Sliding and falling process of rock block in jointed roof under dynamic disturbance

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Abstract. The roof fall disaster in underground mine always threatens the safety of workers and equipment. Under the disturbance of blasting or earthquakes, it is easy to induce a sliding-type instability caving for a jointed roof rock mass. Experimental research on roof trapezoid key block is performed to study the sliding and instability process due to dynamic disturbance. A disturbed sliding test is conducted under the conditions of 5, 8, 10, 15, and 20 kN static lateral clamping load with different disturbance energies. The evolution law of sliding displacement and deformation during the disturbed sliding process of a key block is analyzed. Meanwhile, the critical disturbance energy of key block instability under different clamping load conditions is obtained, which exhibits an exponential relationship. Moreover, a theoretical calculation method of the disturbed sliding distance of key blocks under different disturbance energies and clamping load conditions is proposed based on the law of conservation of energy. Besides, the critical instability sliding distance can also be obtained from the proposed method. The calculated results agree well with the experimental results, which can provide theoretical guidance for the real-time risk assessment of roof rock blocks under the condition of displacement monitoring.

1. Introduction

To guarantee the safety of workers and enterprise property in underground mining, it is necessary to study the development mechanism of roof fall disasters [1,2]. Some scholars believe that the roof fall disaster is due to the sliding of rock blocks along joint planes [3,4]. Owing to the development of cracks in the surrounding rocks around the excavation space, a roof rock mass can easily form independent rock blocks via crack cutting [5]. When one of the rock blocks slides along joint surface firstly, it will lead to the falls of adjacent rock blocks one after another [6,7].

Dynamic disturbance factors, such as blasting and earthquakes, are more likely to cause the sliding and instability of roof rock blocks than static disturbance factors, such as excavation, underground water pressure, and in situ stress [8]. Ma et al. [9] simplified the roof blocky rock mass of underground tunnels or caverns into a multiple-degree-of-freedom mass-spring-dashpot system and conducted parametric studies on the roof stability with respect to the pulse width, pulse amplitude, pulse shape, and damping ratio based on Newmark sliding block theory. Liu et al. [10] established a rock block test model with many fractures and complex stacking of blocks to study the sliding and instability of granite strip rock blocks in roadway roofs due to dynamic disturbance. Considering the external...
disturbance in an orthogonal direction might lead to large-scale deformation or sliding rock burst of tunnel surrounding rocks, Shi et al. [11] vertically stacked five cubic granite blocks to study the ultralow friction phenomenon of rock block systems under a vertical impact disturbance load. However, existing studies on the instability of roof rock block systems under dynamic disturbance mainly focus on cubic block rocks. For roof block systems comprising trapezoidal blocks with inclined edges, there are obvious differences in the propagation process of stress waves and the sliding instability laws, which need in-depth theoretical and experimental studies.

In this article, the roof rock of roadway is simplified as a rock block system comprising trapezoidal blocks, and the sliding and instability process of trapezoidal key blocks under vertical dynamic disturbance is studied experimentally and theoretically.

2. Experimental design and device development
Owing to the limitation of laboratory-blasting operations, the mechanical impact is usually employed to simulate the blasting dynamic disturbance [12]. Therefore, to quantitatively study the process of disturbed sliding and instability of key rock blocks in roadway roofs, practical conditions can be simplified as a physical model comprising trapezoidal rock blocks under plane stress conditions (Fig. 1).

![Figure 1. Simplified test model for roadway roof key block.](image)

To satisfy the condition of the experiment test, a special dynamic disturbance test device was designed [Fig. 2(a)]. The maximum lateral and vertical loads of the test device were 600 kN. The drop hammer impacted the incident bar to generate dynamic disturbance in the device. The diameter, height, weight, and maximum falling height of the drop hammer were 80 mm, 100 mm, 5.8 kg, and 2500 mm, respectively. The diameter, length, and elastic modulus of the incident bar were 40 mm, 500 mm, 210 GPa, respectively.

![Figure 2. Test device and monitoring equipment.](image)
3. Experiment test

3.1. Test preparation
A natural sandstone was cut into three blocks. The left and right surrounding rocks were straight-angled trapezoids with a top edge, bottom edge, height, and thickness of 196, 143, 300, and 160 mm, respectively. The key block rock is an isosceles trapezoid with a top edge, bottom edge, height, and thickness of 148, 254, 300, and 160 mm, respectively. The elastic modulus, uniaxial compressive strength, tensile strength, cohesion, internal friction angle, Poisson's ratio, and density of sandstone were 8.4 GPa, 29.8 MPa, 2.4 MPa, 6.2 MPa, 30.2°, 29, and 2170 kg/m³, respectively. The basic friction angle of the cutting face was approximately 35°.

