

Article

Study on Crack Propagation and Dynamic Characteristic Evolution of Cantilevered Unstable Rock Masses Based on XFEM

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Abstract

Cantilevered unstable rock masses constitute a prevalent geological hazard, with their stability intrinsically governed by the depth of trailing edge cracks. Traditional stability assessment methods, which largely rely on static calculations or displacement monitoring, often suffer from poor timeliness and insufficient early warning capabilities. To address these limitations, this study employs the Extended Finite Element Method (XFEM) to simulate the natural crack propagation trajectory and investigate the associated dynamic response characteristics under loading. The simulation results demonstrate that XFEM effectively captures the natural “vertical-to-oblique” fracture morphology, overcoming the limitations of pre-defined crack models. A critical correlation is established between crack evolution and natural frequency: the first-order natural frequency exhibits a staged decline, characterized by a precipitous drop of approximately 7 Hz during the late stage of fracture development (80–97% depth). Consequently, a “crack evolution–frequency response” model is proposed. This model confirms that natural frequency is a significantly more sensitive indicator of internal damage than displacement, providing a novel theoretical foundation and technical pathway for the early identification and dynamic evaluation of rock mass stability.

Keywords: cantilevered unstable rock mass; extended finite element method (XFEM); crack propagation; natural frequency



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1. Introduction

Unstable rock masses, often referred to as perilous rocks, are prevalent geological hazards in nature [1,2]. Cantilevered unstable rock masses typically occur within massive, thick rock formations, often underlain by soft rock strata. While the rock body itself generally retains a high degree of integrity, factors such as differential weathering or anthropogenic excavation frequently result in the formation of recessed cavities at the base [3]. Driven by unloading and rebound effects, tensile cracking initiates at the trailing edge of the rock mass. As these trailing edge fissures deepen continuously, the stability of the rock mass progressively deteriorates, potentially culminating in catastrophic collapse [4]. Structurally, the upper rock mass resembles a cantilever beam suspended over the parent rock, with its stability primarily governed by the depth of the trailing edge fissure [5]. The instability and subsequent collapse of such rock masses pose severe threats to human life and property;

therefore, investigating their failure modes is a critical prerequisite for effective disaster prevention and control [6]. The failure mechanism is generally characterized by tensile stress failure. Under the influence of external natural forces—such as rainfall, earthquakes, and weathering—these rock masses are highly susceptible to collapse, resulting in significant casualties and economic losses [7,8].

In the study of unstable rock mass stability, quantitatively characterizing the degree of stability is a fundamental task for the prevention and control of collapse hazards [9,10]. However, existing methods for calculating stability coefficients suffer from multiple deficiencies, such as insufficient reliability, low accuracy, and poor timeliness, making a challenge to meet practical engineering requirements [11]. The determination of trailing edge fissure depth also presents a critical problem that remains urgently unresolved; as static methods are ineffective in addressing this issue, in-depth analysis relying on dynamic methods is necessary [12]. Furthermore, although monitoring and early warning systems can assess stability by real-time tracking of deformation, the deformation rate of unstable rock masses is inherently slow. Distinct deformation features typically emerge only immediately prior to failure, creating temporal uncertainty regarding instability and complicating significantly the implementation of effective early warning systems.

While traditional geodetic monitoring techniques, such as Global Positioning System (GPS) and Interferometric Synthetic Aperture Radar (InSAR), have been effective in capturing surface deformation, they are often limited by sampling frequency and environmental noise. Moreover, these kinematic-based methods primarily detect the ‘consequence’ of damage accumulation (i.e., displacement) rather than the damage itself. In the context of brittle rock failure, significant displacement often manifests only moments before catastrophic collapse, leaving a negligible window for evacuation. Consequently, there is an urgent need for a kinetic-based monitoring indicator that is sensitive to the internal stiffness degradation of the rock mass prior to macroscopic deformation.

