# Observation of Movement of Ground Particles Given Vibration When Rod Is Dragged

Tomohiro Watanabe and Kojiro Iizuka

***Abstract*—Supporting force, that a rod receives from the ground, is increased when vibration gives to the ground. This phenomenon is effective to improve the running performance for the legged rovers. In this study, the flow of the ground particles when a rod is dragged is measured using PIV for improving the running performance of the legged rovers. As observed from the experimental result, the larger the supporting force is, the larger the area that the particles move is. Therefore, the supporting force is related to the movement of the ground particles. Moreover, the area that the particles move becomes large by providing vibration whose frequency is high. The reason is considered that density is increased in a wide range of the ground when the vibration whose frequency is high. It is considered that the supporting force is increased by providing vibration to the ground because the area, that the particles move, grows by increasing density of the ground. The findings of this study suggest facilitating further planetary exploration using legged rovers.**

***Index Terms*—Loose soil, vibration, legged rover, particle image velocimetry.**

## I. Introduction

Concern of the planetary exploration has been growing. Many missions will be conducted to explore planetaries. For example, JAXA will launch the Smart Lander for Investigating Moon (SLIM) [1]. Moreover, GATEWAY that is a platform orbiting the Moon, will be developed [2]. Therefore, robots will be required to explore planets. Exploring robots called rovers have been used in planetary exploration. They have explored planets and obtaining significant information [3]-[5]. In recent years, legged robots have been focused on as exploration rovers with high running performance [6]-[8]. The ground of Mars and the Moon is covered with loose soil, called regolith. The loose ground is easily deformed by external force. Therefore, rovers mainly slip due to deformation of the loose ground. We have addressed this problem. Our study group proposed a walking method that reduces the slip distance on the loose ground for planetary exploration legged rovers [9]. Moreover, the effectiveness of the proposed walking method was confirmed.

The supporting force is increased when the loose ground is compacted by providing vibration. In the proposed walking method, the slip distance is reduced by increasing the supporting force using vibration. Therefore, it is important that the supporting force is increased by providing vibration to the ground for improving the running performance of the legged rovers. It has already been confirmed that the relationship between the supporting force and vibration [10], [11]. However, the flow of the ground particles when supporting force is caused is not confirmed. In the related study, the models that estimate supporting force have been constructed based on the area that the ground particles move [12]. Therefore, purpose of this study is understanding the mechanism that the supporting is increased by providing vibration. Moreover, movement of the ground particles is measured.

In this study, movement of the ground particles is measured by PIV. In recent years, the understanding terra mechanics of internal the ground has been promoted using PIV. Yamakawa et al. studied about soil-vehicle interaction for predicting trafficability of off-road vehicles [13]. They observed that a wheel runs on the loose ground. Moreover, the flow of the ground particles was measured using PIV. Moreover, the effects of wheel slip ratios for traveling on the loose ground was discussed. Ono et al. observed soil flow when a grouser wheel ran on the loose ground in order to evaluate the running performance of a grouser wheel [14]. In this study, cohesive and non-cohesive soils were used as the ground. The soil flow, when a grouser wheel ran, was measured using PIV. In experimental results, the soil flow was prevented when the wheel ran on the ground whose cohesive was high. Mori et al. designed an end-effector shape suitable to sample Mars soil for future planetary exploration missions [15]. They constructed a soil-tool interaction model from soil flow that was measured by PIV. Finally, the accuracy of this model was evaluated by comparing with experimental data.

In the remainder of this paper, the proposed walking method is explained in section 2. This walking method prevents the rovers from slipping on the loose ground by providing vibration. Moreover, it is suggested that increasing the supporting force by providing vibration to the ground is important for the proposed walking method. In section 3, the flow of the ground particles when a rod is dragged is measured using PIV. The experimental method, experimental results and discussion are explained. Finally, this study is summarized in section 4.

The contribution of this study is as follows:

1) The supporting force is related to the movement of the ground particles.
2) The larger the supporting force is, the larger the area that the particles move is.
3) The area that the particles move becomes large by providing vibration.

Manuscript received December 20, 2021; revised February 11, 2022. The development of the experimental system was funded by JSPS KAKENHI (Grant Number JP 21J11944).

The authors are with Shibaura Institute of Technology, Saitama city, Minuma-ku Hukasaku 307 Japan (e-mail: nb19109@shibaura-it.ac.jp; iizuka@shibaura-it.ac.jp).

DOI: 10.7763/IJET.2022.V14.1193

## II. Study Background

First, mechanism that a rover slips on the loose ground with a slope is explained. Fig. 1 shows the force that a leg of the rover provides to the ground with a slope. The leg of the rover provides the ground shear force in the downslope direction. In Fig. 1, m is weight of a leg. g is gravitational acceleration. θ is angle of ground slope. The more the angle of the slope increases, the more the shear force increases. When the ground is received the shear force, the supporting force that a leg receives from the ground changes. Fig. 2 shows the change of the supporting force. When a leg starts to move, the supporting force increases rapidly. The ground is broken when the supporting force reaches its maximum value. Finally, the supporting force converges to a constant value. Slipping of the legged rovers occurs when the shear force exceeds the maximum value of the supporting force (Fig. 3). Therefore, it is possible to prevent legged rovers from slipping on the loose ground by increasing the supporting force. In a previous study, we proposed a walking method for preventing legged rovers from slipping on the loose ground [9]. In this walking method, vibration was provided to the loose ground. By imparting vibration, the loose ground becomes hard and is difficult to be broken.

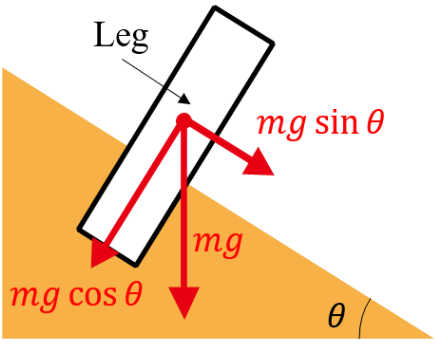

Fig. 1. Force that a leg gives to ground on a slope.