The strain gauges were pasted on the surface of the sample and vertical incident bar to monitor the dynamic strain with a 100-kHz sampling frequency. The dynamic displacements of blocks' top surfaces were monitored using a laser displacement meter with a 10-kHz sampling frequency and 8-mm measuring range. A lateral load sensor was employed to monitor the lateral clamping load of the block system with a 1-Hz sampling frequency [Fig. 2(b)].

3.2. Test results
Fig. 3 shows the disturbed sliding displacement curves of the key block under different impact energy when the initial clamping loads are 5, 8, 10, 15, and 20 kN, respectively.

When the impact energy was small, the key block would slide an irreversible displacement under the dynamic disturbance and restore the stability after a period of fluctuation. Under the condition of the same initial clamping load, greater dynamic disturbance energy induces a larger irreversible displacement of the key block. For example, when the initial clamping load was 10 kN and the impact energy was 13.36, 19.04, 24.73, and 27.57 J, the disturbed sliding displacement of the key block was 1.93, 1.32, 0.96, and 0.52 mm, respectively.

When the impact energy was high and close to the instability threshold, the key block would produce a macroirreversible sliding under the first impact of the drop hammer and then fall under the secondary rebound impact after a short stagnation period. For example, when the clamping load and impact energy were 8 kN and 12.68 J, respectively, although the key block produced a large macro-sliding of 1.12 mm at the first impact, it did not become unstable and fall. Contrariwise, it would lose stability and falls under a secondary impact.

When the impact energy was large and exceeded the instability threshold, the key block would slide and fall immediately under the impact disturbance. With the increasing initial lateral clamping load, high disturbance energy was required to induce the instability of key blocks. For example, when the initial lateral clamping load was 5, 8, 10, 15, and 20 kN, the disturbance energy for inducing the instability of key block was 6.82, 17.34, 30.41, 46.32, and 53.15 J, respectively.
Before the dynamic disturbance was applied, the rock block system was subjected to the initial clamping load, resulting in an initial lateral compressive deformation. In this study, the initial strain value was manually eliminated before the dynamic disturbance. Therefore, a decrease in strain value indicated an increase in compressive strain, and an increase in strain value indicated the release of initial compressive strain.

When the initial clamping load was 20 kN and the impact energy was 50.87 J, the strain curve of the key block center point was detected (Fig. 4). The vertical strain curve of the key block center point showed obvious harmonic wave characteristics. The strain curve always fluctuated around the zero value, and the first wave amplitude was approximately 400 \( \mu \varepsilon \); the fluctuation amplitude gradually decreased to the initial value with time [Fig. 4(a)]. The lateral strain curve also showed the fluctuation characteristics, which were irregular and without a fixed period. The lateral strain eventually increased by approximately 20 \( \mu \varepsilon \) compared with the initial value as the curve fluctuation gradually decreased to a constant [Fig. 4(b)]. It is because the sliding of isosceles trapezoid key block would inevitably cause the unloading of clamping load and releasing of the initial compressive strain.
Figure 4. Strain response of incident bar and key block under the initial clamping load of 20 kN and dynamic disturbance energy of 50.87 J.

The magnitude of irreversible displacement induced by impact disturbance was closely related to the disturbance energy and initial clamping load level. When the initial clamping load was the same, the irreversible sliding displacement of the key block increased exponentially with the disturbance energy [Fig. 5(a)]. When the disturbance energy was basically the same, the larger the initial clamping load was, the smaller the disturbed irreversible displacement of the key block was.

Because the key block was an isosceles trapezoid, the sliding of the key block also caused the unloading of the initial clamping load. The unloading amount of the clamping load was basically linearly related to the sliding displacement of the key block [Fig. 5(b)].

Figure 5. Disturbed sliding displacement of key block and unloading amount of lateral load.

4. Critical condition of rock block instability

4.1. Critical disturbance energy

As shown in Fig. 6, with an increase in the initial clamping load, the critical disturbance energy to induce the key block instability and fall exhibited a logarithmic growth trend. When the initial clamping load was low, the critical disturbance energy rapidly increased with an increase in the initial clamping load. However, when the initial clamping load was high, the critical disturbance energy increased slowly with the increase in the initial clamping load. The upper and lower regions of the curve represent unstable danger and stable safety zones, respectively.
Figure 6. Critical disturbance energy of key block instability under different initial clamping loads.