Dynamic characteristic parameters, particularly natural frequency, serve as critical indicators of rock mass damage [13–15]. As damage evolves, dynamic features such as amplitude and frequency exhibit distinct variations [16–20]. Research indicates a quantitative relationship between natural frequency and the depth of trailing edge fissures, which can be utilized for the monitoring and early warning of slope instability [21]. However, current physical model experiments and numerical simulations primarily simulate cracks via artificial cutting (pre-defined slots). This approach differs significantly from actual crack propagation [9,22]. Moreover, artificial cutting typically requires pre-determining the crack location, which may deviate from actual geological conditions.

Numerical simulation has been widely applied as a vital research tool in stability studies [23,24]. To more accurately simulate crack development, the Extended Finite Element Method (XFEM) has been introduced into this field [25–27]. XFEM is an effective numerical approach capable of simulating crack propagation and rock failure processes. By introducing additional degrees of freedom into the finite element model to describe discontinuities, XFEM eliminates the need for mesh conformity to the crack geometry, thereby offers significant advantages in handling rock fracturing and failure problems [28]. Compared to the traditional FEM or pre-defined crack models, XFEM used in this study provides significant advantages: the crack description is independent of the background mesh, eliminating the need for complex remeshing during crack growth. This allows the model to more realistically capture the natural evolution of rock masses from vertical cracking to inward oblique propagation.

In light of these issues, this study primarily employs numerical simulation to investigate cantilevered unstable rock masses. Using the Extended Finite Element Method (XFEM) in Abaqus, we simulate the natural crack propagation laws and analyze the response char-

acteristics of dynamic features during the propagation process. Additionally, the variations in dynamic characteristics under different elastic moduli are examined. This research aims to provide a useful reference for the damage analysis of cantilevered rock masses, offering a scientific basis for stability assessment and disaster prevention, and further advancing research in related fields to safeguard human life and property.

2. Theoretical Model

(1) The Extended Finite Element Method (XFEM)

The Extended Finite Element Method (XFEM) is an emerging numerical technique developed from the foundation of the standard Finite Element Method (FEM) to address discontinuous problems. This method incorporates enrichment functions capable of capturing the discontinuous nature of crack faces and the singularity at crack tips into the standard displacement approximation. Consequently, XFEM does not require the crack geometry to conform to the element boundaries, effectively overcoming the limitations of conventional FEM in fracture analysis—specifically, the tedious mesh generation and the necessity for remeshing during crack propagation.

XFEM is founded on the Partition of Unity Method (PUM). It treats the nodal influence domain formed by adjacent elements as a set of covers. By defining displacement modes over each cover, the global displacement approximation is expressed as:

$$u_{\text{app}}(x) = \sum_i N_i(x) \sum_j \beta_{ij} p_j(x) \quad (1)$$

where i represents the node within the influence domain. $N_i(x)$ is the partition of unity function (shape function) defined over the nodal influence domain. $p_j(x)$ represents the local basis in the approximation space, which can be continuous or discontinuous. For instance, when a discontinuous interface intersects a node's influence domain, a Heaviside function is selected as an enrichment term to represent the displacement jump across the interface. When $p_j(x)$ consists solely of constant terms, β_{ij} corresponds to the nodal displacement. Consequently, Equation (1) degenerates in the standard displacement approximation formulation of the traditional Finite Element Method.

XFEM represents a specific instance of the PUM that utilizes the finite element mesh to generate the cover system, employing element shape functions to construct the partition of unity. Simultaneously, it extends traditional FEM by allowing the displacement mode defined on the cover to include non-constant terms. Compared to standard FEM, this PUM-based construction enhances the capability to describe complex displacement fields. In particular, it increases flexibility in tracking evolving non-continuous boundaries, thereby eliminating the need for mesh regeneration.

(2) Dynamic model of the cantilevered unstable rock mass

To analyze the dynamic response, the unstable rock mass is simplified as a cantilever beam model. The governing equation for its free vibration is expressed as:

$$[M]\{\ddot{u}\} + [K]\{u\} = \{0\} \quad (2)$$

where $[M]$ is the mass matrix. $[K]$ is the stiffness matrix. $\{\ddot{u}\}$ and $\{u\}$ are the nodal acceleration and displacement vectors, respectively.

