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The study of monitoring and stability evaluation of rocky shore slope in reservoir area based on microseismicity: a case study of the Giant Landslide at Jiuxianping, Yunyang

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Abstract. Extensive distribution of rocky slopes in the Three Gorges Reservoir area poses risks of sudden landslides, yet traditional displacement and rainfall monitoring lack effective early-warning capacity. Addressing technical challenges including weak microseismic signals, noise interference, and low localization accuracy in rocky landslides, this study innovatively developed a multi-method joint denoising model and an artificial bee colony inversion localization model. Using Yunyang Jiuxianping mega-landslide as a case study, we decoded internal damage evolution through microseismic monitoring, revealed spatiotemporal correlations between microseismic events and slope stability, and explored a novel instability warning approach. Key findings include: 1) A denoising method integrating Complete Ensemble Empirical Mode Decomposition with Adaptive Noise (CEEMDAN) and Singular Spectrum Analysis (SSA) enhanced signal-to-noise ratio by 10.19 dB and reduced root mean square error by 74.24% compared to EMD and wavelet threshold methods. Simulation and field tests confirmed effective background noise suppression while preserving weak signal features. 2) The artificial bee colony inversion algorithm with layered velocity model and cosine similarity function achieved superior localization accuracy. Source distribution patterns from Jiuxianping landslide aligned with deformation features including left-boundary displacement, road cracks, and structural distortions in cemetery walls and crematorium facilities, validating method reliability. 3) Comprehensive analysis integrating microseismic data with rainfall and displacement revealed rainfall-triggered microseismic events with limited energy correlation. Spatial consistency between localized microseismic clusters and high-displacement zones supported the development of an unloading-response ratio warning method using amplitude-frequency variations, providing innovative insights for slope risk prediction.

Key words: *rock slope, stability, denoising, seismic source localization, microseismic monitoring*

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Мониторинг и оценка устойчивости скалистого берегового склона в районе водохранилища микросейсмическими методами (на примере гигантского оползня Цзюсяньпин в уезде Юньян)

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Аннотация. Обширное распространение скалистых склонов в районе водохранилища Три ущелья создает риски внезапных оползней, однако традиционный мониторинг смещения и осадков не имеет эффективных возможностей раннего оповещения. Решая технические проблемы, включая слабые микросейсмические сигналы, шумовые помехи и низкую точность локализации в скалистых оползнях, это исследование инновационно разработало многометодную модель совместного шумоподавления и модель локализации инверсии искусственной колонии пчел. Используя гигантский оползень Цзюсяньпин в уезде Юньян в качестве примера, мы расшифровали внутреннюю эволюцию повреждений с помощью микросейсмического мониторинга, выявили пространственно-временные корреляции между микросейсмическими событиями и устойчивостью склона и изучили новый подход к предупреждению нестабильности. Основные результаты включают: 1) Метод шумоподавления, интегрирующий полное ансамблевое эмпирическое модальное разложение с адаптивным шумом (CEEMDAN) и сингулярный спектральный анализ (SSA), улучшил отношение сигнал/шум на 10,19 дБ и снизил среднеквадратичную ошибку на 74,24% по сравнению с методами EMD и порогового вейвлета. Моделирование и полевые испытания подтвердили эффективное подавление фонового шума при сохранении слабых характеристик сигнала. 2) Алгоритм инверсии искусственной колонии пчел с многослойной моделью скорости и функцией косинусного подобия достиг превосходной точности локализации. Модели распределения источников от оползня Цзюсяньпин совпали с особенностями деформации, включая смещение левой границы, трещины на дороге и структурные искажения в стенах кладбища и крематориях, что подтвердило надежность метода. 3) Комплексный анализ, интегрирующий микросейсмические данные с осадками и смещениями, выявил микросейсмические события, вызванные осадками, с ограниченной энергетической корреляцией. Пространственная согласованность между локализованными микросейсмическими кластерами и зонами с высоким смещением способствовала разработке метода предупреждения о соотношении разгрузки и реакции с использованием амплитудно-частотных колебаний, что дало инновационные идеи для прогнозирования риска склонов.

