Hindawi
Advances in Civil Engineering
Volume 2018, Article ID 9156304, 9 pages
https://doi.org/10.1155/2018/9156304

Research Article

Influence of Bidirectional Impact Loading on Anomalously Low-Friction Effect in Block Rock Media

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Received 11 May 2018; Revised 28 August 2018; Accepted 17 October 2018; Published 13 November 2018

Guest Editor: Wei Wu

The anomalously low-friction effect is a key scientific problem in deep mining. The deep coal rock media is usually a block structure with joint fracture. When the deep block coal rock is subjected to repeated strong dynamic impact caused by long-term excavation activities, the anomalously low-friction effect will occur, resulting in dynamic disasters such as rock bursts. Taking granite block rock media as research object and using bidirectional impact loading to simulate the dynamic disturbance of rock media, a numerical model was established. The vertical acceleration and the horizontal displacement on working block media were defined as the characteristic parameters of the anomalously low-friction effect. The effects of delay time and horizontal impact loading amplitude and frequency on the characteristic parameters under bidirectional impact loading were examined by numerical simulation. The generation and variation of the anomalously low-friction effect of block rock media subjected to bidirectional impact loading were presented. The results show that the delay time has a significant effect to the vertical acceleration amplitude and horizontal displacement on the working block media under bidirectional impact loading. There exists a delay time threshold; when reach to the threshold, quasiresonance and the anomalously low-friction effect on block media will easily occur. With the increase in horizontal impact amplitude, the residual horizontal displacement on the working block media also increases by power function, while it decreases by power function with the increase of horizontal impact loading frequency. Finally, this study denotes that it is great significance to investigate the bidirectional impact loading in order to capture the mechanism of anomalously low-friction effect.

1. Introduction

The anomalously low-friction effect, defined as friction "disappear" effect, is one of the key scientific problems in deep mining, which has attracted more attention of the researchers all over the world [1–8]. The rock near the excavation surface is highly fractured and cannot be simplified as an elastic continuous medium. It is usually deemed as block rock mass. The deep block rock would cause vibrations under dynamic impact loading; when the impact energy reached to a certain energy level, the friction between the interacting blocks would be reduced, or even be extremely low, and the friction disappearance effect would occur. This phenomenon was first observed by Russian scholars Kurlenya et al. [9–11] in the simulation experiment of block rock subjected impact loading.

In order to verify the existence of anomalously low-friction effect, many studies were developed by domestic scholars. Qian [12] pointed out that the anomalously low-friction effect was a key scientific problem in deep mining and closely related to dynamic disaster. Wang et al. [13, 14] explained theoretically the anomalously low-friction effect. The theoretical model was adopted and further improved by Wang et al. [15, 16] to derive the analytical expression of horizontal displacement of working block and reveal the mechanism of the anomalously low-friction effect.

Considering the volatility characteristics of block rock under impact loading, the occurrence criterion of anomalously low friction was given by Pan and Wang [17] through the maximum value of relative displacement between adjacent blocks in the tensile direction based on the pendulum wave propagation dynamic model. Wu et al. [18] extended

Kurlenya's conclusion about peak frequency to extreme frequency in situ test. In addition to carry out the experiment on anomalously low-friction effect, quasiresonance characteristics and pendulum wave of deep rock mass, Wang et al. [19] developed a multifunctional dynamic test system for the deep rock media. However, deep rock mass is in high stress state. Li et al. [20–23] presented a theoretical model of deep block rock media subjected to normal impact loading and overburden pressure and a new concept of anomalously low-friction rock burst, which combined the study of anomalously low-friction effects with rock burst.

These studies have mainly focused on the theoretical and experimental research and the numerical simulation was poorly employed. The numerical simulation method is one of the important means of scientific research, and it is convenient to carry out sensitivity research of parameters and simulate physical experiments that are difficult to carry out under current technical conditions. In addition, there might be an explanation in the case of single vertical impact loading, but they little explain the bidirectional impact behavior in deep block mass. In fact, the phenomenon is closely associated with the bidirectional impact and affected by many factors, such as vertical impact loading amplitude and frequency, horizontal impact loading amplitude and frequency, and delay time. Especially, no scholar has studied how the amplitude and frequency of the horizontal impact affect the anomalously friction effect. Based on previous studies, in this paper, the vertical acceleration and the horizontal displacement of the working block are regarded as the characteristic parameter of anomalously low-friction effect. The influences of delay time and horizontal impact loading amplitude and frequency on anomalously low-friction effect under bidirectional impact loading are analyzed with numerical simulation, which makes it possible to reveal the damage mechanism of anomalously low-friction rock burst. It also verifies the feasibility of FLAC-3D for numerical simulation of anomalously low-friction effects.

