

RESEARCH ARTICLE

Discrete Element Analysis of Reduced Bearing Capacity under Ground Vibration

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Abstract: Numerous missions have targeted planetary bodies, highlighting the need for advanced mobility technologies that enable exploration beyond the surface. Vibration-driven underground locomotion is a promising approach because vibration can alter soil behavior and reduce resistance to movement. However, the particle-scale mechanisms responsible for this reduction remain unclear, limiting the development of efficient vibration-based locomotion systems. In this study, particle-based numerical simulations and experiments were used to investigate how vibration reduces the resistance acting on an object moving through granular ground. A numerical model was developed to reproduce rod-dragging experiments conducted with a vibration amplitude of 0.25 mm at frequencies of 30 Hz and 50 Hz. The simulated resistance showed good agreement with the experimental results under the no-vibration and 50 Hz conditions, with errors within 2%. The results demonstrated that vibration reduced the resistance acting on the moving rod compared with the no-vibration condition. Particle-scale analysis further revealed that vibration generated high-velocity particle regions ahead of the rod and promoted particle rearrangement around it. These effects suppressed particle accumulation in front of the rod, thereby reducing resistance to motion. The findings clarify the relationship between vibration-induced particle flow and reduced soil resistance, providing a physical basis for the development of vibration-driven underground locomotion systems. Beyond planetary exploration, the numerical modeling of vibration-induced changes in granular ground may also contribute to broader engineering applications, including civil engineering problems involving vibrated granular materials.

Keywords: planetary exploration rover, underground locomotion, bearing capacity, vibration, discrete element method

1. Introduction

Space exploration plays a crucial role in advancing scientific knowledge and has attracted significant research interest. In particular, it provides valuable insights into planetary formation processes and the evolution of extraterrestrial environments. To date, numerous missions have been conducted to explore planetary bodies within the solar system. For example, the China National Space Administration carried out the Chang'e 5 mission in 2020, successfully achieving a lunar landing, collecting surface samples, and returning them to Earth [1]. In addition, the National Aeronautics and Space Administration (NASA) landed the Perseverance rover on Mars in 2021, enabling detailed investigations of the Martian surface and the search for potential biosignatures [2]. Mars exploration has also been advanced by rover-based investigations. The Zhurong rover, developed by China, landed on Mars in 2021 and performed subsurface exploration using ground-penetrating radar, as well as analyses of the regolith's dielectric properties [3]. These observations have provided new insights into the subsurface structure and material characteristics of the Martian surface [4]. Furthermore, NASA's Mars Science Laboratory mission deployed the Curiosity rover

to Gale Crater in 2012 to investigate the planet's past habitability [5]. The results revealed evidence of long-lived lacustrine environments formed by fluvial processes, and geochemical analyses suggested that these environments could have supported microbial life. Despite these significant achievements, the range of planetary rovers' exploration remains limited by their mobility. Therefore, improving rover locomotion capabilities is essential for expanding accessible areas and enhancing the efficiency of future planetary exploration missions.

Subsurface samples are of particular scientific importance because they are largely unaffected by space weathering and therefore preserve their original physical and chemical properties. Space weathering refers to the gradual alteration of surface materials caused by prolonged exposure to the space environment. On airless planetary bodies such as the Moon and asteroids, the surface is continuously exposed to galactic and solar cosmic rays, leading to progressive changes in the regolith over time. A representative example is the Japan Aerospace Exploration Agency Hayabusa2 mission, which successfully collected subsurface soil samples from asteroid Ryugu. In this mission, the Small Carry-on Impactor was used to create an artificial crater on the asteroid surface, enabling the recovery of interior materials that had been shielded from space weathering [6].

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In this context, rovers capable of subsurface locomotion have attracted attention as a promising approach for acquiring undisturbed underground samples. In addition, underground operation offers advantages in terms of thermal protection. The lunar surface experiences extreme temperature variations, with maximum temperatures reaching approximately 110 °C and minimum temperatures dropping to around -170 °C. Such harsh conditions can damage the rover's electronic components. In contrast, the subsurface environment maintains a relatively stable temperature due to the insulating effect of the ground, thereby helping to protect onboard systems. More recently, Zhang et al. developed a mole-inspired burrowing robot for planetary soil exploration, in which biomimetic forelimbs are used to excavate and displace granular soil during locomotion [7]. Nayak et al. proposed a different approach for submerged granular media, using water-jet-induced local fluidization to reduce drag during burrowing and a soft radial-expansion mechanism for unburrowing [8]. These studies demonstrate that recent underground locomotion systems employ diverse strategies, including mechanical excavation and active modification of the surrounding granular medium. Previous studies have proposed various mechanisms for underground locomotion. Nakatake et al. developed a robot inspired by the peristaltic motion of earthworms [9]. Nicholas et al. proposed another approach in which air is expelled from the front of the robot to reduce soil resistance during forward motion [10]. Iwano et al. proposed a lunar excavation robot equipped with an annular spiral crawler mechanism that improves excavation speed while maintaining attitude stability during drilling [11]. Yuan et al. developed a dynamic model of an autonomous burrowing robot to simulate drilling and steering processes for accessing subsurface samples on the Moon. Such systems can navigate through layered sediments and avoid obstacles during excavation [12]. However, these mechanisms tend to be structurally complex. For planetary exploration, simpler designs are preferable because they reduce the likelihood of mechanical failure.

As an alternative approach, vibration-assisted locomotion has been proposed by our research group. Rather than generating propulsion through active excavation or complex body deformation, this approach utilizes vibration to modify the mechanical state of the surrounding soil, thereby reducing locomotion resistance. Our previous studies have shown that vibration significantly alters soil properties. During vibration, particle motion becomes more active, and the soil exhibits fluid-like behavior, resulting in a temporary reduction in soil strength. In contrast, after vibration ceases, the ground becomes compacted, and its stiffness increases [13].

