method. Therefore, in this study, we define the slip ratio s of a wheel with lugs as [7]



(a) In case l_t is greater than l_u. (b) In case l_t is smaller than l_u.

Fig. 4. Traveling distance per wheel rotation on hard ground, d_d.

$$s = \frac{d_d - d}{d_d} = 1 - \frac{d}{d_d}, \tag{3}$$

where d denotes the actual traveling distance per wheel rotation, and d_d denotes the traveling distance per wheel rotation on hard ground.

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

$$l_t = D\sin\frac{180^\circ}{N}, \tag{4}$$

where D is the diameter of the wheel including the lug height.

We define l_u as the horizontal distance across the surface of the soil from the vertical to a lug tip at the moment when both the surface of the wheel and the lug contact the ground (see Fig. 4(a)). Assuming that a wheel does not sink into the hard ground, l_u is expressed as

$$l_u = \frac{D}{2}\sin\alpha = \sqrt{(\frac{D}{2})^2 - r^2}, \tag{5}$$

where α denotes the angle from the vertical to the lug tip at the moment when both the surface of the wheel and the lug contact the ground, and r denotes the wheel radius.

If l_t is greater than l_u, less than one lug contacts the ground when a wheel travels (see Fig. 4(a)), and d_d is geometrically obtained as

$$d_d = 2Nl_u + 2r(\pi - \alpha N), \tag{6}$$

where the first term on the right-hand side denotes the traveling distance of the wheel when the lugs contact the ground, and the second term denotes the traveling distance of the wheel when the wheel surface contacts 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 (see Fig. 4(b)), and d_d is obtained as

$$d_d = Nl_t. \tag{7}$$

In (3), the slip ratio has a value between 0 and 1. When a vehicle moves forward without slippage, the slip ratio is 0; when it 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 traveling performance.

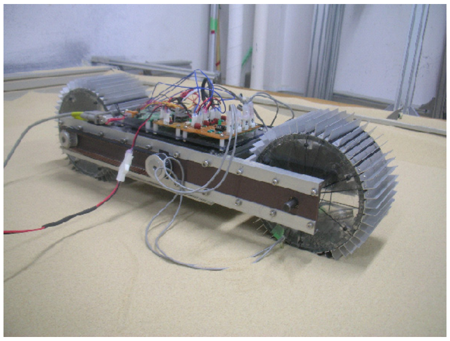


Fig. 5. Two-wheeled rover.

IV. Estimation method for traveling performance of wheel over slope

If the forces acting on a rover in a slope-climbing test (see Fig.1) are simulated in a traction test, we can estimate the traveling performance of the rover, i.e., the slip ratio based on the slope angle, from the traction test. In this section, we propose such an estimation method by considering the drawbar pull and vertical force in each test.

In the traction test, the drawbar pull F_x required for the wheels of a rover corresponds to a traction weight (see Fig.2). Here, if the traction weight (g) M is set on the basis of the relationship

$$Mg \quad = \quad mg \sin \alpha, \tag{8}$$

the wheels are required to generate the drawbar pull needed over a slope with angle α (see Figs.1 and 2). That is, by adjusting the weight, the drawbar pull in the traction tests would be equal to that in slope-climbing tests with corresponding slope angles.

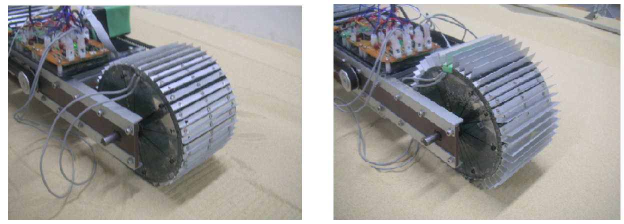
While the vertical force F_z is always constant in a traction test, it decreases as the slope angle increases in a slope-climbing test (see Figs.1 and 2). Here, from the calculation using (2), it is found that F_z over a slope with an angle of $28°$ is 88% of that over a flat terrain. Therefore, we assume that this difference in the vertical force is small enough to not affect the traveling performance of wheeled rovers.