By solving the eigenvalue problem of this equation, the natural frequencies and mode shapes of the rock mass can be obtained. When cracks emerge within the rock mass, the global stiffness $[K]$ decreases, leading to a shift in natural frequency. Therefore, natural frequency serves as a sensitive indicator for characterizing structural damage in unstable rock masses.

3. Evolution of Crack Propagation and Dynamic Characteristics in Cantilevered Unstable Rock Masses

3.1. Model Construction

This study focuses primarily on a representative cantilevered rock mass model. A conceptual model of a cantilevered unstable rock mass was established, as illustrated in Figure 1. The dimensions of the unstable rock block are 4 m × 4 m, while the base rock measures 20 m × 20 m, with a total model thickness of 5 m.

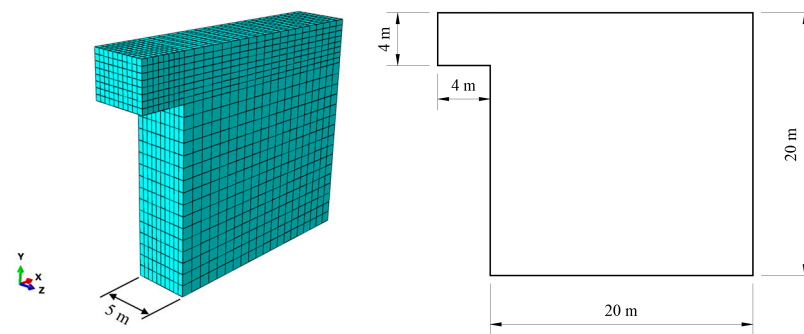


Figure 1. Hazardous rock mass model.

To establish a generalized model for cantilevered unstable rock masses, the rock material is assumed to be an isotropic and homogeneous elastic medium. The bottom and lateral surfaces of the base rock are subjected to fully fixed constraints to simulate the support provided by the parent mountain body, while the top surface is subjected to a constant distributed load and self-weight.

The material properties are defined as follows: density $\rho = 2.5 \text{ g/cm}^3$, elastic modulus $E = 5 \times 10^4 \text{ MPa}$, and Poisson's ratio $\mu = 0.25$. Boundary conditions were applied by fixing the left, bottom, and lateral surfaces of the base rock. To simulate the effects of self-weight and external loading, a vertical distributed load of 20 kN was applied to the top surface of the unstable block, eventually leading to structural failure via crack initiation.

The numerical model employs 8-node linear brick elements with reduced integration (C3D8R). The complete model consists of 6567 nodes and 5440 elements. Local mesh refinement was applied to the region where crack propagation was expected to ensure computational accuracy.

The XFEM module in Abaqus was employed to simulate crack propagation, allowing for natural initiation and extension without pre-defined initial cracks. The maximum principal stress criterion was adopted for crack initiation, with the crack plane oriented perpendicular to the maximum principal stress. The post-initiation behavior was governed by a linear damage evolution law based on the critical fracture energy release rate. For natural frequency extraction, an undamped system was assumed to simplify the eigenvalue problem, as damping has a minimal impact on frequency values in brittle rock. Results were extracted at intervals of 0.02 step time to capture the evolution of stress and displacement fields. A restart mechanism was implemented to evaluate dynamic parameters during the instability process. Specifically, the Dynamics Implicit solver was utilized to output vibration signals at 0.005 step time intervals for a total duration of 5 step times per restart. Dynamic characteristic parameters were subsequently calculated from these vibration curves at every 0.02 step time increment, providing a continuous law of dynamic parameter evolution throughout the failure process. The overall numerical simulation procedure is illustrated in Figure 2.