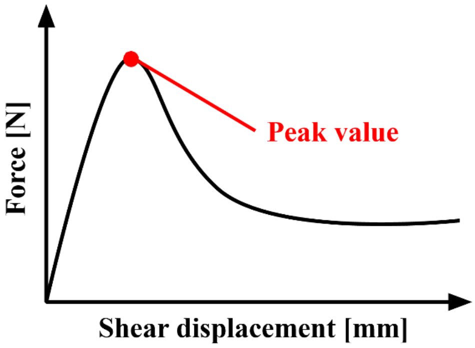

Fig. 2. Supporting force versus shear displacement.

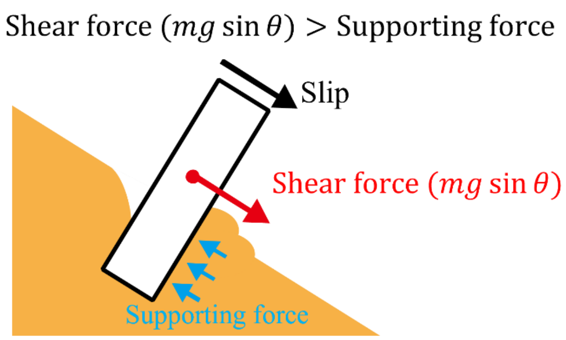

Fig. 3. Overview of leg's slip.

Secondly, the changes in the ground, when vibration is provided, are explained. The ground particles flow when vibration is provided the ground, as shown in Fig. 4. Spaces between particles exist before vibration is provided (Fig. 4 (a)). These particles are flowing by providing vibration to the ground (Fig. 4 (b)). The shear strength of the ground decreases by flowing the particles. After the vibration ceases, the ground is compacted because the spaces between the particles mostly disappear (Fig. 4 (c)). The shear strength and density are increased after the vibration is provided to the ground.

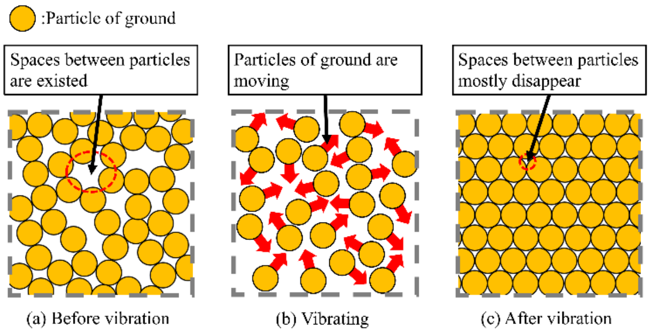

Fig. 4. Movement particles which constitute ground when vibration is provided to ground.

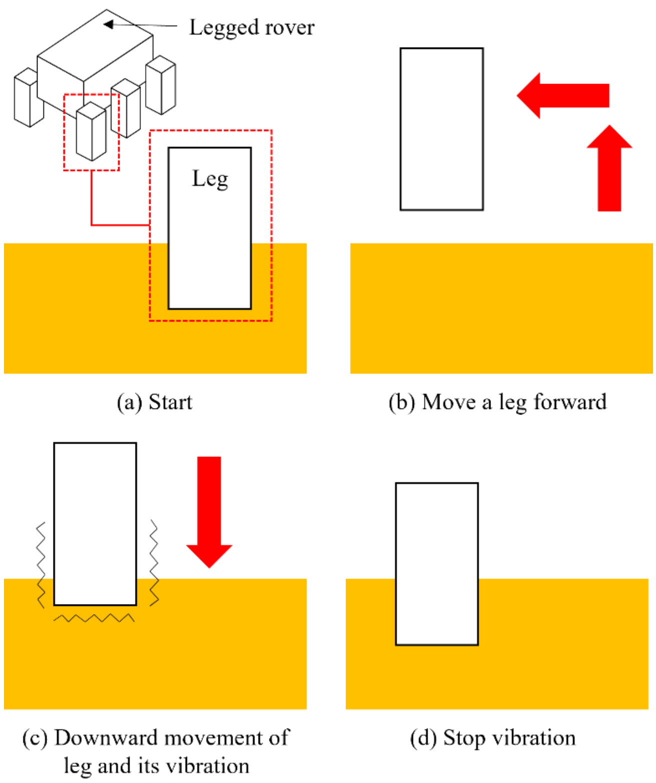

Fig. 5. Vibration timing when walking.

Next, the proposed walking method, that prevents the rovers from slipping on the loose ground by providing vibration, is explained. Fig. 5 shows the movement of the leg and the timing of vibration of the leg. First, the leg is raised and moved forward (Fig. 5 (b)). Second, the leg moves downward toward the ground and vibrates (Fig. 5 (c)). During this motion, the sinkage of the leg to the ground is increased by the flowing particles of the ground. Finally, the vibration ceases when the leg finishes sinking into the ground (Fig. 5 (d)). During this motion, the shear strength of the ground is increased by compacting the ground. In a previous study, the legged testbed walked on the loose ground with a slope using the proposed walking method [9]. As observed from the experimental results, the running performance was improved by employing the proposed walking method. Therefore, the effectiveness of the proposed walking method was confirmed.

In the proposed walking method, it is important that the supporting force is increased by providing vibration to the ground for improving the running performance of the legged rovers. Therefore, it is needed to understand the mechanism of the increase in supporting force by providing vibration. We investigate this mechanism by measuring movement of the ground particles because supporting force is related to movement of the ground particles. In this study, PIV analysis is used to measure movement of the ground particles.

