Research Article

Study on Three-Dimensional Dynamic Stability of Open-Pit High Slope under Blasting Vibration

Xiaoshuang Li,1,2,3 Qihang Li,4 Yunjin Hu,1 Qiusong Chen,5 Jun Peng,2 Yulin Xie,4 and Jiawen Wang4

1Key Laboratory of Rock Mechanics and Geohazards of Zhejiang Province, Shaoxing University, Shaoxing 312000, China
2College of Civil Engineering, Qilu Institute of Technology, Jinan 250200, China
3School of Civil Engineering, Shaoxing University, Shaoxing 312000, China
4School of Resources and Environmental Engineering, Jiangxi University of Science and Technology, Ganzhou 341000, China
5School of Resources and Safety Engineering, Central South University, Changsha 410083, China

Correspondence should be addressed to Qihang Li; qihangli0325@126.com and Yunjin Hu; huyunjin@tsinghua.org.cn

Received 27 November 2021; Accepted 30 December 2021; Published 29 January 2022

Academic Editor: Yonghui Wu

Copyright © 2022 Xiaoshuang Li et al. Exclusive Licensee GeoScienceWorld. Distributed under a Creative Commons Attribution License (CC BY 4.0).

The propagation process of blasting vibration has always been a difficult problem affecting the stability of high slopes in open-pit mines. Taking the Jianshan Phosphorus Mine as the research background, combined with engineering geological investigation, field blasting test, blasting vibration monitoring, numerical simulation technology, and theoretical analysis, the three-dimensional dynamic stability of the adjacent high slope after blasting vibration was systematically studied. In our study, a small-diameter buffer shock-absorbing blasting technology near the slope was proposed, which greatly improved the production efficiency. Through regression analysis of a large amount of vibration test data, the law of blasting vibration propagation in Jianshan stope and Haifeng stope was obtained. In addition, by establishing four three-dimensional geomechanical numerical models, the slope’s own frequency, damping characteristics, and dynamic response acceleration distribution after detonation were studied, respectively. On the other hand, under the action of Ei Centro wave with 8-degree seismic intensity, the maximum total acceleration and maximum total displacement of the slope were calculated and analyzed. Both the explosion unloading of the 8-degree earthquake and the Ei Centro wave simulation results showed that the high slope near the Jianshan Phosphorus Mine was generally in a stable state. Thus, this study can provide technical support and theoretical guidance for mine blasting.

1. Introduction

During the production process of the open-pit mine, the blasting vibration effect not only threatens the stability of the slope but also even leads to local or large-scale landslide accidents [1, 2]. Globally, from 1967 to 1979, there were 25 landslide disasters in Daye Iron Mine due to the impact of blasting vibration, and the total amount of landslides reached 1.2303 million m³. Among them, the largest one-time landslide was 876,000 m³ [3]. In 1974, a landslide disaster occurred in Nanfen Iron Mine, and the total amount of landslides reached 6,500 m³ [4]. In November 1980, Baguanhe Limestone Mine was horizontally blasted with 3 tons of 10 holes at an elevation of 1388 m, causing a landslide disaster of 26,000 m³. Later, in June 1981, a cavern blasting was carried out in the western part of the stope (total charge was 1,200 tons), and a large-scale landslide disaster of 4.16 million m³ occurred [5]. These landslide disasters have caused heavy casualties and property losses [6, 7]. Affected by the high temperature and high pressure generated by shock waves and explosive air waves, the rock mass has inelastic effects such as crushing and cracking, and a fracture zone is formed. In addition, the blasting vibration destroyed the integrity of the rock mass, causing the adjacent slopes to lose stability and causing landslide disasters [8]. Therefore, it is necessary to develop blasting technology and blasting vibration for the open-pit of Jianshan Phosphorus Mine, which can ensure the safety
of rock slopes and provide guidance for subsequent mining and blasting [9, 10].

With the increase in demand for rock mining by blasting in mines, many scholars have carried out in-depth research in theoretical analysis, field tests, and numerical simulations [11, 12]. Guo et al. analyzed the response of different types of slopes to blasting vibration [13]. Zhang et al. used the field test method of blasting vibration to carry out an experimental study on the propagation law of blasting vibration under the influence of elevation factors [14]. Wang proposed a calculation formula for dynamic time history stability coefficient of bedding high-steep rock slopes driven by underground blasting for the common high-steep bedding rock slopes in engineering [15]. Narayan et al. proposed a novel directional controlled blasting technology for unstable highway slopes, which effectively improved the stability of the slope after blasting [16]. Wu et al. evaluated the stability of high and steep slopes driven by repeated blasting of the fault zone by combining shaking table tests, limit equilibrium theory, and least-squares method [17]. On the basis of previous research results, Deng and Chen comprehensively discussed the blasting excavation and stability control technology of ultrahigh and steep rock slopes in China’s hydropower projects and discussed its research progress and limitations [18]. On the other hand, Ma et al. studied the weakening of slope stability under the dual effects of rainfall infiltration and blasting vibration [19]. However, these methods only conduct experiments and theoretical analysis on the stability of the slope after blasting and have no effective verification and are limited.

In recent years, computer technology has developed rapidly, and numerical simulation technology has gradually been widely used in the stability analysis of rock slopes under blasting vibration [20, 21]. Among them, a series of numerical simulation verification studies have been carried out in the mine blasting process. Xie et al. used SLIDE software to simulate the actual slope model of the open-pit mine and proposed a slope stability criterion based on the safety factor [22]. Gu et al. established a numerical simulation considering the geological characteristics of the site by means of the finite difference method and concluded that the propagation of the explosion wave in the free field is significantly controlled by the geological conditions of the site [23]. Jiang et al. used the dynamic finite element method to analyze the characteristics of the explosive load and produced three-dimensional numerical models of open-pit mines and underground mines [24]. Chen et al. used the tensile and compression damage model to simulate the entire process of blasting and excavation of a typical bedrock slope, through parameter analysis, the stability of the slope under the blasting load was ensured [25]. Li et al. used a comprehensive study method combining theoretical analysis, field testing, and numerical simulation to develop a collaborative blasting technology for high and steep slopes and underground tunnels [26].

