Efficiency of dynamic compaction on high backfilled ground in VSC-HVDC BTB convertor station

YANG Jinhu1*, ZHAI Wei1, JIANG Wen1, XU Guangbing1

1Hubei Electric Engineering Corporation, Wuhan, 430040, China
*Corresponding author’s e-mail: yangjh@heec.com

Abstract. To evaluate the effect of dynamic compaction on high backfilled ground in VSC-HVDC BTB convertor stations, a modified numerical simulation procedure was proposed with the changes of stiffness and strength considered reasonably. Simulation results show that dynamic compaction is substantially efficient to high backfilled ground treatment in VSC-HVDC BTB convertor stations. There are critical tamping times in dynamic compaction. When tamping times are higher than the critical number, further increase of tamping times contribute little to the holistic improvement of foundation. With the increase of drop energy, the bearing capacity of the improved ground raises exponentially. These findings can be helpful for the foundation design of future VSC-HVDC BTB convertor stations.

1. INTRODUCTION
The increasing progress of high voltage direct current (HVDC) technology continually have a significant impact on the development of relevant facilities. For instance, with the increase in quantity and scale of HVDC convertor stations, the construction sites have begun to advance unfavorable areas such as ravines where deep valleys must be backfilled to level grounds. This leads to greater challenges in the settlement control of foundations. Generally, high backfilled grounds need to be improved in advance to reduce the long-term settlement, and dynamic compaction method is a feasible improvement technology.

Plenty of existing studies have investigated the improvement mechanism and efficiency of dynamic compaction method at different angles. Chow and Yong[1] established a simplified model for ground stress and displacement analysis based on the one-dimensional wave equation, which accounts for the interaction of rammer and soil and the propagation of stress wave in soil during dynamic compaction. Gu et al.[2] studied the mechanics of dynamic compaction via two-dimensional finite element analysis with a large-strain dynamic formulation and a cap model of soil behavior. Kong and Yuan[3,4] proposed solutions of the surface contact stress distribution for multi-layered ground, which combined the rammer rigid kinetic equation and the transform matrix method of three-dimensional (3-D) axisymmetric elastodynamics, but these solutions did not account for the plastic deformation of soil. Jiang et al.[5] adopted the geometric nonlinear finite element method (FEM) to simulate the dynamic compaction process, which took into account the rammer weight but overly simplified the nonlinear governing equation.

Above research outcomes have roughly revealed the fundamental mechanism of dynamic compaction method. Nevertheless, these studies tend to take little account of the actual changes of stiffness and strength in improved regions during dynamic compaction. However, the modulus and strength of soil will increase gradually during the ground improvement process, and the analysis results depend heavily on these soil parameters. Therefore, previous studies which neglected the actual changes...
of soil parameters tended to give rise to unreasonable conclusions. To overcome above limitations, a modified numerical simulation procedure considering the changes of stiffness and strength during dynamic compaction was developed and adopted to evaluate the efficiency of dynamic compaction on high backfilled ground in a VSC-HVDC BTB convertor station.

2. NUMERICAL SIMULATION MODEL

2.1 Problem description
This VSC-HVDC BTB convertor station is to be constructed in Enshi, China. Figure 1 shows the soil profile of a target cross-section in the construction site. At this target cross-section, the hill-cutting materials (gravels) will be backfilled layer by layer and over the natural ground mainly composed of completely and heavily weathered limestones with a maximum filling depth of approximately 32m. Dynamic compaction method is to be employed to improve each filling layer. After the ground being filled to designed elevation, facilities related to the VSC-HVDC BTB convertor station such as electric reactor and valve hall will be built on the high backfilled ground. According to the preliminary design, the raft foundations will be used for light facilities such as electric reactors, while the pile foundations for heavy and important facilities such as valve hall. The raft foundations are embedded 1.5m below the surface, and the bearing capacity characteristic value of subsoil is required to be higher than 150kPa. The completely and heavily weathered limestones are taken as the bearing stratum for pile foundations, which means the pile length will reach around 32m. The designed pile diameter is 0.8m, and the required bearing capacity characteristic value of single pile is higher than 1500kN.

