

Postprint of Model Test Study on Electromagnetic Control of Unstable Rock Stability Based on Natural Frequency

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Date: 2025-07-30T00:00:00+00:00

Abstract

Rockfall disasters along highways in China are characterized by wide distribution, high frequency, and sudden occurrence, and prevention efforts face the challenge of lacking reliable early warning indicators. This study innovatively proposes an electromagnetic-controlled rockfall model testing method and systematically investigates the stability and natural vibration frequency characteristics of three types of unstable rock masses—sliding, falling, and toppling—through laser vibrometry technology. Experimental results demonstrate that the natural vibration frequency of unstable rock masses exhibits characteristic changes prior to instability; when the slope inclination exceeds 70° , it manifests as a stepwise decrease accompanied by a “double/multi-peak” phenomenon in the frequency spectrum. Compared with displacement monitoring, vibration frequency indicators can identify failure precursors in advance, with significant improvement in early warning timeliness. The electromagnetic-controlled testing method established in this study offers advantages such as simple operation and reliable data, providing new technical support for the early warning of slope collapse disasters.

Full Text

Experimental Study on Electromagnetic Control Model for Unstable Rock Stability Based on Natural Vibration Frequency

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Abstract

Rockfall disasters along China's highway slopes feature widespread distribution, frequent occurrence, and high unpredictability, presenting significant challenges for hazard prevention due to the lack of reliable early warning indicators. This study introduces an electromagnetic control model experiment to systematically examine the stability and natural vibration frequency characteristics of three typical unstable rock types: sliding, toppling, and falling, employing laser vibration measurement technology. The results reveal that prior to failure, unstable rock exhibits distinctive vibration frequency variations, including a stepwise decline pattern along with dual- or multi-peak spectral phenomenon when slope angle exceeds 70°. Compared with conventional displacement monitoring, vibration frequency measurements demonstrate superior timeliness in detecting impending failure. The electromagnetic control model experiment offers operational simplicity and data reliability, providing an effective technical approach for rockfall early warning systems.

Keywords: slope; rockfall disasters; natural vibration frequency; early warning

With continuous socioeconomic development, China's highway network has expanded rapidly, reaching a total length of 117,000 kilometers that covers 98.8% of urban populations and all cities with over 200,000 people plus prefecture-level administrative centers, connecting 88% of county-level districts nationwide and greatly facilitating public mobility. The Ministry of Transport's 2035 highway network planning objectives specifically emphasize "safety and reliability" in highway engineering, requiring enhanced engineering reliability of highway networks in natural disaster-prone regions to ensure infrastructure safety and respond to major geological hazards. Therefore, identifying safety hazards along highways and implementing timely remediation and protection measures are critical for achieving a safe and reliable national highway network and constitute important safeguards for reducing casualties and property losses.

Common geological hazards along expressways include landslides, rockfalls, and debris flows, among which rockfall disasters are particularly prevalent, characterized by strong suddenness and high destructiveness. In China's southeastern hilly regions and western mountainous areas, highway slopes often consist of exposed high-steep rock masses. Weathering effects intensified by precipitation and diurnal temperature variations facilitate the development of joints and fractures within slopes, reducing rock mass strength and forming unstable rock blocks. Disturbances from earthquakes, extreme weather, and engineering activities can trigger rockfall disasters, leading to a high-frequency occurrence of slope rockfall hazards that are difficult to comprehensively prevent and control. For instance, the MW5.8 Lushan earthquake in Ya'an, Sichuan Province on June 1, 2022, triggered over 2,300 collapses and landslides, causing casualties and property losses while severely impeding subsequent rescue efforts. According to National Bureau of Statistics data, 2,176 rockfall disasters occurred in

China in 2023, representing an increase compared to previous years [Figure 1: see original paper].

Unstable rock masses exhibit diverse failure modes with varying definitions and classifications. Dorren and Hoek et al. categorized rockfalls into sliding, toppling, and falling types based on differences in rockfall motion patterns caused by varying average slope angles. Hu Houtian classified unstable rock collapses into toppling, sliding, bulging, tension-cracking, and shearing types, plus transitional types such as bulging-sliding and bulging-toppling, considering rock properties, structural plane characteristics, and initial motion forms. Chen Hongkai et al., through investigations of unstable rocks in the Three Gorges Reservoir area, macroscopically divided them into individual and group unstable rocks, further subdividing individual rocks into compression-shear sliding, tension-shear toppling, tension-cracking falling, and tension-cracking compression-shear falling types based on mechanical mechanisms and instability modes. Overall, the three primary types of slope rockfall failures based on mechanical mechanisms and motion patterns are sliding, toppling, and falling [Figure 2: see original paper].