In summary, the above methods did not systematically explore and analyze the adjacent high-steep rock slopes after blasting vibration. As well as the magnitude of the shock wave generated by the blasting vibration, the evaluation of slope stability has always been a difficult problem. In addition, for the adjacent rock slopes, the large-aperture mine blasting technology has certain limitations, which will seriously damage the stability of the slope. Against these challenges, a small-aperture shock-absorbing blasting technology with a diagonal line of hole-by-hole initiation was proposed, which can greatly improve production efficiency. In addition, based on engineering geological investigation, field blasting test, blasting vibration monitoring, numerical simulation technology, and theoretical analysis, the three-dimensional dynamic stability of adjacent high slopes was systematically studied. Among them, by establishing four slope geomechanics numerical models, the slope’s own frequency, damping characteristics, and the dynamic response acceleration distribution of the slope under blasting vibration were studied, respectively. Combined with the 8-degree seismic intensity El Centro wave on the slope, it shows the high slope near the Jianshan Phosphate Mine maintains overall stability under the action of blasting vibration unloading or seismic waves. Our study can provide theoretical guidance and technical support for the stability analysis of open-pit high slopes under blasting vibration.

2. Jianshan Phosphate Mine Engineering Background

2.1. Geographical Location of Mining Area. The Dianchi Lake area of Yunnan Province is one of the main distribution areas of phosphate deposits in China. These include the Jianshan Phosphate Mine and Kuning Phosphate Mine. Yunnan Province has a subtropical monsoon climate with hot and rainy summers and an average annual rainfall of about 886.99 mm. As shown in Figure 1, the rainfall in a single month of summer in Yunnan Province is 120~150 mm. In our study, the Jianshan Phosphorus Mine is located near Haitou Town, Xishan District, Kunming City, Yunnan Province, China, adjacent to Dianchi Lake and Fuxian Lake, and the surrounding railway is relatively convenient. The study area is located at 102°06′09″–102°49′56″ east longitude and 24°48′24″–25°05′35″ north latitude (Figure 1). According to the geological investigation, the Jianshan Phosphate Mine is located in the middle of the Jianshan mining area. It is characterized by a high mountain topography, with the characteristic of being flat on the south and steep on the north. The topography of the foothills is roughly the same as the slope of the rock formations. In Figure 1, the highest peak height of the mining area is 2205.75 m, and the lowest erosion benchmark elevation is 1883.15 m. More than 20 perennial rivers in the surface water system converge into Dianchi Lake, and the river at the exit of Dianchi Lake is Haikou River. It flows from east to west through the northern edge of the mining area. At present, the water level of mining is 1982 m, which is much higher than the groundwater level and the water level of the surface water system.

2.2. Geological Structure Characteristics. The mining area is located in the north wing of the Xiangtiao Village anticline. The secondary folds are relatively simple in structure and small in scale. There are mainly two types of folds:
(1) *Wide and Gentle Folds*. Distributed in the western part of the mining area, the folds are generally between 150 and 200 m in length and width, and less than 10 m in height. It is a short-axis dorsal and syncline with small undulations, which often appear in groups.

(2) *Traction Folds*. Mainly distributed in the eastern part of the mining area, small folds produced by local compression, with a short extension.

The fault structure in this mining area is not well developed. In contrast, joints and fracture structures are more developed, especially in the brittle rock and ore layers of the second member (Є1m2) of the Meishucun Stage. Compression fracture zones can be seen locally on reverse faults (main faults, with a vertical fault distance of no more than 30 m), which are mostly a compressive structural surface, but only two ore layers of the fault are broken and small traction folds appear [27]. On the other hand, normal faults are small in scale, mostly tensile structural planes, with small vertical fault distances. In general, when the section cut by the fault is brittle rock formations such as phosphorite and dolomite, the fracture zone structure of normal faults and reverse faults is relatively loose. And when the section cut by the fault is a plastic rock layer such as phosphorite clay rock, whether it is a normal fault or a reverse fault, the fracture zone structure is relatively dense.

### 2.3. Weathering Degree of Phosphorite

After geological survey, the degree of weathering of the phosphorite deposit by the fault is mainly related to the material composition and structure of the fault fracture zone. As shown in Figure 2, the fracture zone with loose material structure is mostly phosphorite and dolomite, with looser structure and higher porosity. In this environment, the water conductivity of the ore bed is strong, and the fault structure greatly improves the weathering degree of the phosphorite [28, 29]. In addition, most of the fracture zone with dense material structure is composed of phosphorus-bearing clay rocks. Porosity and fissure rate are low, which can prevent water from the footwall of the fault [30, 31]. In this case, the degree of weathering of the phosphorite in the hanging wall of the fault is still high, but the degree of weathering of the phosphorite in the footwall is relatively weak. This is because the penetration and migration of groundwater are blocked, and the lower mine layer is protected from weathering [32, 33]. Therefore, the fault structure plays a certain role in controlling the weathering degree of phosphorite in its affected area.

### 3. Blasting Test and Monitoring

#### 3.1. Blasting Plans

Based on the results of the geological investigation, using the layered characteristics of layered slopes, the natural fissures between layers are used as presif- fures to implement a slope-controlled blasting test similar to presplitting blasting. To reduce the damage to the slope surface by blasting, blasting and excavating are given priority to 15 m away from the adjacent reserved side slope to form a free surface with a height of 10.5 m. Second, carry out piercing operations on the remaining platforms adjacent to the
slope and implement controlled blasting [34]. As shown in Figure 3(b), from the reserved side slope 3.5 m away, the second row of buffer holes is 7.5 m deep, and the hole spacing is 4 m. The distance between the first row and the second row is 4 m, the hole spacing is 4 m, and the drilling depth is 10.5 m. The drilling angles of the two rows of holes are 60° and 75°, and the angle of the holes in the third row and outside the main blasting zone is 90°. At the same time, the millisecond network plastic detonator is used to start from the free surface, and the detonation is performed hole by hole with a slight difference between the rows. In the test, we used the diagonal detonation method, with a 8 × 4 m hole mesh parameters. The delay time of the detonator was 35 ms between the holes, 65 ms between the rows, and 300 ms within the holes.

