Study on dynamic response of rock foundation pit blasting excavation to adjacent buildings

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Abstract: Focusing on safety problems of the blasting excavation of foundation pits near existing buildings, this study takes the Jinggangshan Road Station of Qingdao Metro Line 1 as the engineering background and establishes a three-dimensional numerical model of a foundation pit blasting excavation based on the dynamic response characteristics of buildings using the FLAC3D finite difference software. Moreover, the present study examines the dynamic response law of foundation pit blasting excavations under blasting vibrations and analyzes blasting vibration velocities at different measuring points near buildings. Results show that the blasting vibration velocity of key measuring points is consistent with the numerical simulation results. This finding demonstrates that the numerical model is reasonable; the influence of blasting vibrations on buildings presents different trends with varying heights, mainly concentrated in the lower part of the blasting side; the vibration velocity of the measuring points of buildings varies with different horizontal distances; and the impact of the monitoring points near the blasting side is far greater than that of the measuring points far from the blasting side. Velocity decreases as the distance between the detonation centers increases. The results have certain reference value and guiding significance in the selection of reasonable blasting parameters and the effective improvement of the safety threshold of foundation pit blasting vibrations.

Keywords: foundation pit; rock; blasting; building; vibration velocity; blasting center distance

1. Introduction
In recent years, with the gradual development of subway construction, station foundation pits as key projects in the field have increased. However, the hydrogeological conditions of different regions vary considerably. Thus, foundation pit engineering encounters various complex geological conditions. For example, mechanical excavation cannot meet the needs of deep foundation pit projects with hard rock layers at the bottom, and blasting excavations, which entail short construction periods and high rock breaking efficiency, are the first choice for engineering construction [1]. Examples of blasting excavation subway foundation pit construction in China include the Suoyuwan South Station of Dalian Metro Line 5 and the Jinggangshan Station of Qingdao Metro Line 1. Therefore, exploring the dynamic response effect and influence law of blasting excavations in the stability analysis of foundation pit blasting is necessary [2-4].

The blasting excavation of foundation pits damages and disturbs surrounding rocks and affects ground building safety, which can lead to building instability and destruction [5]. Within a certain blasting area range, vibrations caused by blasting will affect the retaining structure of a foundation pit, adjacent buildings, and the ground surface. This phenomenon and the consequences generated by blasting vibrations are called the blasting vibration effect. Liu et al. [6] discussed the influence of foundation pit excavations on existing adjacent subway structures from the perspective of small excavation deformations. Meanwhile, Tao et al. [7] examined the blasting vibration characteristics of a rock mass with a composite energy dissipation structure. Song Guangming et al. [8] proposed a new method to
reflect the dynamic response state and damage degree of rock and soil structures under blasting vibrations. Long Yuan et al. [9] analyzed the frequency, amplitude, and duration of blasting waves and obtained the empirical formula of acceleration. Furthermore, Parviz et al. [10] analyzed the impact of blasting on adjacent pipelines. With the development of computer technology, scholars used numerical simulations to study the dynamic response characteristics of pipelines under blasting vibrations [11,12]. Borvik et al. [13] analyzed the corresponding situation of blasting loads in a plane, and Havenith et al. [14] assessed the response of blasting waves on a slope. Liu Dunwen et al. [15] simulated the vibration velocity of a blasting side using Ansys LS-DYNA, with a maximum charge of 6, 24, and 96 kg, and proposed several measures to control blasting vibrations. At present, research on the influence of foundation pit blasting excavations on the stability of surrounding environments is abundant. However, studies on the dynamic response of foundation pit blasting excavations to adjacent buildings under the rock stratum have yet to be conducted, and the environmental effect of foundation pit blasting excavations must be improved further.

Based on existing research results, a dynamic response system for rock foundation pit blasting to adjacent buildings is established. In addition, based on rock and soil parameters, a three-dimensional numerical model is developed. Moreover, based on FLAC3D, the influence of blasting excavations on adjacent buildings under different blasting parameters is determined through dynamic load calculation. This study aims to improve the safety controls of foundation pit blasting excavations and the protection of adjacent buildings.