Du Yan et al. introduced dynamic monitoring indicators such as kurtosis index and impact energy to study early monitoring and warning of rock mass collapse processes. Results showed that impact energy and vibration parameters could identify early signs of accelerated rock mass failure, with impact energy demonstrating greater sensitivity. Du Yan et al. also conducted various model tests including remote sensing monitoring [9], rock bridge length measurement [10], safety monitoring [11], and cumulative damage evaluation [12], summarizing that the slope rock mass failure process generally comprises stable, separation, and accelerated failure stages, with the separation stage representing the critical early warning period for unstable rock identification.

Indoor model test results demonstrate that monitoring natural vibration frequency can provide warning criteria and effectively transform passive prevention of brittle failure disasters like rockfalls. However, existing indoor model tests based on natural vibration frequency exhibit small differentiation, low controllability, and poor continuity, with related research failing to cover different failure types of unstable rocks. To address these issues, this study proposes an improved electromagnetic control model test based on unstable rock vibration theory to investigate the relationship between unstable rock stability and its natural vibration frequency.

2.1 Experimental Overview

As shown in [Figure 3: see original paper], this study simulated unstable rock masses using gypsum specimens with six electromagnets placed equidistantly on the bottom surface. A Laser Doppler Vibrometer (LDV) and Linear Variable Differential Transformer (LVDT) measured specimen natural vibration frequency and displacement. By adjusting the power supply voltage from top to

bottom to change electromagnetic attraction, the simulation of progressive crack propagation to failure in unstable rock masses was achieved.

For rockfall disasters, the engineering community typically uses displacement as the parameter characterizing accelerated failure precursors to monitor slope stability. However, displacement changes are minimal and insensitive before unstable rock cracking and collapse, resulting in low disaster monitoring foresight with existing equipment precision and potentially missing the golden period for disaster prevention. To address this limitation, scholars have proposed using natural vibration frequency as a characteristic parameter to identify separation failure precursors in unstable rocks, which can improve warning sensitivity for rockfall disasters.

As shown in [Figure 4: see original paper], adjusting the test platform inclination angle enabled simulation of failure processes for different slope-angle sliding-type unstable rocks. Setting the platform angle to 90° allowed falling-type tests, and further installation of blocking devices enabled toppling-type tests. The key parameters include: μ (friction coefficient), θ (slope inclination angle, °), F_m (electromagnetic force, N), m (specimen mass, kg), and g (gravitational acceleration, 9.81 m/s²).

2.2 Calculation Principles

To conveniently describe specimen stability, this study adopts the limit equilibrium method, using the ratio of sliding-resisting factors to sliding factors as a reference index, denoted as the theoretical factor of safety (TFS). When calculating TFS, electromagnets and pressure sensors within the specimen are ignored, and the gypsum specimen is treated as a homogeneous block with uniform stress distribution.

As shown in [Figure 5: see original paper], for sliding-type specimens, force analysis indicates that the slide-resisting force (F_{sr}) is friction, while the sliding force (F_s) is the gravity component. The theoretical safety factor is:

$$TFS = \frac{F_{sr}}{F_s} = \frac{\mu mg \cos \theta}{mg \sin \theta} = \mu \cot \theta \quad (3)$$

The theoretical safety factor for falling-type tests becomes the ratio of slide-resisting moment to sliding moment. As shown in [FIGURE:6(b)], after installing blocking devices, the test transforms into a toppling-type test. The theoretical safety factor is the ratio of slide-resisting moment of force to sliding moment of force, which relates to the bottom block height a . The slide-resisting moment is:

$$M_{sr} = F_m \left(\frac{H}{2} - a \right) + F_f \frac{L}{2} \quad (4)$$

The sliding moment is:

$$M_s = mg \left(\frac{H}{2} - a \right) + F_d \frac{L}{2} + F_n a \quad (5)$$

where TFS is theoretical factor of safety; F_{sr} is slide-resisting force (N); F_s is sliding force (N). Substituting equations (4), (5), and force equilibrium relationships into equation (3) and simplifying yields the appropriate safety factor for each test type.

