Arabian Journal of Geosciences (2022) 15: 609
https://doi.org/10.1007/s12517-022-09921-7

ORIGINAL PAPER

Experimental study on ultra-low friction effect of sandstone block based on whipping structure

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Received: 10 November 2021 / Accepted: 15 March 2022 / Published online: 24 March 2022

Abstract
In order to further study the mechanism of rockburst, the relationship between the test model of block rock mass and the structural characteristics of "whipping effect" was established. Based on the structural characteristics of height ratio and width ratio, the self-developed ultra-low friction test loading device was used to investigate the response characteristics of ultra-low friction effect of working block under the combined action of axial compression, stress wave disturbance, and horizontal impact. The results show that: (1) there is a close relationship between the ultra-low friction whipping strength of the working block and its mass, size, and external load. (2) In the absence of stress wave disturbance, the height-width ratio has significant influence on the horizontal displacement response of the working block, $H_W/S_W = (0.8 \sim 1.2)$; under the stress wave disturbance, the dynamic response characteristics of the working block are studied from the perspectives of width ratio and height ratio respectively. The significant effects of height-width ratio are 0.5–0.63 and 0.8–1.2. (3) When the amplitude of stress wave disturbance is different, the horizontal displacement of the same working block shows the same variation trend with the frequency of stress wave disturbance, and fluctuates with the increase of frequency (first increase, then decrease, and then increase). When H_W/S_W is equal to 0.5, 0.56, 0.8, and 1.2 respectively, the response of ultra-low friction effect produced by corresponding working conditions is particularly significant.

Keywords Stress wave disturbance · Sandstone block · Rockburst · Ultra-low friction effect · Height-width ratio

Introduction

The phenomenon of ultra-low friction has been widely concerned in the field of underground space engineering and the dynamic responses of many rock masses under compression shear and impact disturbance are closely related to it. Under the continuous action of high in-situ stress, the deep rock mass becomes denser and the stress state becomes more complex. If the rock mass is disturbed by stress waves and horizontal impacts, such as blasting, roof fracture, and centralized mining, the ultra-low friction effect has easily occurred in the rock mass, and then, dynamic disaster accidents such as rockburst are induced. To a large extent, rockburst dynamic disaster is caused by rock mass releasing and unloading the energy accumulated for a long time through cracking, collapsing, and ejecting. Liaoning HongYang coal mine bumps field observation shows that there are still some special power phenomenons that could not be a reasonable explanation. The whipping effect is widely used in the construction industry and some dynamic responses of the deep rock masses phenomenon are very similar. Therefore, based on the structural characteristics of whipping effect research the ultra-low friction response characteristics of rock mass under bidirectional stress. It is a new attempt to explain the rockburst disaster and has certain reference significance.

The ultra-low friction effect occurs mostly in a deep underground rock mass with a tectonic level. Kurlenya et al. (1992, 1999, 2001) in Russia first proposed the ultra-low friction effect of rock mass by establishing a dynamic model of the block rock mass. They believed that when block medium is affected by dynamic impulse. There exists a "vanishing" effect of friction between two adjacent blocks at a certain energy level. Scholars at home and abroad have carried out relevant researches on the key scientific issue of

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ultra-low friction effect and accumulated rich and valuable achievements.

Aleksandrova et al. (2004, 2005, 2008) established a one-dimensional block medium model and conducted experimental and theoretical research on strain wave propagation, finding that wave propagation speed and attenuation degree largely depend on the viscosity of intermediate materials. Aharonov and Scholz (2017) based on the physics theory have explained the phenomenon that the friction coefficient is very large in the process of slow sliding and follows the rate-state friction constitutive law, but it weakens obviously as the sliding velocity approaches the seismic sliding velocity. The proposed new model elucidates the physical properties of friction and predicts the relationship between friction laws and independently determined material parameters. Prassetyo et al. (2019) proposed a new coal pillar strength formula considering that the strength of the coal pillar is affected by the interface friction between coal and roof and coal and bottom plate. Academician Qian (2007) pointed out in the 230th Xiangshan Scientific Conference in 2004 that ultra-low friction exists in the structure of rock masses, and emphasized the importance of studying the occurrence mechanism and rules of ultra-low friction effect in the development of deep underground space. Wang et al. (2005, 2006, 2015) studied the relationship between the mechanism of ultra-low friction phenomenon of deep rock mass with structural grade and the dynamic deformation and stability of block interface. The introduction of the ground impact energy factor reveals the essential law of the ultra-low friction effect. Based on the dynamic model of block rock mass established by Kurlenya et al. (1999), Wang et al. verified the ultra-low friction effect through theoretical analysis and numerical calculation and revealed the internal mechanism of the ultra-low friction effect. Tarasov and Randolph (2007) proposed that under high confining pressure, shear fractures developed in original hard rocks can show extremely low shear resistance within a certain range of displacement due to the inherent nature of fracture structure, which is due to the formation of a special fault structure in the process of fault development. This phenomenon can explain many of the anomalies observed under field and laboratory conditions, particularly the very high energies released by deep earthquakes and rock bursts. Ujiie (2005) revealed through strong motion data and fault rock analysis results that fast seismic sliding in deep fault (strong-motion radiation source region) can be adjusted by frictionless sliding in the shallow part of the fault. Smooth sliding related to low dynamic friction occurred in both deep and shallow parts of the fault, and there was a large slip between the source area and the surface. Rashed and Peng (2015) conducted uniaxial tests on coal samples with a W/H of 1–10 under the conditions of 0.1 and 0.25 interfacial friction and compared and analyzed the relationship between the violent failure strength of coal samples and the interfacial friction and height-width ratio of coal samples. The height-width ratio and interfacial friction of coal samples were determined when the failure mode changed from abrupt brittle failure to ductile failure. Rutter et al. (2013) synthesized the mechanical test of fault gouge and studied the microstructure of running products, and found that embedding a small amount of graphite can significantly reduce the friction of the sliding surface, and weak interlayer plays an important role in ultra-low friction sliding of fault in the experimental study of the influence of weak interlayer on the friction effect of fault gouge. Ito et al. (2017) found that significant slip attenuation was caused by speed step through the slow slip phenomenon of a fault zone, and the slip velocity after pre-shock was slightly faster than that of discrete fault, which was conducive to fault weakening. The increase of slip velocity would lead to the change of steady-state friction strength or slip strengthening friction into slip weakening friction behavior. Lomas et al. (2018) analyzed the relationship between the friction coefficient of coke from different coal sources and the composition of mother coal mixture by conducting friction tests on metallurgical grade coke. Pirzada et al. (2020) conducted experiments to study the influence of joint surface roughness on the friction characteristics of rock joints and analyzed that the actual contact area was the main parameter controlling the friction strength. Without considering the actual contact area, surface roughness cannot determine the shear characteristics of rock joints. Wu et al. (2008, 2009) studied and analyzed the internal mechanism of the phenomenon of pendulum wave from the perspective of its ability to induce rockburst and rockburst in a deep rock mass. Based on Kurlenya's ultra-low friction experiment, a one-dimensional dynamic model of deep block rock mass was established to study the mechanical conditions and mechanism of irregular ultra-low friction phenomenon in a deep rock mass. It is pointed out that the ultra-low friction effect of deep block rock mass is the result of the redistribution of normal force between blocks and the constant change of dynamic friction coefficient.

