Numerical simulation of dynamic responses caused by dynamic compaction on backfilling foundation

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Abstract

Since the ground vibration caused by dynamic compaction threatens the structures around the site, a dynamics numerical simulation of the process of dynamic compaction is carried out based on the dynamic compaction experiment in the backfill soil site with the Finite Element Method (FEM) software. The calculated results present the vibration-time curves in radial and vertical directions on the ground in different distances. The characteristics of the vibration-time curves and how the peak velocity and acceleration change with distance are analysed. By comparing the simulated results with field data, the reasons which cause the differences are pointed out. Through comparison it is considered that the near-field dynamic responses in the simulation are more reliable than the far-field ones. According to standards the safe distances of each type of structures are evaluated. The relationship between energy utilization and the vibration energy is discussed, and that raising the aspect ratio of the hammer can reduce vibration is pointed out.

Keywords: dynamic compaction, dynamic response, backfill soil, simulation

1 Introduction

Dynamic compaction is a method of foundation reinforcement that first proposed by L.Menard [1] in 1969. The method for its economy and simplicity are widely used in foundation of miscellaneous fill, loose sand, clay, etc. But in the process of impaction, due to the great stress on the contact surface caused by the powerful collision in a very short time, a strong stress wave is generated in the soil and spreads outward. When the wave transmits to the structures near the tamping point, the energy of wave enters the structures and causes the structures to vibrate. If the vibrational amplitude and frequency reach a certain condition, the structures will be damaged. Therefore, it is necessary to analyse the vibration response of dynamic compaction to avoid the threat to the surrounding structures.

Researches on the dynamic response in the foundation caused by the dynamic compaction are commonly in two ways – the on-site experiments and the theoretical analysis based on a certain mechanical model. Due to the complexity of the dynamic problem, it is difficult to use analytical method to describe the mechanical effects of dynamic compaction. But in this aspect there were some studies, like Scott [2] used lumped equivalent method to establish the motion equation of the hammer-soil system and got the displacement of tamped point; Mayne [3] according to the momentum theorem derived maximum contact stress between hammer and soil, the duration of contact and the maximum stress at a certain distance below the tamping point; Y.K.Chow [4] divided a cylinder which is the same diameter with the hammer from the soil and analysed the propagation characteristics of one-dimensional stress wave; Kong [5] according to the relationship between the contact stress and displacement, used Laplace-Hankle transform and transfer matrix method to solve the three-dimensional elastic dynamic equations , and got the stress distribution in the layered foundation. However, because of the complexity, the problem is commonly focused on a certain aspect and the model is simplified to meet the feasibility of analysis, like Scott's study only described one-dimensional motion of the hammer; the discussion in reference [5] is based on the assumption of linear elastic medium. These simplifications bring feasibility as well as limitation to the problem solving, so that the numerical simulation is considered as a better method in the research of dynamic compaction. In this aspect, many scholars have studied from different ways, like Niu [6] simulated the finite element dynamic compaction problems and gave the numerical solution of stress field, displacement field and acceleration field; Cai [7] obtained the deformation characteristics, reinforced depth and the stress distribution characteristics of dynamic compaction with large deformation finite element and boundary element method; Jiang[8] introduced the erosion element to eliminate the impact of mesh distortion and on this basis used large deformation finite element to simulate the deformation of tamped pit. Otherwise, there are some researches [9-11] that also have done remarkable works.

This paper in the background of a dynamic compaction project, according to the environmental characteristics of the reinforced area, establishes an axisymmetric FEM numerical model, and by means of FEM software, analyses the dynamic response of the process of dynamic compaction in the backfill foundation with the explicit algorithm which adapt to the large collisional deformation.

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Then in combination with the real-time monitoring results, the laws of dynamic response of backfill soil consolidation, as well as the influence on surrounding structures are discussed.

2 Analysis model of dynamic compaction

2.1 DYNAMIC EQUILIBRIUM EQUATION

In the process of dynamic compaction, the potential energy is converted into kinetic energy, and then spreads in the foundation under the damping of soil. So it should be simplified as a dynamic system and analysed with dynamic FEM.

