Study on Connection between Kind of Vibration and Influence of Ground for Leg Typed Rovers

Tomohiro Watanabe
Graduate School of Engineering and Science, Shibaura Institute of Technology, Saitama City, Japan
Email: nb19109@shibaura-it.ac.jp

Kojiro Iizuka
Department of Systems and Engineering and Science, Shibaura Institute of Technology, Saitama City, Japan
Email: iizuka@shibaura-it.ac.jp

***Abstract*— Surveys of the moon and Mars are important missions in space exploration. The rovers which are exploration robots moving on the ground work in these exploration missions. They achieved significant results in these missions. In recent years, the leg typed rovers are focused on as an exploring rover with high running performance. However, it is difficult to walk on the loose ground for the leg typed rovers. The surface of the loose ground is easy to destroy at motion of its legs. Destroying behavior at motion of the leg which is contacting on the surface means that the rovers are easy to occur slip. We previously proposed the walking method which reduces slip distance on the loose ground for leg typed rover. Our study group considered that traction of the leg typed rovers is passive earth pressure given to the leg. Proposed walking method is used changes of the ground when giving vibration. Passive earth pressure given to the leg is increased by changes of the ground when giving vibration. Furthermore, some experiments using a testbed to walk on the loose ground were carried out. In experimental results, the displacement of proposed walking with vibration became long compared with the one without vibration. From previous experimental results, we could get knowledge that the method using vibration was very effective for the leg typed rovers. However, the relationship between the parameters of vibration and the influence of the ground is not still understood. Vibration has the parameters of frequency, amplitude and acceleration. It is considered that influence of the ground when giving vibration is changed by changing the parameters of vibration. If this relationship is understood, suitable vibration can be selected for the proposed walking method. In this study, the effects which are given by vibration to the ground are confirmed from experiment using a few kinds of vibration. Measurement contents are density of ground and passive earth pressure. Vibration parameter to change are frequency, amplitude and acceleration. In experimental results, as these parameters of vibration were large, density of ground and passive earth pressure were increased.**

***Index Terms*—loose soil, vibration, terramechannics, leg typed robot, passive earth pressure**

I. Introduction

Surveys of the moon and Mars are important missions in space exploration. Knowing the atmosphere and internal structure of them makes it possible to elucidate the origin of the solar system. In addition, if traces of water and organic matter are discovered, they lead to the discovery of life. The rovers which are exploration robots moving on the ground work in these exploration missions. They achieved significant results in these missions [1][2]. The rovers which were used in these exploration missions are vehicle typed robots with wheels [3]. However, these rovers have the problem of low movement performance on the rough terrain and the loose ground [4]. Some rovers with moving mechanism except wheels are developed in order to improve the movement performance. In recent years, the rovers with leg mechanism are focused on as an exploration rover with high movement performance [5][6][7]. The leg typed rovers have high movement performance on the rough terrain consisted of steps and rocks. However, the leg typed rovers must move not only on steps and rocks but also on the loose ground. The grounds of Mars and the moon are covered with loose soil called regolith. So, study of walking on the loose ground is important for development of the leg typed rovers. The surface of the loose ground is easy to destroy at motion of its legs. Destroying behavior at motion of leg which is contacting on the surface means that the rovers are easy to occur slip. Therefore, the leg typed rovers must mount the methods to reduce slip distance on the loose ground.

We previously proposed walking method which prevents from slip on the loose ground for leg typed rover [8][9][10]. Our study group considered that traction of the leg typed rovers is passive earth pressure given to the leg. Proposed walking method is used changes of the ground when giving vibration. Passive earth pressure given to the leg is increased by changes of the ground when giving vibration. The changes of the ground when giving vibration are two points. First point is increasing density of the ground by giving vibration. Density of the ground is increased when giving vibration to the ground because the ground is compacted by vibration. By increasing

Manuscript received September 4, 2019; revised April 1, 2020.

doi: 10.18178/ijmerr.9.7.979-986

density of the ground, the ground becomes hard to collapse. Second point is increasing sinkage of the leg to the ground. Shear strength of the ground is decreased because particles of the ground move when giving vibration to the ground. Subsidence of the leg is increased by decreasing shear strength of the ground. In Rankin's passive earth pressure, as density of the ground and subsidence of the leg to the ground are increased, passive earth pressure is increased. These changes of the ground when giving vibration were confirmed from experimental results of previous study [10]. Furthermore, some experiments using a testbed to walk on the loose ground were carried out. In experimental results, the displacement of proposed walking with vibration became long compared with the one without vibration. From previous experimental results, we could get knowledge that the method using vibration was very effective for the leg typed rovers.