2.3 Experimental Equipment

This study employed an RSV-150 long-range laser vibrometer with a maximum working distance of 150 m. Frequency data were collected for time-domain and frequency-domain vibration analysis, using fast Fourier transform (FFT) to obtain specimen vibration frequency distribution images and subsequently determine natural vibration frequency.

The cast gypsum specimens had a mass of 10.5 kg and dimensions of 250\$×150×150mm\$, with surfaces ground flat. Six small electromagnets rated at 24V with 4kg holding force were used. Testing confirmed that electromagnetic attraction is linearly and positively correlated with voltage. A high-precision LVDT measured specimen displacement along the sliding direction with a resolution of 0.1 mm.

3.1 Sliding-Type Tests

Testing confirmed that the friction angle between gypsum specimens and the test platform surface was approximately 32°, so the initial slope angle for sliding-type tests was set at 35°. All electromagnets were initially controlled at 24V, with voltage decreased top-down by 3V increments until specimen sliding occurred.

Using the 35° slope angle as an example, the specimen's natural vibration frequency-displacement-theoretical safety factor relationship is shown in and [Figure 7: see original paper]. As the specimen's safety factor gradually decreased, the frequency initially declined slowly, then dropped sharply after the safety factor fell to 0.998. Displacement increased slowly at first, then rose rapidly after the safety factor decreased to 0.980. Natural vibration frequency predicted the sliding inflection point earlier than displacement.

The internal stress distribution within specimens exhibits significant non-uniformity, with localized stress concentration zones forming near shear bands. The energy dissipation pattern transitions from uniform viscoelastic dissipation to non-uniform plastic and brittle dissipation. The low-frequency peak corresponds to elastic vibration of the overall structure, reflecting the elastic energy storage-dominated stage where energy is slowly released through internal friction and viscous deformation. The high-frequency peak originates from local instability and friction within shear bands, characterizing the nonlinear

failure stage of local shear bands and manifesting as high-frequency vibration signals.

3.2 Falling and Toppling Tests

The slope angle was increased to 90° for falling-type and toppling-type tests, following the same procedure as sliding-type tests. In toppling tests, block lengths of 1, 2, 4, and 6 cm were used. The calculated natural vibration frequency-displacement-theoretical safety factor relationships are shown in [Figure 10: see original paper].

[Figure 9: see original paper] shows the frequency distribution diagram for a specimen at 75° slope angle. For sliding-type specimens, natural vibration frequency predicts the sliding inflection point earlier than displacement, providing better warning effectiveness. As slope angle increases, the initial natural vibration frequency decreases, indicating reduced specimen stability. When slope angle is less than 70° , frequency variation follows a slow decline→sharp drop pattern, showing a single inflection. When slope angle exceeds 70° , frequency variation exhibits a slow decline→sharp drop→slow decline→sharp drop pattern, showing a stepwise characteristic.

Observation of specimen frequency distributions revealed that when slope angle exceeds 70° and specimens approach sliding failure, the frequency distribution presents a “dual-peak” pattern [Figure 9: see original paper], which can serve as another instability indicator. The dual-peak phenomenon may result from internal stress differentiation and energy dissipation mechanism transitions. As electromagnetic attraction decreases top-down, the frequency variation pattern becomes stepwise, but with faster change rates compared to sliding-type tests—a shorter first stage and longer third stage. Both falling and toppling types exhibit “dual-peak” or “multi-peak” frequency distributions near failure, with more chaotic distributions than sliding-type tests [Figure 11: see original paper].

The frequency and displacement variation trends in this study are similar to those obtained by Du Yan et al., demonstrating the applicability of electromagnetic control model tests for unstable rock stability research. Compared with previous tests, the electromagnetic control model test offers better process continuity and repeatability, more intuitive data, and greater controllability. However, fewer data were recorded under large-angle conditions, likely because electromagnetic attraction becomes increasingly difficult to control for specimen stability as slope angle increases. Under large-angle conditions, specimens still tend to slide even with all electromagnets at full voltage, attributed to test surface smoothness, air humidity, and specimen installation errors.