For general dynamic FEM question, by Hamilton's principle [12] the dynamic equilibrium equation of system could be received.

$$\boldsymbol{M}\ddot{\boldsymbol{u}}+\boldsymbol{C}\dot{\boldsymbol{u}}+\boldsymbol{K}\boldsymbol{u}=\boldsymbol{Q}\,, \tag{1}$$

where $\boldsymbol{M}$ is the system mass matrix in which are the nodes mass coefficients of soil; $\boldsymbol{C}$ is the system damping matrix that relates to the damping properties of the soil; $\boldsymbol{K}$ is the system stiffness matrix which determined by mechanical parameters of the soil; $\boldsymbol{Q}$ is the equivalent nodal load vector; $\boldsymbol{u}$ is the nodal displacement vector of system.

2.2 NUMERICAL MODEL OF DYNAMIC COMPACTION

The geometric parameters of dynamic compaction model in this paper come from the project. According to the site situation (Figure 1), the model can be divided into hammer and soil in two parts and simplified as a axisymmetric model (Figures 2 and 3). In order to simulate the transmission effect on boundary, the part of soil is divided into finite element zone and infinite element zone.

As shown in Figure 4, the radius of whole model is 120m while the radius of finite element zone is 60m, and outside the zone is the infinite element zone so that the distance from the nodes in the extending direction of infinite element to the pole is twice the distance from the points in the interface to the pole. The function of infinite element is similar with damping boundary condition that when the wave transmits to the interface the reflected wave disappears.

FIGURE 1 The site of dynamic compaction construction

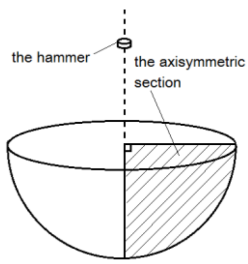


FIGURE 2 The schematic diagram of axisymmetric mechanical model of dynamic compaction

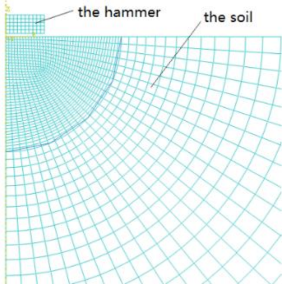


FIGURE 3 The mesh of the FEM axisymmetric mechanical model

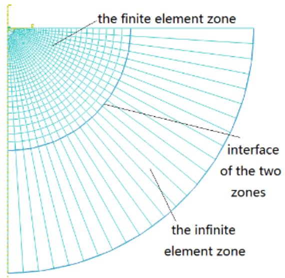


FIGURE 4 The finite element and Infinite element zone in the soil

2.3 CONSTITUTIVE MODEL OF SOIL

In FEM the Drucker-Prager model is often applied to the geo-material in simulation of elastic-plastic dynamic problem. This paper uses the linear Drucker-Prager model expanded from the classical Drucker-Prager model [13]. The yield function of this model is:

$$F=t-p\tan\beta-d=0\,, \tag{2}$$

where $t=\frac{q}{2}\left[\left(1+\frac{1}{k}\right)-\left(1-\frac{1}{k}\right)\left(\frac{J_3}{q}\right)^3\right]$, β is the dip angle of $p\sim t$ stress space that could be conversed by the friction angle; k is the intensity ratio of triaxial extension to triaxial compression; d is the intercept of the yield surface on the $p\sim t$ stress space. J_3 is the third invariant of the deviator stress tensor. The mechanical parameters of the backfill soil are shown in Table 1.

TABLE1 The main input parameters of the soil

Specific weight γ ($kN\cdot m^{-3}$)	**Elastic modulus E (Mpa)**	**Poisson's ratio v**	**Friction angle φ**	**Dilation angle θ**	**Flow stress ratio k**
19	12	0.4	25	5	0.778