However, the relationship between the parameters of vibration and the influence of the ground is not still understood. Vibration has the parameters of frequency, amplitude and acceleration. It is considered that influence of the ground when giving vibration is changed by changing the parameters of vibration. If this relationship is understood, suitable vibration can be selected for the proposed walking method. In this study, the influence which are given by vibration to the ground are confirmed from experiment whose parameters of vibration are changed. Measurement contents are density of ground and passive earth pressure. Parameters of vibration to change are frequency, amplitude and acceleration.

II. Walking Method Used Vibration

In this chapter, mechanism of walking method used vibration which is proposed by our study group is explained. In addition, how to use changes of the ground when giving vibration in proposed walking method is explained. Moreover, we choose changes of the ground when giving vibration to confirm in the experiment whose parameters of vibration are changed.

Fig. 1 shows the force that the leg of the rover gives to the ground on the slope. On the slope, the leg of the rover gives the ground shear force in down slope direction. As angle of slope is increased, shear force given to the ground is increased. Passive earth pressure is force just before the ground is broken when pushing ground. Passive earth pressure is shown in Fig. 2. If force that the leg gives to the ground does not exceed passive earth pressure when the leg typed rover walks, the leg typed rover can walk without slip. Therefore, the method to increase passive earth pressure was proposed to reduce slip distance. Passive earth pressure model is explained. In this study, Rankin's theory of passive earth pressure is used. Rankin's passive earth pressure is expressed by Equation (1) [11]. Additionally, illustration of passive earth pressure is shown in Fig. 3.

$$P = \frac{1}{2} r H^2 \tan^2\left(45^\circ + \frac{\varphi}{2}\right) \tag{1}$$

H is subsidence of the leg to the ground. φ is angle of internal friction. r is unit volume weight of the ground and calculated from Equation (2).

$$r = \rho g \tag{2}$$

ρ is density of ground. g is gravitational acceleration. In Equation (1) and Equation (2), As density of the ground is increased, passive earth pressure is increased. Density of ground is increased when giving vibration to ground because the ground is compacted by vibration. In previous study, the method to increase density of ground using vibration was proposed. Therefore, slip distance of leg typed rover is reduced because passive earth pressure is increased by increasing density of ground.

Next, mechanism of walking method used vibration is explained in detail. Fig. 4 shows timing to vibrate the leg. First, the leg raises and moves forward, as shown in Fig. 4 (a). Next, the leg is vibrating when the leg is lowering, as shown in Fig. 4 (b). Finally, vibration stops when the leg finished lowering, as shown in Fig. 4 (c). This motion makes that density of the ground and passive earth pressure are increased. Actually, increasing density of the ground and passive earth pressure is confirmed by giving and stopping vibration in previous study [10].

Therefore, changes density of the ground and passive earth pressure by giving and stopping vibration are important for proposed walking method used vibration. In this study, changes density of the ground and passive earth pressure are confirmed from experiment whose parameters of vibration are changed.

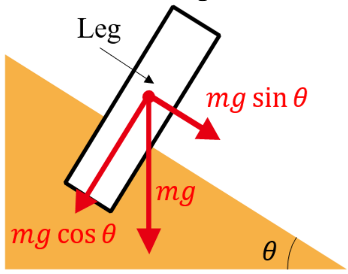

Figure 1. Force that leg gives to ground on slope

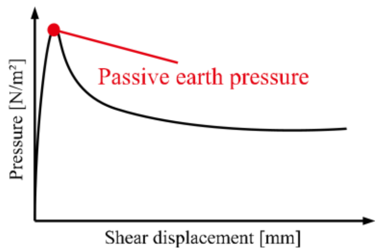

Figure 2. Pressure vs shear displacement

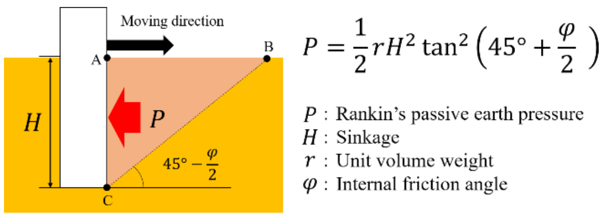

Figure 3. Rankin's passive earth pressure model

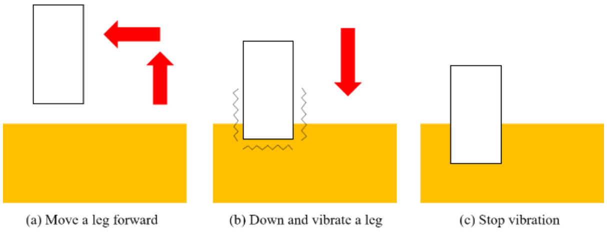

Figure 4. Vibration timing when walking

III. Measurement of Density When Giving Vibration to Groun

In this chapter, the experimental method and the result of density measurement experiment are reported. Measuring method of density is explained. Fig. 5 shows the graph about shear displacement vs shear strength in shear test. The graph like Fig. 5 is shown when single shear test or vane shear test are carried out [12] [13]. Value of this peak is changed by condition of the ground density. Value of the peak is high when density of the ground is high. On the other hand, value of the peak is low when density of the ground is low. Therefore, as density of the ground is increased, value of the peak is high.