2. Model Establishment and Verification

Based on the research results of Kurlenya et al. [9–11], a numerical model of anomalously low-friction effect in block rock media was established. Considering the need to apply force on the numerical model, it is necessary to convert impact energy into force loading on the surface of block rock media.

2.1. Energy Conversion. Based on Hertz's law, ignoring system vibration, the impact energy W is converted into half sine force where the action time is t_0 and the amplitude of the half sine force is P_m. The function of the impact loading is as follows:

$$P(t) = \begin{cases} P_m \sin(\omega t), & t < t_0, \\ 0, & t \geq t_0, \end{cases} \tag{1}$$

where P_m is dynamic loading amplitude, N; t is the time, s; $\omega = 2\pi f$, in which f is dynamic loading frequency, Hz; and P_m and ω are calculated by Hertz's law. Mechanical transformation of impact energy is shown in Figure 1.

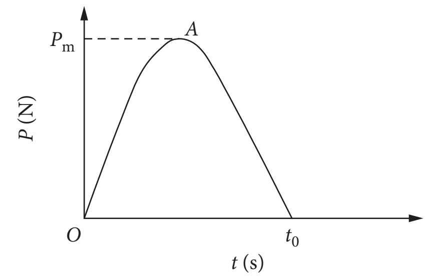

Figure 1: Mechanical transformation of impact energy.

2.2. Model Design. The numerical model consists of six granite blocks of 300 mm × 120 mm × 90 mm, respectively. The blocks are vertically stacked from top to bottom and the third block is defined as the working block for monitoring. The interconnections between the blocks are chosen as a Kelvin viscoelastic models. Each block is divided into 8 hexahedral units. Model meshing, boundary conditions, and forces are shown in Figure 2.

The Mohr-Coulomb model suitable for rock-like materials is selected as the constitutive model for the numerical simulation. Using static boundary conditions, the model boundary conditions are set as shown in Figure 2(b). The mechanical damping is the form of Rayleigh damping [24], and the mechanical parameters of the model are determined by literature [25] (Table 1). The impact is loaded based on Hertz's law. The vertical impact loading is applied to the central point of the top surface of the first block and its direction straight down. The horizontal impact loading is applied to the central point of right surface on the third block and the direction is horizontal to the left. The center of the bottom surface of the sixth block is regarded as the origin of coordinates. In this paper, the vertical acceleration of the block is along the z-axis direction, and the horizontal displacement of the block is along the x-axis direction. The values of positive and negative are the same as the axis direction.

2.3. Validation of Numerical Simulation. To verify the feasibility of using FLAC-3D to simulate the anomalously low-friction effect, the simulation results were compared with previous experimental results [7], as shown in Figure 3, based on the response of granite blocks under the combined action of vertical impact energy and horizontal static force.

It can be seen from Figure 3 that the numerical simulation results are consistent with the experimental results in the overall trend. The feasibility of using FLAC-3D to simulate anomalously low-friction effect is further proved.

3. Results

3.1. Effect of Delay Time. The delay time reflects the time interval of vertical and horizontal impact energy loading on the blocks model for simulating the sequence of dynamic disturbances of coal rock media under deep mining conditions. The effect of delay time on the anomalously low-friction effect is investigated when the time sequence of vertical and horizontal impact loading is different (negative values represent horizontal impact is loaded before vertical impact).

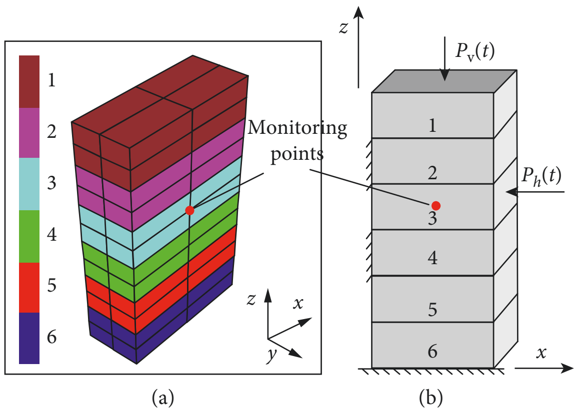

Figure 2: Diagram of block model and meshing.

Table 1: The mechanical parameters of mode.

