A simplified DEM numerical simulation of vibroflotation without backfill

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Abstract. Vibroflotation is one of the deep vibratory compaction techniques for ground reinforcement. This method densifies the soil and improves its mechanical properties, thus helps to protect people's lives and property from geological disasters. The macro reinforcement mechanisms of vibroflotation method have been investigated by numerical simulations, laboratory and in-situ experiments. However, little attention has been paid on its micro-mechanism, which is essential to fully understand the principle of the ground reinforcement. Discrete element method (DEM), based on discrete mechanics, is more powerful to solve large deformation and failure problems. This paper investigated the macro-micro mechanism of vibroflotation without backfill under two conditions, i.e., whether or not the ground water was considered, by incorporating inter-particle rolling resistance model in the DEM simulations. Conclusions obtained are as follows: The DEM simulations incorporating rolling resistance well replicate the mechanical response of the soil assemblages and are in line with practical observations. The void ratio of the granular soil fluctuates up and down in the process of vibroflotation, and finally reduces to a lower value. It is more efficient to densify the ground without water compared to the ground with water.

1. Introduction
Vibroflotation is one of soil improvement techniques to increase soil strength and bearing capacity of ground using vibration and the jetting of water. It is an efficient method to protect the ground from geohazards such as liquefaction under seismic. It was firstly proposed by Steuerman in 1936, and well developed in America.

The applicability and mechanism of vibroflotation have been studied by different scholars. Webb and Ian Hall [1] thought the densification zone and efficiency will significantly reduce with the increase of silt content, according to vibroflotation tests with backfill. Skcombe et al. [2] pointed out that 15% is the maximum fines content to permit the performance of vibroflotation method without the addition of stone aggregate. The vibroflotation method is also used to improve the dynamic property such as liquefaction-resistant behavior from Baez [3] and Dobson [4]. Bement and Selby [5] took a laboratory tests to investigate the compaction settlement of granular soils during pile driving. Arnold et al. [6]
presented an elastic finite element analysis of vibrocompaction, comparing horizontally circling deep vibrators with vertically oscillating top vibrators. Results show better performance of deep vibrators with multidirectional shearing mode. However, owing to several simplifications (i.e., without considering the influence of pore water), the observations between numerical simulations and in-situ data were not good. Susana et al. [7] also utilized a new finite element model to simulate the mechanical response of sandy soils using the vibroflotation technique.

Although meaningful results have been obtained, the micro-mechanism in the process of vibroflotation remains poorly understood. On the other hand, finite element method (FEM) has inherent disadvantages to analyze geohazard problems which related to large deformation (e.g., the study of shear band in cemented sands [8]). It’s also a challenge to obtain a proper constitutive model of complex soils. In contrast, the discrete element method (DEM), firstly proposed by Cundall and Strack [9], has obvious advantages to solve large deformation and failure problems. It treats the soil as non-continuous aggregates to better simulate the macro-micro mechanical behavior by choosing appropriate contact models and corresponding parameters. The paper analyzes the compaction mechanism using the 2D DEM to simulate the vibroflotation process without backfill under two conditions (i.e., below and above ground water).

2. The contact model considering inter-particle rolling resistance
The inter-particle rolling resistance model proposed by Jiang et al. [10] was used in this paper. The model only introduces one additional parameter $\beta$ to consider the influence of irregular shapes of soil particles. Comparing to other standard DEM models (e.g., Iwashita et al. [11]), this model thus solves the drawback of using a lot of parameters to define rolling resistance, which needs to be determined through trial and error. The influence of different rolling resistance coefficient on passive earth pressure was also examined from the micro-macro scale [12].

The contact models of two rigid disks illustrated in Figure 1 are composed of normal, tangential and rolling contact components. The mechanical responses of each component are presented in Figure 1. The normal contact model resists normal pressure which is proportional to the normal stiffness $k_n$ and the amount of particle overlap $u_n$, as shown in Eq. (1).

$$F_n = k_n \times u_n$$

The tangential force is proportional to the tangential displacement $u_t$ and the tangential stiffness $k_s$, as illustrated by Eq. (2), maintains constant when it reaches to the maximum value that is calculated by friction coefficient multiplied by the normal contact force.

