Numerical study of the dynamic compaction via DEM

Zongyuan Ma i), Hongjian Liao ii), Chunming Ning iii) and Lei Liu iv)

i) Lecturer, Institute of Geotechnical Engineering, Xi’an University of Technology, 5 South Jinhua Road, Xi’an, 710048, China
ii) Professor, Department of Civil Engineering, Xi’an Jiaotong University, 28 Xianning West Road, Xi’an, 710049, China
iii) Senior Engineer, Department of Capital Construction, Xi’an Jiaotong University, 28 Xianning West Road, Xi’an, 710049, China
iv) Lecturer, Shaanxi lifegen co, Ltd., Northwest University, Taibai north road 229, Xi’an, 710069, China

ABSTRACT

Based on the rapid impact compaction (RIC) technique, the dynamic compaction process of gravel soil ground and dynamic interaction between the concrete bridge foundation and the soil were simulated using the particle flow discrete element method (DEM). The improvement effect and the influence depth of the dynamic compaction of the gravel soil foundation were analyzed based on the porosity variation of the foundation soil during the dynamic compaction process. The influence of the dynamic compaction on the bridge foundation was also analyzed in this study. The feasibility of the numerical simulation for the dynamic compaction process of the gravel soil ground and dynamic interaction of the soil-structure were discussed.

Keywords: gravel soil foundation; dynamic compaction; particle flow distinct element; soil-structure interaction

1 INTRODUCTION

The ground is usually improved for surface soil compaction by static or dynamic rollers with different types of exciters and drum shapes. The improvement depth for the ground by static or dynamic rollers is limited to relatively low values (the maximum depth is approximately 0.2 to 1.0 m). Dynamic compaction (DC) is a type of ground improvement method that uses heavy tamping techniques, and these methods usually reach a depth of approximately 10 to 20 m (Gu and Lee 2002; Harder and Seed 1986). The rapid impact compaction (RIC) technique is an innovative method for dynamic compaction based on a piling hammer, which is used to increase the strength and the dry density of soils (Kristiansen and Davies 2004; Serridge and Synac 2006). Generally, this method consists of dropping a falling weight from a relatively low height onto the ground at a fast rate. The weights of hammers range from approximately 3 to 9 t and are dropped from falling heights between 1 and 2 m. A comparison to other dynamic compaction techniques shows that RIC is an ideal treatment for near-surface compaction near the bridge or buildings.

The improvement effect for clay or silt ground can be easily assessed via the dry density of soil, and the porosity is a reasonable parameter to evaluate the improvement effect for gravel soil ground (Harder and Seed 1986). The stress distribution or deformation of the foundation under dynamic load can be easily obtained by the numerical or analytical method in continuum mechanics (e.g. finite element method FEM). However, the improvement effect of dynamic compaction for gravel soil ground is difficult to analyze using the numerical or analytical method in continuum mechanics. The porosity of gravel soil can be easily calculated via the discrete element method (DEM) with discontinuous deformation analysis algorithm. Cundall and Strack proposed a new discrete element method named particle flow discrete element method (Cundall and Strack 1979). The mechanic behavior of granular material (e.g. gravel soil, sand or rocks) can be easily simulated by the particle flow discrete element method. Cheng et al. (Cheng, Nakata and Bolton 2003) simulated a conventional tri-axial test of agglomerate crushing soil using a three-dimensional particle flow discrete element method. Iwashita and Oda simulated the shear band development of sand using a two-dimensional particle flow discrete element method (Iwashita and Oda 1998). Wada investigated the impact cratering process of granular material using a two-dimensional particle flow discrete element method (Wada, Senshu and Matsui 2006). Jiang studied the cone penetration tests for sand via a two-dimensional DEM code (Jiang, Yu and Harris 2006). The process of dynamic compaction for gravel soil ground is investigated by Ma using the particle flow discrete element method (Ma, Dang and Liao 2006).