Ключевые слова: *скальный склон, устойчивость, шумоподавление, локализация сейсмического источника, микросейсмический мониторинг*

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Introduction

The Three Gorges Reservoir area is a key region for geological hazard prevention in China, characterized by complex geological conditions. Since the dam's completion, reservoir bank stability has been significantly affected, with widespread steep rocky slopes posing challenges for stability assessment [*Zhao et al., 2023*]. The 660 km reservoir undergoes periodic water level fluctuations, accelerating rock and soil deterioration in the fluctuation zone and increasing slope instability risks [*Tang et al., 2019*]. A notable example is the 2003 Qianjiangping landslide, which blocked the river channel and caused major economic losses [*Xiao et al., 2010*]. Annual losses in the reservoir area reach billions of yuan [*Chen et al., 2005*]. Following the 175 m impoundment, steep rocky slopes—due to their high elevation and substantial potential energy — exhibit significantly larger disaster impact ranges and surge effects compared to gentle areas [*Li et al., 2020; Zhang, 2020*]. Conventional monitoring methods (surface displacement [*Liao et al., 2021*], pore water pressure [*Zhao et al., 2024*], rainfall [*Wang et al., 2024*]) have limitations for rocky slopes.

Taking the Jiuxianping landslide in Yunyang as an example, this typical landslide exhibits continuous deformation influenced by rainfall [*Ai et al., 2017*] and water level fluctuations [*Liu et al., 2025; Zhang et al., 2020*], showing stepped displacement characteristics [*Liu et al., 2025; Dai et al., 2022*]. The essence of rocky slope failure lies in internal fracture propagation [*Yang et al., 2019*]. Microseismic monitoring captures rock fracture signals, enabling the inversion of spatiotemporal parameters and geometric dimensions of fractures. This represents a breakthrough from traditional "point-line monitoring" to 3D spatiotemporal monitoring. While InSAR [*Zhang et al., 2020*] and UAV technologies have advanced deformation monitoring, they struggle to reveal internal rock fracture mechanisms. This study focuses on microseismic technology, researching seismic source parameter inversion methods, constructing a multi-factor comprehensive evaluation system, and establishing a microseismic-based slope early warning model. This provides new theoretical support for risk management of high-steep reservoir banks.

Methods

The Jiuxianping landslide spans a vast area, making it essential to choose the right sensor parameters and installation configurations. Rainfall in Jiuxianping landslide is predominantly from May to October, constituting 79% of the yearly precipitation, with the primary period of water-level variations occurring between May and November. Consequently, the main monitoring window will extend from May to December 2024, segmented into three phases for data collection and equipment replacement. The initial phase will take place from May to July 2024, the second phase from July to September 2024, and the final phase from September to December 2024.

Fig. 1. Equipment monitoring array

To address the limitations of traditional methods in early detection of internal rock damage for slope stability monitoring, this study constructs an early warning system based on microseismic monitoring technology, using the Jiuxianping landslide as a case study. The system employs a sensor network to capture subtle subsurface vibrations in real-time. It efficiently identifies microseismic events through the STA/LTA (Short-Term Average/Long-Term Average) algorithm, enhances the signal-to-noise ratio of weak signals using the CEEMDAN-SSA joint denoising model, accurately picks P-wave arrivals based on the Akaike Information Criterion (AIC), and optimizes the seismic source localization inversion process via the Artificial Bee Colony algorithm. This approach overcomes the hysteresis of traditional displacement monitoring, enabling early warnings for hidden fractures and landslide precursors. It achieves holistic technical integration spanning event screening, signal processing, and localization analysis.

