Research Article

Effect of the Location of the Detonation Initiation Point for Bench Blasting

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Uneven floor and fragmentation play an important role in blasting operations due to the direct effects on the efficiency of hauling and loading. This paper focuses on the influences of initiation position on bench blasting in order to improve blasting effects. The numerical simulations of bench blasting at different initiation points (top, middle, and bottom) are implemented based on secondary development of LS-DYNA with a tensile-compressive damage model. The damage spatial distribution characteristics of different initiation points are compared. The outlines of rock foundation and boulder areas are analyzed with the damage threshold of critical breakage that is ascertained by acoustic characteristic of damage rock mass. Results of the numerical simulations demonstrate that different initiation points make a great influence on the stress and energy distribution in blasting process and induce different blasting effects. Middle initiation turns out to be the best initiation to increase the flatness of the floor and decrease the oversize boulder ratio simultaneously, which will increase the damage areas of the bottom and top regions and give a better blasting effect. Field experiment in Baihetan Station was carried out to validate conclusions of numerical simulation. Research could provide a good reference for the improvement of rock blasting.

1. Introduction

Bench blasting is the most widely used excavation method in mining, quarrying, and civil construction excavation. In bench blasting, if the complex blasting parameters are not matched with this blast, there will be toe rocks on the floor and oversize boulder in the muck pile, which may affect the efficiency of blasting operation [1–3]. In order to solve these problems, several field and simulation experiments have been proposed [4–6], and some measures have been taken, such as reducing blasting burden distance, deepening overdrilling depth, and using high power explosive [7–11].

However, the measures proposed above from the engineering experiences are not the essential causes of the rock toe and oversize boulder. In recent decades, the theory of rock damage mechanics has been developed to study the processes of rock failure [12–14] and has been used to analyze the rock breaking effects of bench blasting [15]. Several typical methods and damage models have been proposed, such as

G-K damage model [16], TCK damage model [17], and KUS damage model [18]. Liu et al. [19] established an anisotropic damage model to describe the damage evolution characteristics of remaining rock of bench blasting. Hu et al. [20, 21] made a conclusion of the widely used rock damage models and proposed the rock tensile-compressive damage model, which is used to simulate the blasting excavation damage zone of the high rock slope, and the result matched with the in situ measured data. The existing research achievements show that it is feasible to analyze the effects of bench blasting by the rock damage model.

Deep-hole bench blasting indicates that the blasting process of column charge is more complex than the superposition of some spherical charges. More attention is focused on the explosive stress field and the superposition effect of blasting stress wave, based on numerical simulations and experiments. Gong and Li [22] got the dynamic stress fringe patterns of column charge in different detonation positions and showed that the stress field of the detonation region is

low and that of the other region is high. Zhu [5] developed a cylindrical rock model through the use of AUTODYN code and showed the great influence of initiation position on rock fracture and fragmentation. Long et al. [23] showed the influence of initiation position on fragmentation with field blasting experiments in iron mine. Some more researches also indicate that there is a great influence of the initiation position on the explosive stress field [24, 25]. However, until recently there is still some lack of knowledge about the influence of initiation position on the flatness of bench floor, and very few cases have been reported on the effects of different initiation points in bench blasting.

In the present study, the superposition effects of explosive stress in cylindrical charge at different initiation points are analyzed. The processes of blasting in different initiation points are simulated based on the secondary development of the dynamic finite element code LS-DYNA. Then, the distribution characteristics of blasting induced damage zones are analyzed and the initiation position of improving blasting effects is discussed. At last, the simulation results of different initiation points are validated by the field experiment in Baihetan Water Power Station.

2. The Damage Threshold of Critical Breake Rock Mass

The damage variable is an index of the degradation of rock mass, with the symbol of the decrease in elasticity modulus. It is widely accepted that the relationship between damage variable and elasticity modulus is

$$E = E_0 (1 - D), \quad (1)$$

where E is the modulus of damaged rock masses, E_0 is the modulus of undamaged rock masses, and D is the damage variable.