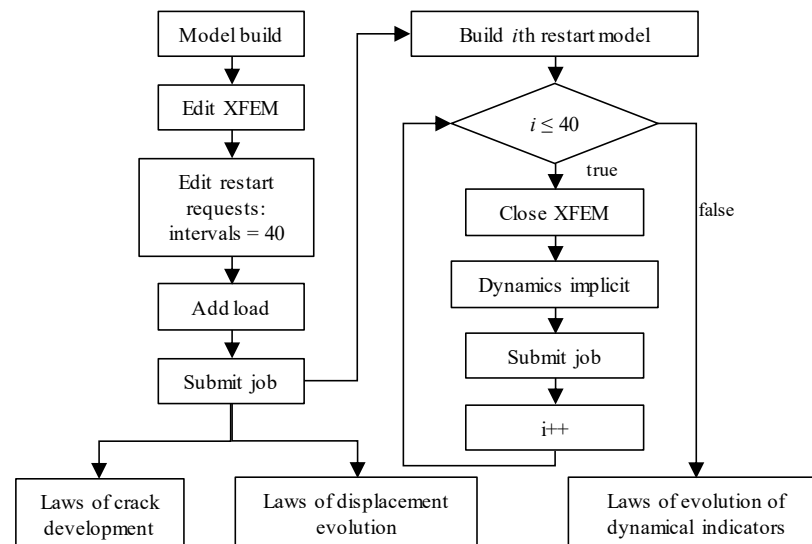


Figure 2. Flowchart of the numerical simulation.

3.2. Analysis of Results

The simulation results from Abaqus were extracted as contour plots at regular intervals of 0.05 step time to observe the progressive development of the cracks. The spatial and temporal evolution of the crack propagation is illustrated in Figure 3.

(1) Analysis of the crack propagation process

Figure 3 illustrates the crack propagation process as captured from the lateral view (side surface) of the numerical model. Due to the symmetrical boundary conditions and uniform loading, the cracking behavior observed on this side profile is considered representative and symmetrical for both sides of the rock mass. The simulation indicates that cracks initially initiate at the stress concentration zone located at the interface between the unstable block and the base rock (Figure 3a). During the early stage, the crack extends approximately vertically downward (Figure 3b,c). Upon reaching the mid-section of the rock mass, the propagation path deflects toward the free face of the cavity (Figure 3d–f), eventually leading to complete detachment from the parent rock (Figure 3g). The overall crack trajectory exhibits a “vertical-then-oblique” morphology, reflecting a combined tension-shear failure mechanism.

Simulation results indicate that crack initiation occurs at the interface between the rock block and the bedrock. The fracture initially propagates vertically downward; however, upon reaching the mid-section, the trajectory deflects, extending obliquely toward the rock cavity. This progression continues until the unstable rock mass completely detaches from the bedrock, exhibiting a characteristic “vertical-then-oblique” morphology.

The deflection of the crack trajectory is fundamentally governed by the evolution of the crack-tip stress field. Initially, under the dominant influence of the bending moment caused by the overhang weight, the maximum principal tensile stress is horizontal, driving the crack vertically downward. However, as the crack deepens (mid-section), the neutral axis of the remaining rock bridge shifts. The shear stress component induced by self-weight becomes increasingly significant relative to the bending stress. This causes a rotation of the principal stress vectors, leading the crack to deviate towards the free face (the cavity) to maximize the energy release rate.

The curve illustrating crack depth versus step time is presented in Figure 4. The propagation process manifests a distinct three-stage evolutionary pattern: “slow initiation—accelerated expansion—approaching penetration”.