$$F_t = k_s \times u_t$$

The rolling contact model is characterized by the stiffness parameter $k_m$, which is dependent on rolling resistance coefficient $\beta$, particle contact normal stiffness $k_n$, and the common radius $r$. The rolling resistance maintains at a value in Model 1 or abruptly reduces to zero in Model 2 after reaching a critical relative rotation angle $\theta_r$. Model 1 is adopted in this paper, thus the moment is calculated by Eq. (3) as follows:

$$M = \begin{cases} K_n \theta - \frac{\theta \times k_s \times r^2 \times \beta^2}{12}, & \theta \leq \theta_r, \\ M_s = \frac{1}{6} [F_x \times r \times \beta], & \theta > \theta_r. \end{cases}$$

where $r$ is the average radius of the two contact particles, namely:
where \( r_1 \) and \( r_2 \) are the radius of two contact particles respectively.

\[
 r = \frac{2r_1r_2}{r_1 + r_2}. \tag{4}
\]

Figure 1. Schematic illustration of the contact model proposed for grains and its mechanical response: (a) Normal direction; (b) Tangential direction; (c) Rolling direction [10]

3. Biaxial compression tests

Twelve numerical simulations were conducted to study the frictional behavior of the granular materials incorporating the rolling resistance model. Each specimen has a height of 80mm and a width of 40mm, and is composed of 6,000 particles. The materials are all composed of discs with a maximum diameter of 9.0mm, minimum diameter of 6.0mm, and an average grain diameter \( d_{50} = 7.6 \text{mm} \). The initial void ratio is 0.30. The friction coefficient between particles is chosen to be 0.5. The normal and tangential stiffness of particles are \( 1.5 \times 10^8 \text{N} \cdot \text{m}^{-1} \) and \( 1.0 \times 10^8 \text{N} \cdot \text{m}^{-1} \), respectively. The biaxial compression tests under different confining pressures (i.e., 100kPa, 200kPa, and 400kPa) and different rolling resistance coefficients (i.e., 0, 0.4, 0.8 and 1.2) are conducted to obtain mechanical parameters of specimens. Figure 2 shows the deviator stress axial strain and volumetric strain responses obtained from the DEM biaxial compression tests with different \( \beta \) under confining pressure of 200kPa. The sample with \( \beta = 0 \) shows strain hardening and shear contraction while other specimens (i.e., \( \beta = 0.4, 0.8 \) and 1.2) shows a behavior of strain softening and shear dilatant. With the increases of \( \beta \), the strain softening and shear dilatant response are more distinct. Figure 3 presents that the peak and residual frictional angle of the soil with the variations of \( \beta \). The peak and residual internal frictional angles both increase with the increases of \( \beta \).

Figure 2. The mechanical response under different rolling resistance coefficient: (a) deviator stress strain response; (b) volumetric strain response
Figure 3. Relationship between the peak and residual internal friction angle and rolling resistance coefficient $\beta$

4. DEM simulation of vibroflotation

The Multi-layer under-compaction technique (UCM) [13] is chosen to produce the ground. The original ground size is 0.5 m × 0.14 m. Under the action of 20 g gravitational field, the real size of ground is 10 m × 2.8 m. It is composed of 500,000 particles.

This paper aims to simulate the process of vibroflotation without backfill. Note that the stage of the penetration of the vibrator into the ground is ignored. First, a square with 0.2 m long is generated by command clump in the commercial software PFC to represent the vibrator, and the center is located in the point of (5.0, 1.6). Then, as shown in Figure 4, 14 measurement circles (M1-M14) are arranged around the vibrator to monitor the variations of each variable. The vibrator vibrates in the horizontal direction, i.e., the direction from M3 to M6, in accordance with actual circumstances. Figure 5 shows the variation of the loading velocity chosen. Positive velocity represents the vibrator moves left, and vice versa. The amplitude of vibration is similar to that of actual vibrator. In addition, corresponding to soils above the ground water, the density of granular soils below the ground water is set to effective unit weight without changes of any other parameters. The influence of excess pore water pressure, which could occur in the process of vibration, is not considered here in the DEM simulations.