Parameter (unit)	Value
Density (g/cm^3)	2.6
Tensile strength (MPa)	10.12
Cohesion (MPa)	5.87
Internal friction angle (°)	53.05
Poisson's ratio	0.11
Shear modulus (GPa)	22.9
Elastic modulus (GPa)	50.8
Bulk modulus (GPa)	21.7

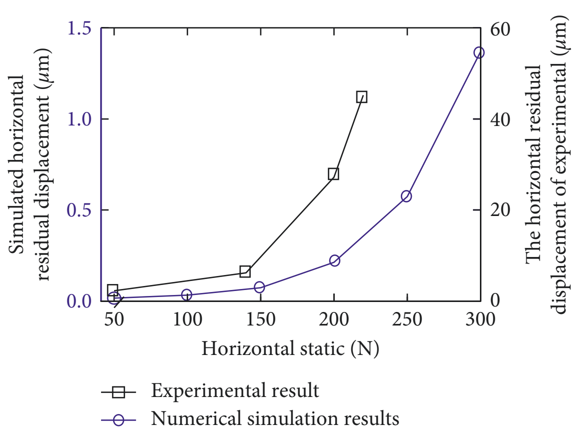

Figure 3: Relation curve between horizontal static and horizontal residual displacement.

(1) The delay time has an important effect on vertical acceleration of the working block. When the model is first subjected to vertical impact loading, the maximum amplitude of vertical acceleration of the working block is greater than first subjected to the horizontal impact loading. When $t_d < 0$, the delay time is different and the maximum amplitude of vertical acceleration of the working block under vertical impact loading is also different. When $t_d > 0$, the delay time is different and the maximum amplitude of vertical acceleration of the working block under horizontal impact loading is also different. The relationship between the maximum vertical acceleration of the working block and the delay time is shown in Figure 4. The working block vibrates under the vertical impact loading and the vertical acceleration fluctuates near the equilibrium position. Under the horizontal impact loading, if the vertical acceleration amplitude of the working block is large, the horizontal displacement is less than that under the horizontal impact. If the vertical acceleration of the working block is small, as the block gravity is constant, that is, the normal force between the blocks is smaller. As a result, the horizontal displacement is larger caused by the impact loading of the working block, which is prone to the anomalously low-friction effect.

(2) Horizontal impact loading is the main reason for the residual displacement of the working block. However, the delay time has a greater effect on the residual displacement when the working block is firstly subjected to vertical impact loading. When the block model is loaded respectively by the vertical and horizontal bidirectional impact loading, the horizontal displacement curve of the working block at different delay time t_d is shown in Figure 5.

In Figures 5(a)–5(c), $t_d < 0$, the working block is moved from the original equilibrium position by horizontal impact loaded first and is gradually stabilized at the new equilibrium position and generates residual displacement. Then, the vertical impact also generates a smaller residual displacement. The horizontal residual displacement of the working block is mainly determined by the horizontal impact loading. The delay time has little effect on the value of the final residual displacement. Residual displacement is all 6.75 μm, and the direction is same. But the delay time affects the time required for the horizontal displacement to final stability. When the delay time is different, the time required for the fluctuation stability in Figures 5(a)–5(c) is 3.6 ms, 2.6 ms and 3.9 ms, respectively.

From Figures 5(d)–5(f), when $t_d > 0$, the horizontal displacement of the working block slightly fluctuates due to vertical impact loading and results in small fluctuations. After that, the main residual displacement is produced under the horizontal impact loading and the magnitude and direction of the residual displacement change with delay time.

At the appropriate time of t_d, the vibration of the block suddenly intensifies and its amplitude becomes larger than that of the single load, as shown in Figures 5(d)–5(f). The residual displacement is respectively −3.8 μm, 1.8 μm, and 6.6 μm. When the model is first subjected to vertical impact loading, the vertical movement of the working block intensifies, and periodic compaction and relative detachment states or high-stress and low-stress states occur between blocks. When the blocks are in the compaction state or high-stress state, the horizontal impact is loaded on the working block. The horizontal friction resistance between the blocks is large and working block has smaller horizontal displacement. When the horizontal impact acts on the working block in a relatively detachment or low-stress state between

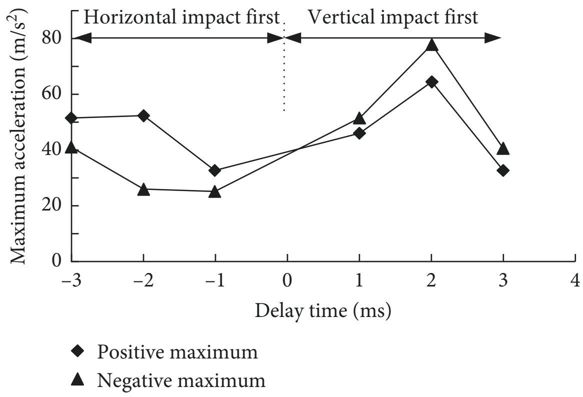

FIGURE 4: Relationship between maximum acceleration and delay time.