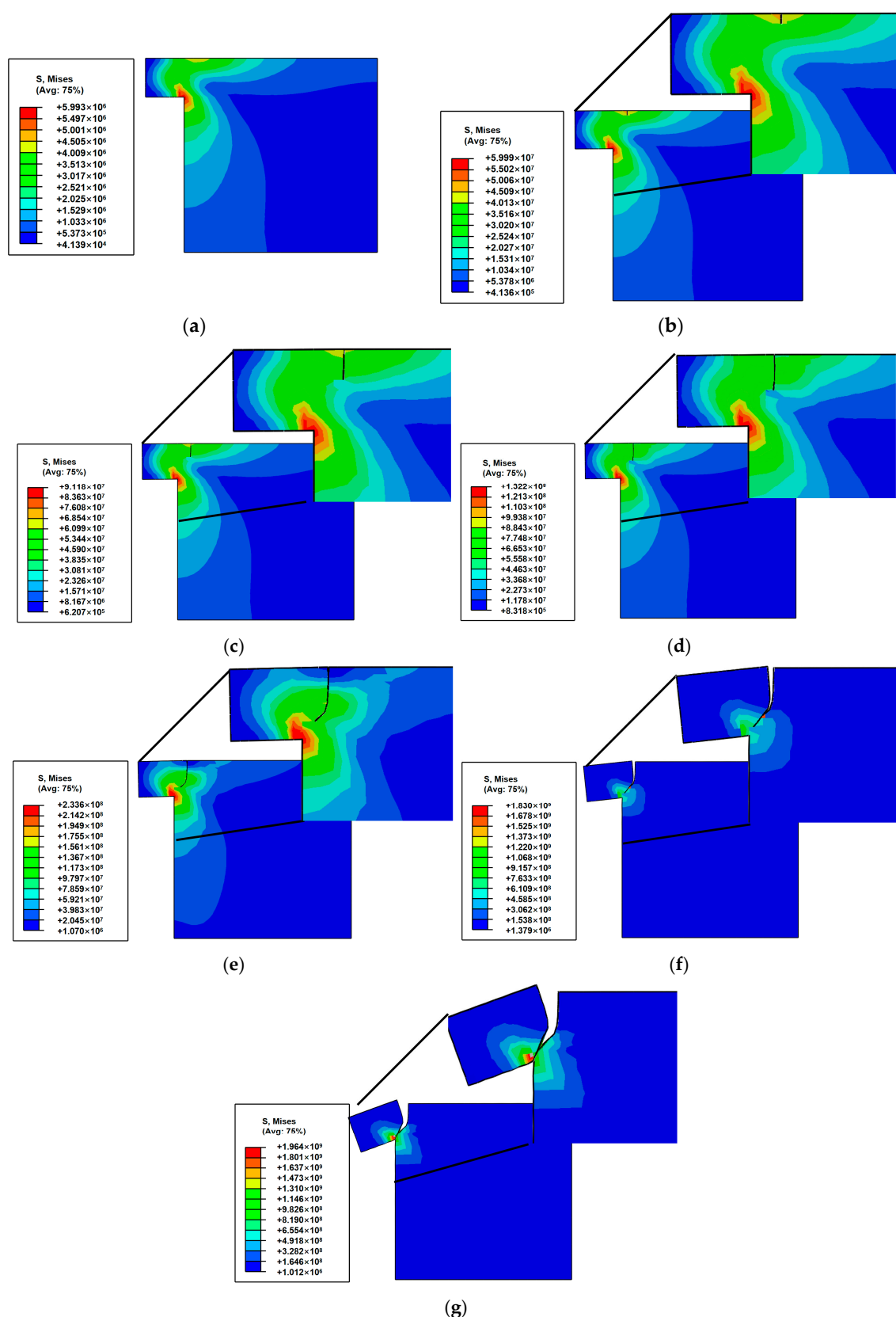


Figure 3. Evolution of crack propagation: (a) Crack initiation stage; (b) Early vertical propagation I; (c) Early vertical propagation II; (d) Deflection initiation stage; (e) Oblique propagation I; (f) Oblique propagation II; (g) Complete detachment stage.

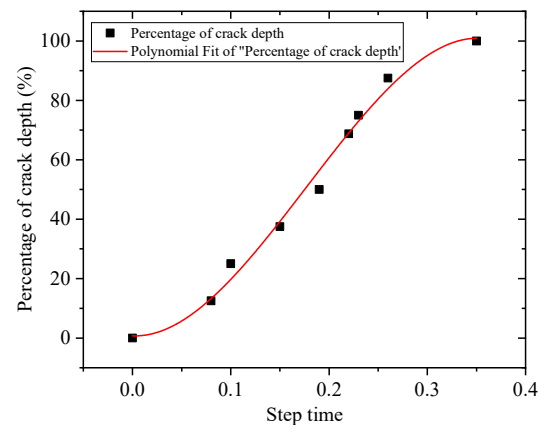


Figure 4. Crack depth curve.

(2) Analysis of displacement

The displacement-time curves for the critical monitoring points of the unstable rock mass are presented in Figure 5.