Pan and Wang (2014) studied and analyzed the occurrence rule of ultra-low friction of block rock mass under dynamic action based on the pendulum wave propagation theory and the Angle of the maximum relative displacement between adjacent blocks, and provided the occurrence criterion of ultra-low friction. Li et al. (2014, 2019a, b) defined a new analytical expression of normal force and horizontal displacement formula of working a block from the perspective of normal force between blocks. The minimum variation rule of normal force between block rock mass under bidirectional load is discussed, and the preconditions of inducing ultra-low friction effect of block rock mass are obtained. Liu et al. (2016, 2018, 2020) experimentally studied the critical dynamic load amplitude of rockburst induced by a dynamic load of sandstone blocks and proposed an experimental method to distinguish whether rockburst induced by a dynamic load is induced by debris characteristics. By changing the amplitude of dynamic load and static load, rockburst test debris under different stress conditions was obtained. It is concluded that the energy consumption of rockburst is more than that of rockburst under static load. Taking cubic granite with holes in the center under dynamic and static loading as the object, the factors of friction reduction between rock blocks are studied, and the existence of ultra-low friction effect is verified. Academician He et al. (2018) independently designed an experiment on the ultra-low friction effect of granite blocks with holes in the center and obtained the curve of granite block friction over time by using the 2d digital image correlation testing method, which verified the existence of ultra-low friction effect. Zhong and Ling (1985) point out the conditions under which the whip effect is most likely to occur in structures at the top of high-rise buildings and the possibility of eliminating or reducing the whip effect from the vibration analysis of coupling vibrators. Yang et al. (2004) analyzed in detail the role of the whipping effect in seismic resistance of high-rise building structures. Ji et al. (2020) when studying the dynamic stability of high steep slope under the action of blasting found that there was a whipping effect at the step and it was directional.

To sum up, the interpretation of rockburst hazards by domestic and foreign scholars mostly focuses on local mechanical characteristics and failure mechanisms, while few scholars start from the overall structural characteristics of deep rock mass such as discontinuous and broken. The structural characteristics of the whipping effect are used to describe some special dynamic response phenomena in the deep mining of mine resources. As the depth of rock mass increases, the discontinuous structure becomes more and more obvious, and the deep rock mass becomes more and more broken. For the first time, the occurrence mechanism of rockburst was supplemented and refined by the whipping effect, and then, the influence mechanism of the working block size on the strength of ultra-low friction effect under bidirectional stress was studied, providing a reference for the prevention and control of rockburst disaster.

Test design

Test devices

A self-developed ultra-low friction loading test device was used in the test, as shown in Fig. 1. The equipment can be used to test the block model system under confining pressure, static load, dynamic load, and impact load. The data acquisition system is composed of Panasonic miniature laser sensor and the control system of the test unit (the measured curve is the horizontal displacement curve of the centroid point on the right side of the working block). The hydraulic control system of the test unit is composed of three parts: the static load hydraulic cylinder, the dynamic load hydraulic cylinder, and the impact hydraulic cylinder. Through the hydraulic control system, the dynamic loading device is controlled to apply vertical stress wave disturbance to the working block (in the form of sinusoidal stress wave loading), the static loading device is controlled to apply axial pressure to the working block, and the impact loading device is controlled to apply horizontal impact to the working block. Multiple complex stress environments can be simulated by combining different loading devices. Through the ultra-low friction test device, the working block can be applied to the following load ranges: confining pressure (front and back of the working block) 0 ~ 30 MPa, horizontal impact force 0 ~ 30 MPa, vertical stress wave disturbance amplitude 0 ~ 3 MPa, disturbance frequency 0 ~ 30 Hz stress wave disturbance, and axial pressure 0 ~ 30 MPa.

Test plans

Based on the structural characteristics of rock mass breaking deeper, the influence mechanism of stress wave disturbance and size on ultra-low friction effect of the working block under different working conditions was investigated. Blocks of different sizes were designed as working blocks to describe the different degrees of fragmentation of rock mass at different depths. Red sandstone specimens with length, width, and height of 100 mm × 100 mm × 100 mm were selected as the test standard blocks to simulate local roof, floor, and structural characteristics of the underground rock mass. The ultra-low friction effect test model is shown in Fig. 2. The actual test figure of the cube with the side length of 50 mm working block is shown in Fig. 3. To restore the actual mining conditions as far as possible, the sandstone blocks involved in the test were all mined from Hongyang No. 3 Mine in Shenyang, Liaoning province. With the ground shock accident of Hongyang No. 3 Mine in Shenyang, Liaoning Province on November 11, 2017, as the background, the experimental study on ultra-low friction effect of block rock mass under bidirectional disturbance was carried out.

The test loading conditions were as follows: the horizontal shock F_h was kept at 3 MPa and the axial pressure was kept at 2 MPa; the stress wave disturbance amplitude was set at 0 MPa ~ 1 MPa; the stress wave disturbance frequency was set at 0 Hz ~ 3.5 Hz; the specific information of the working conditions was shown in Table 1.