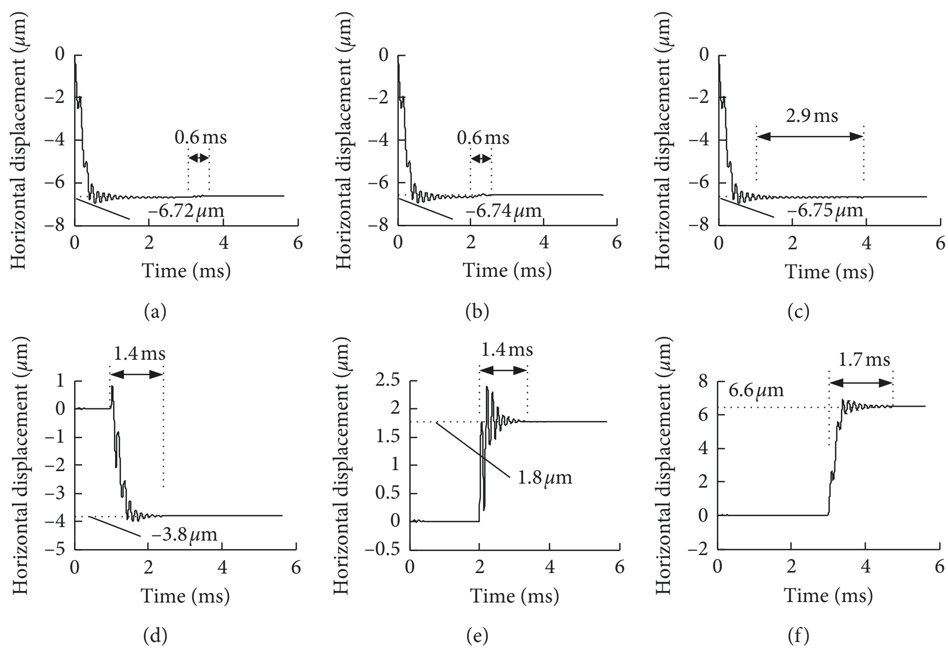

FIGURE 5: Horizontal displacement curve of work block under the action of different delay time. (a) $t_d = -3$ ms. (b) $t_d = -2$ ms. (c) $t_d = -1$ ms. (d) $t_d = 1$ ms. (e) $t_d = 2$ ms. (f) $t_d = 3$ ms.

the blocks, a large horizontal displacement occurs due to the smaller horizontal frictional resistance (anomalously low friction) between the blocks. At this time, the anomalously low-friction effect will occur. This is consistent with the quasiresonance phenomenon mentioned in literature [26].

3.2. Effect of Horizontal Impact Loading Amplitude. The strength of impact energy is closely relevant to the amplitude of impact loading. In the process of fully mechanized top coal caving, the coal pillar in the section is not only loaded under the gravity of the overburden, but also be affected by various disturbances in the mining operations, such as blasting vibration, mine shock, and cyclical pressure. Among them, the periodic pressure is the common impact disturbance in caving coal mining. It has the characteristics of short period, great impact force, and so on. To simulate the above impact disturbance, the amplitude and frequency of impact loading are changed. According to Wang et al. [19] experimental data, the impact loading amplitudes are specified as 500 N, 1000 N, 1500 N, and 2000 N. The horizontal impact frequency and vertical impact energy are fixed values, respectively, 5000 Hz and 63 mJ, and the delay time is 2 ms.

(1) The maximum vertical acceleration of the working block subjected to secondary impact gradually increases with the increase in horizontal impact loading amplitude. When the block model is subjected to vertical and horizontal bidirectional impacts and the amplitude of the horizontal impact loading is different, the vertical acceleration response curve on monitoring point of working block is shown in Figure 6.