2. Engineering background
The Jinggangshan Road Station of Qingdao Metro Line 1 is located under the middle of Yangtze River Road, which is located in a downtown area. Its total length is 203 m, its width is 25 m, and its excavation depth is 24 m. A brick concrete structure, namely, Liqun supermarket, is situated 21 m from the edge of the foundation pit. The total length and width of the existing concentrated foundation pit are 180 and 115 m, respectively, 9 m below the ground and 5 m from the excavation foundation pit. Jiashike supermarket is located northeast of the blasting area, with a distance of 60 m; Liqun supermarket is located 21 m away in the southeast; Jiajiayuan supermarket is positioned 44 m away in the southwest; and Century mall is located northwest, with a distance of 54 m. The blasting area is near surrounding pipelines and buildings, and the surrounding environment is complex. Deep hole blasting cannot meet the vibration control requirements; thus, a scheme combining shallow hole loose blasting with mechanical excavation is employed for the station. The surrounding environment of the Jinggangshan Road station is complex; hence, to protect surrounding pipelines and buildings, excavating a damping ditch and reducing the maximum charge for single sections to control blasting vibrations are necessary. The overall scheme of the station excavation is as follows. A vibration reduction ditch is excavated 2 m away from the excavation side line via shallow hole blasting. The vibration damping ditch is excavated by a machine, and the excavation depth is more than 1.0 m of cyclic footage. In shallow hole blasting, a slot is placed in the middle of the blasting area, with a width of 5 m, and the bench blasting is conducted. The depth of the hole near the pipeline is 0.8 m, and the charge for a single hole is 0.07 kg. A hole blasting method is employed to reduce the impact of blasting vibrations. The number of blasting holes is approximately 50 at a time in the blasting network. When the distance from pipelines and other protected objects is wide, based on the distance and vibration checks, the blast hole depth is increased appropriately (controlled within 1.3 m–2.8 m), a hole is selected by hole or multi-hole initiation, and single hole blasting is controlled. The maximum amount of the detonating charge in the blasting network is approximately 60 holes at a time. According to the calculation of a maximum single hole charge of 1.3 kg, the charge of one blasting is controlled within 78 kg.
Therefore, to guide the development of a reasonable blasting plan, the impact of blasting shock waves and blasting parameters on the foundation pit envelope and its adjacent environment should be analyzed before foundation pit blasting construction.

3. Dynamic analysis model establishment and parameter selection
3.1 Numerical calculation model
A numerical calculation model is established based on actual engineering design drawings. The excavation depth of the foundation pit of Jinggangshan Station is \( H = 24 \) m, and a brick concrete structure, namely, the Liqun supermarket, is situated 22 m from the edge of the foundation pit. The excavation size of the foundation pit is 203 m \( \times \) 28 m \( \times \) 24 m. The stress release of the surrounding rocks is considered after the blasting excavation, and the influence area is approximately 3 times the excavation depth of the foundation pit. Therefore, the calculation range of the entire model is 600 m \( \times \) 520 m \( \times \) 100 m (x \( \times \) y \( \times \) z), where X (\(-200, 400\)) is the horizontal direction parallel to the long side of the foundation pit, Y (0, 520) is the short side direction of the foundation pit, Z (0, 100) is the vertical direction, and the simulated excavation direction is from the X = 200 section along the X-axis forward direction. Monitoring points are set for the X = 90 section of the foundation pit. The numerical calculation model, and the location of the monitoring points are shown in Fig. 1.

![Fig. 1. Numerical calculation model and monitoring point location](image)

Table 1. Model parameter values of Jinggangshan Station

| Geo material                          | Modulus of elasticity E/(MPa) | Cohesion C/(MPa) | Internal friction angle \( \phi \)/° | Poisson’s ratio | Tensile strength t/(KPa) | Density of rock and soil (kg/m\(^3\)) |
|---------------------------------------|-------------------------------|-----------------|-----------------------------------|----------------|------------------------|-------------------------------------|
| Prime fill                            | 6                             | 0.2             | 15                                | 0.42           | 90                     | 1750                                 |
| Silt quality                          | 4                             | 0.1             | 7.87                              | 0.46           | 40.4                   | 1810                                 |
| Strongly weathered granite porphyry   | 100                           | 0.2             | 15                                | 0.4            | 100                    | 1850                                 |
| Moderately weathered granite porphyry | 1500                          | 1               | 30                                | 0.28           | 500.3                  | 2010                                 |
| Slightly weathered granite porphyry   | 7000                          | 2               | 40.65                             | 0.25           | 1000                   | 2630                                 |

According to the Mohr–Coulomb strength criterion, each supporting structure is abstracted as an elastic element, and the supporting effect of the retaining pile is reflected as the elastic modulus of the pile in the form of strength equivalent. A cable element is used to establish an anchor cable system, which is 10.5 m long and arranged in the shape of a plum blossom. The values of the structural parameters are obtained from the field test report, as shown in Table 1.