## III. Measurement of Moving the Ground Particles when a Rod Is Dragged Using PIV

### A. *Experimental Methods*

Particle Image Velocimetry (PIV) is an optical method to measure flow of particles. In PIV, direction and velocity of particles are measured by analyzing some moving pictures (Fig. 6). In this experiment, the flow of the ground particles when a rod was dragged was measured using PIV.

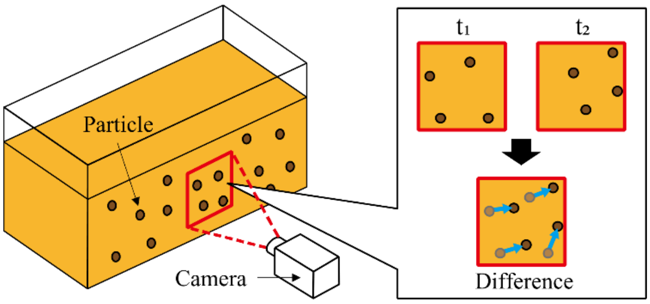


Fig. 6. System of particle image velocimetry.

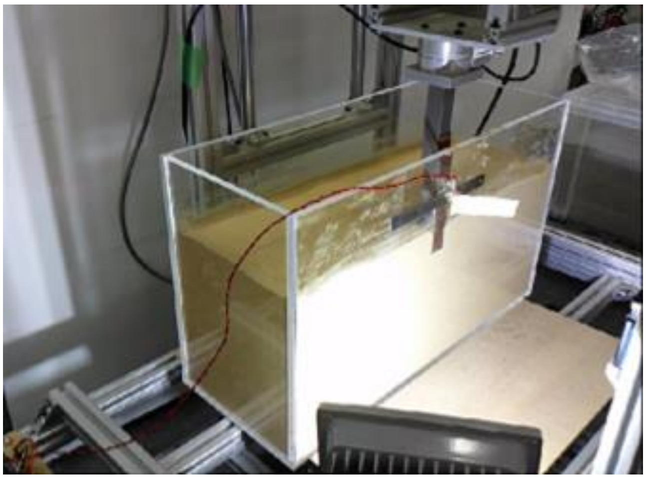

Fig. 7. Environment of PIV experiment when a rod is tracked on ground.

Fig. 7 shows the experimental setup. Moreover, the construction of the experimental setup is illustrated in Fig. 8. It consisted of a soil tank, a rod, a force sensor, and a camera. Fig. 9 shows the size of the rod. The shape of the rod was a quadrangular prism. The bottom of the rod was a square with sides of 20 mm. Vibration generator (Wave Maker05) was mounted on the experimental machine. This generator propagated vibrations to the rod. The vibratory direction was the same as the towing direction of the rod. The waveform of vibration was a sine wave. Transparent acrylic case was used as a soil tank because it is needed to observe the movement of the ground particles. Fig. 10 shows the soil tank. A ruler was attached to the soil tank in order to calculate velocity of the ground particles.

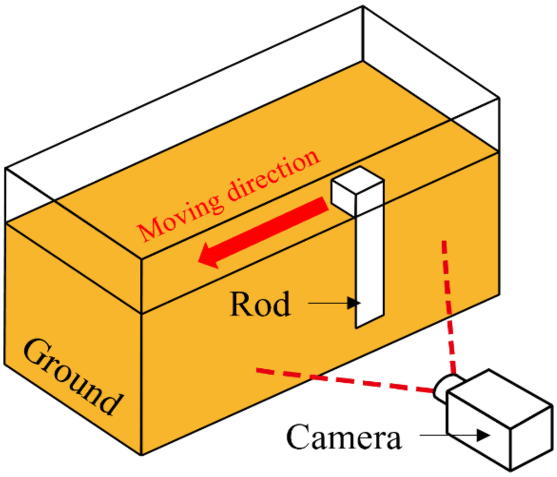


Fig. 8. Structure of PIV experiment when a rod is tracked on ground.

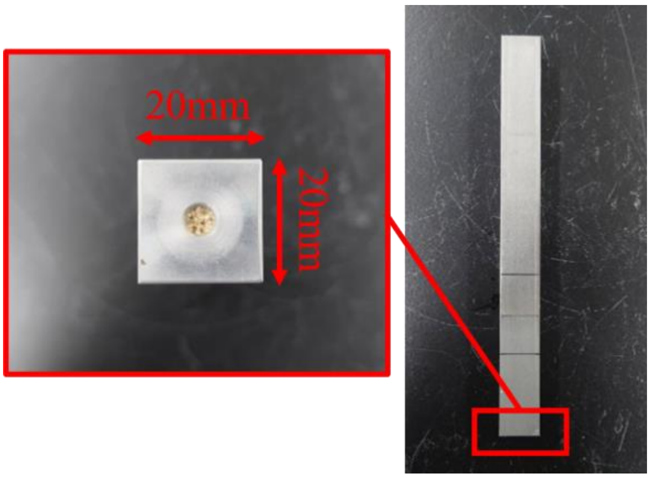


Fig. 9. Overview of a rod.

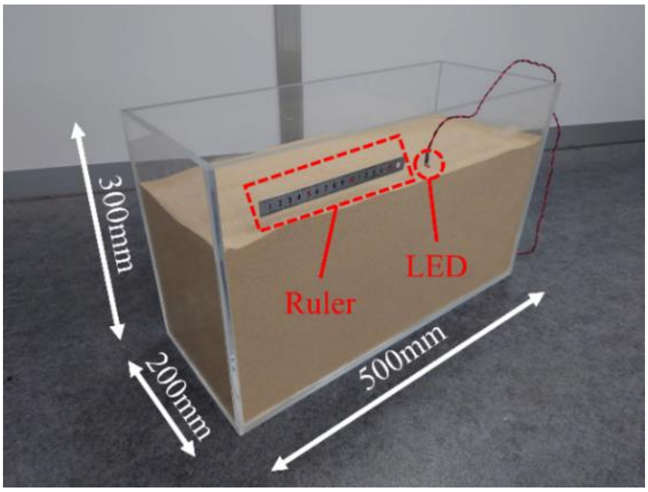


Fig. 10. Overview and structure of sand box.