According to the elastic wave theory, the relationship between elasticity modulus and acoustic velocity in rock masses is

$$E = \rho v^2 \frac{(1 + \mu)(1 - 2\mu)}{1 - \mu}, \quad (2)$$

where ρ is the density of rock masses and μ is Poisson's ratio. It is assumed that density and Poisson's ratio are the same before and after blasting; then, the damage variable D is defined as [20]

$$D = 1 - (1 - \eta)^2, \quad (3)$$

where η is defined as $(1 - v/v_0)$, v_0 is the velocity of rock masses before blasting, and v is the velocity after blasting.

In bench blasting, the rock after blasting is broken seriously, while the damage variables of the rock around the hole and under the hole are not the same. The rock around the hole is badly fragmented and cast out freely because of two free surfaces. However, the rock under the hole is highly confined and hard to crush, and the broken state is weakening and the damage variable decreases with the increase in depth. The damaged rock mass in bench blasting can be divided into four

FIGURE 1: Rock mass partitions after blasting.

zones as shown in Figure 1: cast zone, crushed zone, cracked zone, and vibration zone. When the fragmented rocks are loaded out, the cracked zone is left and is in an ultimate state of rock masses to be excavated. Cracked zone is full of microcracks, but it is not fully fractured. The state is defined as critical breakage. The damage variable matched with critical breakage is critical threshold and can be used to separate the outline of rock foundation in numerical simulation. From (3), it is a good method to test the acoustic velocity of surface rock and calculate the corresponding damage variable that is damage threshold of the critical breakage rock mass. Then, several acoustic tests are collected in the following.

Xia et al. [26] tested the damage characteristics of rock masses under blasting load, with a typical acoustic experiment as plotted in Figure 2 in Hongyanhe Nuclear Power Station. The experiment method is as follows. First, some blast holes are chosen as acoustic holes. The blast holes are 4 meters deep and the acoustic holes are 6 meters deep. Second, the velocity of the acoustic holes is measured before blasting. Third, the acoustic holes are stemmed to toe elevation and blast. Lastly, the velocity of the left acoustic holes is measured after the muck pile is cleared. From the experiment results, the parameter η of the surface rock mass reaches up to 53%, and the damage variable is 0.78.

Jern [27] studied the relationship between the acoustic velocity of damaged rock masses and the distance to the blast hole, based on the field experiment in Angered Mine. From the measured velocity near the hole and far from the hole, the parameter η was 47% and the damage variable was 0.72.

Gorbunov [28] probed into the effect of blasting on rocks based on the acoustic investigation at Inguri Station. From the testing data of velocity of the cracked zone before and after

TABLE 1: Critical damage variable in several experiments.

Sites	Velocity before blasting v_0 (m/s)	Velocity after blasting v (m/s)	Reduction of velocity η	Damage variable D
Hongyanhe			53%	0.78
Angered Mine	6250	3400	47%	0.72
Inguri Station	3750	1500	60%	0.84

FIGURE 2: Arrangements of the holes of acoustic test [26].

blasting, we can learn that the parameter η is 60% and the damage variable is 0.84.

Comparing the three groups' velocity data shown in Table 1, it is observed that the damage variable of cracked rock masses is 0.72~0.84, and it is ascertained that the critical threshold is $D_t = 0.7\sim 0.8$.

3. The Mechanism of the Initiation Position Affecting Blasting Effects

It is known that blast is a very complex dynamic process. As the detonation wave spreads in the hole, a lot of detonation gases of high temperature and pressure are released instantly and the blasting shock wave is loaded on the wall of the hole. The rock adjoining the hole is crushed severely because of the high compressive load. As the radius grows, the shock wave attenuates to stress wave, and the tensile stress loads on rock masses. Because the tensile strength of the rock is much less than the compressive strength, the rock is broken in tensile fracture and full of cracks. At last, the rock mass is ruptured completely with the cracks expanding and thrown out because of stress wave and detonation gas.