The following problems to be resolved include the analysis of ground response during dynamic compaction and the evaluation of ground bearing capacity after treatment. The bearing capacities of backfilled ground and pile foundation are characterized by a numerical bearing plate test and a numerical single pile static load test, respectively. The testing points are also shown in Figure 1.

2.2 Simulation model and parameters
The computational domain for numerical simulation is 80m in transverse section (X-axis) and 52m in height (Z-axis). The longitudinal (Y-axis) dimension is equal to the tamping grid spacing, representing the equivalent improvement region of a row of tamping points. Figure 2 illustrates the meshes of aFLAC3D model for the reference case. The soil is modeled by solid elements following Mohr-Coulomb yielding criteria. The pile is assumed to be elastic and modeled by structural elements (PileSELs). The engineering properties of all materials involved are summarized in Table 1.

![Fig. 1 Soil profile of a target cross-section in the construction site](image-url)
Fig. 2 3-D numerical simulation model

Every compactions are simulated by applying a distributed instantaneous load on the regional surface corresponding to tamping points. The determination of instantaneous load will be depicted in the next subsection. The rammer size is 2m×2m, and the tamping points are arranged on each backfilled layer surface and middle planes along Y-axis. Pile and bearing plate testing points are both located on the middle planes along Y-axis.

The bottom boundary of simulation model is fixed and the side boundaries are laterally constrained.

Table 1 Engineering properties of materials

|        | \( \rho \) (kg/m\(^3\)) | \( c \) (kPa) | \( \phi \) (°) | \( p_t \) (kPa) | \( E \) (MPa) | \( \nu \) |
|--------|-----------------|-------|------|-----------|--------|-------|
| Limestone | 2200            | 100   | 35   | 100       | 1300   | 0.28  |
| Backfilled gravel (initial) | 1800 | 2     | 30   | 5         | 18     | 0.35  |
| Pile | 2500            | N.A.  | N.A. | N.A.      | 30000  | 0.20  |

Note: \( \rho \) = density, \( c \) = cohesion, \( \phi \) = internal frictional angle, \( p_t \) = tensile strength, \( E \) = Elastic modulus, and \( \nu \) = Poisson's ratio

2.3 Dynamic compaction load

According to the field monitoring results reported previously\cite{6,7}, the pulse load generated by dynamic compaction can be simply characterized as a triangular dynamic load shown in Figure 3. The duration \( t_N \) depends on the characteristics of ground and rammer, and is assumed to be 0.1s in this study\cite{7}. The maximum contact stress \( P_{\text{max}} \) can be determined by following empirical formula\cite{8}:

\[
P_{\text{max}} = \frac{v_0 \sqrt{mS}}{\pi r^2}
\]

where \( v_0 \), \( m \) and \( r \) are respectively the landing velocity (m/s), the mass(kg) and the equivalent radius(m) of rammer, and \( S \) equals to \( 2\pi E/(1-\mu^2) \).

Fig. 3 Dynamic compaction load characteristic

2.4 Evolution modes of soil modulus and strength parameters

Figure 4 is a schematic of the improvement effect of dynamic compaction. With the increase in tamping energy and tamping times, the range of plastic zone (treatment zone) continues to extend. Because of the
input energy, the micro-structure of soil inside the plastic zone is destructed and the soil particles tend to be re-arranged in a denser manner, thereby the engineering properties of soil inside the plastic zone will be enhanced.

In this numerical model, the range of plastic zone is recorded after each dynamic compaction, then the engineering properties of soil inside the plastic zone are updated to reflex the improvement effect, while those of the soil outside the plastic zone are kept constant. The ground response under the action of next dynamic compaction is analyzed through the updated model. The evolution process of engineering properties of the soil inside the plastic zone is shown in Fig. 4.