The flow of the experiment is illustrated in Fig. 11. First, the ground was mixed and flattened. The rod was filled in the ground. The sinkage of the rod to the ground was 30 mm and 50 mm. Next, vibration was generated. The rod was tracked after ceasing the vibration. The force sensor received the value of the supporting force. Movement of the ground particles was taken by the camera when dragging the rod started. When dragging the rod started, a LED was turned on and taken by the camera in order to synchronize time between measured data of the supporting force and the movie of moving the ground particles. The speed of moving the rod is 0.13 mm/s. The distance, which the rod is tracked, is 13 mm. Toyoura sand was used as the sand for the ground. In this experiment, three types of vibrations were used. These vibrations differ based on the vibratory frequency. Table I shows the types of vibrations used. Vibration was generated for 200 s. The number of trials was three. Table II shows the conditions of this experiment.

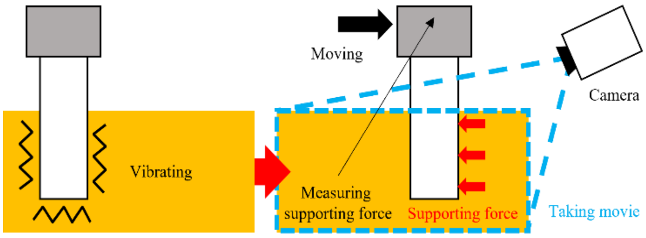


Fig. 11. Flow of PIV experiment when a rod is tracked on ground.

TABLE I: PARAMETERS TABLE OF VIBRATION

| Name | Amplitude [mm] | Frequency [Hz] |
|---|---|---|
| No vib. | 0.0 | 0 |
| Weak vib. | 0.5 | 10 |
| Middle vib. | 0.5 | 30 |
| Strong vib. | 0.5 | 50 |

TABLE II: CONDITIONS FOR PIV EXPERIMENT WHEN ROD IS TRACKED ON GROUND

| Item | Conditions (value) |
|---|---|
| Number of trial | 3 |
| Sinkage of a rod | 30 mm, 50 mm |
| Vibration time | 200 s |
| Traction speed | 0.13 mm/s |
| Traction distance | 13 mm |
| Kind of sand | Toyoura sand |

## B. *Experimental Results and Discussion*

Figs. 12-13 show the average supporting force peak value in each experimental condition. In Figs. 12-13, these graphs have maximum value and minimum value about peak value of supporting force. Figs. 14-21 show the experimental results by analyzing PIV. In Figs. 14-21, one experimental data is chosen because the results, that were obtained in the same experimental conditions, were hardly different in all trials. The upper parts of these figures show the time variation of supporting force. The lower parts of these figures show the pictures that analyzed by PIV. These pictures are shown every 10 s. In these pictures, velocity vectors are shown. The bluer color of these vectors is, the slower velocity of the ground particles is. The redder color of these vectors is, the faster velocity of the ground particles is. The range of velocity vectors is 0 mm/s to 0.1 mm/s.

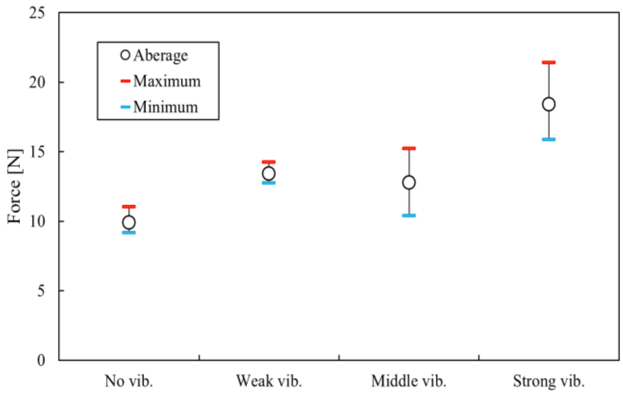


Fig. 12. Peak value of supporting force in each vib. (Sinkage of a rod: 30 mm).

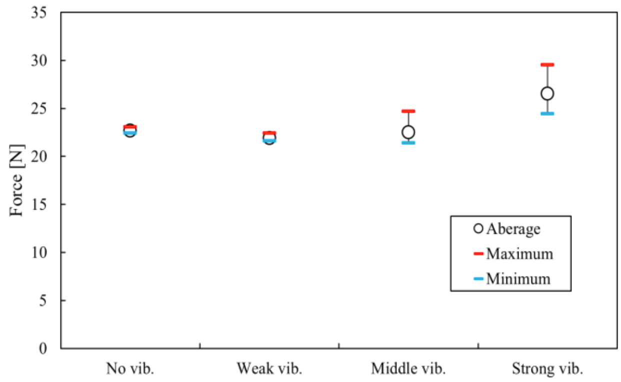


Fig. 13. Peak value of supporting force in each vib. (Sinkage of a rod: 50 mm).