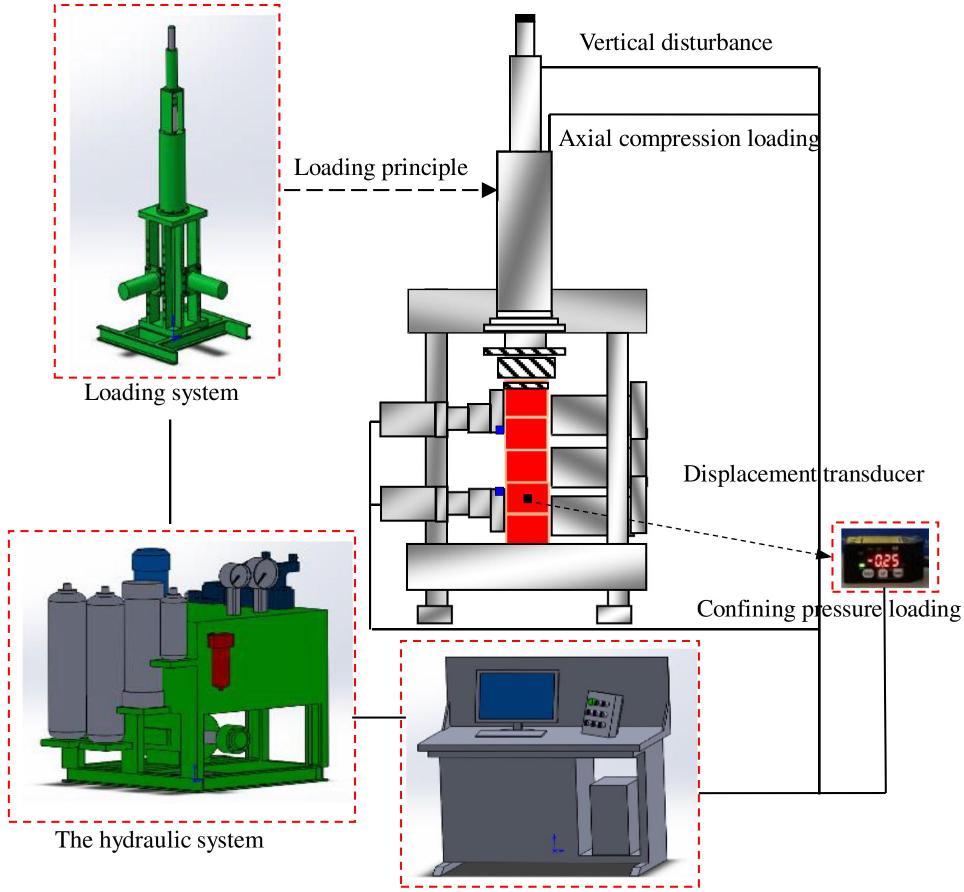


Fig. 1 Anomalously low friction loading test device

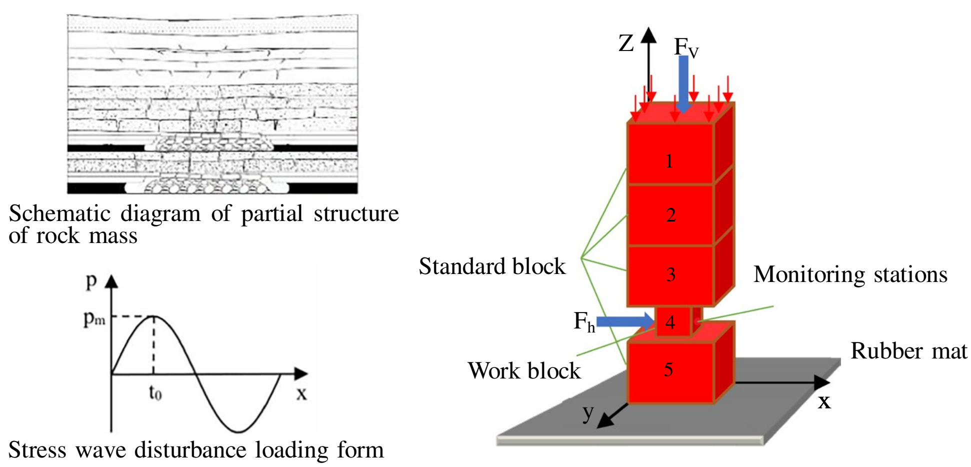


Fig. 2 Test model of ultra-low friction effect

Working block size

The working block size includes high ratio and wide ratio. The 50 mm × 50 mm × 50 mm block is taken as the reference block, and the working conditions involved in height and width (side length of square bottom) are changed respectively based on the reference block size, as shown in Fig. 4. There are 13 working conditions in total. See Table 1 for detailed dimensions.

Test procedures

(1) The test was carried out according to the ratio of height and width. In a single test, four standard blocks and

Fig. 3 Working block side length of 50 mm cube test drawing

one working block were successively stacked into the chamber of the test device from bottom to top, and the working block was placed in the second block.

(2) Connect and check whether the accelerometer, sensor, loading device, and other equipment can be used normally and whether the accuracy, sensitivity, and other indexes reach the standard.

(3) Debug the equipment, adjust the parameters of each loading device to a specified value, and conduct the group test without stress wave disturbance. The axial pressure in the vertical direction was set as 2 MPa, and the horizontal impact was set as 3 MPa.

(4) Open the servo pump for the superimposed stress wave disturbance test, adjust the frequency of 0 ~ 3.5 Hz, the amplitude of 0.5Mpa, and 1 MPa respectively.

(5) Observe the real-time waveform of the test data, and supplement the experimental group with large error.

(6) Shut down the test device in an orderly manner and analyze the obtained data.