3.2. Blasting Methods and Results. Combining the actual perforation needs of the adjacent open-pit slope, and realizing the effects of shock absorption, energy buffering, and slope protection, the buffer blasting control area (the first and second rows of holes adjacent to the slope) choose to drill a straight \( D = 115 \) mm drilling rig. As shown in Figure 3(a), the third row of the blasting buffer zone is imaginary presplit holes (natural fissures in the rock at the excavation line). The second row of buffer holes are \( a = 4.0 \) m, \( b = 3.5 \) m, the parameters of the first row of buffer holes are \( a = 4.0 \) m, \( b = 4.0 \) m, and the hole network parameters of the main explosion zone are \( a \times b = 5 \times 5.5 \). The inclination angle of the slope rock layer surveyed on site is between 48° and 52°, which is taken as 50°. In order to protect the open-pit slope and reduce the damage to the final slope rock formation, based on the perforation technical performance and construction cost of the drilling rig, the perforation angle of the second row of holes in the blasting buffer zone is determined to be 60° [35]. In Figure 3(c), considering the overall blasting effect, two rows of buffer holes are finally selected to adopt the form of segmented charging. The lower part of the first row of buffer holes is charged 2/3, and the upper part is charged 1/3. In order to avoid overcrushing at the bottom of the second row of buffer holes, which would affect the stability of the slope, a method of charging 2/3 of the upper part and 1/3 of the lower part is adopted. The middle part of the two rows of holes adopts 1.5 m inert filling material, and the main blast hole adopts a centralized charge structure. Finally, a diagonal line is used to detonate the network hole by hole (Figure 4). The blast holes in the same row are connected with the same interhole delay. When the rows are connected, the second blast hole in the first row is connected with the interrow delay detonator to the first blast hole in the second row. The platoon connection method is similar to this. Among them, \( T_1 \) is the delay between holes (35 ms), \( T_2 \) is the delay between rows (65 ms), and \( T_0 \) is the delay of the detonator in the holes (500 ms).

The blasting test completed the task of slope cutting and unloading below the 2160 m level of Jianshan Phosphate Mine. In the process of implementation, the impact and damage of flying rocks on the surroundings can be better controlled, and no blasting casualties occurred. In addition, by accelerating the unloading speed of the slope, the rate of change of the slope is effectively slowed down, which provides a guarantee for the continuous progress of the mining work below. Meanwhile, this technology effectively protects the open-pit slope, and the entire slope is smooth and flat, which improves production efficiency and speeds up the slope cutting progress [36].

3.3. Blasting Vibration Monitoring. Figure 5 shows the wave velocity changes of blasting vibration on the high slope of
Jianshan and the slope near Haifeng stope. Among them, the high slope of Jianshan has the strongest wave velocity in the range of 1000 s, and the high slope of Haifeng has the strongest wave velocity in the range of 1700 s to 1900 s. According to the safety allowable vibration speed standard for permanent rock high slopes, the on-site slope vibration speed standard control is determined to be 5 cm/s [31, 33]. However, the peak vibration velocity of the measuring point on the high slope of Jianshan mountain is less than this standard. In order to further study the vibration of mining blasting, we have carried out more than 20 vibration monitoring tasks. And select several groups of measured data on high

![Diagram](image-url)
slopes for comparative analysis. In Table 1, when the maximum single shot charge is the same, the blasting vibration velocity at the same blasting location basically decreases with the increase of the blasting center distance [37]. The reason is that the nature of the rock mass, the integrity of the rock mass, and the slope and the thickness of the slope and the mountain mass are the main factors that affect the elevation effect [38]. In addition, the slope will affect the intensity and frequency of the blasting vibration wave, so different amplification effects will appear.

As shown in Figure 6, to study the seismic effect of blasting vibration on high slopes and to determine whether the high slopes are within the safe allowable range, we have arranged denser measurement points in areas where the slopes are severely deformed. According to the actual situation of blasting in Jianshan Phosphorus Mine, monitoring points are arranged on the high slope of Jianshan stope. Next, the three-dimensional dynamic stability analysis of the high slope after blasting vibration is carried out based on the monitoring points.

Considering the elevation effect of blasting vibration wave propagation, we perform regression analysis on the data in Table 1. The attenuation law and propagation law of high slope blasting vibration are calculated and predicted [39]:

\[ v = k \left( \frac{\sqrt{Q}}{D} \right)^{\alpha} \left( \frac{\sqrt{Q}}{H} \right)^{\beta} \]  

Table 1: Typical vibration data statistics table.

| Vibration measurement sequence | Maximum single shot dose/kg | R (horizontal distance/m) | Maximum vibration speed (cm/s) (x-axis) | Measuring point position |
|-------------------------------|----------------------------|---------------------------|-----------------------------------------|-------------------------|
| #1                            | 68                         | 181                       | 0.81297                                | 2040 m                  |
| #2                            | 68                         | 204                       | 0.95276                                | 2070 m                  |
| #3                            | 68                         | 257                       | 0.39402                                | 2100 m                  |
| #4                            | 68                         | 245                       | 0.34240                                | 2040 m                  |
| #5                            | 68                         | 268                       | 0.50395                                | 2070 m                  |
| #6                            | 68                         | 290                       | 0.37563                                | 2100 m                  |
| #7                            | 68                         | 184                       | 0.45802                                | 2040 m                  |
| #8                            | 68                         | 304                       | 0.43470                                | 2070 m                  |
| #9                            | 68                         | 395                       | 0.24226                                | 2100 m                  |
| #10                           | 69                         | 316                       | 0.28700                                | 2040 m                  |
| #11                           | 69                         | 379                       | 0.31565                                | 2070 m                  |
| #12                           | 69                         | 449                       | 0.43220                                | 2100 m                  |
| #13                           | 69                         | 173                       | 0.76787                                | 2040 m                  |
| #14                           | 69                         | 239                       | 0.55729                                | 2070 m                  |
| #15                           | 69                         | 284                       | 0.44222                                | 2100 m                  |
In formula (1), $D$ is the burst distance (horizontal distance), $m$; $k$ is the site condition factor; $Q$ is the maximum amount of blasting charge, kg; $\alpha$ and $\beta$ are the blasting vibration wave attenuation index; $H$ is the point distance, m.