When the explosive is detonated, the detonation wave spreads along the hole, and the stress wave induced by detonation also propagates to the other side of the hole in conical wave front. The stress wave induced by the later detonated explosive will strengthen the formed stress field, so there will be stress wave superposition effect that will lead to explosion high energy zone and high stress zone at the region of the hole that is far away from the detonation position. When the initiation point is at the top, the detonation wave and stress wave spread from top to bottom, and the high

energy zone is at the bottom region, where the rock will be broken more severely. When initiation point is at the bottom, the direction is opposite and the high energy zone is at the top region. And when initiation point is at the middle, the wave spreads from median to top and bottom sides, and there will be stress wave superposition both at the top and at the bottom regions. The propagations of the detonation wave and stress wave of different initiation positions are plotted in Figure 3.

4. The Numerical Simulation

4.1. The Damage Model of Rock Blasting. As we know, it is full of microcracks in rock mass. In blasting process, the microcracks in the rock mass will be activated by blast load, and the properties and structures will be damaged. According to Grady-Kipp damage mode [16, 20], it is suggested that the damage variable D is used to measure the deterioration of rock mass and the activated microcracks density C_d is in accordance with Weibull distribution:

$$C_d = \gamma N a^3, \quad (4)$$

where γ is the parameter of the microcrack density, N is the unit volume number of crack, and a is the mean radius of crack. N and a are defined as follows:

$$a = \frac{1}{2} \left(\frac{\sqrt{20} K_{IC}}{\rho c \dot{\epsilon}_{\max}} \right)^{2/3}, \quad (5)$$

$$N = k \epsilon_v^m,$$

where K_{IC} is fracture toughness, ρ is rock mass density, c is acoustic velocity in rock mass, $\dot{\epsilon}_{\max}$ is the maximum of

TABLE 2: Blasting parameters of numerical simulation.

Height (m)	Space (m)	Burden distance (m)	Diameter of the hole (mm)	Diameter of explosive (mm)	Length of explosive (m)	Stemming length (m)
10	3.0	2.5	90	90	8.0	2.0

FIGURE 3: Propagations of detonation wave and stress wave.

volume tensile strain rate, ε_v is volumetric tensile strain, and k and m are distribution parameters. So the activated crack density C_d is as follows:

$$C_d = \frac{5k\varepsilon_v^m}{2} \cdot \left(\frac{K_{IC}}{\rho c \dot{\varepsilon}_{\max}} \right)^2. \quad (6)$$

Hu et al. [20, 21] proposed a tensile-compressive damage model that concludes tensile damage and compressive damage from classical TCK damage model. The model is used to simulate bench blasting with secondary development of LS-DYNA. The damage variable D was defined as the maximum of tensile damage and compressive damage:

$$\begin{aligned} D &= \max(D_t, D_c), \\ D_t &= \frac{16}{9} \cdot \frac{(1 - \bar{\nu}^2)}{(1 - 2\bar{\nu})} \cdot C_d, \\ D_c &= \frac{qW_p}{1 - D_t}, \\ W_p &= \int \sigma_{ij} d\varepsilon_{ij}^p, \end{aligned} \quad (7)$$

where D_t is tensile damage variable, D_c is compressive damage variable, $\bar{\nu}$ is the effective Poisson rate, q is damage parameter, W_p is plastic deformation power, σ_{ij} is stress tensor, and ε_{ij} is plastic strain tensor.

4.2. Blasting Parameters. In order to simulate the blasting process effectively, the parameters of numerical simulation are matched with bench blasting in engineering. The parameters are as in Table 2 and Figure 4.

There are three initiation positions of top, middle, and bottom initiation in bench blasting. In case of security, the detonator is not at the end of the hole in blasting application, but at the point that is 0.8~1.2 m away from the hole bottom. So in the simulation, the bottom initiation point is 1 m, middle point is 4 m, and top point is 7 m to the ends of the holes, as shown in Figure 5.

4.3. The Numerical Simulation. Based on the above-mentioned blasting parameters, the parameters of the model created in ANSYS are shown in Table 3. There are two blasting benches of the former one and the current one in the model in order to simulate the cumulative damage, as plotted in

TABLE 3: Blasting parameters of numerical model.