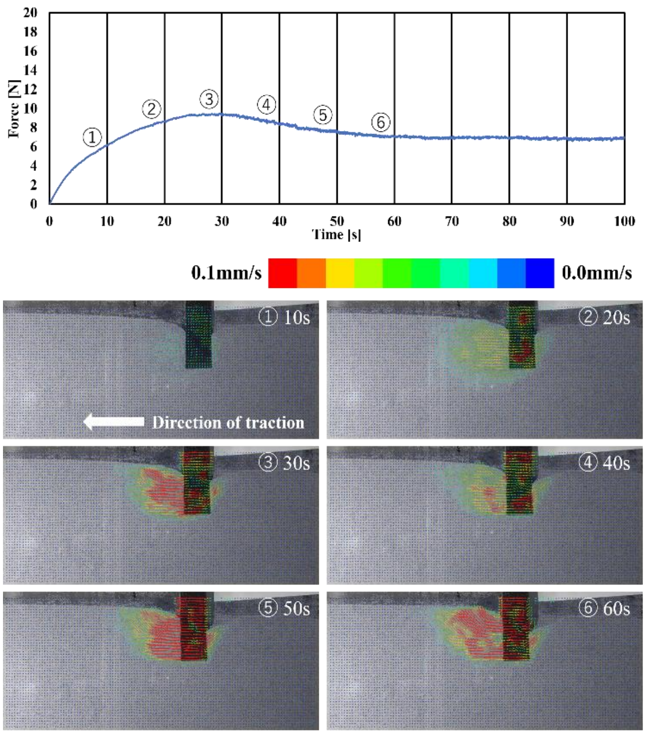


Fig. 14. Sand flow velocity vectors without vib. (Sinkage of a rod: 30 mm).

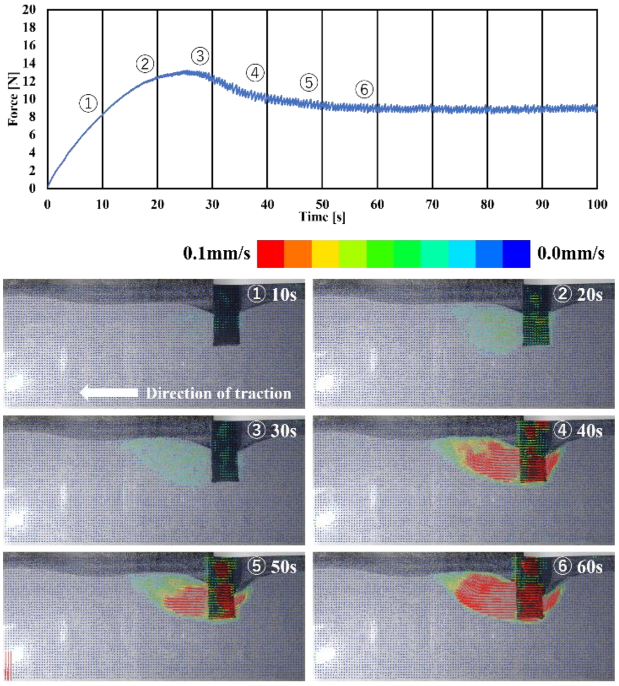


Fig. 15. Sand flow velocity vectors using weak vib. (Sinkage of a rod: 30 mm).

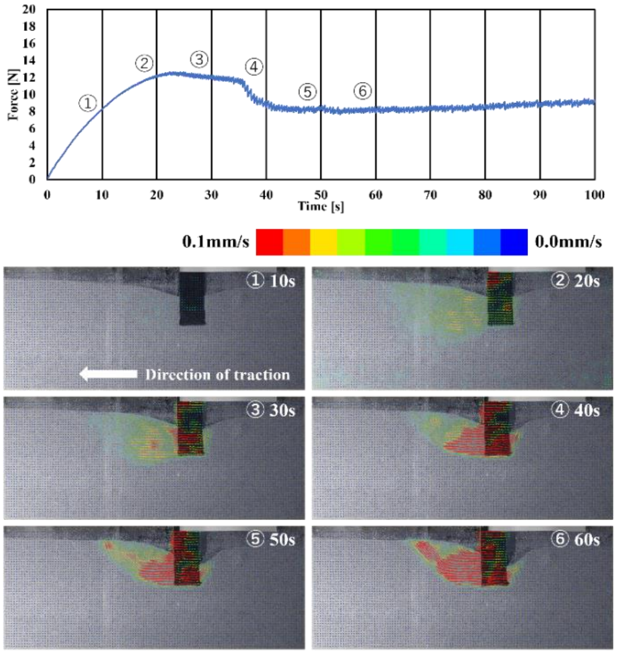


Fig. 16. Sand flow velocity vectors using middle vib. (Sinkage of a rod: 30 mm).

From experimental results, the common results in each experimental condition and the different results in each experimental condition were confirmed. First, the common results in each experimental condition are explained. The common results in each experimental condition are illustrated in Fig. 22. In figures show the pictures that analyzed by PIV, the velocity of the ground particles was slower than the velocity of the rod until supporting force reached its maximum value (Fig. 22, Compaction phase). In this situation, the ground was compressed by pushing the rod. The velocity of the ground particles was about 0.1 mm/s after supporting force reached its maximum value (Fig. 22, Collapse phase). The velocity of the particles was almost same as the velocity of the rod. In this situation, the ground was collapsed by pushing the rod. Moreover, the particles moved with the rod because these velocities were almost same. Finally, the area that the particles moved became small (Fig. 22, Convergence phase). Moreover, the shape of this area became constant. The supporting force decreased and became constant depending on changing the area that the particles moved. In the related study, when the rod is penetrated in the ground, it has confirmed that the slip line is changed by compaction condition of the ground. The slip line is the border of the area that the particles move. In the related study, it has confirmed that the larger density of the ground is, the larger the slip line is. It is considered that growing the slip line by compacting the ground is happened when the rod drags horizontally on the ground. Therefore, the slip line became small finally because the ground was plowed by moving the rod.