According to formula (1), the blasting vibration propagation law of Jianshan Phosphorus Mine is analyzed. Take the logarithm of both sides of the formula:

$$\lg v = \lg k + \alpha \lg \left(\sqrt[3]{Q} / D\right) + \beta \lg \left(\sqrt[3]{Q} / H\right).$$  \hspace{1cm} (2)

In formula (2), let $Y = \lg v$, $X_1 = \lg (\sqrt[3]{Q} / R)$, $X_2 = \lg (\sqrt[3]{Q} / H)$, then

$$Y = \lg k + \alpha X_1 + \beta X_2.$$  \hspace{1cm} (3)

Based on formula (3), the $x$-axis vibration data is subjected to regression analysis, and it can be obtained that $k = 29.724$, $\alpha = 1.524$, and $\beta = -0.515$. Therefore, the $x$-axis propagation law of blasting vibration on the high slope of Jianshan Phosphate Mine is as follows:

$$v = 29.724 \left(\frac{\sqrt[3]{Q}}{D}\right)^{1.524} \left(\frac{\sqrt[3]{Q}}{H}\right)^{-0.515}. \hspace{1cm} (4)$$

The maximum amount of medicine $Q_{\text{max}}$ for slope safety is deduced as

$$Q_{\text{max}} \leq \left(\frac{V}{19.311}\right)^{3.222} \times D^{2.887} \times H^{0.113}. \hspace{1cm} (5)$$

Similar to this, the $y$-axis propagation law of blasting vibration on the high slope of Jianshan Phosphorus Mine, and the maximum amount of charge $Q_{\text{max}}$ for slope safety is as shown in the following formula:

$$v = 19.311 \left(\frac{\sqrt[3]{Q}}{D}\right)^{0.896} \left(\frac{\sqrt[3]{Q}}{H}\right)^{0.035}. \hspace{1cm} (6)$$

The $z$-axis propagation law of blasting vibration on the high slope of Jianshan Phosphorus Mine, and the maximum amount of charge $Q_{\text{max}}$ for slope safety is as shown in the following formula:

$$v = 1430.540 \left(\frac{\sqrt[3]{Q}}{D}\right)^{1.926} \left(\frac{\sqrt[3]{Q}}{H}\right)^{0.070}. \hspace{1cm} (7)$$

In order to further study the propagation law of blasting vibration in the stope of Jianshan Phosphorus Mine, we conducted blasting monitoring on the 1990 m platform of the Jianshan stope and the 1980 m platform of the Haifeng stope. According to the regression analysis of Sadowski formula, the propagation laws of blasting vibration in three directions can be obtained [40]:

$$v = k \left(\frac{\sqrt[3]{Q}}{R}\right)^{\alpha}. \hspace{1cm} (8)$$

Among them, $v$ is the peak vertical vibration velocity of blasting vibration, cm/s; $k$ is the site condition factor; $Q$ is the maximum amount of blasting charge, kg; $R$ is the slope distance between measuring point and burst center, m; $\alpha$ is the blasting vibration wave attenuation index.

The propagation law of blasting vibration in Jianshan stope and Haifeng stope is as shown in Figure 7. The propagation acceleration of the blasting vibration on the $x$-axis monitored at the Jianshan stope is the largest, while the average propagation velocity on the $x$-axis monitored at the Haifeng stope is the largest. Blasting in the open-pit does not fully reflect the propagation law from the blasting area to the entire phosphate mining area, but it can effectively predict the impact on the adjacent slope. Due to changes in geological conditions, topographical environment, and other
factors, the propagation law of blasting vibration may also be different [41, 42].

4. Three-Dimensional Dynamic Stability Analysis of High Slope

4.1. Blasting Shock Wave. The time-history curve of vibration acceleration caused by mining blasting vibration in Jianshan stope and Haifeng stope is as shown in Figure 8. Based on the velocity changes on $x$, $y$, and $z$ in Figure 5, overall, the Jianshan stope blasting vibration wave accelerates in the $x$-direction of the slope and decelerates in the $y$-direction (Figure 8(a)) [43]. On the other hand, the blasting vibration waves make regular variable-velocity motions in the $x$, $y$, and $z$ directions of the side slope of the coastal abundance stope (Figure 8(b)) [44]. Here, the vibration waves in the $x$ and $z$ directions first accelerate and then decelerate in a sequential cycle, and the vibration waves in the $y$ direction first decelerate and then accelerate in a sequential cycle. The rock mass parameters are used in theoretical analysis and calculation as shown in Table 2. In our study, using geotechnical analysis modeling software and some self-compiled preprocessing programs, a three-dimensional model of the topographic contour of the Jianshan open-pit was established [45, 46]. Affected by the difference of terrain, lithology, blasting distance, and maximum charge, the acceleration transmitted by the blast wave will change irregularly. Combining exploration conditions and using geotechnical engineering calculation and analysis software, a preliminary three-dimensional analysis model.
of blasting vibration of four Jianshan open-pit was established (Figure 9).

4.2. Three-Dimensional Static Stability Analysis. To determine the natural vibration characteristics of the four three-dimensional slope models, Midas-GTS (Geotechnical and Tunnel analysis System) software was used to conduct modal analysis on the four three-dimensional slope models [47]. The first 10 frequencies of each model are extracted, the corresponding relationship between the vibration frequency and the period is analyzed, and the natural vibration periods of the four three-dimensional slope models are as shown in Figure 10 [48]. In detail, model II has the largest natural frequency and the shortest period. Model III has the smallest natural frequency and the longest period.