The temporary reduction in soil strength is attributed to vibration-induced particle motion. Baumgartner et al. investigated the dynamics of granular materials under vibrational excitation to better understand the locomotion of the sandfish skink, a lizard that moves through desert sand [14]. Their study demonstrated that high-frequency vibration induces localized loosening of the granular medium near the vibration source, producing a fluid-like state and reducing earth pressure. This behavior is consistent with the Janssen model [15], which describes stress redistribution in granular materials under vibration. These findings suggest that the bearing capacity of granular media can be actively controlled through vibration.

Based on these phenomena, we previously proposed an underground locomotion robot that combines periodic extension-contraction motions with vibration-induced changes in ground conditions [13]. The locomotion strategy exploits two complementary effects of vibration. During vibration, the soil softens, and the drag force acting on the front of the robot

decreases. After vibration, the soil becomes compacted, increasing the drag force acting on the rear of the robot. By combining these effects, forward underground locomotion can be achieved. A prototype testbed was designed and constructed, and experiments demonstrated that the traveling distance under vibration was greater than that without vibration.

Although previous studies have demonstrated that vibration can improve underground mobility by reducing soil resistance, the mechanism by which vibration alters the bearing capacity acting on a moving object has not yet been fully clarified. Our previous study [13] focused on demonstrating the feasibility of the proposed vibration-assisted locomotion strategy through prototype experiments, whereas the particle-scale mechanism underlying the vibration-induced reduction in soil resistance was not investigated. In contrast, the present study focuses on quantitatively elucidating this mechanism, particularly the relationship between vibration-induced particle motion and the resulting reduction in bearing capacity. Therefore, the objective of this study is to clarify this mechanism through a combination of discrete element method (DEM) simulations and experiments.

The mechanical state of the ground altered by vibration plays a key role in vibration-assisted locomotion. To improve the design of such locomotion mechanisms, it is necessary to reproduce these vibration-induced changes numerically. The finite element method (FEM) has been widely employed to analyze soil behavior. For example, Abo-Elnor et al. investigated soil-blade interaction using a three-dimensional FEM with a hypoplastic constitutive model for dry sandy soil, successfully predicting macroscopic soil deformation and cutting forces under various operating conditions [16]. However, because FEM treats soil as a continuum, it is difficult to directly observe the motion and rearrangement of individual particles.

Recently, data-driven approaches have also been introduced into numerical modeling of soil and granular materials. Guan et al. [17] incorporated a deep learning-based soil constitutive model into finite element analysis to predict soil responses under various boundary value problems. Furthermore, Guan et al. [18] proposed a deep learning-accelerated FEM-DEM multi-scale framework to reduce the computational cost associated with granular material modeling. These data-driven approaches provide efficient alternatives for predicting complex soil behavior. To investigate the particle-scale mechanisms associated with vibration-induced changes in bearing capacity, DEM was adopted because it explicitly models individual particles and enables their motion and interactions under vibration to be directly analyzed. Although a direct quantitative comparison with FEM or coupled FEM-DEM approaches is beyond the scope of the present study, such a comparison will be important in future work to evaluate the relative accuracy and computational efficiency of these numerical approaches for vibrated granular media.

In this study, a DEM model was developed to reproduce an experiment in which a rod, representing a simplified rover leg, moves across the soil surface while transmitting vibration into the ground. The bearing capacity during this dragging motion was evaluated, and the simulation results were validated through comparison with experimental data. Unlike recent underground locomotion studies that primarily focus on developing new locomotion mechanisms, the present study focuses on the soil-object interaction underlying vibration-assisted locomotion. Our previous study evaluated the bearing capacity of the ground after vibration had ceased, whereas the present study evaluates the bearing capacity while vibration is continuously applied during rod dragging. Furthermore, the present study analyzes the spatial and temporal particle-velocity distributions around the moving

rod to clarify the mechanism responsible for the reduction in bearing capacity during vibration. The novelty of this work lies in quantitatively revealing the particle-scale mechanism responsible for the reduction in bearing capacity under continuous vibration and validating the numerical findings through experiments.

2. Experiment

In this study, a rod was translated along the ground surface to evaluate the bearing capacity, enabling comparison with results obtained from the DEM simulations. In the experiments, the rod was pulled horizontally across the soil while the vibration frequency was varied, and the corresponding resistance was measured as an indicator of bearing capacity. This experimental approach was developed with reference to a previous study that quantified the force acting on an object during horizontal dragging on the ground [19].

Figure 1 [20] presents the configuration of the experimental setup, consisting of a soil container, a rod, and a force sensor, while Figure 2 summarizes the experimental procedure. First, the soil was mixed and leveled to prepare a uniform ground surface. The rod was then placed on the ground with a penetration depth of 50 mm. Subsequently, the rod was pulled across the surface,

and the bearing capacity was evaluated from the force measured by the sensor under vibrational conditions. The rod was translated at a constant speed of 8.87 mm/s for a duration of 5 s. The soil container measured 309 mm in length, 439 mm in width, and 300 mm in height. As shown in Figure 1 (b), the rod had a square cross-section with side lengths of 20 mm and an overall length of 200 mm, forming a prismatic shape. The ground material used in the experiments was Silica No. 5, a sand commonly adopted in studies related to planetary exploration rovers [21]. The soil properties of Silica No. 5 are summarized in Table 1. The entire setup was installed on a vibration generator (Wave Maker 05), which transmitted oscillations to the rod. Figure 3 [20] illustrates the direction of vibration and the waveform used in the experiment. A sinusoidal waveform was used for the vibration. The vibration frequency was set to 30 Hz and 50 Hz, with an amplitude of 0.25 mm. The direction of vibration was aligned with the dragging direction of the rod. Each test condition was repeated five times. These repeated trials were conducted to evaluate the reproducibility and variability of the experimental results under each