Table 1 Test plans

Category		High ratio	Wide ratio
Size	Bottom side S_w/mm	50	100, 90, 80, 70, 60, 50 、40
	High Hw/mm	100, 90, 80, 70, 60, 50, 40	50
Level of shock F_h /MPa		3	
Axial compression /MPa		2	
Stress wave disturbance	Amplitude /MPa	0, 0.5, 1	
	Frequency /Hz	1, 1.5, 2, 2.5, 3, 3.5	

Fig. 4 Physical drawing of working block

Analysis of experimental results

With the continuous increase of mining depth, the structural stress defects of rock mass such as fissures and joints are increasing, and the rock mass is more and more broken. However, the degree of fragmentation has an important influence on dynamic disasters. The height-width ratio of the working block is taken as a relative index to describe the degree of fragmentation of rock mass. From the angle of high ratio and wide ratio, the relationship between the size, stress wave disturbance, and dynamic response characteristics of sandstone working block under bidirectional loading was investigated.

Study on ultra-low friction effect of working block without stress wave disturbance

In this part of the study, the external load of the working block is axial pressure and horizontal impact, wherein the axial pressure is set as 2 MPa and the horizontal impact as 3 MPa. The response mechanism of ultra-low friction effect of working block in high ratio and wide ratio under corresponding working conditions without stress wave disturbance was investigated respectively.

Data processing

Since both the initial and final stages of the original data show a stable state, 350 ms data of the part with horizontal impact in the middle is intercepted during subsequent data processing to illustrate the specific response of the horizontal displacement of the working block. $t = 100$ ms is set as the moment of horizontal impact, as shown in Fig. 5.

It can be seen from Fig. 5 that the response form of horizontal displacement of the working block with different height-width ratios tends to be consistent over time, and there are three stages: stable stage → sudden increase stage → stable stage. In addition, the dynamic response data of the working block under the same external load and different height-width ratios are also different, that is, the intensity of the dynamic response of the working block is closely related to the height-width ratio. By comparing Fig. 5 (a) and Fig. 5 (b), it can be seen that when the height-width ratio of the working block is equal to 1, its horizontal displacement response is the most significant, which is as high as 0.793 mm. Figure 5 (a) shows that the horizontal displacements of the working block are 0.375 mm, 0.793 mm, 0.623 mm, 0.026 mm, 0.051 mm, 0.088 mm, and 0.065 mm when H_W/S_W is 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, and 2.0 respectively shows a trend of first increasing, then decreasing and then becoming stable, as shown in the red line in Fig. 6. In the same way, Fig. 5 (b) shows that the horizontal displacements of the working block are 0.356 mm, 0.214 mm, 0.047 mm, 0.013 mm, 0.386 mm, and 0.793 when H_W/S_W is 0.5, 0.56, 0.63, 0.71, 0.83, 1.00, and 1.25, respectively and 0.036 mm, showing a trend of decrease first, increase and then decrease, as shown in the black line in Fig. 6. Figure 6 shows the relationship between the height-width ratio (H_W/S_W) of the working block and the horizontal displacement under the action of no stress wave disturbance. The dynamic response of the working block is relatively significant when H_W/S_W is 0.8, 0.83, 1.0, and 1.2. When H_W/S_W is 1.0, the horizontal displacement response of the working block is the most intense, that is, the intensity of the ultra-low friction effect of the working block is the largest. In summary, the dynamic response mechanism of the working block under external

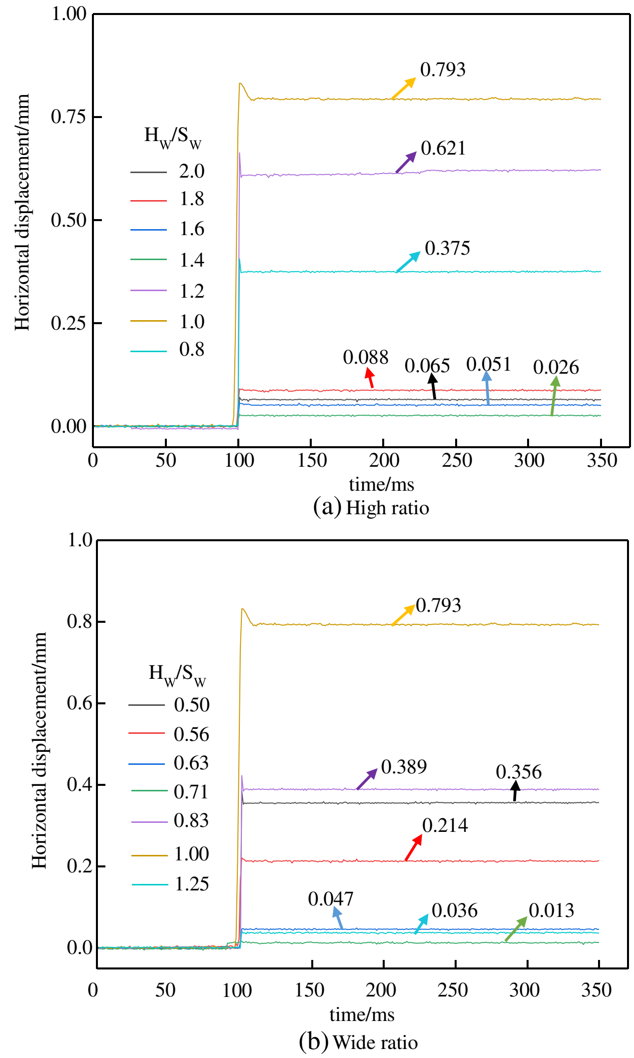


Fig. 5 Variation curves of horizontal displacement of working blocks with different height-width ratios over time. **a** High ratio. **b** Wide ratio

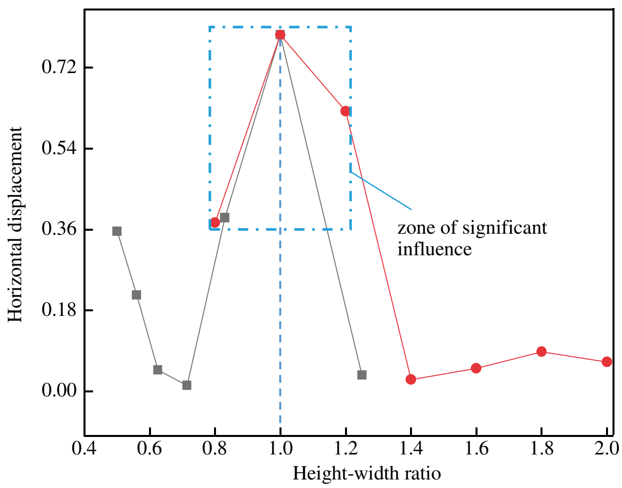


Fig. 6 Working block height-width ratio—horizontal displacement relationship curve

loads such as axial pressure and horizontal impact without stress wave disturbance is as follows:

(1) There is a close relationship between the ultra-low friction flagellating effect strength of the working block and the size of the working block. The horizontal displacement of the working block reaches the maximum of 0.793 mm when $H_W/S_W = 1.0$ under the same working condition.
(2) With the increase of H_W/S_W, the intensity of ultra-low friction whiplash effect of the working block shows a four-stage variation trend (decreasing, increasing, decreasing, and stabilizing), and the overall performance fluctuates first and then becomes stable. The height-width ratio of the working block has a significant influence on the horizontal displacement response degree, $H_W/S_W = (0.8 \sim 1.2)$.

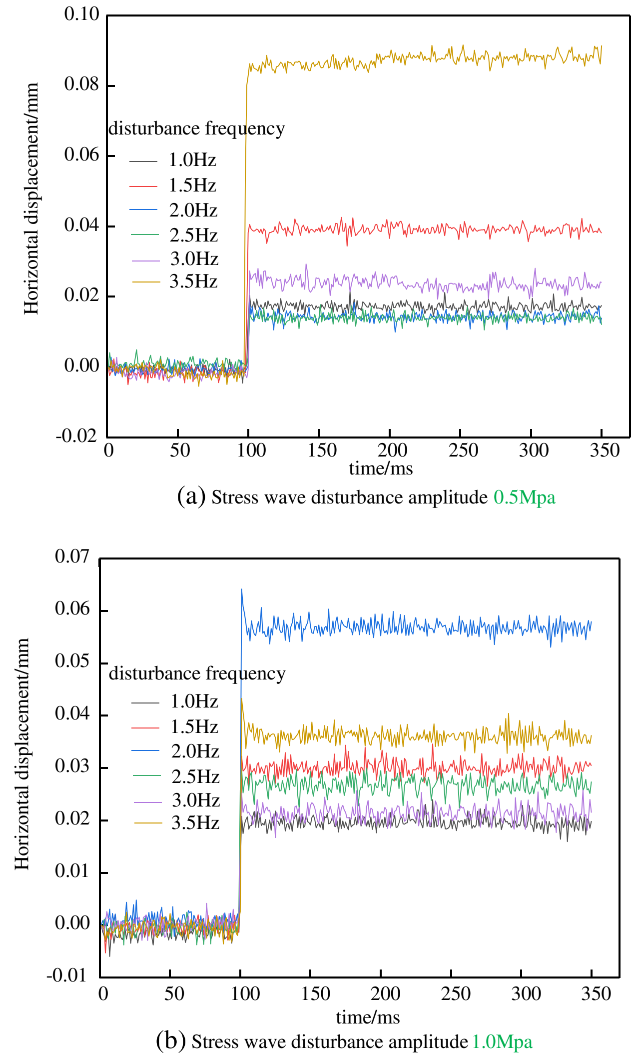


Fig. 7 When $H_W/S_W = 1.0$, the horizontal displacement time history curve of the working block under different stress wave perturbations is obtained. **a** Stress wave disturbance amplitude 0.5Mpa. **b** Stress wave disturbance amplitude 1.0Mpa

Study on ultra-low friction effect of working block under stress wave disturbance

In this part of the study, the working block is affected by axial pressure, axial stress wave disturbance, and horizontal impact. The axial pressure is 2 MPa, the horizontal impact is 3 MPa, and there are multiple working conditions for stress wave disturbance, and the disturbance amplitude is 0.5Mpa and 1 MPa. The disturbance frequency has five working conditions: 1 Hz, 1.5 Hz, 2.0 Hz, 2.5 Hz, 3.0 Hz, and 3.5 Hz. Based on the above different working conditions, the response mechanism of ultra-low friction effect of thirteen sizes of working blocks involved in high ratio and the wide ratio was investigated respectively. With Fig. 5, in the middle of the data processing, intercept part has a level of impact of 350 ms data to illustrate the working block horizontal displacement response, $t = 100$ ms to horizontal impact moment, can work to block ratio, horizontal displacement, and the relationship among stress wave disturbance curve, limited to the space, will not show one, Here, the working condition where the height-width ratio has the most significant influence on the horizontal displacement of the working block without stress wave disturbance is taken as an example, that is, when $H_W/S_W = 1.0$, as shown in Fig. 7.

Figure 7 shows that stress wave disturbance frequency and amplitude are important factors affecting the horizontal displacement response of the working block. The response form of horizontal displacement of the working block with different height-width ratios tends to be consistent with time, which is the stable stage → surge stage → stable stage.

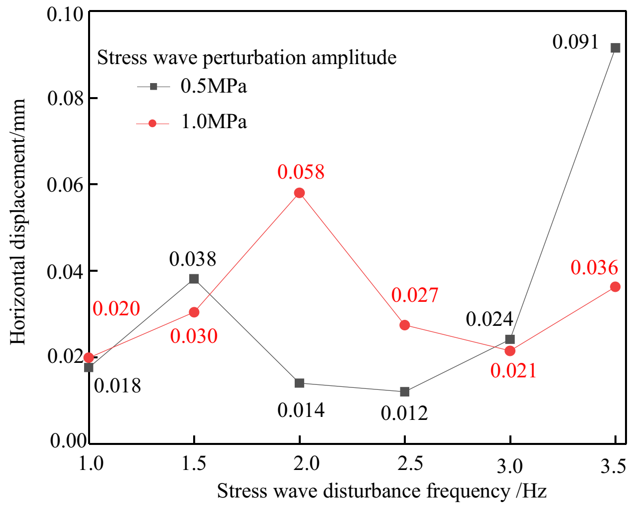


Fig. 8 When $H_W/S_W = 1.0$, the relationship between the horizontal displacement of the working block and its frequency under the action of different amplitude of stress wave disturbance