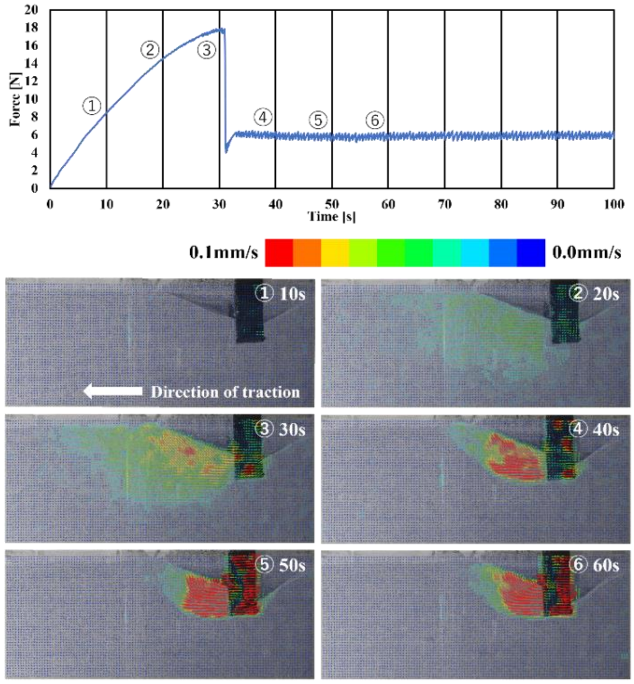


Fig. 17. Sand flow velocity vectors using strong vib. (Sinkage of a rod: 30 mm).

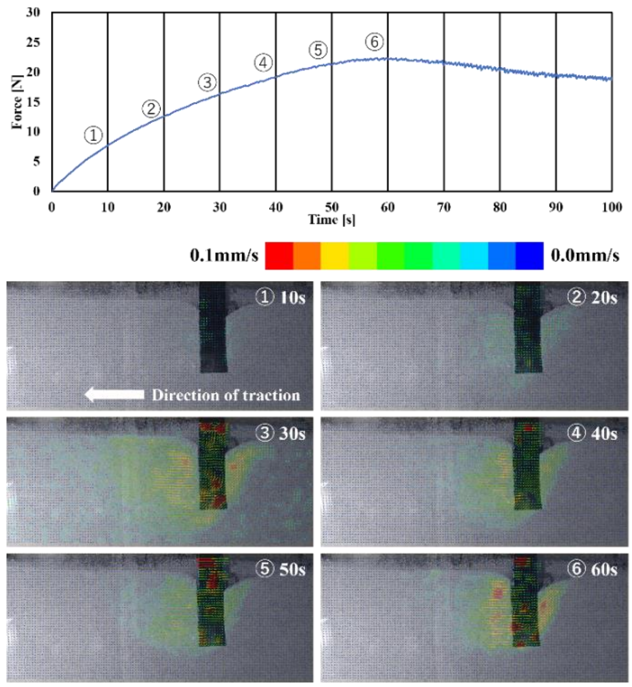


Fig. 18. Sand flow velocity vectors without vib. (Sinkage of a rod: 50 mm).

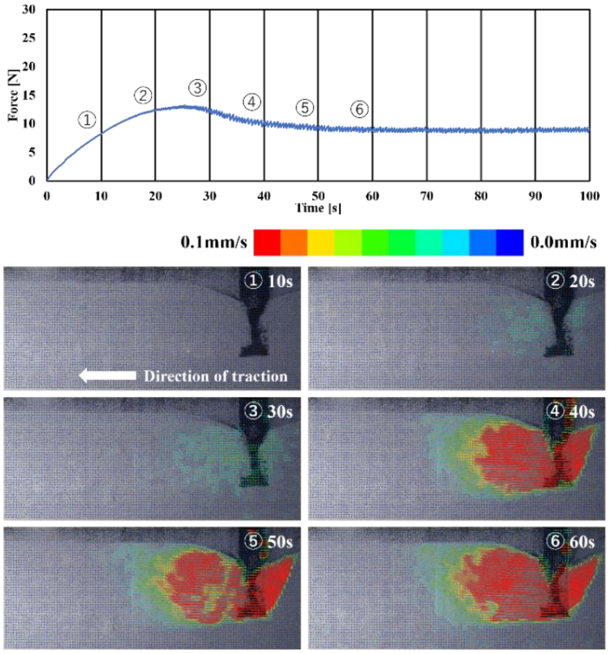


Fig. 19. Sand flow velocity vectors using weak vib. (Sinkage of a rod: 50 mm).

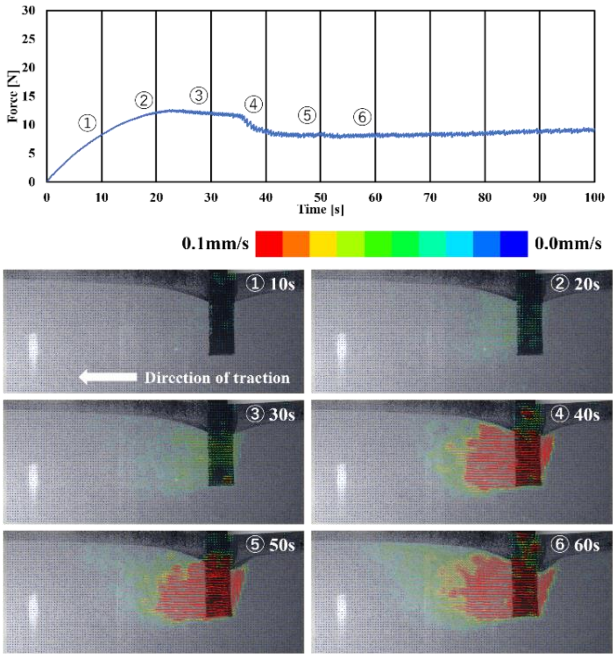


Fig. 20. Sand flow velocity vectors using middle vib. (Sinkage of a rod: 50 mm).