In this experiment, a relationship between density of the ground and value of the peak in shear test is confirmed at first. Next, density of the ground is measured by measuring value of the peak using vane shear tester when vibration gives to the ground. This experiment is carried out using some vibrations which are different in frequency and amplitude to confirm a relationship between parameter of vibration and the influence of the ground.

A. Confirming a Relationship between Density of the Ground and Value of the Peak in Shear Test

In this section, a relationship between density of the ground and value of the peak in vane shear test is confirmed by the measuring experiment. Content of this measuring experiment and the result are reported.

In this measuring experiment, condition of the ground with different density is prepared. Moreover, value of the peak is measured using vane shear tester in the ground with different density. How to change density of the ground is referred by test method for minimum and maximum densities of sands [14]. Fig. 6 shows these tools using in this measuring experiment. These tools are mold, hammer and knife. First, the mold is entered the sand. The sand is Silica No. 5. The sand which enters the mold is divided into ten equal parts. Side of the mold is hit using hammer from various directions every time part of the sand enters the mold. Next, the knife is set on top of the mold. The sand that protrudes from the mold is removed by the knife. Finally, vane shear tester is filled 2cm in the ground and measures value of the peak. Measurement point is center of the mold. Number of hits is changed to change density of the ground. These numbers of hits every time part of the sand enters the mold are 100 times, 20 times, 10 times, 8 times, 6 times, 4 times, 2 times and 0 times. The number of trials is 10 times. The measuring experiment when number of hit is 0 times is referred by test method for minimum density of sand and uses the funnel to enter the sand in the mold.

Fig. 7 shows the result of the measuring experiment. The graph of Fig. 7 shows plot between density of the ground and value of the peak and the linear approximation which is calculated by least squares. The linear approximation is expressed by Equation (3).

$$\rho = 0.16\sigma + 1.34 \tag{3}$$

ρ[g/cm³] is density of the ground. σ[cN・m] is value of the peak in vane shear test. The correlation coefficient of this linear approximation is 0.91. Therefore, high correlation was confirmed. In this result, it was confirmed that a relationship between density of the ground and value of the peak in vane shear test is linear.