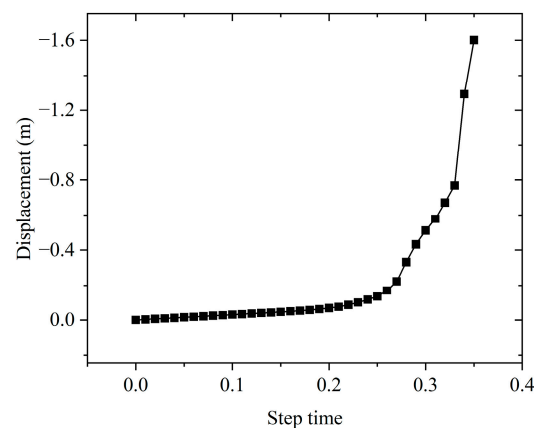


Figure 5. Displacement curve.

Linear Growth Phase: During the initial stage of crack propagation, the displacement increases at a constant and uniform rate. In this phase, the magnitude of displacement increment is relatively inconspicuous, making it challenging to identify early signs of instability through surface deformation alone.

Accelerated Deformation Phase: As the crack transitions into the oblique propagation stage, the displacement rate increases significantly.

Critical Instability Phase: Approaching the point of crack penetration, the rate of displacement change reaches its maximum, exhibiting pronounced accelerated deformation characteristics. This serves as a typical precursor to structural failure.

Notably, upon entering the accelerated phase, the rock mass undergoes large-scale deformation and catastrophic failure within an extremely short timeframe. This “sudden-onset” nature suggests that traditional displacement monitoring may offer insufficient lead time for effective early warning in certain scenarios.

(3) Evolutionary Laws of Natural Frequency

The vibration characteristics of the unstable rock mass were analyzed using the Dynamics Implicit solver. For each monitoring interval, a 5 s vibration time-history curve was recorded, as illustrated in Figure 6. To ensure the fidelity of the frequency extraction, the Welch method was utilized for Power Spectral Density (PSD) estimation. A Hanning window was applied to suppress spectral leakage, with a 50% overlap between segments

to minimize the variance of the estimate. The sampling frequency was set sufficiently high (above the Nyquist rate) to capture the fundamental frequency and the first few harmonics accurately.

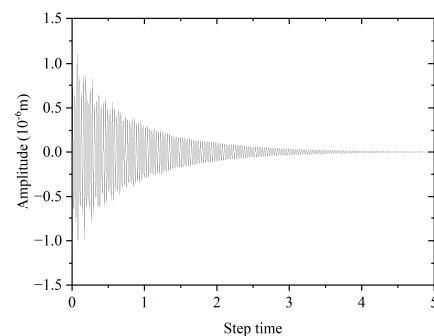


Figure 6. Vibration time history curve.

The evolution of the first-order natural frequency and crack depth over simulation step time is presented in Figure 7. The results indicate a distinct downward trend in natural frequency as the crack propagates. Specifically:

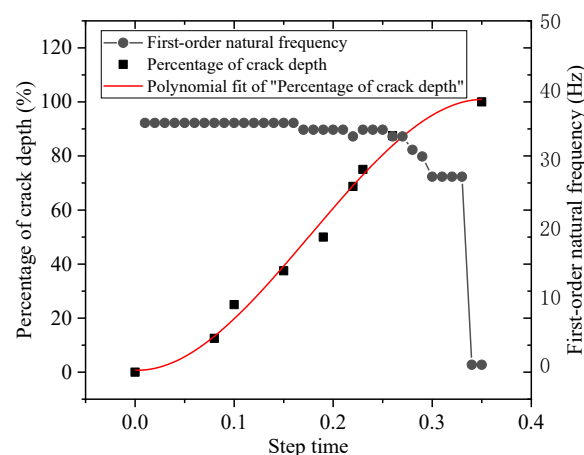


Figure 7. First-order natural frequency and crack depth.

Initial Decline: When the crack depth reaches 50%, the first-order natural frequency exhibits an initial decrease of approximately 1 Hz.

Rapid Decline: During the advanced stage of crack development (80% to 97% depth), the natural frequency undergoes a sharp and significant decline of approximately 7 Hz.