The blasting vibration of the slope will inevitably produce mechanical damping, and the damping mainly comes from the internal friction of the material and the possible sliding of the contact surface. Currently, FLAC3D (Three Dimensional Fast Lagrangian Analysis of Continue) dynamic calculation provides three types of damping, namely, Rayleigh damping, local damping, and hysteretic damping [49]. Considering Rayleigh damping theory is similar to conventional dynamic analysis, and practice has proved that the calculated acceleration response law is more realistic [50]. Thus, in this paper, Rayleigh damping is used to carry out the analysis. When using Rayleigh damping calculation, the relationship between the damping matrix $C$, the stiffness matrix $K$, and the mass matrix $M$ in the dynamic equation is

$$ C = aM + \beta K. \quad (11) $$

In formula (11), $a$ is the damping constant proportional to the mass; $\beta$ is the damping constant proportional to the stiffness; $aM$ is the mass component, which is equivalent to the damper connecting each node and the ground; $\beta K$ is the stiffness component, which is equivalent to the damper between the connected units.

After normalizing the two Rayleigh damping matrices with only stiffness component and mass component, the minimum value of the damping ratio curve can be obtained. By determining two important parameters of Rayleigh damping—$\zeta_{\text{min}}$ (minimum critical damping ratio) and $\omega_{\text{min}}$—

| Lithological material type                  | Bulk density (kg/m$^3$) | Poisson's ratio | Uniaxial tensile strength (MPa) | Deformation modulus (GPa) | Internal friction angle (°) | Cohesion (MPa) |
|---------------------------------------------|-------------------------|----------------|--------------------------------|---------------------------|-----------------------------|----------------|
| Dolomitic mudstone with silty sandstone     | 2750                    | 0.30           | 0.1307                         | 3.5947                    | 30.3                        | 0.103          |
| Dolomite and sandy dolomite                 | 2710                    | 0.28           | 0.1307                         | 3.5947                    | 32.0                        | 0.120          |
| Fine powder crystal dolomite                | 2700                    | 0.24           | 0.2589                         | 4.8193                    | 32.0                        | 0.120          |
| Ore body                                    | 2800                    | 0.22           | 0.0639                         | 2.7646                    | 29.0                        | 0.080          |
| Black shale                                 | 2750                    | 0.30           | 0.0966                         | 2.6269                    | 33.8                        | 0.102          |
Figure 11: Maximum total displacement of different models after blasting vibration. (a) Model I. (b) Model II. (c) Model III. (d) Model IV.

Figure 12: Maximum total velocity of different models after blasting vibration. (a) Model I. (b) Model II. (c) Model III. (d) Model IV.
\( \omega_{\text{min}} = (\alpha/\beta)^{1/2}. \) \hspace{1cm} (13)

For geotechnical materials, the critical damping ratio generally ranges from 2\% to 5\%. Combined with the monitoring section of the slope, the natural frequency is used as the center frequency, and then determine the values of \( \alpha \) and \( \beta \).

\[ \zeta_{\text{min}} = (\alpha \beta)^{1/2}, \] \hspace{1cm} (12)
frequency of Rayleigh damping. Figures 11–14 are the maximum total displacement, maximum total velocity, maximum total acceleration, and maximum element stress (Von Mises stress) of the three-dimensional model I-IV under blasting vibration. Comparing models I-IV, the maximum total displacement of model I is the largest, the maximum total velocity and maximum acceleration of model III are the largest, and the maximum element stress of model II is the largest. The reason is that these differences may be related to the blasting location and the geological conditions of the model area [51].

To deeply analyze the influence of blasting vibration on the slope stability of Jianshan Phosphate Mine. According to the general law of slope dynamic response, that is, the acceleration amplification factor $\eta$ is the ratio of the peak value of slope acceleration to the peak value of slope foot acceleration [52]. Thus, if the acceleration peak of the dynamic response at any point $E$ in the slope body is $a_E$, and the acceleration peak of the dynamic response at the foot of the slope is $a$, then, the acceleration amplification factor $\eta$ at point $E$ can be expressed by the following formula [53]:

$$\eta = \frac{a_E}{a}.$$  \hspace{1cm} (14)

In Figures 11–14, the maximum total acceleration amplification factor during time-history analysis under the action of blasting vibration of the four three-dimensional models can be obtained. As shown in Table 3, the time-history analysis of the four models of blasting vibration has a maximum total acceleration amplification moment of 4.07% to 10.9%, respectively, indicating that the overall acceleration of the slope is basically not amplified. If the slope stability coefficient is reduced according to the acceleration amplification factor [54], blasting has basically no effect on the overall stability of the slope.

4.3. Stability of Eastern Mining Area after Blasting Vibration Coupled with Top Unloading. A three-dimensional finite element model was established for the current status of slope excavation after unloading at the top of the eastern mining area [55]. The time-history analysis results of the high slope three-dimensional model under the action of blasting vibration after unloading are shown in Figure 15. As shown in Figure 15, the maximum total displacement, total acceleration, and total velocity of the high slope after unloading under the action of blasting vibration are 2.363 cm, 0.776 m/s$^2$, and 0.013 m/s, respectively. Therefore, the high

| Serial number | Model | Maximum total acceleration peak value of dynamic response (m/s$^2$) | Peak acceleration of dynamic response at the foot of the slope (m/s$^2$) | Acceleration amplification factor |
|---------------|-------|---------------------------------------------------------------|------------------------------------------------------------------|----------------------------------|
| 1             | Model I | 0.00091581                                                  | 0.00088                                                         | 1.040693                         |
| 2             | Model II | 0.00095383                                                 | 1.083898                                                        | 1.076052                         |
| 3             | Model III | 0.00103301                                                | 0.00096                                                         | 1.076052                         |
| 4             | Model IV | 0.00106478                                                 |                                                                  | 1.109146                         |

Figure 15: Three-dimensional model of high slope after unloading under blasting vibration.
5. Discussion

5.1. Analysis on the Antiseismic Stability of High Slope. To verify the dynamic stability of the Jianshan open-pit slope under earthquake loads. In this study, the Ei Centro wave (as shown in Figure 16) with an earthquake intensity of 8-degrees was used to analyze and calculate the dynamic stability of the three-dimensional model I [56, 57]. In Figure 17, when the three-dimensional model I is under the action of the 8-degree seismic intensity Ei Centro wave (\(a = 0.2 \, \text{g}\)), the maximum total displacement of the high slope of Jianshan Phosphate Mine is 98 cm, and the maximum total displacement occurs at the top of the high slope (area 1). The maximum unit shear stress generated is 780 Kpa, and the maximum unit shear stress occurs on the slope of Jianshan Phosphorus Mine (area 4). In addition, the maximum total velocity and maximum total acceleration generated by the slope are 1.34 m/s and 2.96 m/s\(^2\), respectively. Among them, the maximum total velocity and maximum total acceleration both appear at the top of the slope (area 2 and area 3). In summary, when the bottom of the three-dimensional model I encounters an earthquake intensity of 8-degrees, the high slope of Jianshan Phosphate Mine can still maintain overall stability.