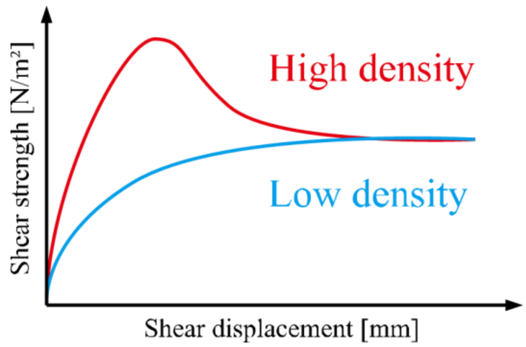

Figure 5. Shear displacement vs shear strength

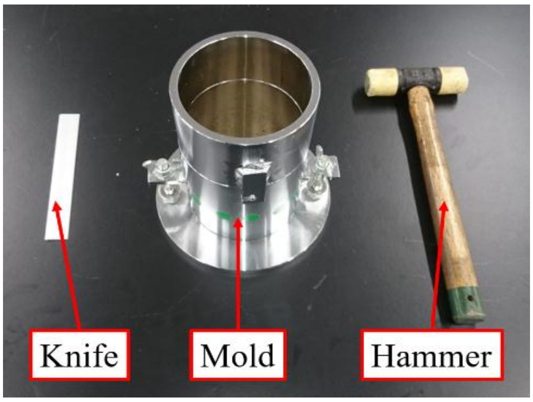

Figure 6. Overview of using experiment tools

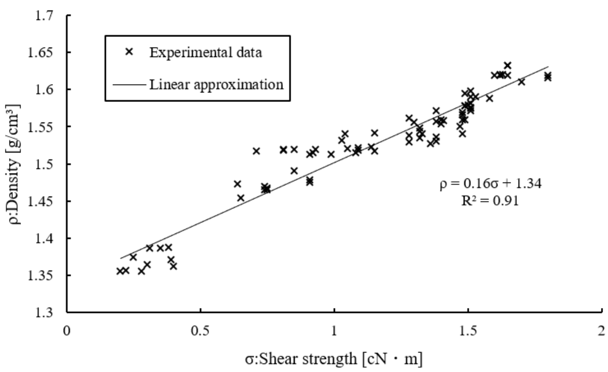

Figure 7. Value of peak in vane sure test vs density of ground

B. Measuring Density Experiment

Flow of experiment is explained. Fig. 8 shows environment of measuring density experiment. Environment of this experiment is consisted of the ground, the rod, the vibration generator and the vane shear tester. First, the ground is mixed and flattened. The rod is filled 5cm in the ground. Fig. 9 shows size of the rod. Next, the vibration generator vibrates for 30 seconds. The vibrations are 5 kinds. These vibrations are different in frequency and amplitude. Table I shows kinds of using vibration. Finally, vane shear tester is filled 2cm in the ground and measures peak value of shear strength. Measurements are done after stopping vibration. The number of trials is 30 times. Fig. 10 shows measurement point. Table II shows condition of this experiment.

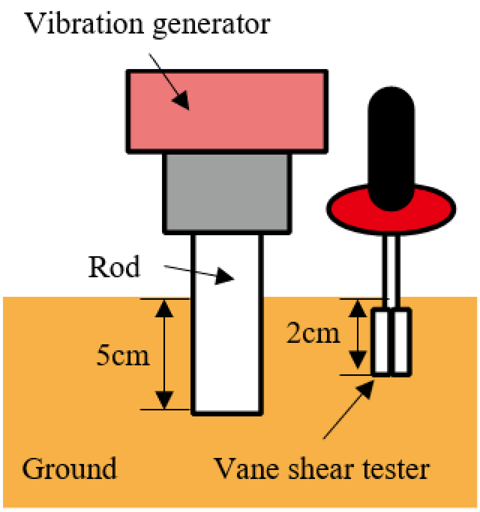

Figure 8. Environment of measuring density experiment

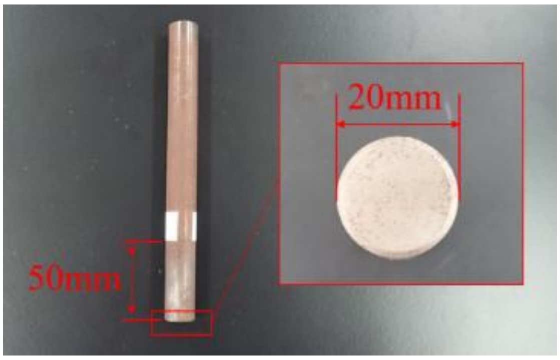

Figure 9. Overview of rod

TABLE I. PARAMETERS TABLE OF VIBRATION

Number	Frequency	Amplitude
No.1 (No vibration)	0Hz	0mm
No.2	10Hz	1mm
No.3	30Hz	1mm
No.4	50Hz	1mm
No.5	30Hz	2mm
No.6	30Hz	3mm

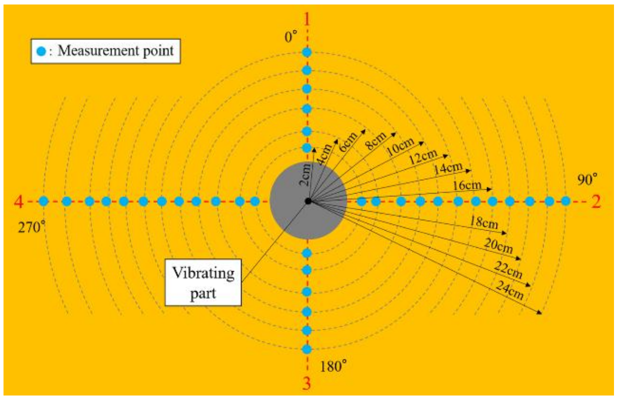

Figure 10. Measurement point of density

TABLE II. CONDITION OF MEASURING DENSITY EXPERIMENT

Item	Condition (value)
Number of trials	30
Measurement contents	Measuring density
Kind of sand	Silica No.5

C. Results and Discussion

Fig. 11 and Fig. 12 show peak value of shear strength in row 2 because similar results were obtained in the 4 lows of Fig. 10. Fig. 11 shows peak value of shear strength using vibrations which different in frequency and the same as amplitude. In Fig. 11, as frequency of vibration is high, peak value is increased. Fig. 12 shows peak value of shear strength using vibrations which different in amplitude the same as frequency. In Fig. 12, as amplitude of vibration is high, peak value is increased.