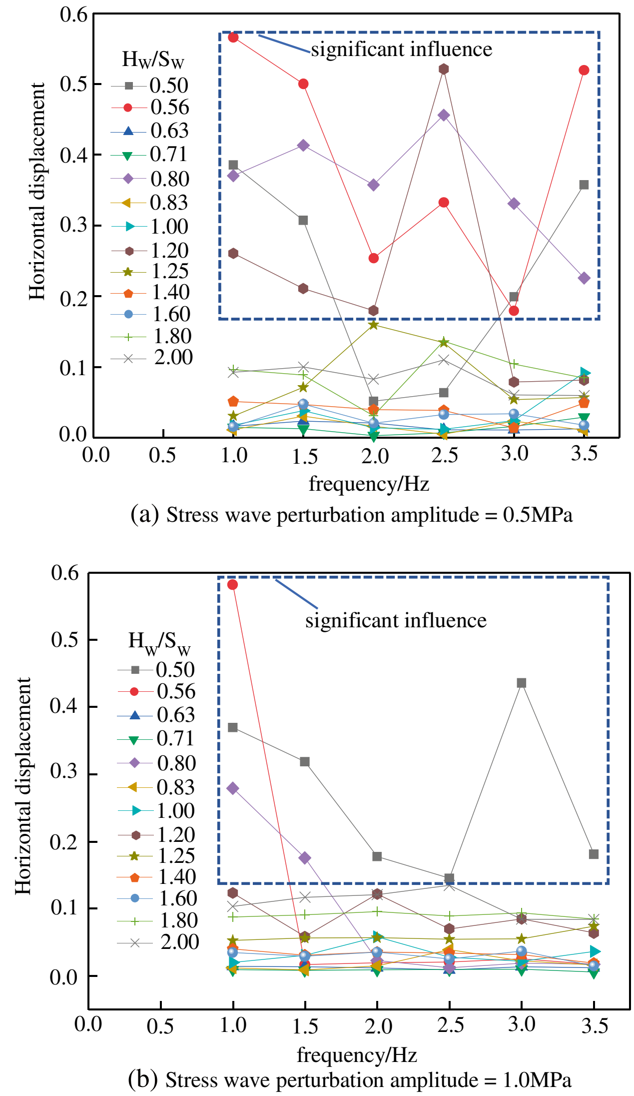


Fig. 9 The relation curve between horizontal displacement and height-width ratio of working block under different stress wave disturbance. **a** Stress wave perturbation amplitude = 0.5 MPa. **b** Stress wave perturbation amplitude = 1.0 MPa

Influence of stress wave disturbance factors

It can be seen from Fig. 7 (a) that when the stress wave disturbance amplitude is 0.5Mpa, the horizontal displacement of the working block with $H_W/S_W = 1.0$ increases first, then decreases, and then increases with the increase of stress wave disturbance frequency (1.0 Hz ~ 3.5 Hz). When the frequency is 3.5 Hz, the horizontal displacement of the corresponding working block is the largest, as high as 0.091 mm, as shown in the black line in Fig. 8. Similarly, it can be seen from Fig. 7 (b) that when the stress wave disturbance amplitude is 1.0Mpa, the horizontal displacement of the working block with $H_W/S_W = 1.0$ increases first, then decreases, and then increases with the increase of stress wave disturbance frequency (1.0 Hz ~ 3.5 Hz). When the frequency is 2.0 Hz, the horizontal displacement of the corresponding working block is the largest, up to 0.058 mm. See the red line in Fig. 8. By comparing Fig. 8 black line and Fig. 8 red line, it can be seen that the influence of stress wave disturbance amplitude on horizontal displacement response value of the working block is not a single increasing or decreasing relationship. Based on 13 sizes of H_W/S_W equal to 0.5, 0.56, 0.63, 0.71, 0.8, 0.83, 1.00, 1.20, 1.25, 1.40, 1.60, 1.80, and 2.00, it is concluded that the dynamic influence of stress wave disturbance on working blocks of different sizes is not consistent, as shown in Fig. 9. According to the horizontal displacement response of working blocks with different sizes under the action of the same stress wave disturbance frequency, it can be seen that the significant influence areas of stress wave disturbance frequency for different working blocks have different sizes.

Figure 9 (a) shows that the horizontal displacement of the working block fluctuates to a certain extent under the action of stress wave disturbance amplitude of 0.5Mpa and frequency of 1.0 Hz, 1.5 Hz, 2.0 Hz, 2.5 Hz, 3.0 Hz, and 3.5 Hz respectively. When H_W/S_W is equal to 0.5, 0.56, 0.8, and 1.2, the horizontal displacement of the working block changes significantly. When H_W/S_W is 0.63 Hz, 0.71 Hz, 0.83 Hz, 1.0 Hz, 1.25 Hz, 1.40 Hz, 1.60 Hz, 1.80 Hz, and 2.00 Hz, the horizontal displacement of the working block is relatively stable. Figure 9 (b) shows that the horizontal displacement of the working block fluctuates to a certain extent under the action of stress wave disturbance amplitude of 1.0Mpa and frequency of 1.0 Hz, 1.5 Hz, 2.0 Hz, 2.5 Hz, 3.0 Hz, and 3.5 Hz respectively. When H_W/S_W is equal to

0.56 and when the disturbance frequency of the stress wave is 1.0 Hz, the dynamic response of the working block is the most intense. The horizontal displacement of the working block with H_W/S_W equal to 0.50 under different stress wave disturbance frequencies is generally larger than that of the working block with other sizes. Work on analysis was found, in Fig. 9, block horizontal displacement and the stress wave disturbance frequency relation curve of the presence of cross-block phenomenon can be explained by the work itself inherent frequency differences of model system is a piece of work under different stress wave disturbance frequency disturbance degree block resonance happened not consistent.

To sum up, the dynamic response characteristics of the working block under external load such as axial pressure, horizontal impact, and stress wave disturbance are as follows:

(1) When H_W/S_W is equal to 0.5, 0.56, 0.8, and 1.2 respectively, the dynamic response of ultra-low friction effect under corresponding conditions is relatively significant, and the multi-group frequency comparison response of the test is relatively concentrated.
(2) The variation trend of horizontal displacement of the same working block with different stress wave disturbance amplitudes is the same as that of the stress wave disturbance frequency, which fluctuates with the increase of frequency (first increase, then decrease and then increase), but the horizontal displacement amplitude of the working block with different disturbance amplitudes is obtained under the action of different disturbance frequencies.