Table 1
Parameters and specifications of Silica No. 5

Item	Conditions (value)
Size of particle	150–840 [μm]
Maximum bulk density	1629 [kg/m^3]
Minimum bulk density	1320 [kg/m^3]
Soil cohesion	762 [N/m^2]
Internal friction angle	40.2 [deg]

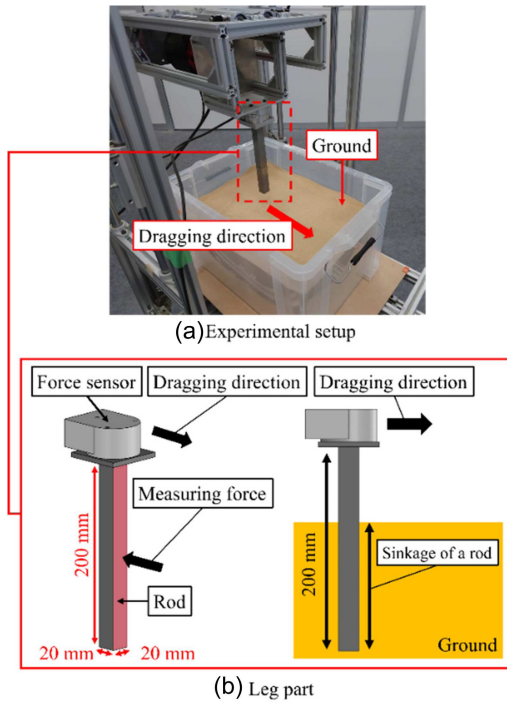


Figure 1

Experimental setup for measuring bearing capacity

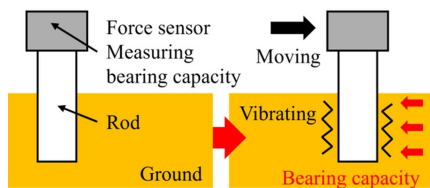


Figure 2

Experimental flow for measuring bearing capacity

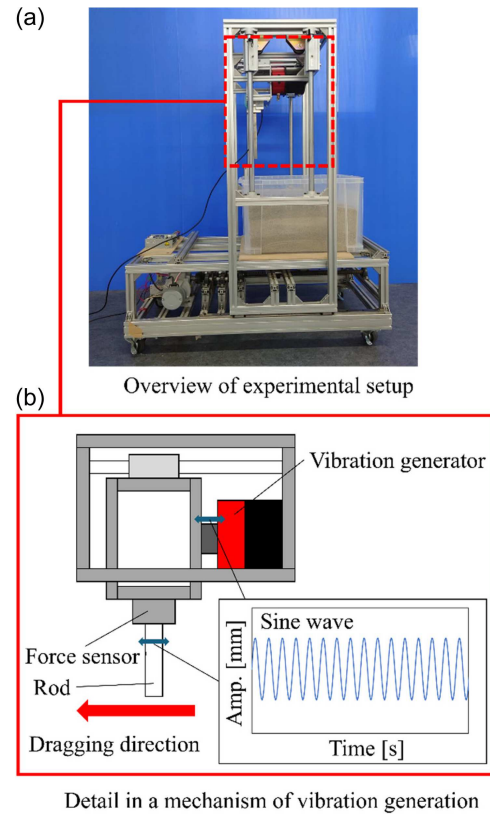


Figure 3

Mechanism of vibration generation

vibration condition. This procedure enabled a consistent comparison of the bearing capacity under different vibration frequencies. The detailed experimental parameters are summarized in Table 2. Statistical differences in the experimental bearing capacity among the three vibration conditions were evaluated using two-tailed Welch's t-tests based on five independent trials for each condition. Pairwise comparisons were performed between the no-vibration and 30 Hz conditions, the no-vibration and 50 Hz conditions, and the 30 Hz and 50 Hz conditions. To account for multiple comparisons, the Bonferroni correction was applied, resulting in a corrected significance level of $p < 0.0167$.

Table 2
Experimental conditions

Item	Conditions (value)
Number of trials	5 trials
Sinkage of a rod [mm]	50
Dragging speed [mm/s]	8.87
Dragging time [s]	5
Kind of sand	Silica No. 5
Vibration generator	Wave Maker 05
Vibration amplitude [mm]	0.25
Vibration frequency [Hz]	30, 50
Force sensor	PFS055YA251U6

3. Simulation

3.1. Conditions and procedures for DEM simulation

The DEM simulation was conducted using LS-DYNA R11.1.0. The simulation domain consisted of a soil container with dimensions of 522 mm $\times$ 141 mm $\times$ 230 mm. The soil container size in the DEM simulation was reduced compared with that in the experiment to maintain a practical computational cost and simulation time. The soil container was modeled as a rigid body, with all translational and rotational degrees of freedom constrained. To generate the initial ground condition, particles were deposited under a gravitational acceleration of 9.8 m/s² until a stable soil bed was formed. After the deposition process, the ground was allowed to reach a static equilibrium state before the rod penetration analysis was initiated. This procedure was used to establish a stable initial ground condition before the interaction between the rod and soil particles was evaluated. The same initial preparation procedure was applied to all simulation cases to allow consistent comparison among the different vibration conditions. The simulation environment, boundary conditions, and initial conditions are summarized in Table 3.