Model height (m)	Bench height (m)	Model width (m)	Model length (m)	Hole diameter (mm)	Hole depth (m)	Explosive length (m)	Stemming length (m)
30.0	10.0	3.0	10.0	90	10.0	8.0	2.0

FIGURE 4: Parameters of blast holes.

Figure 6. The left and up sides are free faces without restraint. The right and down sides are base rock with nonreflecting boundaries conditions. The front and back sides are symmetric planes with symmetric boundary conditions.

In the simulation experiment, the cumulative damage of bench blasting is recorded with history variable $hsv(i)$ based on the restart method in LS-DYNA, which may restart the simulation with a restart file and a restart input that define the changes to the model, including deleting contacts, materials, and elements. The stress and damage will be inherited by using the keyword `*STRESS_INITIALIZATION` of LS-DYNA, which allows all parts to be initialized on restart based on the results of the former bench excavation. As shown in Figure 6, the two bench excavations are set in two parts: the former one and the current one, and the current bench inherits the damage induced by the former bench so as to simulate the cumulative damage distribution of bench blasting.

Material type of `MAT_HIGH_EXPLOSIVE_BURN` in LS-DYNA is used to simulate the explosive, and the ALE method in LS-DYNA is used to simulate the dynamic shock of explosive. Initiation points are defined by using the keywords `*INITIAL_DETONATION` in LS-DYNA. Combined with JWL state equation, the relationship of pressure and volume in blasting process is as follows:

$$P = A \left(1 - \frac{\omega}{R_1 V} \right) e^{-R_1 V} + B \left(1 - \frac{\omega}{R_2 V} \right) e^{-R_2 V} + \frac{\omega E_0}{V}, \quad (8)$$

where P is the pressure decided by JWL state equation, V is relative volume, E_0 is the initial internal energy, and A , B , R_1 , R_2 , and ω are parameters of JWL equation. The parameter values are shown in Table 4 [20], and the characteristics of rock mass are shown in Table 5.

TABLE 4: Explosive parameters.

Density (kg/m ³)	Detonation velocity (m/s)	PCJ (GPa)	A (GPa)	B (GPa)	R_1	R_2	ω
1000	3600	3.24	220	0.2	4.5	1.1	0.35

5. The Simulation Results and Analysis

5.1. The Parameters of Blasting Effects. To assess the blasting effects, some parameters are defined here to count the damage area and the outline of the left bench floor. The parameters of bottom damage zone are plotted in Figure 7. In the blasting design, the bottom ends of the holes are at the same elevation and the line is called bottom horizontal line. h_0 is the maximum of damage depth to the line and h_1 is the minimum (when h_1 is above the horizontal line, h_1 is negative, and there will be toe rock). h is the relief amplitude and $h = h_0 - h_1$. When $h_1 < 0$, the height of toe rock is $-h_1$; when $h_1 > 0$, there is no rock toe.

As to the damage zone of top region, the assessment index is boulder ratio w . In the damage distribution profile, w is defined as the ratio of the area of $D < D_t$ in stemming section to the area of the blasting bench section.

5.2. The Damage Distributions of Typical Initiation Points. Based on the above damage model and calculation method, the blasting process in different initiation points of two benches is simulated with cumulative damage simulation technology. The colorful nephrograms of damage distribution are plotted by dividing the model along the transverse profile. The profile figures are mirrored along the axis of symmetry to simulate the multiple-hole effect. The damage distribution zones in transverse profile are shown in Figures 8 to 10. The area of $D = 0.9 \sim 1.0$ presents the completely broken rock. The isoline of $D = 0.7 \sim 0.8$ in bottom region represents the outline of latter bench floor.

In bottom initiation, as shown in Figure 8(b), the red area is in the top region where inherited cumulative damage is more than that in the bottom region, which means better breakage of the rock in the top region. However, as to the bottom region, the damage area is in the shape of a cone. The isoline of $D = 0.7 \sim 0.8$ between the two holes is above the bottom horizontal line, where there may be rock toe, and the isoline is not smooth. In the middle initiation, as shown in Figure 9(b), the red areas of top region are nearly full of the stemming section, which means good fragmentation there. The damage area in the bottom section is smooth and it is good to reduce rock toe. In the top initiation, as shown in Figure 10(b), the damage area in the bottom section is relatively smooth and has a good blasting effect. However, as to the top region, the damage area is in the shape of an

TABLE 5: Parameters of numerical rock material.