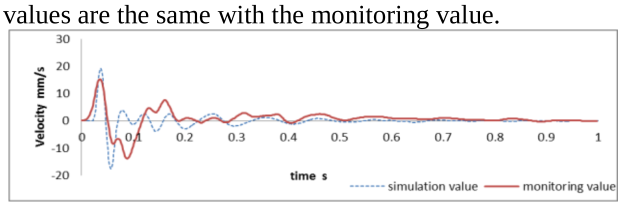
3 Analysis of the dynamic responses

3.1 TIME HISTORY CURVES OF VELOCITY AND ACCELERATION

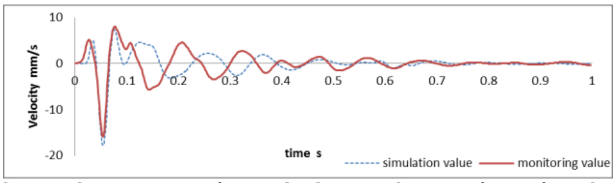
When studying the effects on the structures that caused by the ground vibration, a viewpoint [14] thinks of that the vibration velocity should be considered importantly because the dynamic stress of the structure is related to the vibration velocity of the ground, at the same time there is another opinion [15] that by using acceleration the inertial force of structure can directly obtained and then the inertial force of the structure can be calculated, so the acceleration should take the first place. Considering the both aspects, this paper displays the time history curves of vibrational velocity and acceleration respectively. Figure 5 shows the monitoring and simulated time history curves of vibration at different distances. The result of simulation shows the characteristics that the main frequency of the vibration is about 10Hz and the time history curves picked more closely to the tamping point have an obvious peak value, which is significantly greater than the nearby peaks. At the distance of 6.7m this peak value of velocity and acceleration are about 18mm/s and 1.9m/s2, respectively. While at the further place, due to the dispersion of wave packet in the process of propagation, there is not a distinctive peak, and the vibration attenuates more slowly than that in nearby.

In the test, the sensors laid in a line that crossed by the tamping point at different distances. Now the representative monitoring values collected from the sensors, which are 6.7m, 14.7m and 26.7m away from the tamping point are compared with the simulated values. As Figures 5 shows the simulation and monitoring curves picked from the closer points are more similar than the ones picked from further points. This is because in the simulation the material is isotropic but actually the backfill soil is complex in component and uneven in distribution. In the shorter range the differences are not evident because the wave has transmitted just for a short distance that the differences cannot fully exhibit, but in long range the changes accumulate that the differences are obvious.

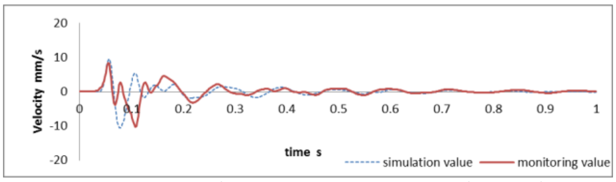
The velocity curves in 6.7m and 14.7m to a certain extent are similar, but in 26.7m the similarity reduces. It is because on one hand with the increasing of distance, the vibration energy reduces and the ratio of background vibration increases, and on the other hand, in the process of propagation the wave packet gradually disperses, so the waveform changes. Furthermore, the duration of vibration increases as the distance increases, but vibration has basically subsided in 1s, and in this aspect the simulation values are the same with the monitoring value.



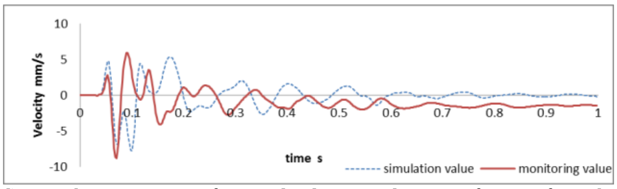
a) Time history curves of radial velocity at distance of 6.7m from the tamping point



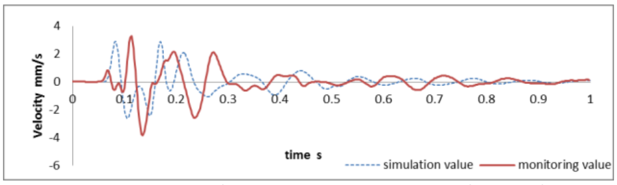
b) Time history curves of vertical velocity at distance of 6.7m from the tamping point



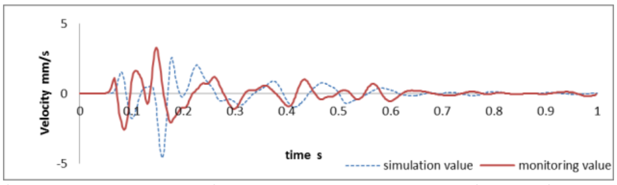
c) Time history curves of radial velocity at distance of 14.7m from the tamping point



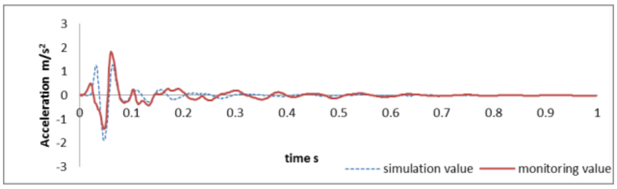
d) Time history curves of vertical velocity at distance of 14.7m from the tamping point