The simulation procedure is illustrated in Figure 4 [20]. The rod geometry and operating conditions were identical to those used in the experiments. At the beginning of the analysis, the rod was placed on the ground with a penetration depth of 50 mm (Figure 4 (b)). Two cases were considered in the simulation: one without vibration and the other with vibration. In the vibrational case, the rod was translated while oscillatory motion was applied (Figure 4 (c)). The rod was moved at a constant velocity of 8.87 mm/s for 5 s. The rod's dimensions were identical to those shown in Figure 1. The soil container's dimensions were 500 mm $\times$ 121 mm $\times$ 120 mm. The vibration input was approximated by sampling

Table 3
Conditions of simulation environment

Item	Conditions (value)
Software	LS-DYNA
Software version	R11.1.0
Size of simulation domain	Length: 522 mm Width: 141 mm Height: 230 mm
Gravitational acceleration	9.8 m/s ² (constant)
Soil container	Modeled as a rigid body
Boundary condition of soil container	All translational and rotational degrees of freedom constrained
Initial soil preparation	Particle deposition under gravity
Initial soil state	Static equilibrium after particle deposition

eight equally spaced points from a sinusoidal waveform and connecting them to reproduce a sine-like profile (Figure 5) [20]. The conditions are summarized in Table 4.

3.2. DEM parameters

In the DEM, interactions between particles are described in terms of contact forces, including elastic repulsive forces and frictional forces. The motion of each particle is determined by solving the equations of motion based on these contact interactions.

Figure 6 [20] shows the DEM model used for predicting the bearing capacity. This model is a commonly used framework

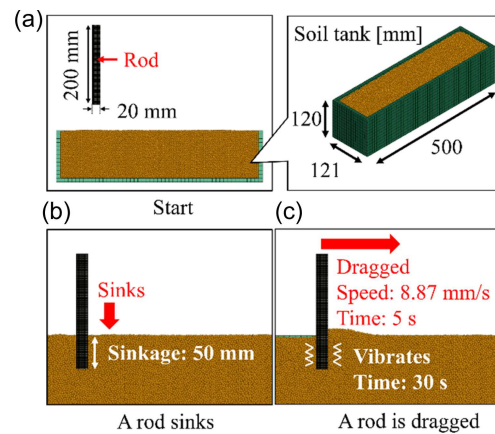


Figure 4
Simulation flow for measuring bearing capacity

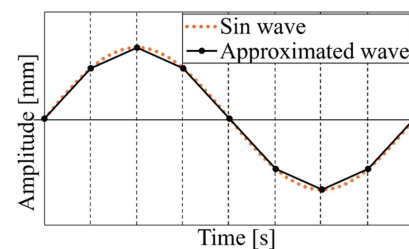


Figure 5
Vibration waveform in DEM simulation

Table 4
Conditions of simulation parameters

Item	Conditions (value)
Sinkage of a rod [mm]	50
Dragging speed [mm/s]	8.87
Dragging time [s]	5
Vibration amplitude [mm]	0.25
Vibration frequency [Hz]	30, 50

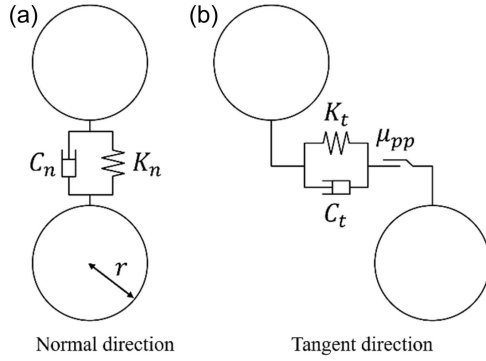


Figure 6
Simulation model

reported in many previous works [22]. For the normal direction, a spring-dashpot system is assigned in parallel at each contact point (Figure 6 (a)). In the tangential direction, frictional behavior is modeled using a slider element (Figure 6 (b)). The translational and rotational motions of particle i are calculated by Eq. (1) and Eq. (2), respectively. By solving these equations for all particles, the overall system behavior can be simulated. In Eq. (1), t denotes time, m_i is the particle i mass, v represents the particle velocity, and F is the force acting on particle i . In Eq. (2), I indicates the moment of inertia, ω is the angular velocity, and N represents the torque acting on particle i .

$$m_i \frac{dv_i}{dt} = \sum F \quad (1)$$

$$I_i \frac{d\omega_i}{dt} = \sum N \quad (2)$$

The parameter settings used in the DEM analysis are summarized in Table 5. The normal stiffness K_n was selected based on preliminary trial calculations. The tangential stiffness K_t was determined according to Eq. (3), following the methodology described in earlier studies [23]. The coefficient value of 0.25 was adopted based on the difference between P-wave and S-wave propagation velocities in earthquake engineering.

$$K_t = 0.25K_n \quad (3)$$

The damping coefficients in the normal and tangential directions are obtained from Eq. (4) and Eq. (5), respectively [23]. These formulations are derived from the corresponding spring constants based on the assumption of critical damping. Here, m denotes the mass of the element.

$$C_n = 2\sqrt{mK_n} \quad (4)$$

Table 5
DEM simulation parameter

Item	Value
Element radius [m]	0.002
Element density [kg/m ³]	2700
Normal spring constant K_n [N/m]	300
Normal damping coefficient C_n [Ns/m]	$C_n = 2\sqrt{mK_n}$
Tangential spring constant K_t [N/m]	$K_t = 0.25K_n$
Tangential damping coefficient C_t [Ns/m]	$C_t = 2\sqrt{mK_t}$
Friction coefficient for particle elements μ_{pp} [-]	$\mu_{pp} = \tan \phi_{pp}$
Friction coefficient for particle-rod contact μ_{pr} [-]	$\mu_{pr} = \tan \phi_{pr}$
Friction coefficient for particle-wall contact μ_{pw} [-]	$\mu_{pw} = \mu_{pp}$
Coefficient of rolling friction μ_r [-]	$\mu_r = 0.02r$
Angle of repose for soil particles ϕ_{pp} [deg]	40.2
Limiting slope angle of a steel plate ϕ_{pr} [deg]	29.0

$$C_t = 2\sqrt{mK_t} \quad (5)$$

The inter-particle friction coefficient, μ_{pp} , was determined from the angle of repose using Eq. (6), where the angle of repose was obtained through experiments. The friction coefficient between the particles and the wall of the soil container, μ_{pw} , was assumed to be identical to μ_{pp} .