This study aimed to investigate the improvement effect of dynamic compaction for gravel ground and dynamic interaction of the soil-structure using the
particle flow discrete element method (DEM). Based on the technique of RIC, a series of numerical computations are presented to reproduce the process of dynamic compaction, and the improvement effect of gravel ground was evaluated via the porosity variation of gravel soil at different depths.

2 NUMERICAL METHOD AND PROCEDURE

PFC2D is a two-dimensional particle flow discrete element code with an explicit computation scheme. The movement and interaction of particles with circular geometry (balls) is directly calculated in large deformation mode by solving the equation of motion for each particle in PFC2D, in which the mechanical interactions can be considered between particles in contact (ITASCA Consulting Group 1998). For two dimensional problems, the particles can be treated as disks (with unit thickness) or spheres in PFC2D. Every ball has three degrees of freedom (two degrees of freedom in displacement and one degree of freedom in spin) in PFC2D. For the linear contact relationship of two cohesionless balls contact, the contact stiffness, $k$, relate the contact forces and displacements in the normal and shear directions following Eq.(1):

$$F_n = k_n U_n, \quad F_s = k_s U_s, \quad F = \mu F_n$$

where $F_n$ and $F_s$ are the total normal force and the total shear force for two balls in contact, $U_n$ and $U_s$ are the total normal displacement and the total shear displacement, $k_n$ and $k_s$ are the normal stiffness and the shear stiffness, and $\mu$ is the friction coefficient.

The dynamic hysteretic relationship for particles contact is shown in Fig.1. The normal stiffness on loading, $k_{n\_load}$ and unloading, $k_{n\_unload}$ used in the hysteretic damping model are calculated using the following equation:

$$k_{n\_load} = \frac{2R_h k_m}{1+R_h}, \quad k_{n\_unload} = \frac{2k_m}{1+R_h}$$

where the parameter $R_h$ is the ratio of $k_{n\_load}$ to $k_{n\_unload}$ (1.0 $\leq R_h < 0.0$). The dynamic hysteresis effect of the soil is more apparent when the $R_h$ is close to zero. The parameter $km$ is the average normal stiffness of $k_{n\_load}$ and $k_{n\_unload}$. The normal stiffness on unloading is greater than that on loading in the dynamic contact process, and a simple hysteresis loop is formed by the linear contact relationship for particles on loading and unloading. For cohesionless ball contacts (no tension strength), e. g. granular material, the hysteresis loop only occurs in the positive axis of the contact force.

3 RESULTS AND DISCUSSION

3.1 Improvement effect of dynamic compaction

In this study, the particles of the gravel soil are treated as spheres. The particle model of the gravel soil ground was created based on the gravity sedimentation in the space enclosed by the walls. The particles were released and floated in the designated space free from gravitational influence, and the particles fell to the bottom of the space when the gravity was activated (the acceleration of gravity was set to 10.0 m/s$^2$ in this study). An interval of particle radii was specified with a minimum and maximum radius to generate particles according to a random distribution.

The two-dimensional particle model of the gravel soil ground created by the gravity sedimentation method is shown in Fig. 2. The hammer for dynamic compaction was simulated by a ball with a radius of 0.5 m. The drop height of the hammer was 2.0 m, and the time of hammer lift
equaled to the time of hammer drop. The values of the normal stiffness, \(k_n\), and the shear stiffness, \(k_s\), for ball-to-ball and ball-to-wall contact were equivalent in this study. The initial values of the parameters for the computations were specified as follows: radius interval \(r=0.05\) to \(0.1\) m, friction coefficient \(\mu=0.5\) and \(R_0=0.5\). Fig. 2 also shows a measurement circle for a porosity calculation. For two-dimensional problems, the porosity of the particles assembly is defined as the ratio of the total void area within the measurement circle to the circle area:

\[
n = \frac{A_{\text{void}}}{A_{\text{circle}}} \times 100\% = \frac{A_{\text{void}}}{A_{\text{void}} + A_{\text{particles}}} \times 100\% \tag{3}
\]

where \(A_{\text{circle}}\) and \(A_{\text{void}}\) are the area of the measurement circle and the voids, and \(A_{\text{particles}}\) is the area of the measurement circle occupied by the particles. For three-dimensional problems, the porosity of the particles assembly is calculated by the measurement sphere. The porosity of the soil defined in soil mechanics is shown in the following formula:

\[
n = \frac{V_{\text{void}}}{V_{\text{total}}} \times 100\% = \frac{V_{\text{void}}}{V_{\text{total}} + V_{\text{particles}}} \times 100\% \tag{4}
\]

As Eq. (3) and Eq. (4) show, the definition of the porosity of the particles assembly in the PFC code is equivalent to that of the soil mechanics.