As illustrated in Figure 8, the temporal evolution of natural frequency and displacement exhibits a distinct divergence in their sensitivity to structural degradation. While the displacement response maintains a uniform linear progression—reflecting steady-state strain accumulation—the natural frequency lacks a constant-rate phase, instead displaying discrete fluctuations that correlate with the successive stages of crack initiation and propagation. Notably, a significant temporal lead is observed in the frequency response, where the initial shift precedes the departure of the displacement curve from its linear trend. This phenomenon underscores the capacity of modal parameters to detect internal stiffness degradation well before it manifests as macroscopic geometric deformation, thereby establishing natural frequency as a superior indicator for the early-stage identification of structural damage.

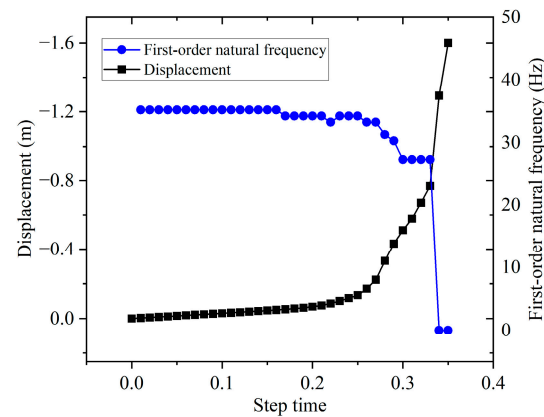


Figure 8. First-order natural frequency and displacement.

The precipitous drop of 7 Hz in the late stage (80–97% depth) represents a critical phase transition. Mathematically, the natural frequency $\omega = \sqrt{K/M}$. While the mass M remains constant, the global stiffness K is provided by the effective rock bridge area. As the crack penetrates the deep section, the moment of inertia of the connecting section reduces explicitly (following a cubic relationship with the ligament depth), leading to a drastic, non-linear reduction in stiffness. This creates a ‘sensitivity amplification’ zone where a small crack extension results in a massive frequency shift.

(4) Influence of Elastic Modulus

Figure 9 illustrates the evolution of the first-order natural frequency as a function of crack development under varying elastic modulus.

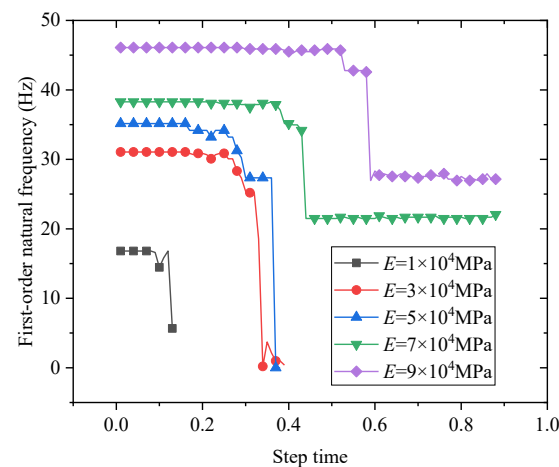


Figure 9. First-order natural frequency versus elastic modulus.

It is observed that, for a fixed geometry, an increase in the rock mass’s elastic modulus corresponds to a higher initial natural frequency. However, despite differences in absolute values, the normalized frequency degradation trends across different elastic moduli remain consistent throughout the crack propagation process. This consistency indicates that the dynamic response laws revealed in this study possess general applicability and are not limited to specific material stiffness parameters.

4. Discussion

(1) Validity of numerical simulation and crack evolution mechanism

In this study, the Extended Finite Element Method (XFEM) was employed to faithfully recapitulate the entire failure process of cantilevered unstable rock masses, ranging from

damage initiation and crack propagation to final penetration. Unlike traditional finite element approaches that rely on pre-set crack geometries, XFEM overcomes mesh topology limitations through nodal enrichment techniques. Consequently, it successfully captured the natural “vertical-to-oblique” fracture morphology driven by gravity and boundary constraints. These simulation results not only align with the tensile-shear composite failure criteria of rock fracture mechanics but also demonstrate the distinct methodological superiority of XFEM in addressing discontinuous evolutionary problems in geological bodies.