Based on the three-dimensional models I-IV of the high slope after unloading, the dynamic stability of the high slope after unloading is calculated and analyzed when it encounters an earthquake intensity of 8-degrees (\(a = 0.2 \, \text{g}\)) [58, 59]. After unloading, the three-dimensional model of high slope under the action of 8-degrees seismic intensity Ei Centro wave response acceleration time-history and maximum total displacement analysis results are as shown in Figures 18 and 19. In Figure 18, different blasting areas produce different accelerations, but their function values basically fluctuate very little. The maximum acceleration function value of the four groups of models within 10 s is between 2.2 and 3.3, and the minimum acceleration function value is about 0. Among them, the maximum value is 3.2486 (model I), and the minimum value is 0.0023 (model IV). It can be seen from Figures 18 and 19 that when the three-dimensional model I is under the action of the 8-degree seismic intensity Ei Centro wave, the maximum total displacement of the Jianshan Phosphate Mine slope is 105 cm, and the maximum total displacement occurs at its top. In addition, the maximum total acceleration generated by the slope of Jianshan Phosphate Mine is 3.2487 m/s\(^2\), which also occurs at the top of the slope. Thus, the slope of Jianshan Phosphorus Mine can still maintain overall stability [60].

In summary, under the action of the 8-degree seismic intensity Ei Centro wave, the Jianshan Phosphate Mine remains stable near the high slope regardless of whether it is unloaded or not. The simulation results show that the maximum total displacement, maximum total acceleration, maximum total velocity, and maximum total unit stress generated by the seismic waves all occur at the top of the slope. In other words, the top of the slope is the most vulnerable.
area. Therefore, focusing on the blasting site monitoring of the top of the slope can effectively ensure the safety of the adjacent high slope after the blasting vibration.

5.2. Prospect of Blasting Technology for High Slope. In our study, by using the small-diameter buffer shock-absorbing blasting technology of the adjacent slope, the production efficiency is greatly improved and the slope cutting progress is accelerated. Currently, based on numerical simulation technology, the maximum total displacement, velocity, acceleration, and stress values of the four groups of high slope models after blasting vibration are calculated from the time dimension, revealing the dynamic stability of Jianshan Phosphate Mine after blasting vibration. In the future, we will develop a new blasting method from the perspective of economic benefits, which can not only improve the safety and efficiency of blasting but also save raw materials. In addition, new blasting technology is injected into the technology.
existing dynamic stability analysis research results, combined with deep learning, Bayesian interpolation, and numerical simulation technology, to explore the stability of the adjacent high slope after blasting vibration in the two dimensions of time and space.

6. Conclusions

According to the investigation of engineering geology and rock weathering degree of Jianshan Phosphorus Mine, combined with field blasting, vibration propagation monitoring, numerical simulation calculation, and theoretical analysis, the three-dimensional dynamic stability of adjacent high slopes after blasting vibration is systematically studied. By establishing four three-dimensional slope models to simulate the maximum total displacement, velocity, acceleration, and stress changes of Jianshan Phosphate Mine under blasting vibration and unloading, the following conclusions are drawn.

1. Based on the geological conditions of Jianshan Phosphate Mine, a small-diameter buffer shock-absorbing blasting technique for adjacent slopes is proposed. In the actual engineering application, the production efficiency is improved and the slope cutting progress is accelerated. In addition, the proposed blasting method effectively protects the slope surface and provides a guarantee for the continuous mining work below.

2. Regression analysis is performed on a large number of blasting vibration test data, and the law of blasting vibration propagation in Jianshan stope, Haifeng stope, and adjacent high slopes is obtained.

3. Under the action of blasting vibration, the maximum total acceleration magnification of the four three-dimensional models in the eastern mining area of Jianshan Phosphorus Mine reached 4.07% to 10.9%, respectively. Therefore, the overall acceleration of the slope is basically not amplified. If the slope stability coefficient is reduced according to the acceleration amplification factor, the blasting basically has no effect on the overall stability of the slope. In addition, after blasting vibration is unloaded, the maximum total displacement, total acceleration, and total velocity of the three-dimensional model of the eastern mining area of Jianshan Phosphorus Mine are 2.36 cm, 0.776 m/s², and 0.013 m/s, respectively, and the high slope tends to be stable as a whole.

4. Affected by the 8-degree seismic intensity Ei Centro wave, the maximum total displacement produced by the eastern slope of Jianshan Phosphorus Mine is 105 cm, and the maximum total acceleration is 3.2487 m/s². Among them, the maximum total displacement and maximum total acceleration occur at the top of the slope, but the high slope of Jianshan Phosphorus Mine still maintains overall stability. In the future, focusing on the blasting site monitoring of the top of the slope can effectively ensure the safety of the adjacent high slope after the blasting vibration.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

This work was supported by National Natural Science Foundation of China (no. 41867033), Postdoctoral Science Foundation of China (no. 2019M650144), and State Key Laboratory of Safety and Health for Metal Mines (dzsys2019-005). The authors wish to acknowledge these supports.