The influence of the values of the contact mechanical parameters on the computation results of dynamic compaction was analyzed in this study. The values of the other parameters for the computation were fixed at their initial values when the value of a parameter was changed for analysis. The calculate results of this study shows that the initial porosity of the gravel ground positively correlated with the values of the contact stiffness, \(k\). The calculate results of this study also shows that the values of the friction coefficient, \(\mu\), only slightly influenced the porosity variations of the foundation soil after several cycles of compaction.

The porosity reduction, \(\Delta n\), (the initial porosity, \(n_0\), minus the current porosity, \(n\)) varied as the number of compaction steps increased for gravel soil ground as shown in Fig. 3 for hammers weight and contact stiffness, \(k\). Fig. 3(a) shows that the porosity reduction, \(\Delta n\), of the gravel soil at the same depth positively correlated with the values of contact stiffness, \(k\). Fig. 3(b) shows the relationship between the porosity reduction, \(\Delta n\), of the ground and the number of compaction cycles for different hammer weights. The porosity reduction, \(\Delta n\), of the foundation soil is increased significantly with the increasing values of the hammer weight. The regularity of the porosity and the particle radius indicated that the improvement effect of the dynamic compaction will be enhanced if the grain composition of the gravel soil is more disparate. A uniform grain composition of the gravel soil will yield a poor improvement effect.

![Porosity reduction, \(\Delta n\), for gravel soil ground versus number of compaction steps with different contact stiffness, \(k\), and hammer weights.](image)

**Fig. 3.** Porosity reduction, \(\Delta n\), for gravel soil ground versus number of compaction steps with different contact stiffness, \(k\), and hammer weights.

### 3.2 Influence of dynamic compaction on bridge foundation

The two-dimensional particle model of the gravel soil ground and the concrete bridge foundation is shown in Fig. 4. The concrete bridge foundation is consisted by the close-packed arrays particles with equivalent size. The drop height of the hammer also was 2.0 m. The initial values of the parameters for the computations were specified as follows: radius interval \(r=0.05\) to \(0.2\) m, contact stiffness \(k_0=k_0=5.0 \times 10^6\) N/m=5.0 MN/m, friction coefficient \(\mu=0.5\). Several measure circles were set in the bridge foundation to calculate the dynamic horizontal stress induced by the dynamic compaction. The average stress \(\bar{\sigma}_{ij}\) calculated by the measure circles is following the equation (Eq. 5).

\[
\bar{\sigma}_{ij} = -\left(1 - \frac{n}{\sum V(p)}\right) \sum_{p} \sum_{c} x_i^{(c)} - x_i^{(p)} \kappa_j^{(c,p)} e_j^{(c)}
\tag{5}
\]
where the average stress is the summations of the $N_p$ balls with centroids contained within the measurement circle and the $N_c$ contacts of these balls; $n$ is the porosity within the measurement circle; $V_{p_0}$ is the volume of particle (p), taken equal to the area of particle (p) with unit-thickness; $x_{c_i}$ and $x_{p_i}$ are the locations of a particle centroid and its contact; $n_{p(c)}^{(p)}$ is the unit normal vector directed from a particle centroid to its contact location; and $F_{c_i}$ is the force acting at contact (c) arising from both particle contact and parallel bonds.