(2) Insights into dynamic response and early warning systems

The core finding of this research reveals that the natural frequency exhibits a characteristic “step-wise abrupt reduction” as the crack propagates. This evolutionary law is highly consistent with the conclusions derived from physical model tests and theoretical derivations by Zhang et al. [12], thereby corroborating the physical reliability of using dynamic parameters as stability evaluation indices.

At a deeper level, the decline in natural frequency intrinsically reflects the global stiffness degradation of the rock mass during crack propagation. Specifically, the precipitous drop in frequency observed during the late stage of fracture development (80–97% depth) serves as a critical indicator that structural damage is approaching a threshold of instability. In contrast to traditional displacement monitoring—where significant acceleration often manifests only at the moment of failure, leading to a lag in detection—natural frequency acts as a highly sensitive index of structural integrity. It is capable of detecting the accumulation of internal damage prior to the onset of macroscopic accelerated deformation. Therefore, an early warning methodology based on frequency monitoring offers a superior temporal window compared to traditional displacement monitoring, holding significant theoretical value and application prospects for the “early identification” of geological hazards.

(3) Practical engineering implications

Based on the established ‘crack-frequency’ relationship, a hierarchical early warning strategy is proposed for engineering practice. Normal Monitoring Phase: When frequency fluctuations are within the noise floor, routine monitoring is maintained. Alert Phase: A frequency drop of 1–2 Hz (corresponding to 50% crack depth) should trigger an increase in sampling rate and the activation of auxiliary monitoring methods. Critical Warning Phase: A precipitous frequency drop (>5 Hz) signifies that the crack has entered the accelerated propagation stage (80–97% depth). Immediate evacuation measures should be enacted. This frequency-based protocol provides a quantifiable workflow that complements existing qualitative assessments.

(4) Limitations and future perspectives

It should be noted that to establish a generalized theoretical model, this study adopted certain simplifications regarding the geological environment, assuming the material to be isotropic and homogeneous under a single constant load. However, the actual occurrence environment of cantilevered unstable rock masses is more complex, often involving geometric dimensions, joint fissure networks, heterogeneous lithology, and the coupling effects of transient loads such as seismic dynamics and rainfall infiltration. Consequently, when extrapolating the “crack-frequency” evolutionary laws revealed in this study to complex engineering sites, the correction effects of these environmental factors must be meticulously considered. Additionally, although this study identifies a clear correlation between crack propagation and frequency decline, the limited number of cases makes it premature to define universal early-warning thresholds. Future research efforts will focus on conducting large-scale parametric studies to quantify the relationship between natural frequency response and warning levels, developing multi-field coupled numerical models (incorporating hydraulic, mechanical, and seismic factors) and integrating long-term in

situ monitoring data from typical unstable rock masses to further calibrate and refine the proposed dynamic evaluation system.

5. Conclusions

This study employed the Extended Finite Element Method (XFEM) to numerically simulate the crack propagation and the evolution of dynamic characteristics in cantilevered unstable rock masses. The primary conclusions are summarized as follows:

(1) The XFEM approach successfully simulated the natural initiation and propagation of cracks in cantilevered unstable rock masses. The simulation revealed a distinct “vertical-then-oblique” fracture trajectory under vertical loading, effectively overcoming the limitations associated with traditional methods that rely on pre-defined crack geometries.

(2) Based on the natural propagation process, a staged decline pattern of the natural frequency with respect to crack development was identified. Notably, the frequency exhibited a precipitous drop of approximately 7 Hz when the crack depth reached the 80–97% range, indicating that the natural frequency is exceptionally sensitive to the late stages of crack propagation.

(3) The “natural crack propagation–dynamic frequency response” model established in this study provides a more realistic theoretical and numerical foundation for the stability evaluation and early warning of unstable rock masses based on dynamic characteristics.

In summary, this research confirms the validity of using dynamic characteristic parameters—particularly natural frequency—to assess the stability of cantilevered unstable rock masses, offering a novel approach for geological hazard monitoring and early warning. Future research should further investigate the impact of complex environmental conditions, such as cyclic loading and hydro-mechanical coupling, on the dynamic characteristics of unstable rock masses.

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