![Diagram](image)

*Fig. 4 Improvement effect of dynamic compaction*

The quantitative evolution trend of modulus and internal frictional angle of the plastic zone can be expressed by a empirical formula recommended by Qian and Shuai [9]:

\[ X = X_0 (N - n)^\alpha \] (2)

where \( X \) is the updated modulus or internal frictional angle, \( X_0 \) the initial modulus or internal frictional angle, \( N \) the tamping times, \( n \) the minimum tamping times required for driving a soil element into plastic state, and \( \alpha \) the empirical coefficient. In this paper, \( \alpha \) is 0.5 for modulus and 0.15 for internal frictional angle.

The backfilled soil belongs to non-cohesive gravel with stable soil cohesion. Therefore, the soil cohesion during the dynamic compaction is set to be constant during the entire modeling process.

### 2.5 Modeling program

Single-point tamping times, tamping grid spacing and drop energy are considered as variables in this paper. All modeling cases are listed in Table 2, and the meshes of models in different modeling cases are different.

| Case No. | Grid tamping | Single-point tamping times | Tamping grid spacing (m) | Drop energy (kN.m) | Full compaction |
|----------|--------------|---------------------------|--------------------------|-------------------|----------------|
| 1        |              | 6                         | 8                        | 4000              |                |
| 2        |              | 8                         | 8                        | 4000              |                |
| 3 (Reference case) | | 10                        | 8                        | 4000              |                |
| 4        |              | 12                        | 8                        | 4000              |                |
| 5        |              | 10                        | 8                        | 3000              |                |
| 6        |              | 10                        | 8                        | 2000              |                |
| 7        |              | 10                        | 8                        | 1000              |                |
| 8        |              | 10                        | 10                       | 4000              |                |
| 9        |              | 10                        | 6                        | 4000              |                |

Drop energy: 1000kN.m; Single-point tamping times: 2; Imprint overlapped
3. RESULT ANALYSIS AND DISCUSSION

3.1 Results of the reference case

Modeling results for the reference case (Case No. 3) are analyzed in this subsection to demonstrate the fundamental response of backfilled ground during compaction and the improvement efficiency after compaction.

(a) Development of plastic zone during compaction

Figure 5 depicts the ranges of plastic zones developed below a single tamping point respectively after 1, 5, 8, 10 times of compactions in the reference modeling case (Case No. 3). The plastic zones corresponding to different tamping times are similar and bell-shaped. The area of plastic zone expands significantly with the increase in tamping times when the tamping times are less than 8 times, whereas it increases marginally when the tamping times exceed 8 times, indicating that there is a critical tamping times (around 10 for the reference case), beyond which the range of plastic zone tends to be stable. In other words, when the tamping times are higher than the critical value, further increase in tamping times contribute little to the holistic improvement efficiency. Figure 5 also shows the effective improvement depth for reference case is around 7-8m.

(b) Development of settlement during compaction

Figure 6 presents the settlement changes of tamping pit in the reference modeling case (Case No. 3) during dynamic compaction. The settlement of tamping pit tends to increase with the backfilled thickness. Under the same situation, the settlement of tamping pit on the 4th backfilled layer surface is approximately 50% higher than that on the 1st. Moreover, the settlement of tamping pit develops rapidly with the tamping times first and then tends to approach a constant value, also indicating that single increase of the tamping times may contribute little to the holistic improvement efficiency.

Figure 7 shows the settlement curves at different depths below a 10-time tamping pit. With the increase in depth, the settlement decreases significantly and becomes smoother and smoother.
Fig. 6 Settlement of the tamping pit during compaction

Fig. 7 Settlement of the subsoil below a 10-time tamping pit

(c) Bearing capacity after compaction

Figure 8 shows the loading-settlement curves obtained from numerical bearing plate tests respectively performed on the backfilled ground without compaction and the improved ground by dynamic compaction, which indicates the substantial improvement efficiency of dynamic compaction. Compared with the case without foundation treatment, the bearing capacity characteristic value of the improved ground increases by 65% from around 200kPa to around 330kPa.