The influence of height-width ratio factors

In the experimental study on the effect of ultra-low friction effect on working block with height-width ratio, the corresponding height-width ratio is set from two aspects of high ratio and wide ratio.

It can be seen from Fig. 10 that, from the perspective of wide-ratio, the horizontal displacement of the working block increases with the height-width ratio (0.5 ~ 1.25) mainly in two stages, the intense response stage and the gentle response stage. The acute response stage refers to the range of H_W/S_W equal to 0.5 ~ 0.63, and the gentle response stage refers to the range of H_W/S_W equal to 0.63 ~ 1.25, in which the maximum horizontal displacement of the working block is in the acute response stage. Under the action of stress wave disturbance (amplitude 0.5Mpa, frequency 1.0 Hz) and stress wave disturbance (amplitude 1.0Mpa, frequency 1.0 Hz), the results were obtained at the point where the height-width ratio was 0.56, and the sizes were 0.57 mm and 0.58 mm, respectively.

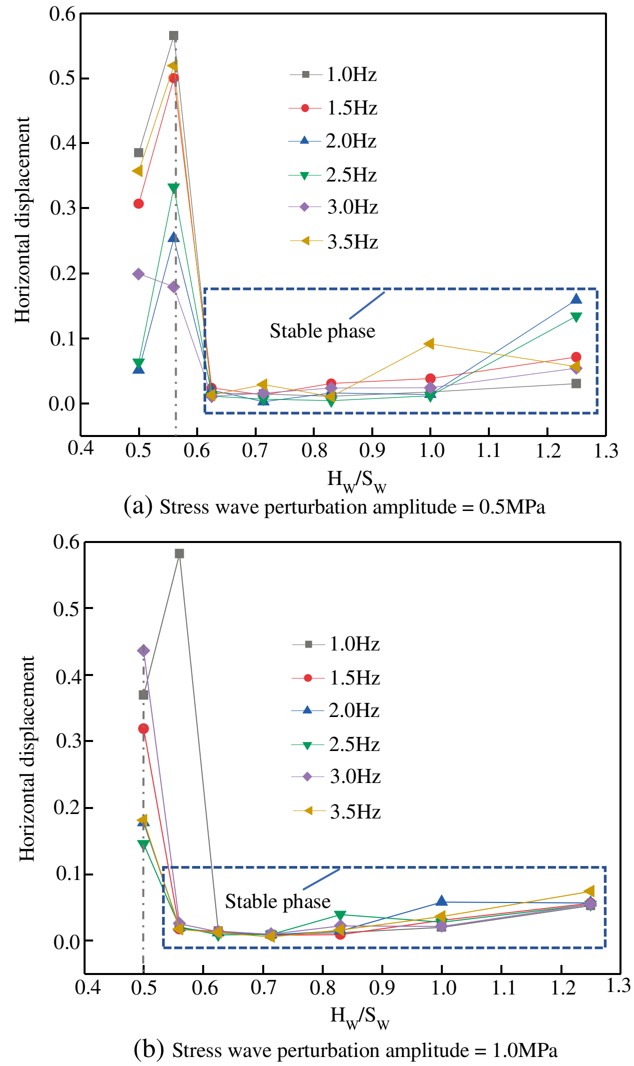
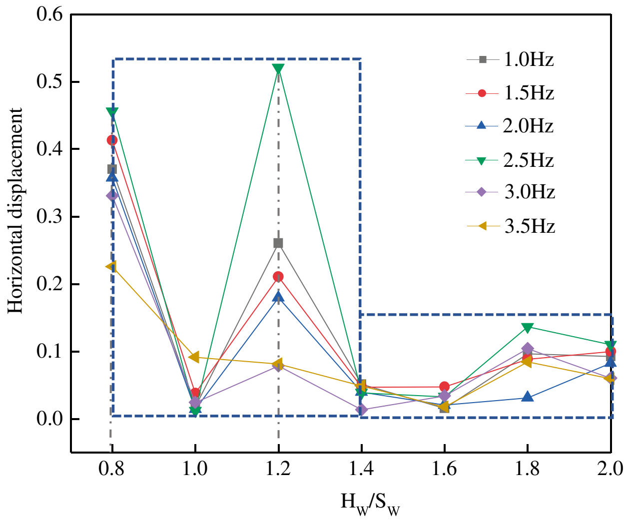
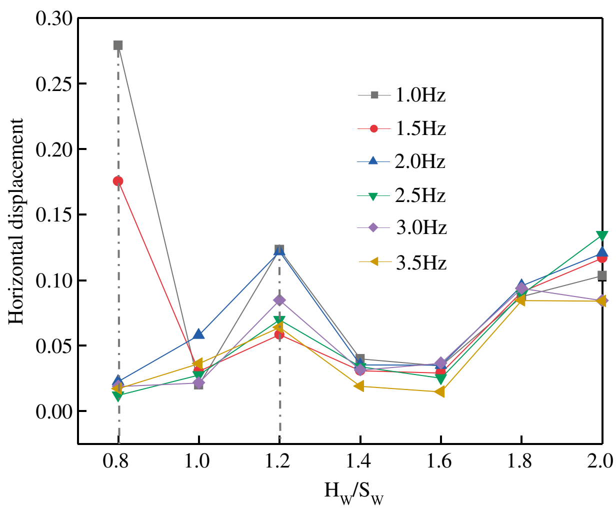


Fig. 10 The relation curve between horizontal displacement and height-width ratio of working block under different stress wave disturbance. **a** Stress wave perturbation amplitude = 0.5 MPa. **b** Stress wave perturbation amplitude = 1.0 MPa