According to the above discussion, we considered that the slip ratio of a wheel over a slope can be estimated by measuring the slip ratio in a traction test, whose traction weight corresponds to the slope angle.

In this method, we assumed that the influence of the difference in the vertical force was negligible; however, this assumption may affect the estimation results. Furthermore, in the slope-climbing test, because of the weight of the soil, a force along a slope acts even on the soil. This may affect the stability of the soil and make the soil collapse easily over a slope. To verify these influences and the proposed estimation method, we conducted the experiments in the next section.

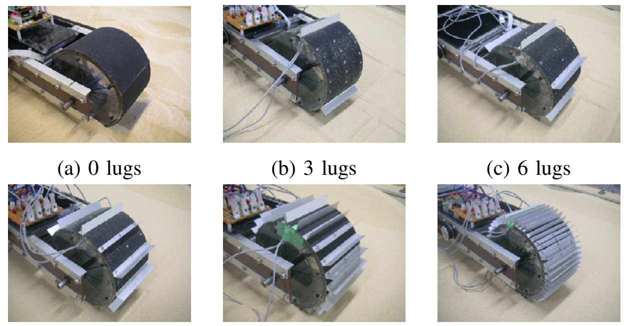
V. Verification experiments

To verify the abovementioned influences and the proposed estimation method, we first conducted slope-climbing tests and measured the slip ratio for different slope angles. Next, we performed traction tests and estimated the slip ratio over the slopes corresponding to each angle. Finally, the slip ratios in the slope-climbing tests were compared with those estimated from the traction tests. In each test, we used a two-wheeled rover with wheels having different numbers of lugs of different heights. In this section, the experiments and experimental results are reported in detail.



(a) lug height 5 mm (b) lug height 15 mm

Fig. 6. 48-lug wheels with different lug heights.



(a) 0 lugs (b) 3 lugs (c) 6 lugs

(d) 12 lugs (e) 24 lugs (f) 48 lugs

Fig. 7. Wheels equipped with different numbers of lugs (for a lug height of 15 mm).

A. *Two-wheeled rover*

In this study, we developed a lightweight two-wheeled rover with interchangeable wheels (see Fig. 5). The distance between the front and the rear wheels was fixed at 400 mm. The rover weight was set to 4.0 kg for all the different wheel types.

Eleven wheel types were developed. Except for the wheel without lugs, the other wheels have two different lug heights and five different numbers of lugs, as shown in Figs. 6 and 7. The wheel has a diameter of 150 mm and a width of 100 mm; each lug has a height 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.

To rotate the wheels and control their angular speed, the rover has a microcontroller (H8-3048one; Renesas Technology Corp), and a motor embedded with an encoder (RE-max 29 with GP32C planetary gear and MRenc encoder; produced by Maxon Co., Ltd). The microcontroller obtains the sensing value from the encoder via an analog-to-digital converter, and the angular speed of the wheels is measured.

Furthermore, the motion measurement system using an optical sensor and laser sources is mounted on the rover to

Fig. 8. Slope-climbing test; two-wheeled rover travels over a slope.

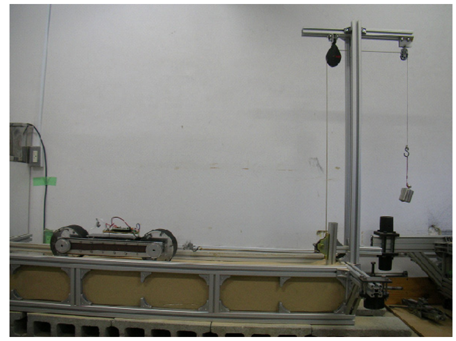


Fig. 9. Traction test; a two-wheeled rover travels by pulling weight attached behind it.

measure the actual rover traveling distance and speed without using external devices embedded in the target environment [8]. From the traveling distance, the slip ratio s is calculated using (3)-(7).