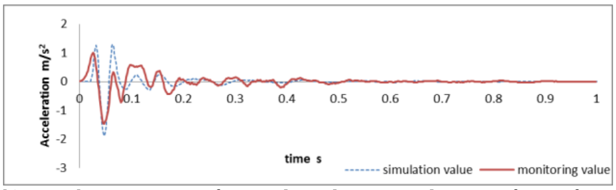
e) Time history curves of radial velocity at distance of 26.7m from the tamping point



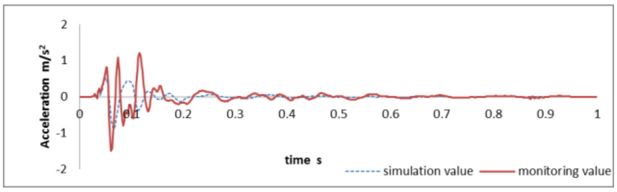
f) Time history curves of vertical velocity at distance of 26.7m from the tamping point



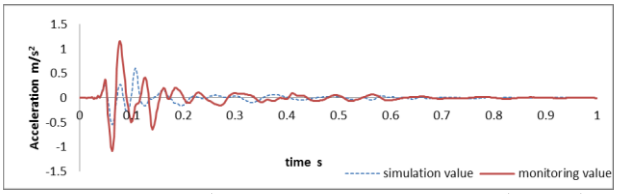
g) Time history curves of radial acceleration at distance of 6.7m from the tamping point



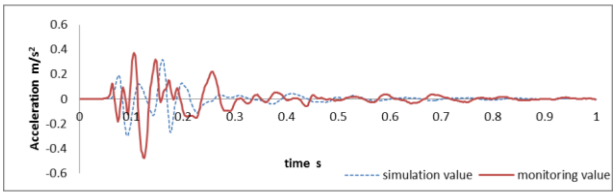
h) Time history curves of vertical acceleration at distance of 6.7m from the tamping point



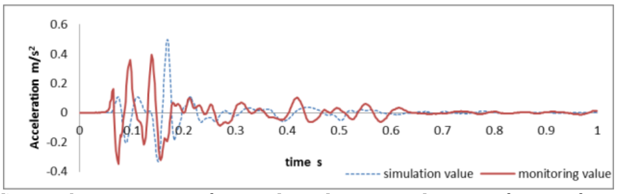
i) Time history curves of radial acceleration at distance of 14.7m from the tamping point



j) Time history curves of vertical acceleration at distance of 14.7m from the tamping point



k) Time history curves of radial acceleration at distance of 26.7m from the tamping point

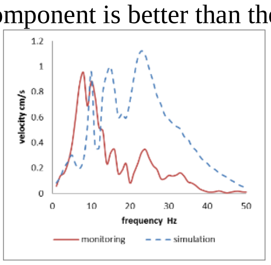


l) Time history curves of vertical acceleration at distance of 26.7m from the tamping point

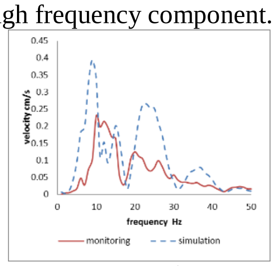
FIGURE 5 The curves of vibration velocity and acceleration at different distance from the tamping point on the ground

Figure 6 shows the monitoring and simulated vibration frequency spectrum. Through the picture, it can be seen that the two frequency spectrum curves have the similar change tendency, but the high frequency component of the simulated frequency spectrum curves accounts for a larger proportion. Both the two curves have a peak value at about 10Hz. With the increasing of distance, the frequency spectrum concentration decreases and become more abundant.

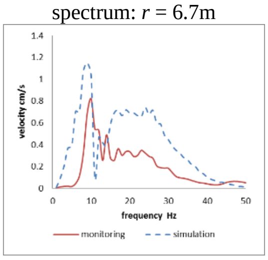
By the comprehensive analysis above, it can be concluded that the simulated dynamic response, which is in the point that closer to the tamping point is more accurate, and the simulation to the low frequency component is better than the high frequency component.