As can be seen from Fig. 11, from the perspective of height ratio, the overall trend between (a) and (b) is roughly similar, except for the slight difference when the height-width ratio (H_W/S_W) is between 0.8 and 1.0. As shown in Fig. 10, it mainly includes two stages: the intense response stage and the gentle response stage. In the stage of violent response, the fluctuation phenomenon is obvious, which corresponds to the significant dynamic response of the working block. In the gentle stage, the horizontal displacement of the working block tends to be consistent with the increase of the height-width ratio under corresponding working conditions, and the phenomenon of ultra-low friction effect is not easy to occur at this stage. By comparing the two figures (a) and (b) in Fig. 11, it can be seen when H_W/S_W is between 1.0 and 1.4, the horizontal displacement of the working block



(a) High ratio stress wave disturbance amplitude 0.5MPa



(b) High ratio stress wave disturbance amplitude 1.0MPa

Fig. 11 The relation curve between horizontal displacement and height-width ratio of working block under different stress wave disturbance. **a** High ratio stress wave disturbance amplitude 0.5 MPa. **b** High ratio stress wave disturbance amplitude 1.0 MPa

presents an inverted V-shaped trend; when the height-width ratio of the working block is between 1.4 and 2.0, the horizontal displacement of the working block fluctuates to a certain extent and enters a relatively stable state. When H_W/S_W is equal to 0.8, the stress wave disturbance amplitude is 1.0Mpa and frequency is 2.0 Hz, 2.5 Hz, 3.0 Hz, and 3.5 Hz respectively, which reflects different mechanical properties from other working conditions.

Contrast Fig. 8 and Fig. 9, based on the width ratio and height ratio of two angles of the results of the study, known as work in the same height-width ratio (such as H_W/S_W is equal to 0.8 ~ 1.25), the width ratio and height ratio of working blocks of ultra-low friction effect than caused degree

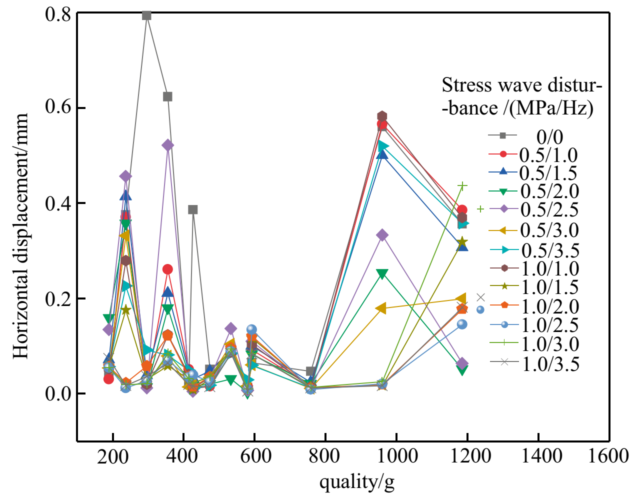


Fig. 12 Relation curve between working block mass and horizontal displacement under different working conditions

of response is completely different, explain quality play an important role in this process.

In summary, the following rules can be obtained:

(1) When the dynamic response characteristics of the working block were studied from the perspectives of the wide ratio and high ratio, it was found that there were significant influence zones with the height-width ratio of 0.5–0.63 and 0.8–1.2, respectively.

(2) It is found that unstable sliding occurs when the height-width ratio is less than 0.63, and stable sliding occurs when the height-width ratio is greater than 0.63. It is found that the horizontal displacement of the working block decreases with the increase of the height-width ratio ($H_W/S_W = 0.8 \sim 2.0$) in an inverted V shape and gradually tends to be stable.

Influence of quality factors

By comparing Figs. 10 and 11, it can be seen that the factors affecting the dynamic response of the working block include not only the external load and height-width ratio of the working block but also the mass of the working block which is closely related to its horizontal displacement response.

Figure 12 shows the relation curve between the working block mass and its horizontal displacement under different working conditions. As can be seen from the figure, when the mass is between 200 and 800 g, the horizontal displacement of the working block shows a trend of steady attenuation in the inverted V shape. When the mass of the working block exceeds 800 g, the inverted V increases greatly in most working conditions, and slowly in a small part of working conditions. The following rules can be obtained:

Block quality to the work of ultra-low friction effect of the lash is non-linear, and its dynamic response with the increase of the quality is not present a single change, different quality work in the block under different disturbance generated by the dynamic response of different levels when the disturbance frequency is close to the working block when the natural frequency block dynamic response is especially striking.

Conclusions

1) The ultra-low friction effect intensity of working block is closely related to the size of working block. The horizontal displacements of the working block without and with stress wave disturbance have significant influence areas with respect to its height-width ratio, which are $H_W/S_W = (0.8 \sim 1.2)$ and $H_W/S_W = (0.5 \sim 0.63,\ 0.8 \sim 1.2)$, respectively.
2) For the same working block with different stress wave amplitude, the variation trend of horizontal displacement with the stress wave frequency is basically the same, and the fluctuation phenomenon occurs with the increase of frequency (first increase, then decrease and then increase), but the maximum horizontal displacement of the working block is obtained under the action of different disturbance frequency. When H_W/S_W is equal to 0.5, 0.56, 0.8, and 1.2 respectively, the dynamic response of ultra-low friction effect under corresponding conditions is relatively significant, and the response is relatively concentrated by comparing the tested multiple frequencies.
3) The influence of mass and size on the ultra-low friction effect of the working block is nonlinear. In deep mining, more attention should be paid to the ultra-low friction effect of the broken block due to mass and size under the action of three 'high' and one 'disturbance'.

Funding This research was financially supported by the National Natural Science Foundation of China (Grant No. 51974148) and Liaoning Province "Xingliao Talent Program" (Grant No. XLYC1807130).

Declarations

Studies with human participants or animals This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent Informed consent was obtained from all individual participants included in the study.

Conflict of interest The authors declare no competing interests.

Disclaimer I certify that this manuscript is original and has not been published and will not be submitted elsewhere for publication while being considered by Arabian Journal of Geosciences, and the study is not split up into several parts to increase the quantity of submissions and submitted to various journals or to one journal over time. No data have been fabricated or manipulated (including images) to support our conclusions. No data, text, or theories by others are presented as if they were our own. The submission has been received explicitly from all co-authors, and authors whose names appear on the submission have contributed sufficiently to the scientific work and therefore share collective responsibility and accountability for the results.

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