$$\mu_{pp} = \tan \phi_{pp} \quad (6)$$

The friction coefficient between the soil particles and the rod was determined using Eq. (7). Here, μ_{pr} corresponds to the limiting slope angle of a steel plate—made of the same material as the rod—at which the sand begins to slide. The angle ϕ_{pr} was obtained experimentally.

$$\mu_{pr} = \tan \phi_{pr} \quad (7)$$

The rolling friction coefficient, μ_r , was determined using Eq. (8) [23]. The value was set to 0.02 based on the relationship between particle radius and the upper limit of the rolling friction coefficient [24].

$$\mu_r = 0.02r \quad (8)$$

The element radius r was set to 0.002 m to maintain a reasonable computational cost and simulation time. The element density was determined with reference to the material density of the silica particles. The normal spring constant K_n was adopted from our previous study [20], in which the parameter was determined by fitting the simulated ground reaction force to the experimental response of Silica No. 5. The angle of repose of the soil particles ϕ_{pp} and the limiting slope angle of the steel plate ϕ_{pr} were experimentally determined in our previous study [20].

4. Results and Discussion

4.1. Comparison of experimental and simulation results

The variation in bearing capacity with shear displacement is presented in Figures 7 and 8. Figure 7 shows the simulation results, whereas Figure 8 presents the experimental results. The experimental data represent the average of five trials. In both the simulation and experimental results, the bearing capacity increases with shear displacement and eventually converges. This tendency indicates that the resistance acting on the rod initially increases as the rod interacts with the surrounding soil and subsequently approaches a relatively stable state as the dragging process continues. Therefore, the converged region was used to evaluate and compare the representative bearing capacity under each vibration condition. In the experiments, the bearing capacity decreased with increasing vibration frequency. In contrast, the simulation results indicated that the bearing capacity without vibration was larger than that with vibration; however, no clear dependence on vibration frequency was observed. The discrepancy between the simulation and experimental results may be attributed to the simplified representation of soil particles in the DEM model. In the present simulation, the soil particles were modeled as spherical elements, whereas actual Silica No. 5 particles have irregular shapes. Therefore, particle interlocking and the associated resistance may not be fully reproduced in the DEM model. In particular, the experimental results showed a clear decrease in bearing capacity from 30 Hz to 50 Hz, whereas the DEM results showed only a small difference between these frequencies. Therefore, the relatively large error at 30 Hz may be associated with the inability of the present DEM model to reproduce the experimentally observed frequency dependence. The simplified spherical particle representation and the resulting

insufficient representation of particle interlocking may contribute to this discrepancy.

Figure 9 shows the average converged bearing capacity during the steady-state period from 1 to 5 s and the standard error range. The standard error was calculated from 400 data points obtained between 1 and 5 s. The mean bearing capacity and standard error for each vibration condition are summarized in Tables 6 and 7 for the simulation and experimental results, respectively. The experimental mean bearing capacity was calculated from the results of five independent trials. The standard deviation and standard error of the experimental results are summarized in Table 8, and the corresponding 95% confidence intervals are presented in Table 9. The statistical comparisons among the different vibration conditions are summarized in Table 10. In the experiments, the mean bearing capacity decreased from 5.29 N without vibration to 4.63 N at 30 Hz and 3.91 N at 50 Hz, corresponding to reductions of approximately 12.5% and 26.1%, respectively. Statistical comparisons among the three vibration conditions were performed using two-tailed Welch's t-tests with Bonferroni correction for multiple comparisons. Based on the Bonferroni-corrected significance level of $p < 0.0167$, no statistically significant differences were observed between the no-vibration and 30 Hz

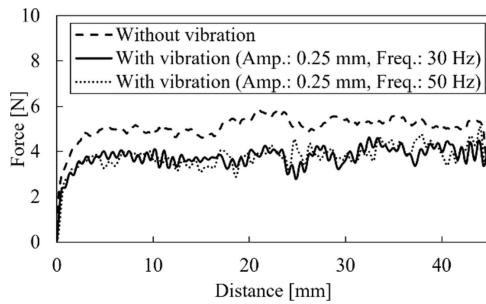


Figure 7

Bearing capacity versus shear displacement for the simulation

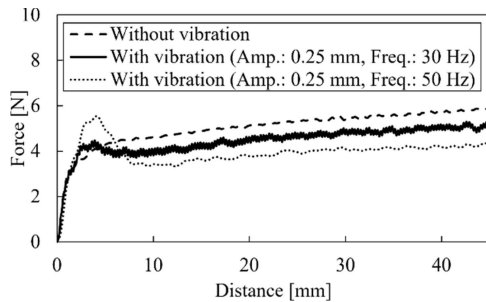


Figure 8

Bearing capacity versus shear displacement for the experiment

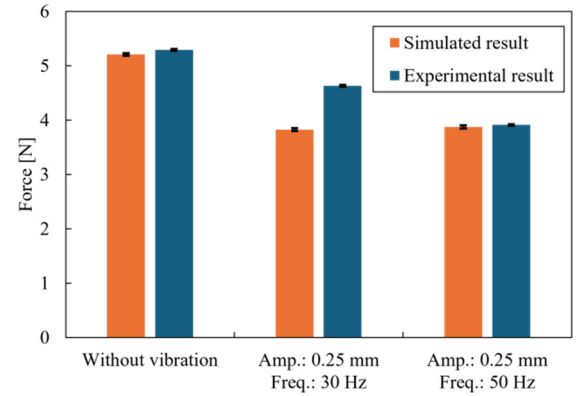


Figure 9

Comparison of bearing capacity under different vibration conditions

Table 6

Simulation results of bearing capacity

Vibration	Mean value	Standard error
Without vib.	5.21 N	0.02 N
Amp.: 0.25 mm Freq.: 30 Hz	3.83 N	0.02 N
Amp.: 0.25 mm Freq.: 50 Hz	3.88 N	0.03 N