Secondly, the difference of experimental results in each vibration is explained. It is considered that there is a correlation between maximum value of the supporting force and the slip line that is caused when supporting force reaches its maximum value. From experimental results in the case that sinkage of the rod is 30 mm (Fig. 12), the larger vibration was provided to the ground, the larger the supporting force was. In Fig. 12, the supporting force using weak vib. increased by about 36 % compared with one using no vib.. The supporting force using middle vib. increased by about 29 % compared with one using no vib.. The supporting force using strong vib. increased by about 86 % compared with one using no vib.. As shown in Figs. 14-17, the larger vibration was provided to the ground, the larger the slip line was too. From experimental results in the case that sinkage of the rod is 50 mm (Fig. 13), the supporting force in case of using the strong vib. was biggest. The values of each the supporting force in case of other experimental conditions were almost same. In Fig. 13, the supporting force using weak vib. decreased by about 3 % compared with one using no vib.. The supporting force using middle vib. decreased by about 1 % compared with one using no vib.. The supporting force using strong vib. increased by about 17 % compared with one using no vib.. As shown in Figs. 18-21, the slip line in case of using the strong vibration was biggest too. The reason is considered that density is increased in a wide range of the ground when the vibration whose frequency is high is provided. In the related study, it has confirmed that form of slip line is changed by value of the ground density when the rod is penetrated in the ground. Fig. 23 shows form of slip line in each condition of the ground density. General shear failure is seen in dense and stiff ground (Fig. 23 (a)). Slip line in this failure is largest of any one. In this failure, the normal force intensity increases rapidly with low settlement up to the point of failure. Local shear failure is seen in relatively loose and soft ground (Fig. 23 (b)). In this failure, normal force increases rapidly with increase in the settlement. Finally, normal force converges. Punching failure is seen in loose ground and clays (Fig. 23 (c)). Slip line in this failure is smallest of any one. In this failure, normal force increases rapidly with increase in the settlement. Finally, normal force converges. Peak value of normal force in punching failure is smaller than one in local shear failure. In Fig. 23, the larger density of the ground is, the larger the slip line and normal force are. It is considered that form of the slip line and supporting force are changed by changing value of ground density when the rod drags horizontally on the ground. Therefore, the slip line and supporting force became large when vibration is provided to the ground because density of the ground is increased by providing vibration.

As observed from the experimental result, a correlation between the supporting force and slip line was confirmed. Therefore, the supporting force is increased by providing vibration to the ground because the slip line grows.

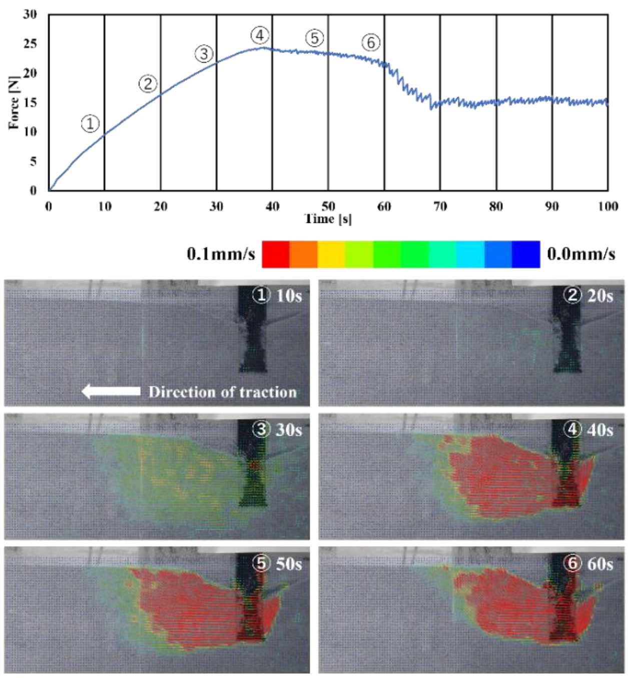


Fig. 21. Sand flow velocity vectors using strong vib. (Sinkage of a rod: 50 mm).

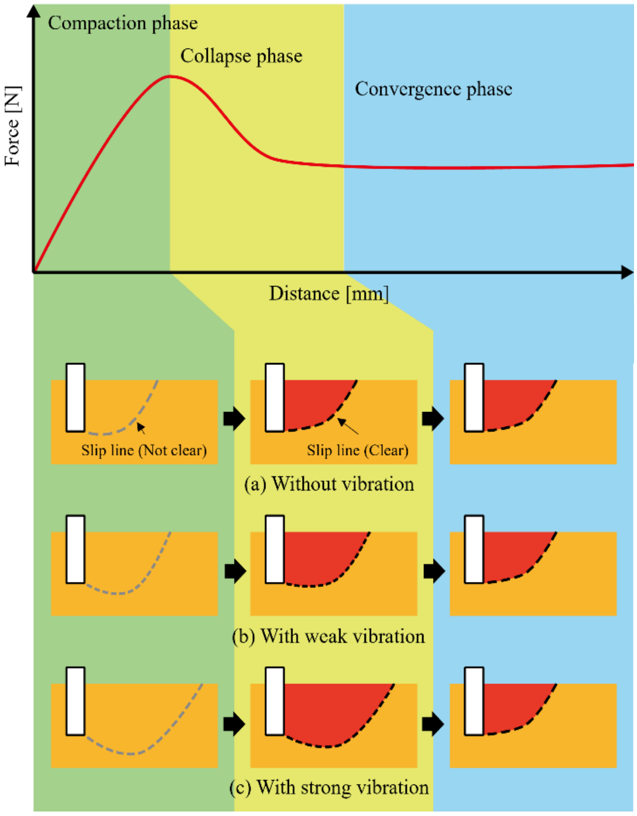


Fig. 22. Conceptual diagram of sand flow velocity vectors.