The initial in-situ stress field considered is the gravity stress field. The initial geostress field is considered only according to the gravity stress field. The upper boundary of the model is the free boundary, whereas the remaining boundary is the viscous boundary.

3.2 Determination of blasting load
The effect of blasting vibrations on the surface, slope, and buildings is a process of energy transfer and transformation. The influence of blasting on buildings is mainly related to vibration intensity and the duration and frequency of blasting vibrations. In geotechnical engineering, the selection of the blast hole pressure variation course is based on a semithetical and semiempirical exponential attenuation load or triangular load. In this study, an exponential attenuation blasting load type is proposed, which must determine two factors: (1) the peak value of the blasting load and (2) the time of the pressure rise and the time of the positive pressure action.

Under the condition of C–J detonation, the average detonation pressure of an explosive is

$$P_0 = \frac{\rho_e D^2}{2(1+\gamma)}$$  \hspace{1cm} (1)

where $P_0$ is the average initial detonation pressure, $\rho_e$ is the explosive density, $D$ is the detonation velocity, and $\gamma$ is the isentropic index.

For coupled charge conditions,

$$P_0 = P_0$$  \hspace{1cm} (2)

For uncoupled charge conditions,

$$P = A\rho^{v_0}$$  \hspace{1cm} (3)

where $P$ is the pressure of the explosive gas in a certain state, $\rho$ is the density of the explosive gas in a certain state, $A$ is a constant, and $v_0$ is the isentropic index of the explosive gas. When $P \geq P_k$, then $v_0 = \gamma = 3.0$. When $P < P_k$, then $v_0 = \gamma = 1.4$, and $P_k$ is the critical pressure of the explosive.

If the uncoupling coefficient of the charge is small, then the expansion of the explosive gas will pass through only a state of $P > P_k$. At this time, the initial average pressure $P_0$ of the blast hole obtained from Equation (3) is

$$P_0 = \frac{\rho_e D^2}{2(1+\gamma)} \left( \frac{d_e}{d_b} \right)^{2\gamma}$$  \hspace{1cm} (4)

If the uncoupling coefficient of the charge is large, then the expansion of the explosive gas must pass through two stages, that is, $P \geq P_k$ and $P < P_k$. Thus, obtaining Equation (3) is easy.

$$P_0 = \left( \frac{\rho_e D^2}{2(1+\gamma)} \right)^{\frac{\gamma}{\gamma-\nu}} \frac{d_e^{\gamma}}{d_b^{\gamma}} \left( \frac{d_e}{d_b} \right)^{2\nu}$$  \hspace{1cm} (5)

In this study, the surrounding smooth blasting load is selected for the numerical calculation. The blasting load acts uniformly on each unit node of the contour line of the excavation surface of the foundation pit in the form of pressure, and the direction of the action is the outward direction of the four-perimeter method of the excavation surface of the foundation pit. Tables 2 and 3 present the calculation results of the blasting parameters and blasting load, and Fig. 2 illustrates the duration of the blasting impact load of several attenuation loads applied to the excavation surface.

**Table 2. Blasting parameters**

| Explosive density $\rho$ (kg/m$^3$) | Detonation velocity of explosive $D$ (m/s) | Charge diameter $d_e$ (mm) | Hole diameter $d_b$ (mm) | Hole spacing $a$ (m) |
|------------------------------------|------------------------------------------|--------------------------|-----------------------|---------------------|
| 1000                               | 3200                                     | 32                       | 40                    | 0.8                 |

**Table 3. Peak blasting load**

| Detonation pressure $P_0$ (GPa) | Pulse load of exponential decay type $P_0$ (MPa) | Equivalent load $P_0$ (MPa) |
|---------------------------------|----------------------------------------------|----------------------------|
| 1.28                            | 87.97                                        | 4.41                       |

Given that most of the blast holes are around the foundation pit, the peak pressure on the blast hole...
wall is approximately equal to the detonation pressure surrounding the foundation pit. Therefore, the exponential attenuation load can be applied to the tunnel wall equally to realize the simulation process of the blasting load. In the dynamics simulation in FLAC$^{3D}$, the dynamic pressure related to the time history mentioned in the statfield is used, as follows:

$$P(t) = nP_e (\exp\left(-\frac{Bt}{\sqrt{2}}\right) - \exp(-\sqrt{2}Bt))$$  \hspace{1cm} (6)$$

where $B = 16338$ is the load constant, which is the dynamic pressure per 1 kg charge; $n$ is the number of holes detonated simultaneously; and $t$ is the blasting action time [16].