B. Experimental conditions

The two-wheeled rover, with the abovementioned eleven types of wheels, was used to conduct slope-climbing tests and traction tests in a sandbox. The sandbox has a length, width, and depth of 1.5 m, 0.30 m, and 0.15 m, respectively and was filled with Toyoura standard sand (JIS R 5200); this sand has very low viscosity and its particle is almost uniform [9].

In the slope-climbing tests, slope angles were set to a maximum of 28° at 4° intervals (see Fig.8). In the traction tests, using (8), the traction weights were set corresponding to each slope angle in the slope-climbing tests (see Fig.9). The relationship between the slope angle and the traction weight is listed in Table I.

In the experiments, the angular speed of the wheel was fixed at 2.50 rpm, and the slip ratio was measured after the wheels stopped sinking. Each trial was conducted under identical soil conditions, and three trials were conducted for each condition.

C. Experimental results and discussion

To compare the slip ratios estimated from the slope-climbing tests with those estimated from the traction tests, we plotted the data for different cases with a fixed number of lugs, as shown in Figs.10 and 11. Figs.10 and 11 show the data for wheels with 5-mm-height lugs and for those with 15-mm-height lugs, respectively.

In Figs.10 (b) and (d), over a slope with an angle of 8°, the value of the slip ratio estimated from the traction test differs from that estimated from the slope-climbing test. Moreover, as shown in Fig 10 (f), over a slope with an angle of 12°, the value of the slip ratio estimated from the traction test differs from that estimated from the slope-climbing test.

TABLE I

RELATIONSHIP BETWEEN THE SLOPE ANGLE AND THE TRACTION WEIGHT.

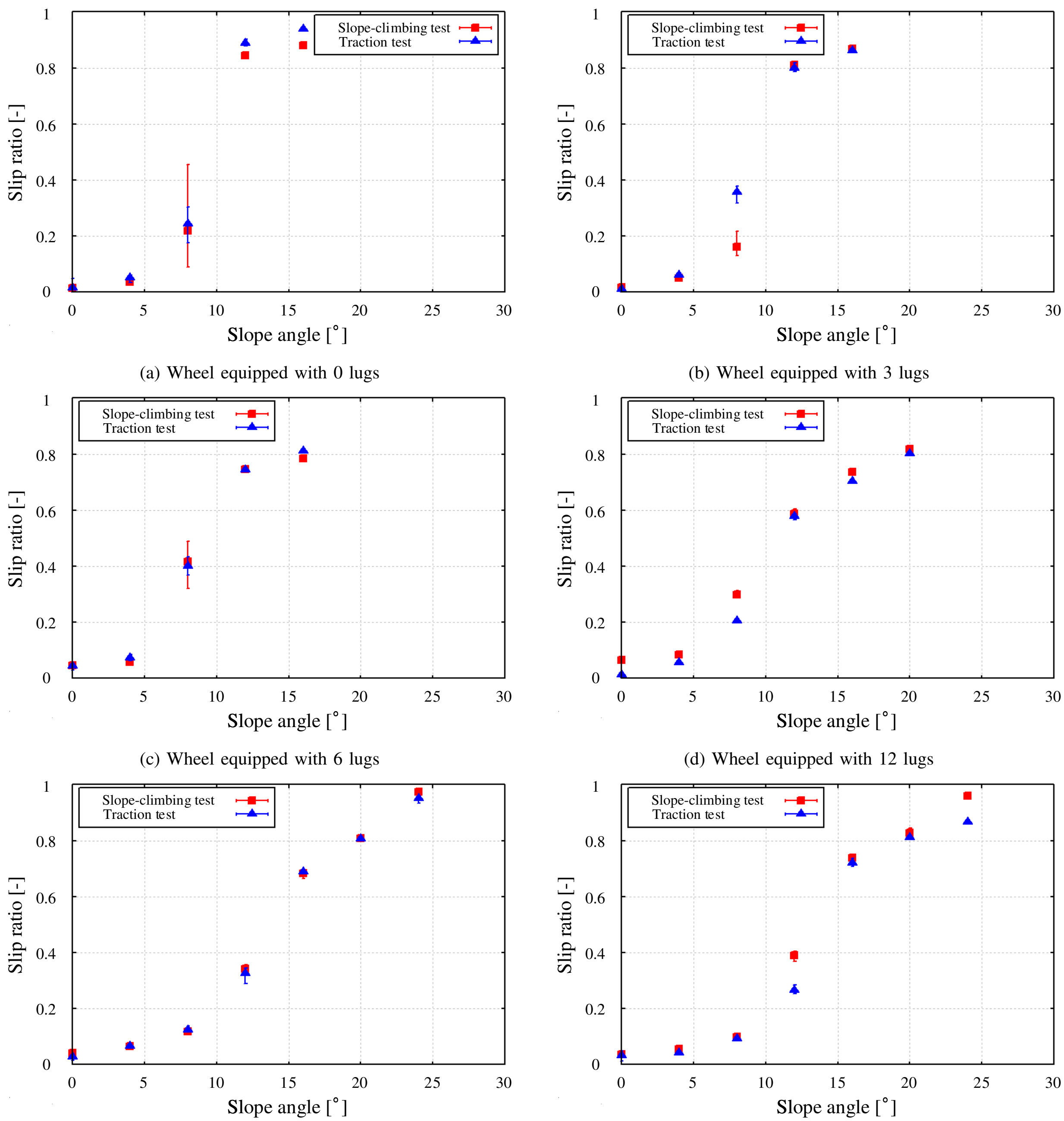
Angle (°)	0	4	8	12	16	20	24	28
Weight (g)	0	280	560	830	1100	1370	1630	1880