From Figure 6(a), the model is loaded by a vertical impact loading first and results in vertical acceleration fluctuation of the working block. The fluctuation form is similar to the quasiperiodic sine curve and the amplitude

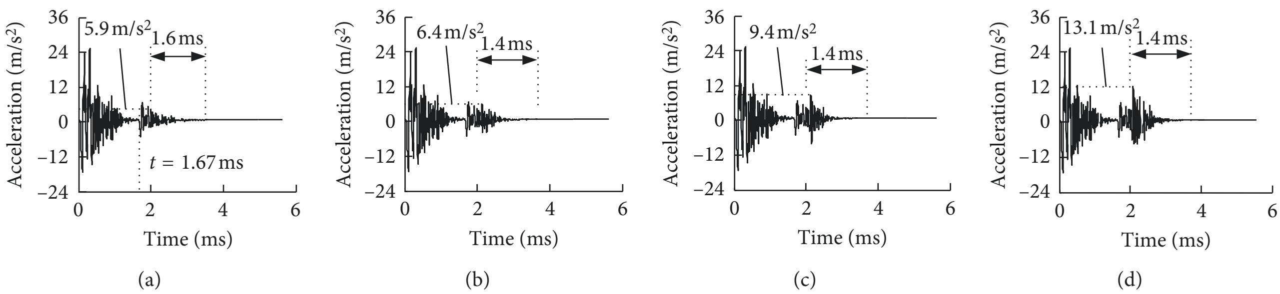

Figure 6: Vertical acceleration response of working block under different impact loading amplitudes. (a) $P_m = 500$ N. (b) $P_m = 1000$ N. (c) $P_m = 1500$ N. (d) $P_m = 2000$ N.

gradually decreases. The maximum amplitude is 25.6 m/s^2 and the positive amplitude is greater than the negative amplitude. At about 1.67 ms, the vertical acceleration of the working block generates slight fluctuation again and the maximum amplitude is 6.6 m/s^2. At 2 ms subjected to horizontal impact loading, the fluctuation amplitude of the working block's vertical acceleration increases again.

After the second impact loading, the maximum vertical acceleration of the working block increases exponentially with the increase in the horizontal impact loading. The maximum vertical acceleration is 5.9 m/s^2, 6.4 m/s^2, 9.4 m/s^2, and 13.1 m/s^2, as shown in Figure 7. Because there is a gap and the connections between the blocks are Kelvin visco-elastic models and between the blocks, that is, the blocks are assumed to be connected by springs and dampers. When subjected to horizontal impact, the blocks begin to horizontally move and the spring between the blocks is deformed to cause the vertical acceleration. When the working block frequency is determined, the energy of the horizontal impact increases with its amplitude increase. The horizontal movement of the working block is more intense. As a result, the magnitude of vertical acceleration of the working block gradually increases.

(2) The horizontal residual displacement of working block increases by power function with the increase of horizontal impact loading amplitude.

The horizontal displacement response curve of monitoring point of working block is shown in Figure 8. For accurate analysis, before impact loading, the displacements in x, y, z direction of each node of the model is cleared.

From Figure 8, the working block moves back and forth in a horizontal direction under the vertical impact loading. The amplitude and stability time are small and no residual displacement. At $t = 2$ ms, the horizontal displacement of working block is changed greatly due to the horizontal impact loading. After the horizontal impacting, the fluctuation of horizontal displacement of the working block gradually stabilizes and has a residual displacement. The residual displacements of Figures 8(a)–8(d) are 0.1366 μm, 0.5462 μm, 1.079 μm and 1.668 μm, and the curve is shown in Figure 7. There is the power function increase relationship between the horizontal residual displacement and impact amplitude. This is because that when the horizontal impact loading frequency is determined, its amplitude and impact

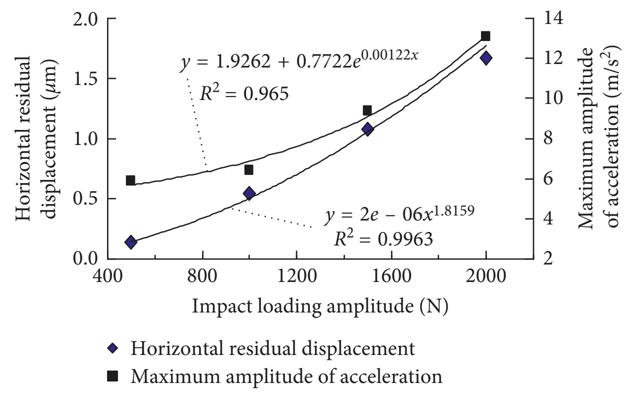

Figure 7: Relation curve between the horizontal residual displacement, the maximum amplitude of acceleration after the horizontal shock of the working block, and the impact loading amplitude.

energy increases, resulting an increases in the horizontal motion and the horizontal residual displacement of the working block. The above result is consistent with the fact that the anomalously low-friction effect is more likely to occur under strong shock disturbances.