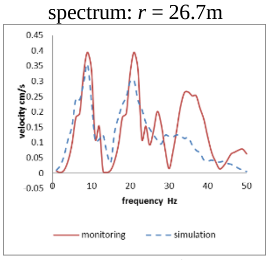
a) radial velocity frequency spectrum: r = 6.7m



c) radial velocity frequency spectrum: r = 26.7m



b) vetical velocity frequency spectrum: r = 6.7m



d) vertical velocity frequency spectrum: r = 26.7m

FIGURE 6 Monitoring and simulated vibration frequency spectrum

3.2 RELATION BETWEEN VIBRATIONAL PEAK VALUES AND THE DISTANCE FROM THE TAMPING POINT

In the impaction, the vibrational energy spreads from the tamping point to the environment so the amplitude decreases with the increasing of distance. Studying the relation between distance and the peak vibration could provide reference for determining safe distance in dynamic compaction construction. Figure 6 shows the relation between velocity and distance as well as that between acceleration and distance. The result indicates that the vibration reduces in the form of a negative power function or a negative exponential function and that the radial vibration curves decline faster than the vertical ones. Furthermore, in a same point, the radial peak velocity and acceleration are greater that the vertical ones. The shorter the distance, the more obvious the difference is. By comparing this result with the measured values, it could be found that the law is roughly the same.

Because the ability of ordinary building to resist horizontal vibration is worse than that to resist vertical vibration, in the construction of dynamic compaction, the influence of radial vibration should be considered firstly. The different structures usually have different seismic capacity. The specific values [14] are shown in Tables 2-4.

TABLE 2 Chinese standards for blasting safety

Structure type	**Safety vibration velocity (mm/s)**
Soil cave, adobe house	10
Non seismic block buildings	20~30
Reinforced concrete frame building	50
Hydraulic Tunnel	100
Traffic tunnel	150

TABLE 3 Swiss standards for building and blasting

Structure type	**Frequency range (Hz)**	**Peak particle Velocity (mm/s)**
Steel, reinforced concrete structures	10~60	30
	60~90	30~40
Brick structure	10~60	18
	60~90	18~25
Masonry walls, wooden pavilion	10~60	12
	60~90	12~18
historic and sensitive buildings	10~60	8
	60~90	8~12

TABLE 4 German standards for building and blasting

Structure type	**Frequency range (Hz)**	**Resultant velocity (mm/s)**
Industrial buildings and commercial buildings	<10	20
	10~50	20~40
	50~100	40~50
Residential building	<10	5
	10~50	5~15
	50~100	15~20

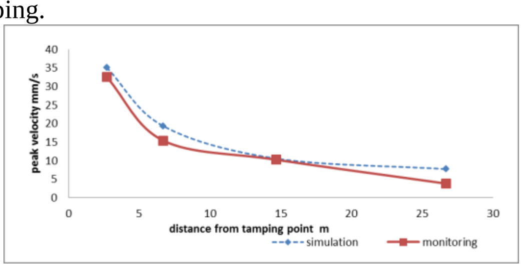
By combining Figure 7 with Tables 2-4, on the vibrational frequency of 10Hz, the area around the tamping point can be divided into three parts:

1) The safety zone. The zone is outward of 30m. In the zone peak velocity is under 5mm/s. all the structures in this zone are safe.

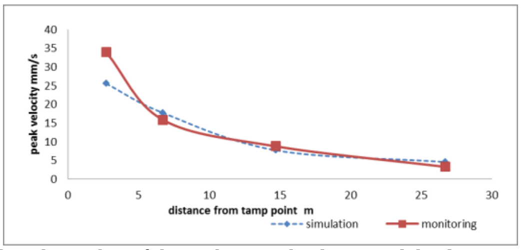
2) The slight vibration zone. The zone is 20m~30m away. In this zone, the peak velocity is about 5~8mm/s and the historic and sensitive buildings will be affected.

3) The middle vibration zone. The zone is at about 7m~20m. In this zone, the peak velocity rises to 10~18mm/s. Ordinary brick buildings and wooden pavilions in this zone will be damaged. (4)The strong vibration zone. The zone is within 7m. In the zone peak velocity is up of 20mm/s and ascends quickly with the decreasing of distance. The steel reinforced concrete structure is threatened in this zone.

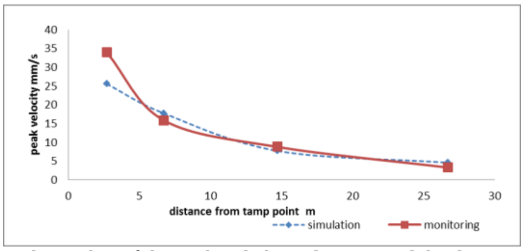
It needs to point out that all the standards have not considered the vibrational duration. In fact, the vibrational duration is also an important factor. The duration of dynamic compaction is usually within 1s, so the duration has little influence to the vibration effect. Besides, the cumulative damage of structures caused by repeat tamping is also not considered in the standards, so it needs to further research to clarify the relation of structure's seismic resistance and the vibrational parameters under repeat tamping.