Under large-angle conditions, specimens exhibit “dual-peak” or “multi-peak” phenomena when approaching instability, typically with high-amplitude low-frequency peaks and low-amplitude high-frequency peaks. As slope angle increases, frequency distribution gradually transitions from “dual-peak” to “multi-peak,” with the dominant frequency corresponding to the low-frequency peak.

This indicates that internal stress differentiation intensifies and energy dissipation modes progressively shift toward non-uniform plastic and brittle dissipation as slope angle increases.

Under this study's test conditions, the critical slope angle dividing stepwise frequency variation and "dual-peak"/"multi-peak" frequency distributions is 70° , though this boundary may be influenced by specimen material properties and friction characteristics between specimen and slope surface. Using numerical-graphical combination concepts, stepwise frequency variation and "dual-peak"/"multi-peak" frequency distributions can serve as instability criteria for unstable rocks on high-angle slopes.

This study proposes an improved electromagnetic control model test for unstable rock stability research, demonstrating its feasibility and result credibility. Compared with previous tests, the electromagnetic control model test offers shorter duration, more accurate control, more intuitive data, and better process controllability. As slope angle increases, unstable rock frequency variation transitions from a single inflection pattern (slow decline→sharp drop) to a stepwise pattern (slow decline→sharp drop→slow decline→sharp drop), with increasingly chaotic frequency distributions exhibiting "dual-peak" or "multi-peak" characteristics. These features appear earlier than displacement surges and can serve as instability criteria for high-angle slope unstable rocks.

References

- [1] Central People's Government of China. National Highway Network Planning [EB/OL]. <https://www.gov.cn/zhengce/zhengceku/2022-07/12/5700633/files/1ca992f13a81434b89e222eb000acada.pdf>, 2022-07.
- [2] Ma Siyuan, Xu Chong, Chen Xiaoli. Comparison of Emergency Assessment Models for Earthquake-Induced Collapse and Landslide Hazards—A Case Study of the June 1, 2022 MW5.8 Lushan Earthquake[J]. *Seismology and Geology*, 2023, 45(04): 896-913.
- [3] National Bureau of Statistics of China. China Statistical Yearbook[M]. Beijing: China Statistics Press, 2024.
- [4] Dorren L K A. A review of rockfall mechanics and modelling approaches[J]. *Progress in Physical Geography*, 2003, 27(1): 69-87.
- [5] Hoek E, Bray J D. Rock slope engineering[M]. CRC press, 1981.
- [6] Hu Houtian. Study on collapse and rockfall[J]. *Journal of Railway Engineering Society*, 2005, (S1): 387-391.
- [7] Chen Hongkai, Tang Hongmei. Classification and macro-criteria of unstable rocks in the Three Gorges Reservoir area[J]. *The Chinese Journal of Geological Hazard and Control*, 2005, (04): 57-61+82.
- [8] Liu Ran, Luo Changwei, Sun Tao, et al. Study on Passive Protection Net

Design Based on Rockfall Motion Characteristics Analysis[J]. Journal of Water Resources and Architectural Engineering, 2023, 21(03): 74-83.

[9] Du Yan, Huo Leichen, Xie Mowen, et al. Experimental study on monitoring and early warning of unstable rock collapse disasters[J]. Chinese Journal of Theoretical and Applied Mechanics, 2021, 53(04): 1212-1221.

[10] Du Yan, Huo Leichen, Zhang Hongda, et al. Experimental study on remote sensing monitoring and early warning of rock block collapse disasters[J]. Journal of China University of Mining & Technology, 2022, 51(06): 1201-1208.

[11] Du Yan, Lu Yongdu, Xie Mowen, et al. Measurement of rock bridge length in unstable rocks based on laser Doppler vibrometry[J]. Journal of China Coal Society, 2019, 44(S2): 560-565.

[12] Du Yan, Xie Mowen, Jiang Yujing, et al. Experimental study on safety monitoring of unstable rocks based on natural vibration frequency[J]. Rock and Soil Mechanics, 2016, 37(10): 3035-3040.

Note: Figure translations are in progress. See original paper for figures.

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