3.3. Effect of Horizontal Impact Loading Frequency. The frequency of impact loading is a key parameter reflecting the impact action. According to Hertz's law and relevant literature [7], the impact loading frequency of four levels including 1000 Hz, 2500 Hz, 5000 Hz, and 7500 Hz was set. Horizontal impact loading amplitude, vertical impact energy, and delay time were taken as a fixed value, respectively, 1000 N, 63 mJ, and 2 ms. Considering that the block model is subjected to the vertical and horizontal bidirectional impact loading, the horizontal impact loading frequency gradually increases to study the response curve of vertical acceleration and horizontal displacement in monitoring point of working block.

(1) With the increasing frequency of the horizontal impact loading, the amplitude of vertical acceleration of working block in the model is significantly affected. The decay rate of the vertical acceleration amplitude gradually also increases.

Figure 9(a) shows that the vertical acceleration begins to fluctuate from the steady state with a quasiperiodic sine

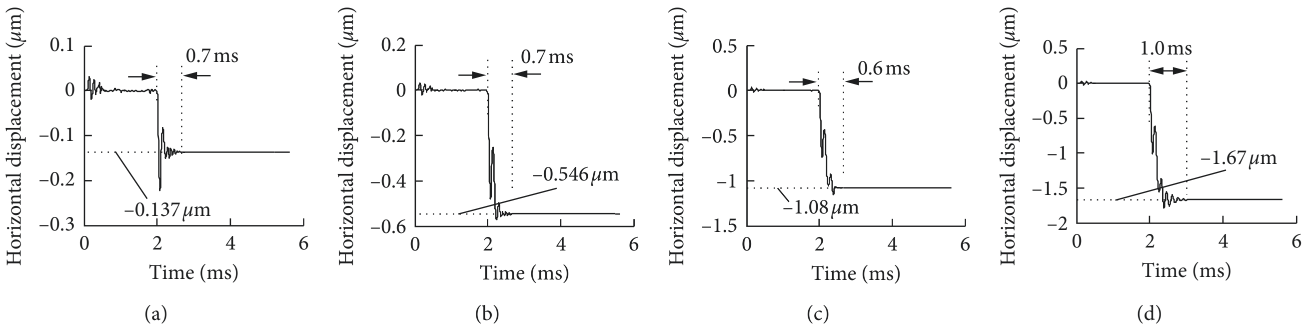

Figure 8: Horizontal displacement curve of work block under the action of different impact loading amplitudes. (a) $P_m = 500$ N. (b) $P_m = 1000$ N. (c) $P_m = 1500$ N. (d) $P_m = 2000$ N.

curve changes due to the vertical impact loading. However, the fluctuation gradually decreases and tends to stabilize. At 1.67 ms, the secondary fluctuation occurs, and the fluctuation is superimposed on the fluctuations of the working block by the horizontal impact loading at 2 ms, but the fluctuation amplitude is generally small.

The stabilization times of the secondary fluctuations in Figures 9(a)–9(d) are, respectively, 2.1 ms, 1.8 ms, 1.4 ms, and 1.4 ms. The maximum amplitude of the second fluctuation is, respectively, 3.3 m/s^2, 5.8 m/s^2, 6.4 m/s^2, and 9.4 m/s^2. Since the period is inversely proportional to the frequency, the horizontal impact loading frequency is gradually increased, and the natural period is shortened. The time that the block model subjected to the impact is also reduced. The energy is more concentrated, resulting in a gradual increase in the decay rate of the vertical acceleration amplitude. Meanwhile, the maximum amplitude gradually increases too.

(2) As the horizontal impact loading frequency gradually increases, the horizontal residual displacement of the working block decreases with the power function. It is indicated that the amplitude of horizontal movement of working block is getting smaller and smaller. The stability of the block model is enhanced. The phenomenon of anomalously low friction is less obvious, and the possibility of occurrence such as rock bursting and other disasters induced by anomalously low-friction effect gradually reduced.

Figure 10 shows the response curve of working block horizontal displacement when the block model was subjected to vertical and horizontal bidirectional impact loading, and the horizontal impact loading frequency gradually increased.