Peak value of shear strength arranged in acceleration of vibration. Acceleration of vibration is calculated from Equation (4).

$$A = (2\pi f)^2 D \tag{4}$$

A is acceleration of vibration. f is frequency. D is amplitude. Fig. 13 shows peak value of shear strength using all vibrations. In Fig. 13, as acceleration of vibration is high, peak value is increased. In Equation (4), as frequency and amplitude of the vibration are increased, acceleration is increased. Therefore, increasing peak value of shear strength by increasing acceleration because acceleration is increased by increasing frequency and amplitude. However, only peak value of shear strength using vibration (frequency: 50Hz, amplitude: 1mm, acceleration: 98.60m/s^2) was lower than one using vibration(frequency: 30Hz, amplitude: 2mm, acceleration: 70.99m/s^2).

As this experimental result, the ground is affected by vibration in all direction because increasing of peak value was occurred at each angle. Moreover, as the measurement point was away from the vibration generator, as peak value was decreased. As parameters of vibration (frequency, amplitude and acceleration) were large, as distance which is propagated vibration was long.

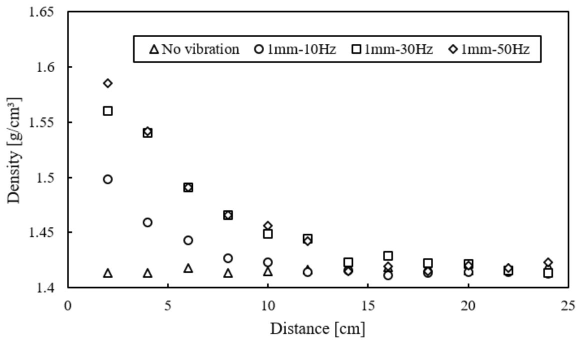

Figure 11. Distance vs density on line 2 (Comparison: Freq.)

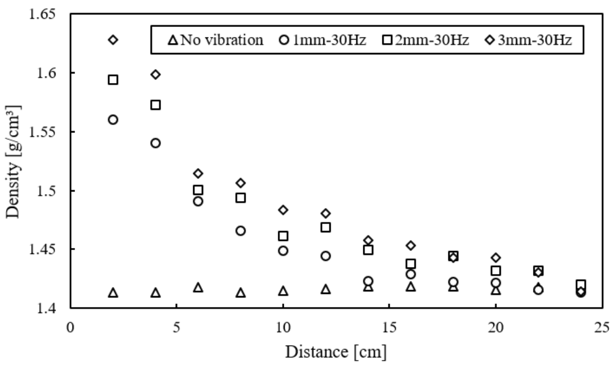

Figure 12. Distance vs density on line 2 (Comparison: Amp.)

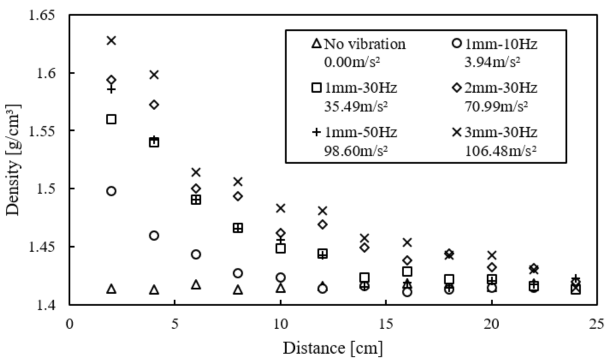

Figure 13. Distance vs density on line 2 (Comparison: Acc.)

IV. Measurement of Passive Earth Pressure

The traction experiment is conducted to confirm relationship between the parameters of vibration and the value of passive earth pressure. In this chapter, the experimental method and the result of traction experiment are reported.

A. Traction Experiment

Fig. 14 shows environment of traction experiment. Environment of this experiment is consisted of the ground and the leg part. Fig. 15 shows overview of the leg part. The leg part is consisted of the rod, the force sensor and the vibration generator. The shape of the rod is the same as the rod shown in Fig. 9. Next, flow of this experiment is explained. First, the ground is mixed and flattened. The rod is filled 5cm in the ground. Next, the vibration generator vibrates for 30 seconds. The vibrations are 5 kinds. The vibrations is the same as the vibrations shown in Table I. The rod is tracked after stopping vibration. The force sensor receives value of passive earth pressure. Speed of moving the rod is 0.13mm/s. The number of trials is 30 times. Fig. 16 shows flow of this experiment. Table III shows condition of this experiment.