Fig. 8 Loading-settlement curves obtained from the numerical bearing plate tests
Figure 9 shows the loading-settlement curves obtained from static load tests respectively performed on the single piles embedded in the unimproved ground and the ground improved by dynamic compaction. Similar to the results shown in Figure 8, the bearing capacity of improved single pile is evidently higher than the unimproved one. There are 2 reasons for the contribution of dynamic compaction to the bearing capacity of single pile, stiffness and strength growths of soil inside the plastic zone growth, which are undoubtedly beneficial to the pile bearing capacity; stress distribution change in the ground and higher confining stress around the pile shaft, which are useful for the mobilization of pile side friction.

Figure 8 and Figure 9 also demonstrate that the backfilled ground improved by dynamic compaction can meet the requirements of raft foundations designed for light facilities such as electric reactors and pile foundations designed for heavy or important facilities such as valve hall in a VSC-HVDC BTB convertor station. Therefore, the preliminary design is feasible.

Figure 10 shows the loading-settlement curves obtained from Case No. 3 and Cases No. 5-7 with different magnitudes of drop energy, indicating the drop energy fundamentally influences the bearing capacity of the ground improved by dynamic compaction that the bearing capacity of improved ground increases exponentially with the increase of drop energy.

3.3 Effect of single-point tamping times
Figure 11 shows the loading-settlement curves obtained from Cases No. 1-4 with different single-point tamping times. The higher single-point tamping times give rise to the greater bearing capacity. However, once the tamping times are more than 10, further increase in tamping times barely effect on the bearing capacity of improved ground. Because the plastic zone is pretty large at that time to absorb most of the input energy by later tamping drops at that time, and thus cannot further expand.
Fig. 10 Effect of drop energy on the improvement efficiency of dynamic compaction

Fig. 11 Effect of single-point tamping times on the improvement efficiency of dynamic compaction

3.4 Effect of tamping grid spacing
Figure 12 illustrates the effect of tamping grid spacing on the improvement efficiency of dynamic compaction (Cases No. 3, 8 and 9), which is evident when greater than 8m. Smaller tamping grid spacing produces higher bearing capacity. However, the influence of tamping grid spacing becomes marginal when it is smaller than 8m. One possible reason is that when the tamping grid spacing is smaller enough, the plastic zones beneath 2 adjacent tamping points has been horizontally overlapped, and thus the further decrease in tamping grid spacing can’t effect evidently on the range of plastic zone in the whole computational domain.

Fig. 12 Effect of tamping grid spacing on the improvement efficiency of dynamic compaction
4. CONCLUSIVE REMARKS
A modified numerical simulation procedure is proposed for ground improvement by dynamic compaction technology. In this procedure, the range of plastic zone is recorded after each dynamic compaction, and the engineering properties (stiffness and strength) of soil inside and outside the plastic zone are reasonably updated and kept constant, respectively, to show the improvement effect. The efficiency of dynamic compaction on high backfilled ground in a VSC-HVDC BTB convertor station is evaluated through this modified simulation procedure, and following conclusions may be drawn:

(1) The improvement efficiency of dynamic compaction is substantial for high backfilled ground. For the VSC-HVDC BTB convertor station in this paper, the backfilled ground improved by dynamic compaction can meet the requirements of raft and pile foundations respectively designed for heavy and light facilities.

(2) There is a critical tamping times, beyond which the range of plastic zone beneath a tamping point tends to be stable. When the tamping times are higher than the critical value, further increase in tamping times contribute little to the holistic improvement efficiency.

(3) Drop energy can fundamentally influences the bearing capacity of the ground improved by dynamic compaction. With the increase in drop energy the bearing capacity of improved ground increases exponentially.

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