From Figure 10, we can see that the horizontal displacement of the working block fluctuates when the block model is first subjected to the vertical impact loading, but the fluctuation is very small. The higher the frequency, the longer time required for the fluctuations to stabilize, but the final residual displacement can be ignored. At $t = 2$ ms, due to the horizontal impact loading, the horizontal displacement of the working block changes greatly. The time required for horizontal displacement to stabilize decreases with frequency increasing. The stable times of Figures 10(a)–10(d) are 1.2 ms, 1.0 ms, 0.7 ms and 0.6 ms, respectively, which changes according to exponential function. Finally, the working block produces residual displacement. The corresponding residual displacements of Figures 10(a)–10(d) are 9.373 μm, 1.673 μm, 0.5462 μm and 0.298 μm, respectively, and decrease regularly with power function. The variation of the two curves is shown in Figure 11. When the amplitude of the horizontal impact loading is determined, the increases in frequency lead to reduce the cycle of impact loading. The time that the model is affected by horizontal impact is decreased and the impact energy is reduced. The block motion tends to be moderated. The horizontal residual displacement also gradually decreases with the impact frequency increases. That is to say, the low-frequency disturbance is more prone to the anomalously low-friction effect. It is easier to induce the dynamic disaster such as the rock bursts, which is consistent with the fact that low-frequency signal before rock bursts is mainly based on low-frequency [27].

4. Discussion

(1) Deep underground conditions are extremely complicated, and the research of anomalously low-friction effect provides a feasible way to reveal the mechanism of some deep dynamic disasters. For example, on November 11, 2017, the rock bursts of the Hongyang no. 3 Mine in Liaoning Province of China have observed that the total amount (214 m × 31.7 m × 3 m) of coal rock was slipped to the roadway 1 m~3 m; however, the roof remains basically intact. This phenomenon can be explained reasonable by anomalously low-friction effects under high ground stress condition. In the accident area of Hongyang no. 3 Mine, the roof of the coal pillar is mudstone. Under the cutting action of the fault, the coal pillar formed a separation body. Under the dynamic disturbance such as roof break, the friction between the coal seam and the roof and the bottom was weakened. The coal pillars had a large horizontal displacement and overall sliding when it is suffered by the horizontal thrust induced for roof break. The accident area composed of roof, coal pillar, bottom,

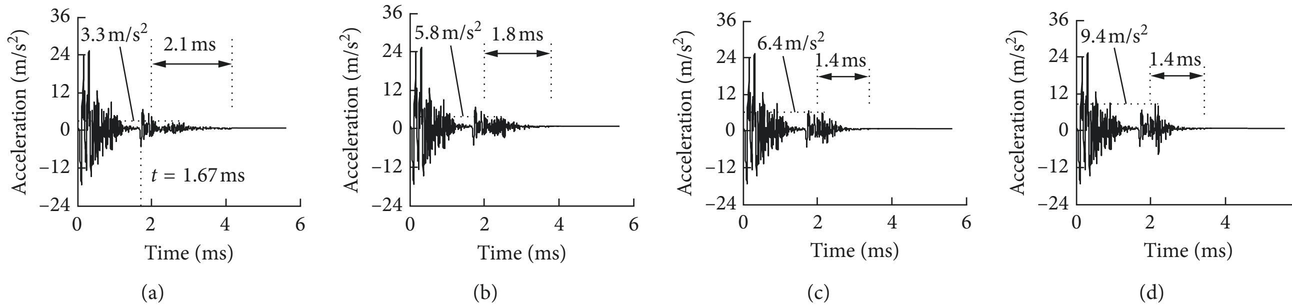

Figure 9: Vertical acceleration curve of work block under different impact loading frequencies. (a) $f = 1000$ Hz. (b) $f = 2500$ Hz. (c) $f = 5000$ Hz. (d) $f = 7500$ Hz.