Material	Density (kg/m ³)	Elasticity modulus (GPa)	Poisson's rate	Shear modulus (GPa)	Compressive strength (MPa)
Rock	2600	40	0.21	16.4	50

TABLE 6: The parameters of blasting effects in different initiation points.

Initiation position	Maximum of damage depth h_0 (m)	Minimum of damage depth h_1 (m)	Height of rock toe (m)	Relief amplitude h (m)	Boulder yield w
Bottom	0.62	-0.56	0.56	1.18	6.0%
Middle	0.62	0.42	—	0.20	2.5%
Top	0.69	0.44	—	0.25	9.5%

FIGURE 5: Charge structures.

inverted cone. Even considering the cumulative damage, the damage area of the top region is still less, which means poor fragmentation.

Based on the damage threshold of critical breakage $D_t = 0.7 \sim 0.8$ above, the broken area is divided by the isoline of $D = 0.7 \sim 0.8$, and the outline of bedrock is plotted in Figure 11.

From Figures 8~11, the parameters of blasting effects of three initiation points are counted, as displayed in Table 6.

5.3. Analysis of the Results. It can be seen that the damage distribution figures and the statistic data are matched with the superposition effect of stress wave in bench blasting. Along the direction of detonation wave spreading, the blast wave

induced by the later detonated explosive will strengthen the formed stress field, and the damage area will increase on the other side.

In the bottom initiation, the detonation wave spreads from bottom to top, so the explosion high energy zone and high stress zone are at the top region, and there is more damage area, which means better breakage of the rock mass. Considering the cumulative damage, the boulder ratio is 6.0%. As to the bottom region, the damage area is small, and some part of the isoline of $D = 0.7 \sim 0.8$ is above the bottom horizontal line. The height of toe rock is 0.56 m, and the relief amplitude reaches up to 1.18 m. The bottom initiation is not good for the flatness of the latter bench floor.

TABLE 7: Rock mass physical character of the experiment zone in Baihetan Station.

Lithology	Nature density (g/cm ³)	Partial density (g/cm ³)	Porosity (%)	Tensile strength (MPa)	Compressive strength (MPa)	Elasticity modulus (GPa)	Poisson's ratio
Basalt	2.87	2.93	2.01	4~8	87~146	55	0.21
Breccias lava	2.66	2.85	7.15	3~8	86~139	30	0.21

FIGURE 6: Numerical model.

FIGURE 7: Rock foundation after blast.

The top initiation is opposite to the bottom initiation. The damage area is smooth and the relief amplitude is only 0.25 m, which means the flatter bench floor. As to the top region, the damage area decreases obviously, and the boulder ratio reaches up to 9.5%, which means poor fragmentation. The top initiation is good for the flatness of the bench floor, but not good for the breakage of the top region rock mass.

The middle initiation takes the advantages of bottom and top initiation, the cumulative effects of stress wave in top and bottom regions are all relatively good, and the blasting results

are better. It can be seen that the damage area is smooth, and the relief amplitude is only 0.2 m; the damage area of the top section is large, and the boulder ratio is only 2.5%. The middle initiation is the best mode to reduce the boulder ratio, rock toe height, and relief amplitude and is good to increase productive efficiency.

6. Field Blasting Experiment

In this section, in order to validate the superposition effect of stress wave and the simulation results above, the field experiments of bench blasting in Baihetan Waterpower Station (China) are provided here.

6.1. Background. The slope of Baihetan dam site is very steep, as the elevation of the nature slope is over 800 m and the height is over 600 m. The rock masses of the left bank mainly include basalt oblique patches, implicit crystalline basalt, basalt columnar joints, amygdaloidal basalt, breccias lava, and tuff. In this paper, the experiment is combined with the productive blasting excavation of the left bank slope. The rocks of experiment zone are basalt and breccias lava, and the properties are shown in Table 7.