Table 7

Experimental results of bearing capacity

Vibration	Mean value	Standard error
Without vib.	5.29 N	0.02 N
Amp.: 0.25 mm Freq.: 30 Hz	4.63 N	0.02 N
Amp.: 0.25 mm Freq.: 50 Hz	3.91 N	0.01 N

Table 8**Standard deviation and standard error of experimental bearing capacity**

Vibration	Standard deviation	Standard error
Without vib.	0.68 N	0.30 N
Amp.: 0.25 mm Freq.: 30 Hz	0.33 N	0.15 N
Amp.: 0.25 mm Freq.: 50 Hz	0.63 N	0.28 N

Table 9**95% confidence intervals of experimental bearing capacity**

Vibration	95% confidence interval
Without vib.	4.45 N – 6.13 N
Amp.: 0.25 mm Freq.: 30 Hz	4.22 N – 5.04 N
Amp.: 0.25 mm Freq.: 50 Hz	3.03 N – 4.59 N

Table 10**Statistical comparison of measurement values among different vibration conditions**

Vibration	p-value	Significance
Without vib. vs Freq.: 30 Hz	0.099	ns
Freq.: 30 Hz vs Freq.: 50 Hz	0.042	ns
Without vib. vs Freq.: 50 Hz	0.007	*

Statistical significance was evaluated using two-tailed Welch's t-tests with Bonferroni correction. The corrected significance level was $p < 0.0167$.

conditions ($p = 0.099$) or between the 30 Hz and 50 Hz conditions ($p = 0.042$). In contrast, the bearing capacity at 50 Hz was significantly lower than that under the no-vibration condition ($p = 0.007$).

The simulation results showed good agreement with the experimental results under the no-vibration and 50 Hz conditions, with relative errors of 1.5% and 0.9%, respectively. In contrast, a larger discrepancy was observed at 30 Hz, where the difference between the simulation and experimental results was approximately 0.81 N, corresponding to a relative error of 17.4%. The differences and relative errors between the simulation and experimental results are summarized in Table 11.

Table 11**Difference and relative error in bearing capacity between experimental and simulation results**

Vibration	Difference	Relative error
Without vib.	0.08 N	1.5 %
Amp.: 0.25 mm Freq.: 30 Hz	0.81 N	17.4 %
Amp.: 0.25 mm Freq.: 50 Hz	0.04 N	0.9 %

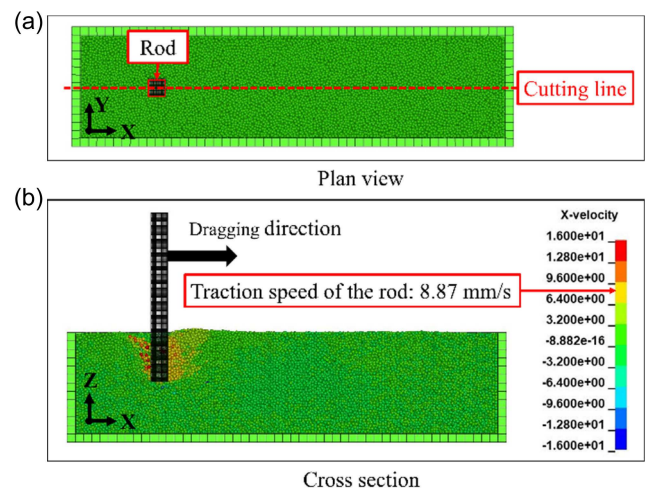
4.2. Mechanism of bearing capacity reduction by vibration in DEM simulations

To clarify the mechanism behind the reduction in bearing capacity during rod dragging under vibration, the particle velocity within the soil was analyzed. It is hypothesized that vibration induces particle flow, causing the particles to move in the dragging direction at a velocity higher than that of the rod, which leads to a reduction in bearing capacity. In the DEM simulation, the flow of ground particles was visualized using color contour maps of particle velocity in the dragging direction (x-direction). Figure 10 shows the color contour results obtained from the DEM simulation. Figure 10 (b) presents a cross-sectional view along the red line indicated in the plan view (Figure 10 (a)). The particle velocity in the x-direction is represented by the color scale. The color contour ranges from -16.0 to 16.0 mm/s and is divided into 10 levels, as shown in Figure 10 (b). The velocity range was set to approximately twice the dragging speed of the rod. As shown in Figure 10 (b), the rod dragging speed corresponds to the third level from the top in the color scale (orange region).

Figures 11–13 show the color contour maps obtained from the simulations in which the rod was dragged through the ground. The results are presented for both non-vibration and vibration conditions (amplitude: 0.25 mm; frequencies: 30 Hz and 50 Hz). In Figures 11–13, the color contour maps are shown at 1 s intervals during the dragging process.

As shown in Figure 11, in the absence of vibration, the particles in front of the rod move together with the rod. The particles around the rod exhibit an orange color corresponding to approximately the third level of the color contour, indicating that they move at a velocity nearly equal to the dragging speed of the rod.

In contrast, as shown in Figures 12 and 13, when vibration is applied, the particles around the rod exhibit a red color corresponding to approximately the first level of the color contour, indicating that they move at velocities exceeding 16.0 mm/s. Before the rod begins to move (Figures 12 and 13 (a)), regions with particle velocities greater than 16.0 mm/s are symmetrically distributed on both sides of the rod in the dragging direction due to vibration. After the rod starts dragging (Figures 12 and 13 (b)–(e)), these high-velocity regions expand predominantly in the forward direction of dragging the rod.