![Time-history curve of equivalent blasting dynamic load](image)

**Fig. 2. Time-history curve of equivalent blasting dynamic load**

According to the above calculation results, the blasting load with a charge of 1.0 kg is obtained. If this pressure acts on the imaginary blasting surface simultaneously, then the equivalent stress peak value is calculated, and the dynamic load function in the FLAC$^{3D}$ numerical simulation is obtained as follows:

$$P(t) = 264.66(\exp(-11554.46t) - \exp(-23101.93t))$$  \hspace{1cm} (7)$$

4. Dynamic response law of blasting vibrations

Numerical calculations for the conditions indicated by the above blasting load are performed. Figure 3 shows the particle velocity time-history curve at heights of 0, 10, 20, 30, 40, and 50 m on the front of a building, and Fig. 4 presents the particle velocity time-history curve at different horizontal distances on the explosion side of a building. In addition, Fig. 5 illustrates the particle velocity time-history curve at different distances in the Y direction of a building.

![Time-history curve of vibration velocity at different heights on a building](image)

**Fig. 3. Time-history curve of vibration velocity at different heights on a building**
Figure 3 shows the speed response law of different height monitoring points of a building in the blasting construction of a foundation pit. Each peak (valley) of the vibration speed curve of different heights basically appears from the bottom of the building to the top, and the impact of blasting vibrations gradually spreads along the building from the bottom to the top. Under the action of the blasting load, the speed response law of each monitoring point of the building is basically the same, but its size is different. As elevation increases, the peak value of velocity in the X direction of the building decreases slowly, which is related to the relative stability of the longitudinal ratio of the building. Moreover, no overall swing appears in the vibration process. Meanwhile, the peak value of velocity in the Z direction of the building increases gradually, which shows that the vertical direction has a certain amplification effect on the blasting vibrations. By comparing the velocity in the X and Z directions of the same monitoring point, it can be seen that the velocity in the Z direction is large and occupies the main role.

In the initial blasting stage, the speed of each monitoring point in the height direction of the building suddenly increases, JZ01 increases to 0.18 cm/s in the Z direction, and JZ06 increases to 0.34 cm/s. With the gradual release of the blasting load, the vertical velocity of the building reaches the maximum value at 0.15 s–0.20 s, JZ01 increases to 0.79 cm/s, and JZ06 increases to 0.91 cm/s then decreases gradually. At 0.2 s–1.0 s, a small amplitude of vibrations appears, and the amplitude of the vibrations decreases gradually. After 1.0 s, the speed response of each height becomes stable and zero gradually.

Figure 4 depicts the speed response law of the monitoring points at different horizontal distances on...
the blasting side of a building under the blasting construction of the foundation pit. Moreover, Fig. 4 shows that under the action of blasting vibrations, as the horizontal distance in the X direction between the building and the blasting point of the foundation pit increases, the speed response degree of the building decreases. In the initial stage of the blasting construction, at 0 s, the speed of each X horizontal distance of the building suddenly increases, JX01 increases to 0.36 cm/s at the place nearest the blasting point, and JX06 increases to 0.17 cm/s at the place farthest from the blasting point. With the gradual release of the blasting load, at 0.1 s, the speed response degree of the building reaches the maximum value, the nearest JX01 reaches 1.86 cm/s, and the farthest JX06 reaches 1.54 cm/s then decreases gradually. At 0.1 s–1.2 s, a small amplitude of vibrations appears, and at 1.2 s, the speed response of each monitoring point becomes stable. The analysis indicates that the speed response of the adjacent buildings decreases as the horizontal distance from the foundation pit blasting increases. The speed response degree reaches the peak value in the process of explosive blasting force release then gradually decreases, and the buildings gradually stabilize.