Fig. 4. Particles model of gravel soil ground and bridge

Fig. 5 shows the relationship of the dynamic horizontal stress in different depth for concrete bridge foundation versus the number of compaction steps with different hammers weights. Fig. 6 shows the contact force between the compaction hammer, gravel soil and bridge foundation. The dynamic stress in the concrete bridge foundation induced by the dynamic compaction is increased significantly with the weight of the compaction hammer raised. The same problem is analyzed using the explicit finite element method with the elastic soil and bridge foundation model. The maximum dynamic stress in bridge foundation during the dynamic compaction process is about 450kPa. The dynamic horizontal stress of the bridge foundation calculated by DEM is relatively smaller than that of the results obtained by the numerical method in continuum mechanics (e.g. FEM). The gravel soil is consisted by the discrete stone particles, and the dynamic compaction energy is dissipated by the contact and impaction of those stone particles. However, most of the dynamic compaction energy will be transmitted though the continuum media, such as clay or silt, and the influence of the dynamic compaction on bridge foundation will be enhanced.
4 CONCLUSIONS

Numerical simulations of the dynamic compaction process for gravel soil ground and soil-structure interaction for bridge foundation were studied in this paper via DEM based on the technology of rapid impact compaction. The following conclusions could be drawn:

(1) The dynamic compaction process for gravel soil ground can be reproduced via DEM. The improvement effect and the maximum influence depth of the dynamic compaction can be easily evaluated via the porosity changes of the gravel soil obtained by DEM.

(2) The porosity reduction of the gravel soil induced by dynamic compaction is influenced by the values of the contact stiffness of the gravel particles.

(3) The dynamic horizontal stress of the bridge foundation calculated by DEM is smaller than that of the results obtained by the numerical method in continuum mechanics (e.g. FEM). The dynamic soil-structure interaction of the dynamic compaction in gravel soil will be lower than that of the clay or silt.

ACKNOWLEDGEMENTS

The research described in this paper was funded by the National Nature Science Foundation of China (No. 41172276, 51279155), and Natural science projects of education department of Shaanxi province China (No. 14JK1547).

REFERENCES

1) Cundall, P.A., Strack, O.D.L. (1979): A discrete numerical model for granular assemblies. Geotechnique, 29: 47-65.
2) Cheng Y.P., Nakata Y., Bolton M.D. (2003): Discrete element simulation of crushable soil. Geotechnique, 53: 633-641.
3) Gu, Q., Lee, F.H. (2002): Ground response to dynamic compaction of dry sand. Geotechnique, 52: 481-493.
4) Harder, L.F., Seed, H.B. Determination of penetration resistance for coarse-grained soils using the Becker hammer drill. Earthquake Engineering Research Center, Report No. UCB/EERC-8606, 1986.
5) Hardin, B.O., Drnevich, V.P. (1972): Shear modulus and damping in soils: measurement and parameter effects. Journal of the Soil Mechanics and Foundation Engineering Division, ASCE, 98: 603-624.
6) ITASCA Consulting Group. Particle Flow Code in 2 Dimensions, version 3.1, user's manual. ITASCA Consulting Group, Minneapolis, 1998.
7) Iwashita, K., Oda, M. (1998): Rolling resistance at contacts in simulation of shear band development by DEM. Journal of Engineering Mechanics, 124: 285-292.
8) Jiang, M.J., Yu, H.S., Harris, D. Discrete element modelling of deep penetration in granular soils. International Journal for Numerical and Analytical Methods in Geomechanics, 30(2006): 335-361.
9) Kristiansen, H., Davies, M. (2004): Ground improvement using rapid impact compaction. The 13th World Conference on Earthquake Engineering, Vancouver, Canada, Paper No. 496.
10) Ma, Z.Y., Dang, F.N., Liao, H.J. (2014): Numerical study of the dynamic compaction of gravel soil ground using the discrete element method. Granular Matter, 16(6): 881-889.
11) Serridge, C.J., Synac, O. (2006): Application of the Rapid Impact Compaction (RIC) technique for risk mitigation in problematic soils. The 10th IAEG International Congress, Nottingham, United Kingdom, pp. 1-13.
12) Wada, K., Senshu, H., Matsui, T. (2006): Numerical simulation of impact cratering on granular material. Icarus, 180: 528-545.