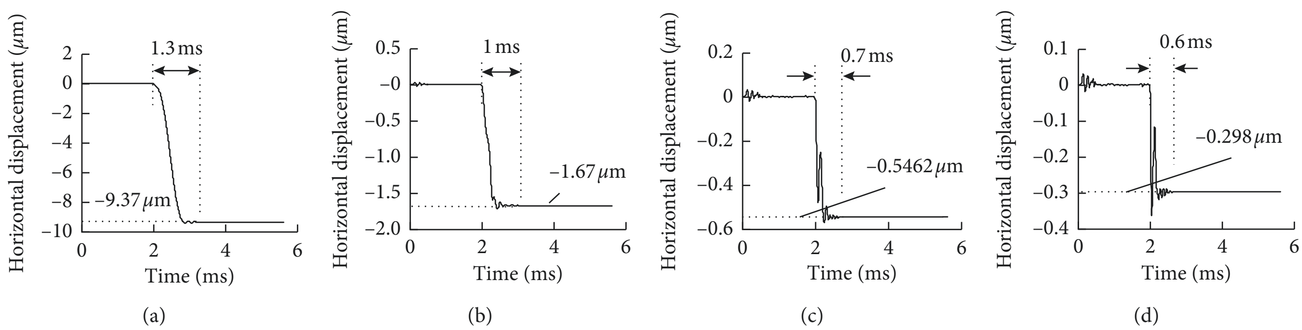

Figure 10: Horizontal displacement curve of work block under the action of different impact loading frequencies. (a) $f = 1000$ Hz. (b) $f = 2500$ Hz. (c) $f = 5000$ Hz. (d) $f = 7500$ Hz.

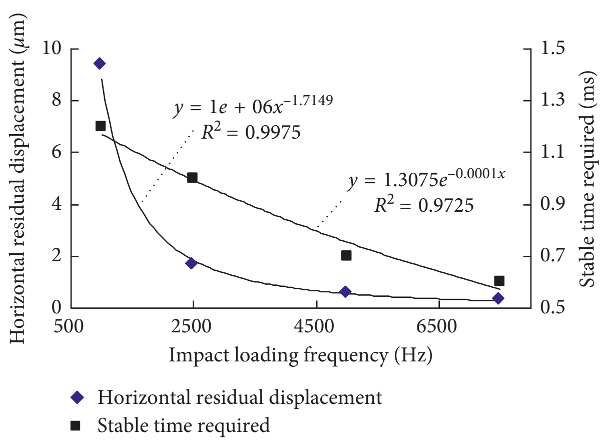

Figure 11: The relation curve of horizontal residual displacement and secondary fluctuation stabilization time of work block between with impact loading frequency.

etc, can be simplified as the horizontal movement problem of the working block of block media model under vertical and horizontal bidirectional impact loading. The disaster of Hongyang no. 3 Mine is shown in Figure 12.

(2) The stress condition of deep rock mass divided by the joints and fractures and the stratification of deep rock media are considered, idealized into one-dimensional block dynamic model. Therefore, it has theoretical and practical significance to study the occurrence of dynamic disasters such as impact and in situ stress from the perspective of anomalously low-friction effect. In this paper, based on previous researches, the numerical simulation method is used to study the vertical acceleration and horizontal displacement of the working block. The conclusion is basically consistent with that in the literature [7], but its application needs to be further expanded. This process does not consider the influence of overburden pressure and confining pressure on the rock mass. Therefore, the mechanism of the anomalously low-friction effect still needs further research.

5. Conclusions

Using FLAC-3D numerical simulation software, the anomalously low-friction phenomenon of granite block rock media model under vertical and horizontal bidirectional impact loading was investigated. The following conclusions are presented:

(1) The vertical impact loading is the precondition for the occurrence of anomalously low-friction effect. The horizontal impact loading is the direct cause of the anomalously low-friction effect, which may even lead to the deep rock media dynamic disasters. This is consistent with phenomena such as earthquakes in which the shear waves produce more damage than longitudinal waves.

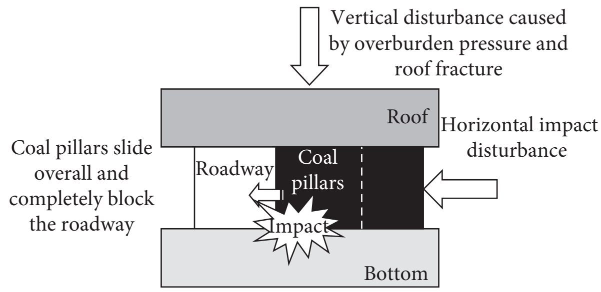

Figure 12: Schematic diagram of anomalously low-friction rock burst in Hongyang no. 3 coal mine.

(2) The horizontal residual displacement is mainly affected by the horizontal impact loading. The delay time has a direct effect on the vertical acceleration and horizontal residual displacement of the working block.

(3) With the amplitude of the horizontal impact loading increases, the horizontal residual displacement of the working block increases with the power function.

(4) The low-frequency disturbance makes the anomalously low-friction effect between the blocks more likely to occur.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was financially supported by the National Key R&D Program (2016YFC0600901), the Natural Science Fund Project in China Liaoning Province (201602353), and the National Natural Science Foundation of China Youth Project (51204090).

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