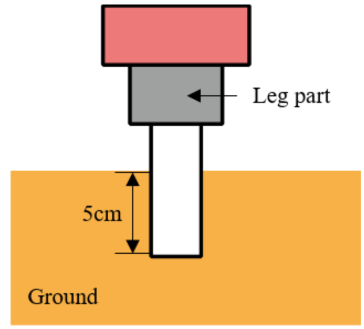

Figure 14. Environment of traction experiment

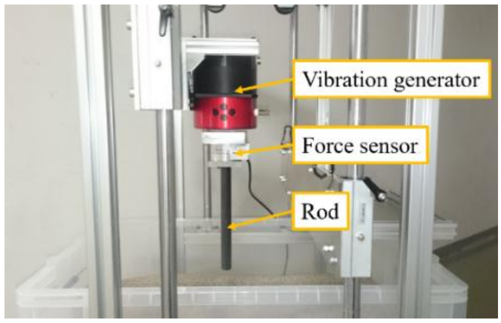

Figure 15. Overview of leg part

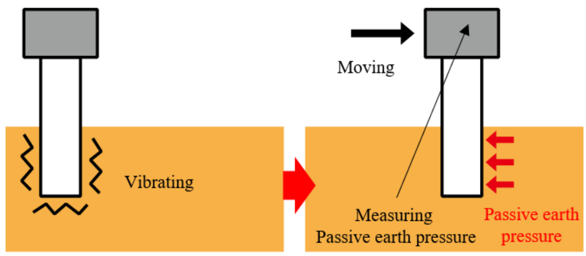

Figure 16. Flow of traction experiment

TABLE III. Condition of Traction Experiment

Item	Condition (value)
Number of trials	30
Measurement contents	Measuring passive earth pressure
Sinkage of rod to ground	5 cm
Vibration time	30 s
Traction speed	0.13 mm/s
Traction time	500 s
Kind of sand	Silica No.5

B. Results and Discussion

Fig. 17 to Fig. 22 show the graph about distance vs traction force. In these graphs, peak was seen at the start of towing. Moreover, the force that the rod receives from the ground finally became steady. The value of this peak is force just before the ground slips and related to passive earth pressure. The value of peak differs depending on kind of vibration.

Fig. 23 shows graph comparing passive earth pressure at vibrations which is different in frequency and the same as amplitude. From Fig. 23, as frequency of vibration was high, passive earth pressure was increased. Fig. 24 shows graph comparing passive earth pressure at vibrations which is different in amplitude and the same as frequency. From Fig. 24, as amplitude of vibration was high, passive earth pressure was increased.

In Fig. 25, passive earth pressure arranged in acceleration of vibration. In Fig. 25, as acceleration of vibration was high, passive earth pressure was increased. However, only passive earth pressure using vibration(frequency: 50Hz, amplitude: 1mm, acceleration: $98.60m/s^2$) was lower than one using vibration(frequency: 30Hz, amplitude: 2mm, acceleration: $70.99m/s^2$). In this result, relationship between the acceleration of vibration and the value of passive earth pressure correspond with relationship between the acceleration of vibration and the value of density.

Increasing passive earth pressure is high when acceleration of vibration is low. However, as acceleration of vibration is increased, increasing passive earth pressure is reduced. Therefore, it is expected that increasing passive earth pressure finally become steady. In Rankin’s passive earth pressure model, passive earth pressure is obtained from triangle surrounded by point A, B and C in Fig. 3. Therefore, it is considered that increasing passive earth pressure stops when propagation of vibration exceeds triangle surrounded by point A, B and C. Moreover, increasing density of ground has limit because value of density can’t exceed maximum density. From above, it is considered that increasing passive earth pressure by giving vibration has limit. Moreover, it is predicted that suitable vibration to increase passive earth pressure can be existed.

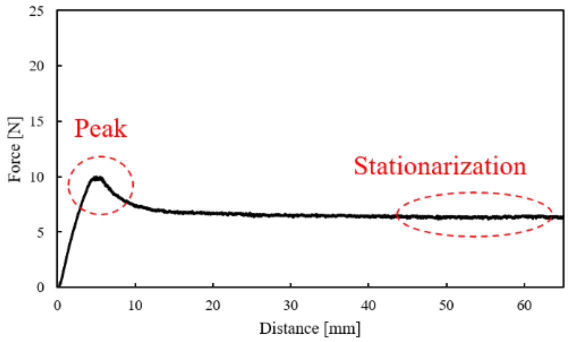

Figure 17. Distance vs traction force (No vibration)

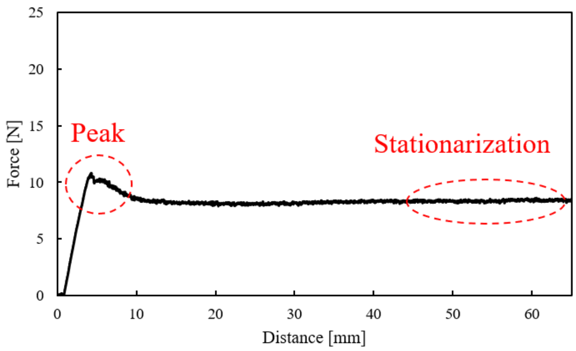

Figure 18. Distance vs traction force (Freq. : 10Hz, Amp. : 1mm)