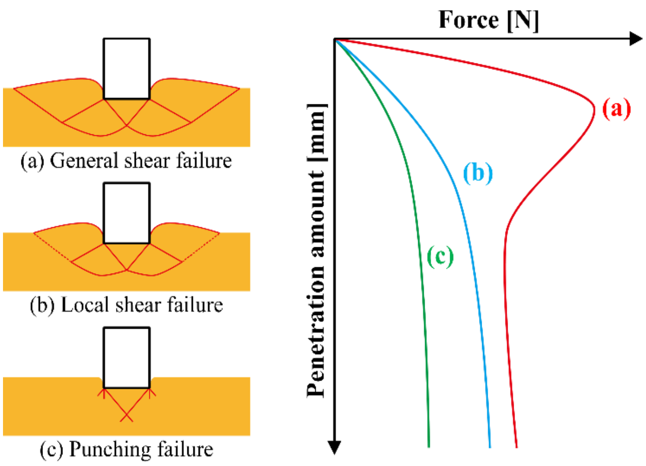


Fig. 23. Case of shear failures when a rod is penetrated in the ground.

## IV. Conclusion

In this study, the flow of the ground particles, when a rod was dragged, was measured using PIV for improving the proposed walking method that prevents the rovers from slipping on the loose ground by providing vibration. The contribution of this study is explained. Firstly, the ground was compressed by pushing the rod when the rod is tracked on the ground. Secondly, the ground was collapsed by pushing the rod. Finally, the area that the particles moved became small. The larger the supporting force was, the larger the area that the particles moved was. Therefore, the supporting force is related to the movement of the ground particles. The area, that the particles moved, became large by providing vibration whose frequency was high. The reason is considered that density is increased in a wide range of the ground by providing the vibration whose frequency is high. The supporting force is increased by providing vibration to the ground because the slip line grows.

In future studies, a model that estimates the supporting force will be developed. In this model, the growth of the area, that the particles move, will be reproduced.

## Conflict of Interest

The authors declare no conflict of interest.

## Author Contributions

Tomohiro Watanabe wrote the manuscript as the corresponding author. Moreover, he developed the experimental setup and performed the experiments. The entire work was supervised by Kojiro Iizuka. All authors had approved the final version.

## References

[1] JAXA. (January 19, 2022). International space exploration. [Online]. Available: https://www.exploration.jaxa.jp/e/program/#slim

[2] NASA. (January 19, 2022). Gateway. [Online]. Available: https://www.nasa.gov/gateway

[3] H. Ueno, "State of art for planetary robotics on space agencies," *Journal of the Robotics Society of Japan*, vol. 32, no. 5, pp. 431-434, April 2014.

[4] S. Chhaniyara, C. Brunskill, B. Yeomans, M. C. Matthews, C. Saaj, S. Ransom, and L. Richter, "Terrain trafficability analysis and soil mechanical property identification for planetary rovers: A survey," *Journal of Terramechanics*, vol. 49, no. 2, pp. 115-128, April 2012.

[5] M. I. Malenkov, "Creation of Lunokhod-1 as an outstanding scientific and technological achievement of the XX century," *Solar System Research*, vol. 47, pp. 610-617, November 2013.

[6] B. Yeomans and C. M. Saaj, "Towards terrain interaction prediction for bioinspired planetary exploration rovers," *Bioinspiration & Biomimetics*, vol. 9, no. 1, pp. 1-15, January 2014.

[7] B. Yeomans, C. M. Saaj, and M. V. Winnendae, "Walking planetary rovers – Experimental analysis and modelling of leg thrust in loose granular soils," *Journal of Terramechanics*, vol. 50, no. 2, pp. 107-120, April 2013.

[8] B. H. Wilcom, "ATHLETE: A cargo and habitat transporter for the moon," in *Proc. IEEE Aerospace Conference*, March 2009.

[9] T. Watanabe and K. Iizuka, "Proposal of walking to reduce slipping behavior using compaction effect of loose soil caused by a propagation of vibration for small light lunar planetary exploration rovers with legs," *Journal of the Society of Mechanical Engineers*, vol. 86, no. 886, June 2020.

[10] T. Watanabe and K. Iizuka, "Study on connection between kind of vibration and influence of ground for leg typed rovers," *International Journal of Mechanical Engineering and Robotics Research*, vol. 9, no. 7, pp. 976-989, July 2020.

[11] T. Watanabe and K. Iizuka, "Experimental Investigation of The Relationship between Frequency of Vibration and Increasing Passive Earth Pressure," in *Proc. ROBOMECH 2021 in Osaka*, June 2021.

[12] A. S. Alqarawi, C. J. Leo, D. S. Liyanapathirana, L. Sigdel, M. Lu, and P. Hu, "A spreadsheet-based technique to calculate the passive soil pressure based on the log-spiral method," *Computers and Geotechnics*, vol. 130, February 2021.

[13] J. Yamakawa, M. Goto, and R. Eto, "Analysis of traveling wheel on loose sandy soil (Sandy soil flow beneath a wheel due to the interaction)," *Journal of the Society of Mechanical Engineers*, vol. 83, no. 852, April 2017.

[14] S. Ono, S. Namikawa, and K. Yoshida, "Analysis of soil flow and traction mechanics for lunar rovers over different types of soils using particle image velocimetry," *Journal of Terramechanics*, vol. 95, pp. 89-100, June 2021.

[15] D. Mori and G. Ishigami, "Excavation model of soil sampling device based on particle image velocimetry," *Journal of Terramechanics*, vol. 62, pp. 19-29, December 2015.

**Tomohiro Watanabe** was born in 31 August 1994, Tothigi, Japan. Mr. Tomohiro received his bachelor's degree in Engineering from Shinshu University in 2017. He received his master's degree in Engineering from Shibaura Institute of Technology in 2019. At the present, he is studying in doctoral course of Functional Control Systems, Shibaura Institute of Technology.

He works as JSPS Research Fellow in Shibaura Institute of Technology.

His research interest is in the area of terramechannics and robotics.

**Kojiro Iizuka** received his doctor's degree in Engineering from the Graduate University for Advanced Studies in 2006.

He is attached with the Department of Systems Engineering and Science as a Professor at Shibaura Institute of Technology. Previously he was attached with Department of Mechanical Engineering and Robotics at Shinshu University for 8 years.

His teaching and research interest is in the areas of terramechannics and robotics.