6.2. The Experiment Method and Results. There set two sections in the blasting experiment zone: Section I is in the middle initiation, and Section II is the contrast zone and is in the bottom initiation. The space and the burden of blasting holes are all 2.5 m, and the layout of the holes is shown in Figure 12. The depth of the vertical hole is 10 m, and the diameter is 105 mm. The charge structures are shown in Figure 13. In Section I, the detonators are set at the middle of the explosive cylinder; in Section II, the detonators are set at the bottom of the explosive cylinder. To make sure the bottom ends of the holes are at the same elevation, more steps are taken as follows. First, the coordinate of each hole is measured by the total station to get the elevation of each hole's crest. Second, the hole depth of each hole is measured to get the elevation of each hole's bottom end. Third, the measured elevation and the desired elevation of each hole's bottom end are compared to calculate the overdrilling depth. Lastly, the quantitative drilling cutting matched with the overdrilling depths is poured into the hole to keep the bottom ends at the same elevation. The stemming and charge structures are shown in Figure 13. The processes of the experiment in practice are shown in Figure 14.

After blasting and hauling, the bench floor is left and cleared. The relief amplitude is measured with the total station by measuring the elevations of two lines through experiment zones. Comparing the final elevations and the designed elevation, the overbreak depth of every point is

FIGURE 8: Damage zones in bottom initiation.

FIGURE 9: Damage zones in middle initiation.

FIGURE 10: Damage zones in top initiation.

FIGURE 11: The outline of rock foundation under the hole.

FIGURE 12: Layout of blast holes.

shown in Figure 15. The overbreak depth is a negative value and the underbreak depth is a positive value. It can be seen that the two measured lines in Section I are smoother and flatter than those in Section II, and the values are negative, which means the floor is flat and there is no rock toe. In Section II, the measured lines are uneven and the values are mostly positive, which means there is rock toe on the floor. The highest rock toe is about 0.6 m, matched with the simulated value. Figure 16 shows the cleared floors of the two sections. From the experiments results, it is validated that the superposition effect of stress wave is important to blasting effects and middle initiation is better to the breakage of the bottom region rock and more advantageous to the flatness of the latter bench floor.

7. Conclusions

In the present study, the characteristics of bench blasting with different initiation points are investigated with the numerical simulation using LS-DYNA and the field experiment in Baihetan Station. From the experiments results above, the primary conclusions are as follows:

- (1) The damage threshold of critical breakage is an important criterion to depict the outline of rock foundation in numerical simulation. And $D_t = 0.7 \sim 0.8$ is ascertained with acoustic experiments in blasting.
- (2) There is a great influence of the initiation position on blasting effects. As the detonation wave spreads along the cylinder charge, there will be superposition effect

FIGURE 13: Charge structures.

of stress wave and high energy zone and high stress zone at the outside of the hole.

- (3) It is beneficial of top initiation to break the rock under the hole and reduce uneven floor. However, this initiation method generates poor breakage of the top region, which may lead to oversize boulder. The bottom initiation is opposite to the top initiation. It is beneficial to the breakage of the top region but may lead to rock toe. The middle initiation is better than the top and the bottom initiations to increase the damage area of the top and the bottom regions, to flatten the bench floor, and to reduce boulder ratio.
- (4) The numerical simulation results are validated by the field experiment in Baihetan Station. The field data matched with simulation results and the middle initiation had better blasting effects.

It should be pointed out that the emphasis of this paper is to present the numerical simulation of bench blasting with different initiation points with LS-DYNA. The isotropic and homogeneous damage model for rock mass is employed in the numerical simulation for rock damage, and the simulation results are validated by the field experiment. While the anisotropism and inhomogeneity of the rock mass in reality are ignored and the field experiment data is only from Baihetan Station and cannot match with all the blasting conditions, the numerical simulations and field experiments

FIGURE 14: Experiment processes.

FIGURE 15: Relief amplitude of two measuring lines.

FIGURE 16: Bench floors after blast.

of different initiation points still provided a good reference for the bench blasting excavation.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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