4.2. Critical sliding displacement

According to the law of conservation of energy, the sliding displacement of key block can be calculated by the energy conversion relationship. Since the lateral clamping load on the block system is linearly related to the vertical sliding displacement of the key block, the normal pressure on the friction interface is also linearly related to the vertical sliding displacement of the key block. Therefore, the vertical disturbed sliding displacement of the key block can be expressed as follows [13]:

\[ d_v = \left( m_{\text{hammer}} \cdot g \cdot h + \frac{L}{2EA} \left( F_{x,0}^2 - F_{x,1}^2 \right) \right) / \left( f_{i1} + f_{i0} - m_{\text{keyblock}} g \right) \]  

(1)

\[ f_{i0} = N_{i0} \cdot u_d = \left( \sin \theta \cdot F_{x,0} - \cos \theta \cdot \frac{m_{\text{keyblock}} \cdot g}{2} \right) \cdot \mu_d \]  

(2)

\[ f_{i1} = N_{i1} \cdot u_d = \left( \sin \theta \cdot F_{x,1} - \cos \theta \cdot \frac{m_{\text{keyblock}} \cdot g}{2} \right) \cdot \mu_d \]  

(3)

where \( d_v \) is the disturbed sliding displacement of the key block; \( F_{x,0} \) and \( F_{x,1} \) are the lateral clamping load on the block system before and after the dynamic disturbance, respectively; \( f_{i0} \) and \( f_{i1} \) are the maximum static friction of the interface before and after the disturbance, respectively; \( m_{\text{hammer}} \) and \( m_{\text{keyblock}} \) are the weights of drop hammer and key block, respectively; \( \theta \) is the included angle between the bevel edge and the bottom edge of the isosceles trapezoid key block; \( \mu_d \) is the sliding friction coefficient; \( E \) is the elastic modulus of sandstone; \( A \) is the cross-sectional area of rock blocks; \( L \) is the total length of rock block system; \( g \) is the acceleration of gravity.

According to Eq. (3), the disturbed sliding displacement of the key block was calculated and compared with the experimental results (Fig. 7). The theoretical calculation results basically agreed with the measurement results, which indicated that the proposed theoretical method could effectively calculate the disturbed sliding displacement of the key block.
The analysis shows that the critical stress conditions to maintain the stability of key block can be expressed as follows:

$$\mu_j \left( 2 \cdot \sin \theta \cdot F_{r,l} - \cos \theta \cdot m_{\text{key block}} \cdot g \right) \geq 2 \cdot \cos \theta \cdot F_{r,l} + \sin \theta \cdot m_{\text{key block}} \cdot g \quad (4)$$

According to Eq. (4), the critical clamping load of the key block was 0.378 kN. Because the unloading amount of clamping load was linearly correlated with the disturbed sliding displacement of the key block, the critical sliding displacement could be calculated by the critical clamping load, and the results are shown in Fig. 8. The variation trend of the critical sliding displacement with the initial clamping load obtained from the theoretical calculation basically agreed with the variation trend of the maximum sliding displacement obtained from the test, which indicated that the calculation method of the critical sliding displacement was reliable and rationale.

5. Conclusion
The roof rock mass was simplified as a blocky system comprising trapezoidal blocks in this study to investigate the sliding and instability process of trapezoidal key block under vertical dynamic disturbance experimentally and theoretically. The following conclusions can be drawn.

(1) The key block will produce irreversible sliding displacement and restore a stable state after a period of fluctuation under a small energy dynamic disturbance. When the initial lateral clamping load is basically the same, larger dynamic disturbance energy induces a larger irreversible displacement of the key block with an exponential correlation.
(2) The key block will slide and fall immediately under the dynamic disturbance when the disturbance energy is large and exceeds the instability threshold. The critical disturbance energy of the key block instability increases exponentially with the initial clamping load.

(3) The critical disturbance energy of the key block exhibits a logarithmic growth trend with an increase in the initial clamping load. Based on the law of conservation of energy, a sliding displacement calculation method is proposed for the trapezoidal key block under vertical dynamic disturbance. In addition, a calculation method for trapezoidal key block critical sliding displacement is proposed, which can be used for real-time monitoring and early warning of roof rock instability.

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