References

[1] Y. Zhao, R. L. Shan, and H. L. Wang, “Research on vibration effect of tunnel blasting based on an improved Hilbert-Huang transform,” Environmental Earth Sciences, vol. 80, no. 5, pp. 1–14, 2021.
[2] J. Feher, J. Cambal, B. Pandula et al., “Research of the technical seismicity due to blasting works in quarries and their impact on the environment and population,” Applied Sciences, vol. 11, no. 2118, pp. 1–17, 2021.
[3] N. Jiang, C. B. Zhou, S. W. Lu, and Z. Zhang, “Propagation and prediction of blasting vibration on slope in an open pit during underground mining,” Tunneling and Underground Space Technology, vol. 70, no. 1, pp. 409–421, 2017.
[4] J. Yang, Z. G. Tao, B. L. Li, Y. Gui, and H. F. Li, “Stability assessment and feature analysis of slope in Nanfen Open Pit Iron Mine,” International Journal of Mining Science and Technology, vol. 22, no. 3, pp. 329–333, 2012.
[5] X. K. Ye, “The analysis of influence of the blasting vibration in slope engineering design for open pit mining,” Mining and Metallurgical Engineering, vol. 7, no. 3, pp. 10–13, 1987.
[6] B. S. Kumar, “Landslide disaster perception of the AILA cyclone in the Darjeeling town, West Bengal, India,” International Journal of Geomatics and Geosciences, vol. 3, no. 1, pp. 13–29, 2012.
[7] R. B. Liang, “Automated mapping of Ms 7.0 Jiuzhaigou earthquake (China) post-disaster landslides based on high-resolution UAV imagery,” Remote Sensing, vol. 13, no. 7, pp. 1318–1330, 2021.
[8] C. Y. Zhang, Y. X. Wang, H. Ruan, B. Ke, and H. Lin, “The strain characteristics and corresponding model of rock materials under uniaxial cyclic load/unload compression and their deformation and fatigue damage analysis," Archive of Applied Mechanics, vol. 91, no. 6, pp. 2481–2496, 2021.
[9] X. S. Li, J. B. Geng, Q. H. Li, W. J. Tian, and T. Zhou, “Behaviors and overlying strata failure law for underground filling of a gently inclined medium-thick phosphate deposit,” Advances in Civil Engineering, vol. 2021, no. 1, pp. 1–17, 2021.
10. S. Li, Z. F. Liu, and S. Yang, “Similar physical modeling of roof stress and subsidence in room and pillar mining of a gently inclined medium-thick phosphate rock,” *Advances in Civil Engineering*, vol. 2021, no. 4, pp. 1–17, 2021.

11. X. Ren, R. Zhao, Q. J. Li, and X. M. Cheng, “Study on blasting safety technology applied in Karst Limestone Mine,” *Procedia Engineering*, vol. 84, no. 1, pp. 873–878, 2014.

12. G. G. U. Aldas and B. Ecevitoglu, “Waveform analysis in mitigation of blast-induced vibrations,” *Journal of Applied Geophysics*, vol. 66, no. 1–2, pp. 25–30, 2008.

13. X. B. Guo, Z. X. Xiao, and Z. C. Zhang, “Slope effect of blasting vibration,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 20, no. 1, pp. 83–87, 2001.

14. X. L. Zhang, H. B. Yi, G. S. Xin, and H. T. Yang, “Influence of elevation on the blasting vibration law in the slope of an open-pit mine,” *Metal Mine*, vol. 2017, no. 7, pp. 55–59, 2017.

15. G. Wang, “Stability analysis of steep and high bedding rock slopes under the action of underground blasting vibration,” *Journal of China and Foreign Highway*, vol. 2018, no. 3, pp. 24–28, 2018.

16. K. B. Narayan, K. M. Arvind, M. M. Singh, R. Aditya, and P. K. Singh, “Directional controlled blasting technique for excavation of unstable slopes along the Konkan railway route,” *Mining Engineering*, vol. 72, no. 7, pp. 106–107, 2020.

17. T. Y. Wu, C. B. Zhou, N. Jiang, Y. Q. Xia, and Y. Q. Zhang, “Stability analysis for high-steep slope subjected to repeated blasting vibration,” *Arabian Journal of Geosciences*, vol. 13, no. 17, pp. 7207–7227, 2020.

18. K. Deng and M. Chen, “Blasting excavation and stability control technology for ultra-high steep rock slope of hydropower engineering in China: a review,” *European Journal of Remote Sensing*, vol. 54, no. 3, pp. 92–106, 2021.

19. C. Y. Ma, L. Wu, M. Sun, and D. X. Lei, “Failure mechanism and stability analysis of bank slope deformation under the synergistic effect of heavy rainfall and blasting vibration,” *Geotechnical and Geological Engineering*, vol. 2021, no. 1, pp. 1–14, 2021.

20. C. J. Edward, R. Alex, R. David, and U. Brian, “Approximating a far-field blast environment in an advanced blast simulator for explosion resistance testing,” *International Journal of Protective Structures*, vol. 11, no. 4, pp. 468–493, 2020.

21. J. S. Sun, Y. S. Jia, Y. K. Yao, and X. Q. Xie, “Experimental investigation of stress transients of blasted RC columns in the blasting demolition of buildings,” *Engineering Structures*, vol. 210, p. 110417, 2020.

22. Z. H. Xie, R. Y. Xie, and X. Y. Lu, “Stability analysis on high and steep slope of open-pit based on limit equilibrium method,” *Applied Mechanics and Materials*, vol. 4075, no. 2, pp. 106–111, 2015.

23. Y. L. Gui, Z. Y. Zhao, H. Y. Zhou, A. T. C. Goh, and L. B. Jayasingle, “Numerical simulation of rock blasting induced free field vibration,” *Procedia Engineering*, vol. 191, no. 1, pp. 451–457, 2017.

24. N. Jiang, C. B. Zhou, S. W. Lu, and Z. Zhang, “Effect of underground mine blast vibrations on overlying open pit slopes: a case study for Daye iron mine in China,” *Geotechnical and Geological Engineering*, vol. 36, no. 3, pp. 1475–1489, 2018.

25. Y. K. Chen, J. H. Xu, X. H. Huo, J. C. Wang, and D. Younesian, “Numerical simulation of dynamic damage and stability of a bedding rock slope under blasting load,” *Shock and Vibration*, vol. 2019, no. 2, pp. 1–12, 2019.