Figure 5 shows the speed response law of the Y-direction monitoring point of a building under foundation pit blasting construction. Figure 5 illustrates that under the action of blasting vibrations, as the horizontal distance between the building and the blasting point in the Y direction of the foundation pit increases, the speed response degree of the building decreases. In the initial stage of the blasting construction, at 0 s, the speed of the horizontal distance of each monitoring point in the Y direction of the building suddenly increases, JY01 increases to 0.36 cm/s, and JY06 increases to 0.18 cm/s at the place farthest from the blasting point. With the gradual release of the blasting load, at 0.1 s, the speed response of the building reaches the maximum value, the nearest JY01 reaches 1.86 cm/s, and the farthest JY06 reaches 1.52 cm/s then decreases gradually. At 0.1 s–1.2 s, a small amplitude of vibrations appears, and with the amplitude of the vibrations gradually reduced, at 1.2 s, the speed response of each monitoring point becomes stable. The analysis shows that the speed response of the adjacent buildings decreases as the horizontal distance from the foundation pit blasting increases. The speed response degree reaches the peak value in the process of explosive blasting force release then gradually decreases, and the buildings gradually stabilize.

In the excavation of a foundation pit with hard rock blasting, as the height of the monitoring points increases, the speed response degree of the building gradually increases. As the X and Y distances between the building and the blasting construction point increase, the speed response degree of the building decreases gradually, and the speed reduction degree in the Y direction of the building is greater than the speed reduction degree in the X direction. Second, in the blasting excavation of a foundation pit, the corresponding peak value of the speed of all detection points is less than 1.5 cm/s, which conforms to engineering safety regulations. Moreover, in the blasting excavation of the foundation pit of Jinggangshan Station, though different vibration responses appear in every direction of the building, the blasting construction is within the specified safety range.

5. Comparison with monitoring data

Using a TC-4850N blasting vibration meter, three monitoring points in the building height directions (JZ01, JZ03, and JZ05) and building Y directions (JY01, JY03, and JY05) are selected for vibration velocity monitoring, as shown in Fig. 1. Given that the vertical vibrations are the main factors affecting the safety of surrounding buildings and the comfort of personnel, the vibration velocity in the Z-axis direction is mainly monitored. The time-history curve of the blasting vibration velocity is shown in Fig. 6. The measured vibration velocity is shown in Table 4. The theoretical calculation value obtained through numerical simulation is compared with the measured value after the foundation pit blasting, and the accuracy of the FLAC3D numerical method in analyzing the impact of foundation pit blasting on the surrounding environment is determined by calculating the error between them.
The equivalent blasting load is used to calculate the blasting pressure of the coupled and uncoupled charges, and the blasting load is quantitatively analyzed effectively. The numerical calculation using FLAC$^{3D}$ shows that the vibration velocity results are within 15% of the field measurement error. Given that the shock absorption factor in the actual construction process is not considered in the numerical calculation, it is considered that the FLAC$^{3D}$ numerical simulation can simulate the impact of blasting excavation on the surrounding environment. According to the measured data, all the measuring points meet the vibration speed requirements of safety regulations. This finding proves the rationality and feasibility of this method, which has practical guiding significance for similar rock foundation pit projects.

6. Conclusion
In view of the construction of a foundation pit for the Jinggangshan Station of Qingdao Metro Line 1, the dynamic response of surrounding buildings during the blasting excavation is studied, and the speed response characteristics of the monitoring points along the height direction, the horizontal X direction, and the Y direction of the buildings are analyzed. The main conclusions are as follows:

1. In the process of blasting vibrations, the growth and attenuation of the vibration response of a building differ. Vibration response increases as building height increases and decreases as distance from the source increases, and the attenuation degree of the response in the Y direction of the building is greater than that in the horizontal X direction.

2. In the process of foundation pit blasting construction, the vibration speed of each monitoring point of a building is less than 1.5 cm/s, which is within the scope of engineering safety regulations and in a safe state in the process of station foundation pit blasting.

3. The blasting construction of rock foundation pit excavations will cause vibrations in adjacent buildings. Buildings’ maximum vibration response emerges in the process of explosive blasting then gradually attenuates and stabilizes.

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**Table 4. Comparison between theoretical calculation and measured maximum vibration velocity**

| Survey point number | Numerical simulation value/cm·s$^{-1}$ | Field monitoring value/cm·s$^{-1}$ | Error |
|---------------------|----------------------------------------|-----------------------------------|-------|
| JZ01                | 0.91                                   | 0.77                              | 15%   |
| JZ03                | 1.15                                   | 1.06                              | 8%    |
| JZ05                | 1.32                                   | 1.24                              | 6%    |
| JY01                | 0.82                                   | 0.73                              | 11%   |
| JY03                | 0.66                                   | 0.60                              | 9%    |
| JY05                | 0.52                                   | 0.46                              | 12%   |
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