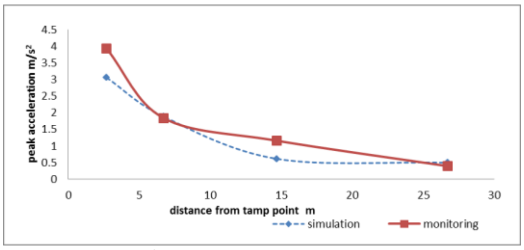
a) The relationship of the peak radial velocity and the distance from the tamping point



b) The relationship of the peak vertical velocity and the distance from the tamping point



c) The relationship of the peak radial acceleration and the distance from the tamping point



d) The relationship of the peak vertical acceleration and the distance from the tamping point

FIGURE 6 The relation between vibrational peak values and distance from the tamping point

3.3 RELATION BETWEEN VIBRATIONAL PEAK VALUES AND THE DISTANCE FROM THE TAMPING POINT

The total energy in the dynamic compaction is $E = mgh$, in which m is the weight of hammer, h is the drop height. During the impaction a part of the total energy is dissipative in the form of sonic, heat, friction and other way. The other part that consolidates the soil under the hammer in a certain range by doing plastic work called useful energy E_u. Precisely this part of energy makes a plastic zone in the foundation. In the zone, the strength parameters rise so that some scholars call the depth of this zone "satisfactory improvement depth".

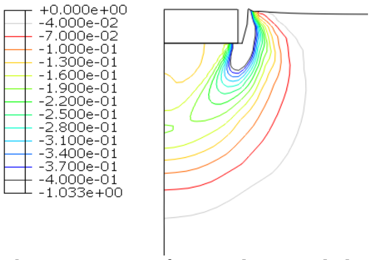


FIGURE 8 The contour map of minimal principal plastic strain

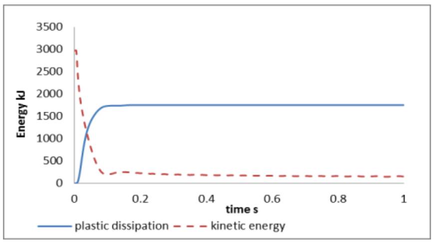


FIGURE 9 The change of kinetic energy and the plastic energy in the simulation

Figure 8 shows the contour map of minimal principal plastic strain in the foundation. In this picture, the plastic zone presents approximate ellipsoid. The energy utilization is $\eta = E_u / E$. Under different conditions include the type of soil, the weight and the drop height of the hammer, η has different values. According to the classical researches, the η is usually about 33%, but some researchers have the results that η may reach 69% in the Clay soil. In this paper, calculated from Figure 9, $\eta = 58.3\%$. It means that 41.7% of the total energy spreads to the environment, including the part, which causes the vibration on the ground. So under the same conditions, as the energy utilization rising, the vibration energy decreases. From paper [16], η is increasing function of m / S, where S is the bottom area of the hammer. It is to say under the same tamping energy level, the vibration can be reduced through reducing the bottom area or increasing the aspect ratio of the hammer.

4 Conclusions

1) In the backfill soil foundation, the duration of the vibration caused by dynamic compaction increases with the increasing of distance, while the amplitude decreases

with the increasing of distance and decays in the form of negative exponential function.

2) The simulated dynamic response, which is in the point that closer to the tamping point is more accurate, and the simulation to the low frequency component is better than the high frequency component.

3) Relative to the peak amplitude of vertical vibration, the radial one is greater, and the shorter the distance, the larger the difference is. In addition, Relative to the vertical vibration, the radial vibration is more threatening to the surrounding structures in the backfill soil in this case, so it is recommended that on the backfill soil foundation, the radial vibration should be considered more in the general construction of dynamic compaction.

4) According to standards, the safe distance of different type of structures can be evaluated by the peak vibration velocity, but it needs to further research to clarify the relationship between structure's seismic resistance and the vibrational parameters under repeat tamping.

5) The energy that does plastic work to the soil is useful energy, and the soil will form an ellipsoidal plastic zone by this part of energy. The energy utilization is the ratio of the useful energy to the total tamping energy. Raising the aspect ratio of the hammer can raise the energy utilization and then reduce the vibration energy.

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