As presented in section 4, the vertical force in the traction tests slightly differed from that in the slope-climbing test. This could affect the wheel sinkage and the motion resistance of the wheel, which results in a slight change in the drawbar pull of the wheel. Thus, this change could affect the estimated slip ratio, particularly over the slope where a wheel can easily increase slippage. In Fig 10, it was observed that the slip ratio of the wheels rapidly increased over a slope with angle of around 8° or 12°. Consequently, over these slopes, the wheels exhibit an unstable behavior, i.e., the wheels can easily increase slippage. We believe that this is why the value of the slip ratio differed for each test in the abovementioned cases.

In Figs.11 (d) and (e), the value of the slip ratio in the slope-climbing test is higher than that estimated from the traction test over steep slopes (i.e., angles greater than 16°). As presented in section 4, in the slope-climbing test, the force along a slope acts on the soil, which results in making the soil collapse more easily as the slope becomes steeper. In cases of wheels with a large number of lugs of considerable height, the wheel frequently digs into a wide range of the soil beneath it and increases its sinkage. We concluded that if the soil collapses easily, this trend would have a great effect on the traveling performance. This is why the value of the slip ratio in the slope-climbing test was higher in these cases.

In most of the cases except for the abovementioned case, there is only a slight difference in the values of the slip ratio over a given slope for different tests (see Figs.10 and 11). Therefore, we confirmed that the difference between the tests, i.e., the slight difference between the vertical force and the force acting on the soil, does not generally affect the estimated results.

From the above discussion, we concluded that the slip ratio of a wheel over a slope could be accurately estimated by measuring the slip ratio in a traction test with a weight corresponding to the slope angle. However, it is important to note that this method may produce a slight error in the slip ratio over a slope where a wheel can easily increase slippage. Furthermore, in the case of wheels with a large number of tall lugs, this method underestimates the value of the slip



(a) Wheel equipped with 0 lugs

(b) Wheel equipped with 3 lugs

(c) Wheel equipped with 6 lugs

(d) Wheel equipped with 12 lugs

(e) Wheel equipped with 24 lugs

(f) Wheel equipped with 48 lugs

Fig. 10. Slope angle versus slip ratio (for fixed lug height of 5 mm).