**Figure 10****Overview of the color contour in the DEM simulations**

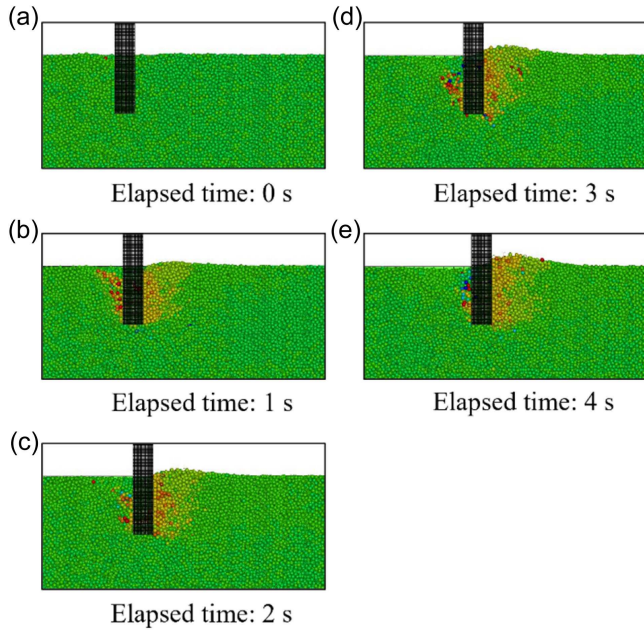


Figure 11

Time evolution of color contour figures in the DEM simulations without vibration

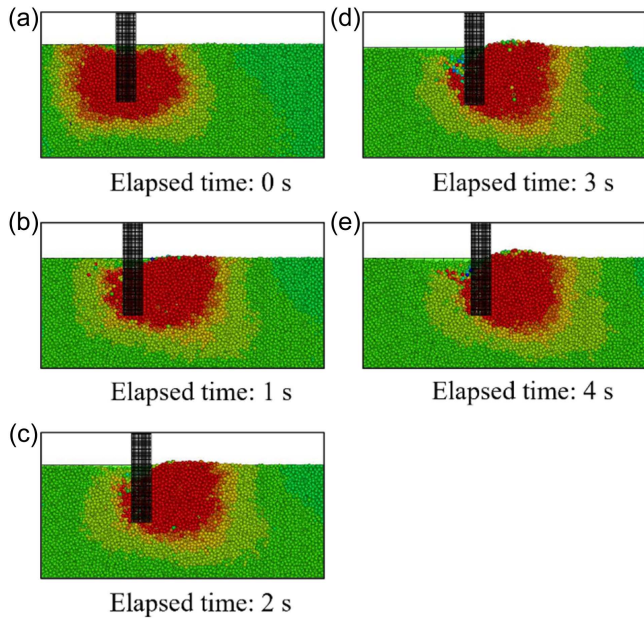


Figure 12

Time Evolution of Color Contours in DEM Simulations under Vibration at an Amplitude of 0.25 mm and a Frequency of 30 Hz

These results suggest that vibration causes particles in front of the rod to move faster than the rod itself, thereby reducing the ground's bearing capacity. Furthermore, as shown in Figures 11–13, the main particle motion remained localized around the rod and did not extend to the boundaries of the simulation domain in either the dragging or vibration direction. This observation suggests that boundary effects associated with the reduced container size had a limited influence on the particle behavior around the rod and, consequently, on the simulated bearing capacity.

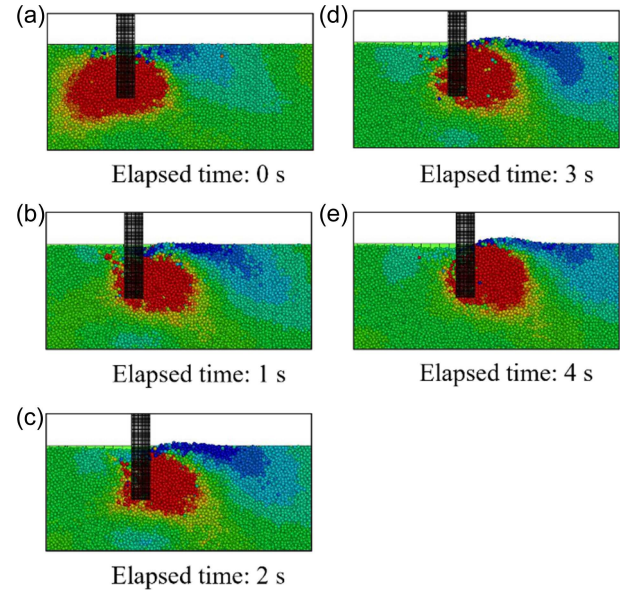


Figure 13

Time Evolution of Color Contours in DEM Simulations under Vibration at an Amplitude of 0.25 mm and a Frequency of 50 Hz

4.3. Implications for vibration-driven underground locomotion

The results obtained in this study provide important insights into the mechanism by which vibration improves underground locomotion in loose ground.

The particle-scale behavior observed in the present study is consistent with previous observations of vibration-induced loosening and fluid-like behavior in granular materials. Baumgartner et al. [14] reported that high-frequency vibration activates particle motion and locally loosens the granular medium, resulting in a reduction in earth pressure. The present study extends these findings by demonstrating that, during the motion of an object under continuous vibration, high-velocity particle regions develop around and ahead of the rod. This enhanced particle mobility promotes particle rearrangement and suppresses particle accumulation in front of the moving object, thereby reducing the bearing capacity. Thus, the reduction in bearing capacity can be interpreted as a consequence of vibration-induced enhancement of particle mobility rather than simply as a macroscopic reduction in soil strength.

This interpretation also differs from our previous study [20], in which the bearing capacity was evaluated after vibration had ceased. The present results indicate that, while vibration is continuously applied, active particle motion around the moving object directly contributes to the reduction in bearing capacity. This suggests that the mechanisms governing bearing capacity during vibration and after vibration may differ.

Compared with conventional underground locomotion approaches, such as peristaltic mechanisms and active excavation systems, the proposed vibration-based method modifies the mechanical state of the surrounding soil itself. Existing methods generally require complex mechanical structures to overcome soil resistance. In contrast, the proposed approach reduces the resistance through vibration-induced changes in soil behavior, potentially enabling simpler and lighter robotic systems for underground exploration.