26. L. B. Li, J. H. Zhang, and L. Wu, “Construction technology of cooperative blasting in high-steep slope and underground tunnel in offshore oil depot,” *Journal of Coastal Research*, vol. 98, no. 1, pp. 1–5, 2019.

27. M. L. Wang, X. S. Li, Q. H. Li, Y. J. Hu, Q. S. Chen, and S. Jiang, “Study on blasting technology for open-pit layering of complex mine adjacent to high and steep slope,” *Frontiers in Earth Science*, vol. 2021, no. 9, pp. 1–18, 2021.

28. X. S. Li, K. Peng, J. Peng, and D. Hou, “Effect of thermal damage on mechanical behavior of a fine-grained sandstone,” *Arabian Journal of Geosciences*, vol. 14, no. 13, pp. 1–16, 2021.

29. X. S. Li, Q. H. Li, Y. J. Hu, L. Teng, and S. Yang, “Evolution characteristics of mining fissures in overlying strata of stope after converting from open-pit to underground,” *Arabian Journal of Geosciences*, vol. 14, no. 24, pp. 1–18, 2021.

30. X. S. Li, K. Peng, J. Peng, and D. Hou, “Experimental investigation of cyclic wetting-drying effect on mechanical behavior of a medium-grained sandstone,” *Engineering Geology*, vol. 293, p. 106335, 2021.

31. S. B. Tang, C. Y. Yu, M. J. Heap, P. Z. Chen, and Y. G. Ren, “The influence of water saturation on the short- and long-term mechanical behavior of red sandstone,” *Rock Mechanics and Rock Engineering*, vol. 51, no. 9, pp. 2669–2687, 2017.

32. C. R. Zhang, Y. X. Ge, J. L. Lv, and G. F. Ren, “Study on elevation effect of blast wave propagation in high side wall of deep underground powerhouse,” *Bulletin of Engineering Geology and the Environment*, vol. 80, no. 5, pp. 3973–3987, 2021.

33. S. B. Tang, R. Q. Huang, C. A. Tang, Z. Z. Liang, and M. J. Heap, “The failure processes analysis of rock slope using numerical modelling techniques,” *Engineering Failure Analysis*, vol. 79, pp. 999–1016, 2017.

34. S. Xu, Y. H. Li, L. An, and Y. J. Yang, “Study on high and steep slope stability in condition of underground mining disturbance,” *Journal of Mining and Safety Engineering*, vol. 29, no. 6, pp. 888–893, 2012.

35. C. Y. Zhang, Y. X. Wang, and T. T. Jiang, “The propagation mechanism of an oblique straight crack in a rock sample and the effect of osmotic pressure under in-plane biaxial compression,” *Arabian Journal of Geosciences*, vol. 13, no. 15, pp. 1–15, 2020.

36. C. Y. Zhang, C. Z. Pu, R. H. Cao, T. T. Jiang, and G. Huang, “The stability and roof-support optimization of roadways passing through unfavorable geological bodies using advanced detection and monitoring methods, among others, in the Sanmenxia bauxite mine in China’s Henan Province,” *Bulletin of Engineering Geology and the Environment*, vol. 78, no. 7, pp. 5087–5099, 2019.

37. R. S. Ganjeh, H. Memarian, and M. H. Khosravi, “A comparison between effects of earthquake and blasting on stability of mine slopes: a case study of Chadormalu open-pit mine,” *Journal of Mining and Environment*, vol. 10, no. 1, pp. 223–240, 2019.

38. J. B. Geng, Q. H. Li, X. S. Li, T. Zhou, Z. F. Liu, and Y. L. Xie, “Research on the evolution characteristics of rock mass response from open-pit to underground mining,” *Advances in Materials Science and Engineering*, vol. 2021, no. 1, pp. 1–15, 2021.

39. I. M. Mulalo, J. H. Zhang, G. Huang, and D. M. Akisa, “Assessment of blast-induced ground vibration at Jinduicheng molybdenum open pit mine,” *Natural Resources Research*, vol. 29, no. 2, pp. 831–841, 2020.
K. Wang, Z. Y. Liu, X. M. Qian, and Y. R. He, “Dynamic characteristics and damage recognition of blast-induced ground vibration for natural gas transmission pipeline and its integrated systems,” Mechanical Systems & Signal Processing, vol. 136, p. 106472, 2020.

L. O.’. C. Drury and T. P. Downes, “Turbulent magnetic field amplification driven by cosmic ray pressure gradients,” Monthly Notices of the Royal Astronomical Society, vol. 427, no. 3, pp. 2308–2313, 2012.

H. H. Cheng, H. Zhang, B. J. Zhu, and Y. L. Shi, “Finite element analysis of steep excavation slope failure by CFS theory,” Earthquake Science, vol. 25, no. 2, pp. 177–185, 2012.

P. Bottelin, L. Baillet, A. Mathy, L. Garnier, H. Cadet, and O. Brenguier, “Seismic study of soda straws exposed to nearby blasting vibrations,” Journal of Seismology, vol. 24, no. 3, pp. 573–593, 2020.

Y. F. Gao, X. L. Yang, Y. Shen, and Y. Zhou, “Numerical computation of anti-liquefaction effect of lattice-type cement–mixed soil countermeasure,” Journal of Central South University of Technology, vol. 15, no. S2, pp. 155–160, 2008.

J. Ji, C. W. Wang, Y. F. Gao, and L. M. Zhang, “Probabilistic investigation of the seismic displacement of earth slopes under stochastic ground motion: A rotational sliding block analysis,” Canadian Geotechnical Journal, vol. 58, no. 7, pp. 952–968, 2021.

W. Shao, Z. J. Yang, J. J. Ni, Y. Su, W. Nie, and X. Y. Ma, “Comparison of single- and dual-permeability models in simulating the unsaturated hydro-mechanical behavior in a rainfall-triggered landslide,” Landslides, vol. 15, no. 12, pp. 2449–2464, 2018.

A. Haghnajad, K. Ahangari, P. Moarefvand, and K. Goshtasbi, “Numerical investigation of the impact of rock mass properties on propagation of ground vibration,” Natural Hazards, vol. 96, no. 2, pp. 587–606, 2019.