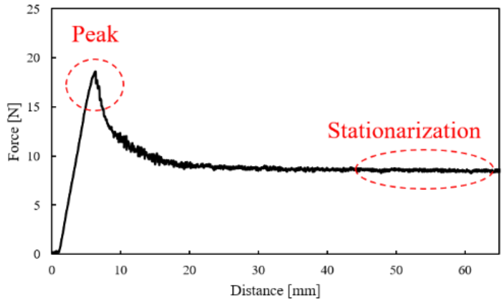

Figure 19. Distance vs traction force (Freq. : 30Hz, Amp. : 1mm)

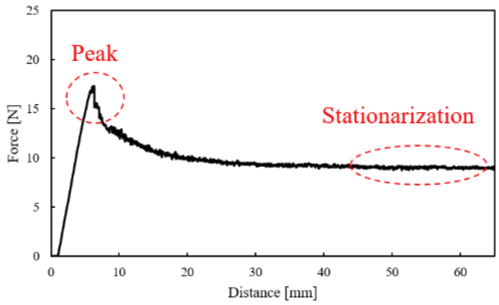

Figure 20. Distance vs traction force (Freq. : 50Hz, Amp. : 1mm)

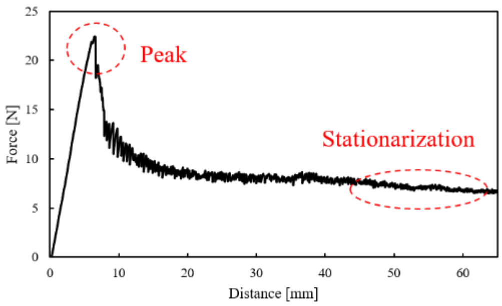

Figure 21. Distance vs traction force (Freq. : 30Hz, Amp. : 2mm)

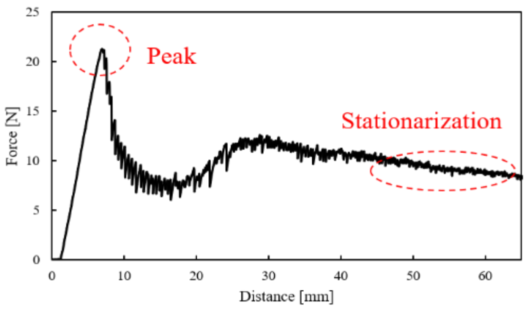

Figure 22. Distance vs traction force (Freq. : 30Hz, Amp. : 3mm)

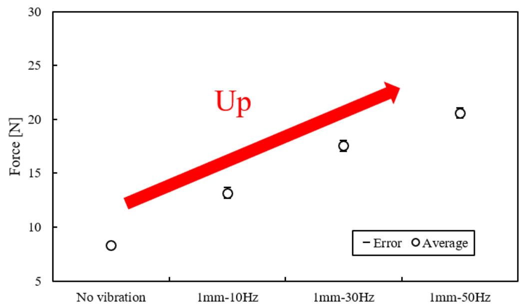

Figure 23. Vibration vs peak value (Comparison: Freq.)

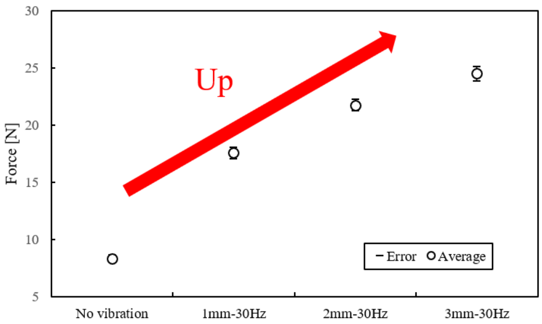

Figure 24. Vibration vs peak value (Comparison: Amp.)

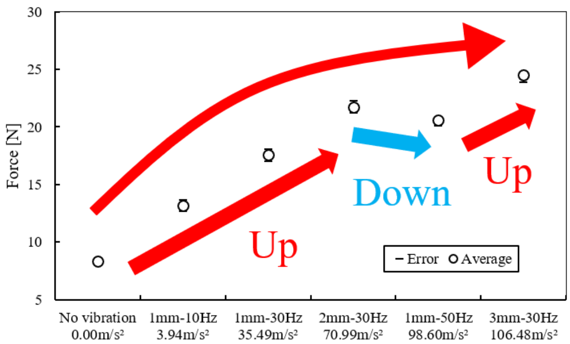

Figure 25. Vibration vs peak value (Comparison: Acc.)

V. Conclusion

In this study, the relationship between kind of vibration and the influence of the ground was confirmed for improving movement performance of the leg typed rover. Density of the ground and passive earth pressure were measured when giving vibration whose parameters are changed. Changed parameters were frequency, amplitude and acceleration. This relationship which was confirmed is shown below.