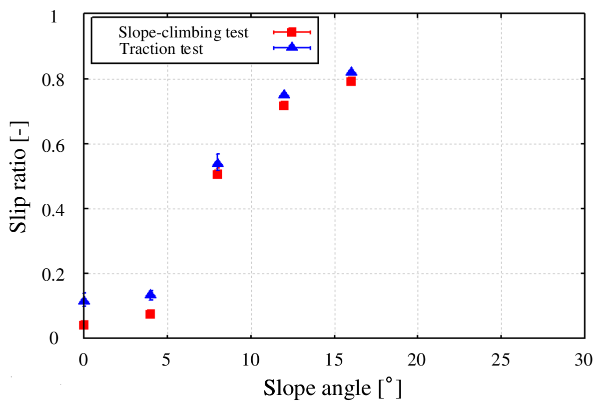
ratio over steep slopes.

VI. Conclusion

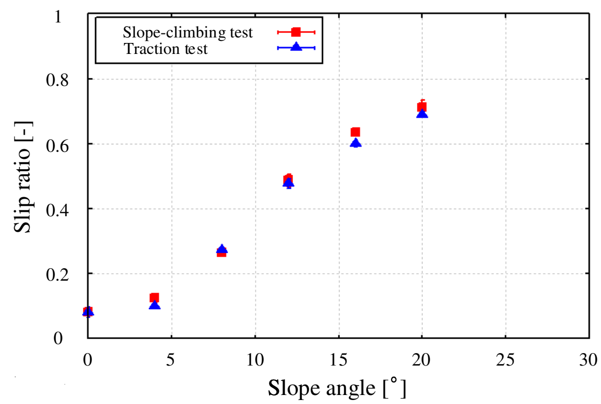
In this study, the equilibrium of the forces on a slope and the slip ratio were explained. Next, we proposed a new estimation method for determining the traveling performance of a wheeled rover over a slope on the basis of a traction test. To verify this method, we conducted slope-climbing tests and traction tests using a two-wheeled rover with wheels having different numbers of lugs of different heights. Furthermore, the slip ratios estimated from the slope-climbing tests were compared with those estimated from the traction tests. From the comparison, we found that for wheels with large numbers of tall lugs, the proposed method underestimates the value of the slip ratio over steep slopes. In general, however, we confirmed that the proposed method can accurately estimate the traveling performance over a slope.

References

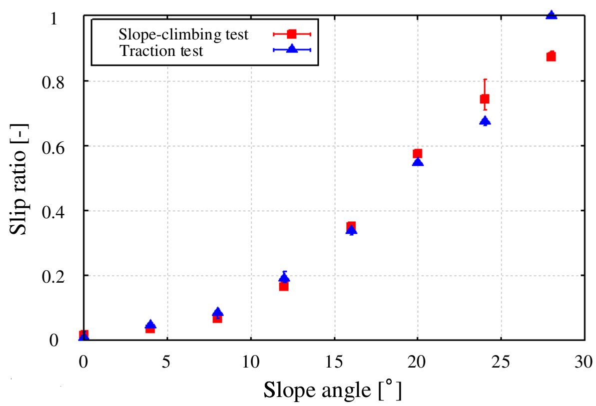
[1] K. Yoshida, N. Mizuno, G. Ishigami, and A. Miwa, "Terramechanics-based analysis for slope climbing capability of a lunar/planetary rover," *Proceedings of 24th International Symposium on Space Technology and Science*, Miyazaki, Japan, June 2004, 2004-k-06.