Figure 4. The ground sample and layout of measurement circles

Figure 5. The variation of the loading velocity
5. DEM simulation results

5.1. Force chains

The force chains of the sample under different circumstances are similar, thus we only present the force chains above the ground water at different times under the rolling resistance coefficient of $\beta = 0.8$, as shown in Figure 6. The black line presents the direction of the pressure and the width presents its size. The color of the force chains in the ground sample are deepen from up to down, which shows the increase of pressure in accordance with actual ground under gravity. As demonstrated in Figure 6, the pressure acts on the left side of the specimen and the value of the force chains is larger than that of the other side when the vibrator moves to the left, i.e., $t = 0.1\ s, 0.3\ s,$ and $0.5\ s$. Thus the soil on the left side is compacted. Correspondingly, when the vibrator moves to the right, i.e., $t = 0.2\ s, 0.4\ s,$ and $0.6\ s$, the force chains concentrate and deepen due to the effect of the vibrator on the right soil.

![Figure 6. Force chains in the ground without water during the vibroflotation process ($\beta = 0.8$).](image)

5.2. Void ratio distributions

Figure 7 presents the variations of the void ratio monitored by 14 measurement circles with different values of $\beta$ under two conditions, i.e., below or above the ground water. Typical measurement circles (i.e., M1, M2, M4, M7, M9, and M13) that represent the near, down, up, and far fields around the vibrator, respectively, are selected to analyse the changing void ratio. As illustrated in Figure 7, the void ratios in all of the measurement circles reduce in the vibroflotation process. Note that the initial void ratios in each measurements are less than the initial void ratio of the sample, and this is due to consolidation process under gravity.

As shown in Figure 7 (a), the variation of void ratio in M1 shows fluctuation up and down. During the first 0.1 s, the reduction of void ratio is due to the vibrator is moving to the left side and the soil in the left part is strengthened. Then the void ratio of M1 increases when the vibrator takes part in the soil compaction of the right side from the time of 0.1 s to 0.2 s. With the vibrator moves in the reciprocating way, accordingly, the void ratio of M1 fluctuates. Figure 7 (b) shows that the void ratio in M2 reduces when the vibrator moves to the left in the first 0.1 s and then rebounds to a relatively lower value in the next 0.1 s. In the next several loops, the void ratio in M2 fluctuates to a lower level and the particles in that area are thus compacted.

Figure 7 (c) presents the void ratio in M4 keeps constant at first, due to the vibrator moves to the left initially, and then reduces similar to the variation of void ration in M1 or M2. The void ratios of M7 and M9 in Figure 7 (d)-(e) show that the soil is strengthened below and above the vibrator.
Figure 7. Variation of the void ratio near the vibrator under different rolling resistance coefficients.

However, in M13, little fluctuations and reductions of void ratio are observed in both two conditions with different rolling resistance coefficients. Therefore, we can conclude that in that area far from the vibrator, it is of no significance to improve the compaction of the ground. Note that the slight difference of initial void ratio is owing to the different position of measurement circles.

The variation of the void ratio above the ground water are greater than that of below the ground water due to the better reinforcement effect. Note that the wet vibration modeled by using effective unit weight considers the buoyancy factor that could be used as a comparison. This is a simplified way to initially consider the effect of water.

6. Discussion on main limitations

The purpose of this paper is to initially analyse the macro-micro mechanics of soil during vibroflotation using DEM for two cases (i.e., the dry vibrations and wet vibrations). For wet vibrations, using effective
unit weight is a simplified way to consider the influence of water. However, under dynamic vibration, granular soil is easily liquefied due to built-up excess pore water pressure. In order to more truly simulate the vibroflotation and analyze the possible arising liquefaction, CFD-DEM could be used to analyze the coupling effect between water and soil particles. The limitations stated above need to overcome in the near future.

7. Conclusion
This paper simulates the vibroflotation process without backfill using the 2D DEM. Rolling resistance model is introduced in the DEM to better reflect the actual soil characteristics. Macro and Micro mechanisms of the vibration process are investigated. The main results are as follows: (a) The force chains show that the reinforcement effect on the ground using the vibroflotation method result from the compaction of soil particles around the vibrator. (c) The horizontal vibration of the vibrator has different reinforcement effect on the surrounding soils. The further the measurement are located from the vibrator, the smaller the variation of void ratio is. (d) Generally speaking, considering the effect unit weight of granular soil will reduce the vibroflotation reinforcement effect and the real interaction between excess pore water and soil particles is not considered in this paper.

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