(1) As parameters of vibration (frequency, amplitude and acceleration) are large, density is increased
(2) As parameters of vibration (frequency, amplitude and acceleration) are large, as distance which propagated vibration is long
(3) As parameters of vibration (frequency, amplitude and acceleration) are large, passive earth pressure is increased
(4) relationship between the acceleration of vibration and the value of passive earth pressure corresponds with relationship between the acceleration of vibration and the value of density

We considered that feature (1) to feature (3) was confirmed because vibration whose parameters are large can move violently particles of the ground. Trend of increasing and decreasing density corresponded with trend of increasing and decreasing passive earth pressure when parameters of vibration were changed. In this result, feature (4) was confirmed. We could get knowledge that frequency, amplitude and acceleration are important parameters for changes of the ground when giving vibration. Moreover, it is predicted that suitable vibration to increase passive earth pressure can be existed because it is considered that increasing passive earth pressure by giving vibration has limit.

In the further study, the experiments will be carried out using the vibration whose value of parameters is selected widely. Further, relationship between kind of vibration and the influence of the ground will be confirmed in detail.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Tomohiro WATANABE did the experimental and wrote this paper. The whole works was supervised by Kojiro IIZUKA. All authors had approved the final version.

Acknowledgment

This work was supported by JKA and its promotion founds from KEIRIN RACE.

References

[1] H. Ueno, "State of art for planetary robotics on space agencies," *Journal of the Robotics Society of Japan*, vol. 32, no. 5, pp.431-432, June 2014.

[2] 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.

[3] NASA, JPL and California Institute of Technology Pasadena, "Mars Pathfinder," *NASA Facts* [Online]. Available: https://www.jpl.nasa.gov/news/fact_sheets/mpf.pdf

[4] T. Kubota, "Rover design for lunar of planetary exploration," *Journal of the Robotics Society of Japan*, vol. 17, no. 5, pp.609-614, June 1999.

[5] S. Dirk, K. Frank and G. Jose, "Ambulating robots for exploration in rough terrain on future extraterrestrial missions," presented at 7th International Symposium on Artificial Intelligence Robotics and Automation in Space, November 2004.

[6] S. Komizunai, A. Konno, S. Abiko and M. Uchiyama, "Development of a static sinkage model for a biped robot on loose soil," presented at IEEE/SICE International Symposium on System Integration, January 2010.

[7] Y. Brian and S. Chakravarthini, "Towards terrain interaction prediction for bioinspired planetary exploration rovers," *Bioinspiration & Biomimetics*, vol. 9, no. 1, pp.1-15, January 2014.

[8] T. Watanabe and K. Iizuka, "Study on movement method of leg mechanism using vibration in loose soil," presented at The Robotics and Mechatronics Conference 2018 in Kitakyushu, 2P2-I04, June 2018.

[9] T. Watanabe and K. Iizuka, "Experimental study moving performance of leg typed robot on rough terrain using vibration propagation," presented at The Robotics and Mechatronics Conference 2019 in Hiroshima, 2A1-J01, June 2019.

[10] T. Watanabe and K. Iizuka, "Study on legged typed rovers with function of vibration/stop to travel on loose soil," presented at 15th ISTVS European-African Regional Conference, September 2019.

[11] Awazu, S., yasukawa, I., "Imanishi, K. and Tateishi, Y., *Etokidoshiturikigaku Revision 3 edition*, Japan: Ohmsha 2014, pp.26-27, 164-165.

[12] S. Kawajiri, M. Tanaka, T. Kawaguchi, Y. Naohara, H. Hirabayashi, D. Nakamura and S. Yamashita, "Interpretation of

shear mode on vane shear test by X-ray CT scan," *Japanese Geotechnical Journal*, vol. 12, no. 1, pp.79-90, March 2017.

[13] M. Kikumoto, S. Nishimura and K. Hayano, *Zukai Wakarudoshiturikigaku*, Japan: Gakugei Publishers, p.22, 31, 94, December 2015.

[14] Japanese Society of Soil Mechanics and Foundation Engineering, *Doshitushikennnohouhoutokaisetu*, Japan: Japanese Society of Soil Mechanics and Foundation Engineering, pp.26-27, 106-115, 1990.

Tomohiro Watanabe received his bachelor's degree in Engineering from Shinshu University in 2017. He then went on to receive master's degree in Engineering from Shibaura Institute of Technology in 2019. His research interest is in the area of terramechannics and robotics.

Kojiro Iizuka is attached with the Department of Systems and 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. He received his doctor's degree in Engineering from the Graduate University for Advanced Studies in 2006. His teaching and research interest is in the areas of terramechannics and robotics.