From an engineering perspective, the experimental results showed that vibration reduced the mean bearing capacity by approximately 12.5% at 30 Hz and 26.1% at 50 Hz compared with the no-vibration condition. Because bearing capacity represents the resistance acting on the rod during dragging, these reductions indicate that vibration can substantially decrease the mechanical resistance that an underground locomotion system must overcome. Although the present study does not directly evaluate robotic traveling speed, distance, or energy consumption, the quantified reduction in resistance provides an engineering basis for designing vibration-assisted locomotion mechanisms with lower required propulsion force.

Furthermore, the present results provide a quantitative and mechanistic basis for the design of vibration-driven underground robots. By clarifying the relationship between vibration, particle flow, and bearing capacity reduction, this study contributes to a better understanding of how soil–robot interactions can be actively controlled through vibrational excitation. These findings may support the development of future planetary exploration robots capable of efficient underground locomotion in granular environments.

5. Conclusion

In this study, the DEM was used to simulate the bearing capacity of the ground under vibration during rod dragging. The experimental results showed that the mean bearing capacity decreased from 5.29 N without vibration to 4.63 N at 30 Hz and 3.91 N at 50 Hz, corresponding to reductions of approximately 12.5% and 26.1%, respectively. The DEM simulation reproduced the reduction in bearing capacity caused by vibration using the same ground model for both vibration and non-vibration conditions. The relative errors between the simulation and experimental results were 1.5%, 17.4%, and 0.9% for the no-vibration, 30 Hz, and 50 Hz conditions, respectively. Analysis of particle velocity revealed that vibration substantially alters particle behavior around the rod. Without vibration, particles move together with the rod at approximately the same velocity. In contrast, when vibration is applied, particles in front of the rod move at velocities exceeding that of the rod, especially in the forward dragging direction. This particle flow is considered to be a key factor contributing to the reduction in bearing capacity. However, the simulation results did not show a clear dependence of bearing capacity on vibration frequency, which differs from the experimental observations. This discrepancy is likely due to the simplified representation of soil particles in the DEM model, where spherical elements are used, and interlocking effects are not sufficiently captured.

The findings obtained in this study also provide new insights into vibration-driven underground locomotion. The DEM analysis demonstrated that vibration-induced particle flow around the moving rod plays a significant role in reducing bearing capacity. This result offers a particle-scale explanation for the reduction in drag force observed in previous locomotion experiments and contributes to the understanding of how vibration can be utilized to actively control soil–robot interactions. Therefore, this study not only validates the applicability of DEM for analyzing vibrated granular media but also provides useful knowledge for the design of future underground exploration robots.

Although Silica No. 5 has been used in previous studies related to planetary exploration rovers, the present study

considered only a single type of granular material. In addition, the vibration conditions investigated in this study were limited to an amplitude of 0.25 mm and frequencies of 30 and 50 Hz. Therefore, the validation of the present DEM model is limited to the material and vibration conditions examined in this study, and the general applicability of the model has not yet been established. Future work will examine a wider range of vibration amplitudes and frequencies to clarify their effects on bearing capacity and particle-scale behavior. Further investigations using planetary regolith simulants and other granular materials are necessary to evaluate the applicability of the proposed approach to a wider range of planetary surface conditions. The particle shape in the DEM model will also be improved to better represent real soil behavior and achieve closer agreement with experimental results. In addition, further quantitative analyses of particle motion will be conducted to better characterize the relationship between vibration-induced particle dynamics and bearing capacity reduction. In particular, particle-velocity profiles and particle kinetic energy under different vibration conditions will be evaluated in future work.

Acknowledgments

This article is a revised and expanded version of a paper entitled “Verification of decreasing bearing capacity while imparting vibration to ground in discrete element method simulation,” which was presented at CLAWAR 2024 in Kaiserslautern, Germany, September 4–6, 2024. In this paper, extending previous studies, the mechanism of bearing capacity reduction due to vibration is investigated from the perspective of particle behavior in DEM simulations.

Funding Support

This research was funded by JSPS KAKENHI Grant Number JP 23K13296.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

Author Contribution Statement

Tomohiro Watanabe: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Dai Watanabe:** Conceptualization, Resources, Writing – review & editing. **Kojiro Iizuka:** Conceptualization, Resources, Writing – review & editing, Supervision.

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How to Cite: Watanabe, T., Watanabe, D., & Iizuka, K. (2026). Discrete Element Analysis of Reduced Bearing Capacity under Ground Vibration. *Journal of Climbing and Walking Robots*. <https://doi.org/10.47852/bonviewJCWR62029793>

Appendix A. List of Acronyms and Variables

For ease of reference, the acronyms and variables used throughout this study are summarized in Tables A1 and A2.

Table A1
List of acronyms

Acronym	Definition
DEM	Discrete element method
FEM	Finite element method
NASA	National Aeronautics and Space Administration
P-wave	Primary wave
S-wave	Secondary wave

Table A2
List of variables

Variable	Definition	Unit
t	Time	S
m	Particle mass	kg
v	Particle velocity	m/s
F	Force acting on a particle	N
N	Torque acting on a particle	N · m
I	Moment of inertia	Kg · m ²
ω	Angular velocity	rad/s
r	Element radius	m
K_n	Normal spring constant	N/m
C_n	Normal damping coefficient	Ns/m
K_t	Tangential spring constant	N/m
C_t	Tangential damping coefficient	Ns/m
μ_{pp}	Friction coefficient for particle elements	-
μ_{pr}	Friction coefficient for particle-rod	-
μ_{pw}	Friction coefficient for particle-wall	-
μ_r	Coefficient of rolling friction	-
ϕ_{pp}	Angle of repose for soil particles	deg
ϕ_{pr}	Limiting slope angle of a steel plate	deg