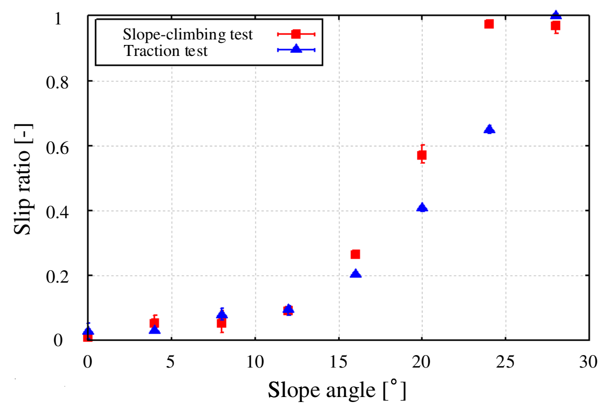
(a) Wheel equipped with 3 lugs



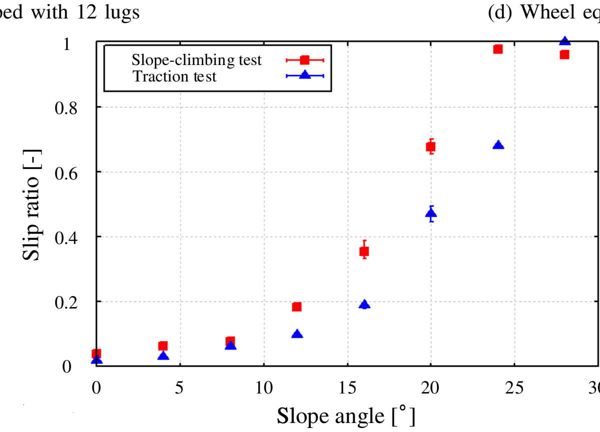
(b) Wheel equipped with 6 lugs



(c) Wheel equipped with 12 lugs



(d) Wheel equipped with 24 lugs



(e) Wheel equipped with 48 lugs

Fig. 11. Slope angle versus slip ratio (for fixed lug height of 15 mm).

[2] G. Ishigami, A. Miwa, K. Nagatani, and K. Yoshida, "Terramechanics-based analysis on slope traversability for a planetary exploration rover," *Proceedings of 25th International Symposium on Space Technology and Science*, Kanazawa, Japan, June 2006, 2006-k-09.

[3] M. G. Bekker, *Off the road locomotion*, The University of Michigan Press, Ann Arbor MI, 1960.

[4] J. Y. Wong, *Theory of Ground Vehicles Third edition*, Wiley-Interscience, New York, 2001.

[5] K. Iizuka, Y. Sato, Y. Kuroda, and T. Kubota, "Experimental study of wheeled forms for lunar rover on slope terrain," *9th IEEE International Workshop on Advanced Motion Control*, Istanbul, Turkey, March 2006, pp.266–271.

[6] H. Nakashima, H. Fujii, A. Oida, M. Momozu, H. Kanamori, S. Aoki, T. Yokoyama, H. Shimizu, J. Miyasaka, and K. Ohdoi, "Discrete element method analysis of single wheel performance for a small lunar rover on sloped terrain," *Journal of Terramechanics*, Vol 47, No 5, 2010, pp.307–321.

[7] M. Sutoh, K. Nagatani, and K. Yoshida, "Evaluation of influence of surface shape of wheel on traveling performance of planetary rovers over slope", *Proceedings of 17th ISTVS International Conference*, Blacksburg VA, USA, September 2011.

[8] I. Nagai, K. Watanabe, K. Nagatani, and K. Yoshida, "Noncontact position estimation device with optical sensor and laser sources for mobile robots traversing slippery terrains," *Proceedings of 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Taipei, Taiwan, October 2010, pp.3422–3427.

[9] R. Bellotti, J. Benoît, C. Fretti, and M. Jamiolkowski, "Stiffness of Toyoura sand from dilatometer tests," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol 123, No 9, 1997, pp.836–846.