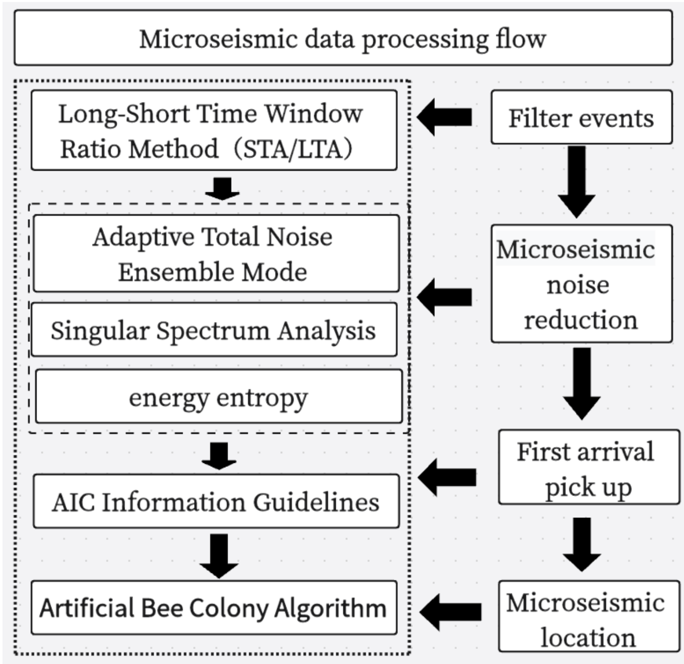

Fig. 2. Data processing flow and method

Results

1) The denoising results using the combined CEEMDAN-SSA method are shown in Figs. 3–5. After processing, random noise across different frequencies in the original signal demonstrates closer approximation to the original simulated signal in both low- and high-frequency bands. Compared with denoising effects achieved by EMD and EMD-wavelet threshold methods, the proposed approach increases the signal-to-noise ratio by 10.19 dB, reduces the root mean square error by 1.47, exhibits smaller deviation from the original signal, and achieves an energy ratio of 98%, confirming superior processing performance.

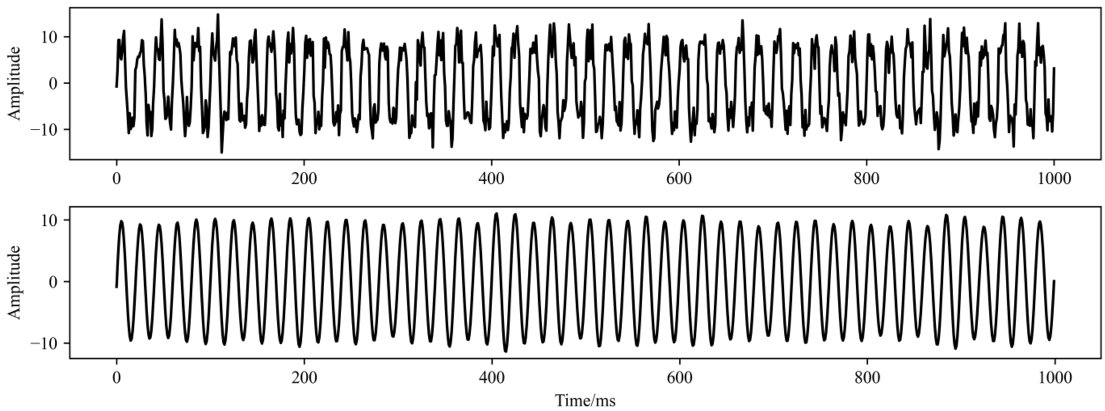

Fig. 3. CEEMDAN-SSA denoised signal

Table 1. Analysis of simulation signal noise reduction effect

Signal	SNR/dB	RMSE	E/%
Analog Signal	11.34	1.98	89
EMD	12.53	1.33	94
EMD-Wavelet Threshold	15.06	0.99	95
This article	21.53	0.51	98

2) The Artificial Bee Colony algorithm demonstrates significant advantages in seismic source localization inversion. Analysis of data from May 23 to December 10, 2024, locates typical microseismic events. The figure displays the distribution of microseismic sources within the Jiuxianping landslide area during this period. Source locations (marked by red dots) concentrate primarily in topographically elevated regions, showing particularly dense clustering in the central and upper-right sections. This distribution strongly correlates with elevation variations, indicating concentrated microseismic activity in steeper or less stable zones.

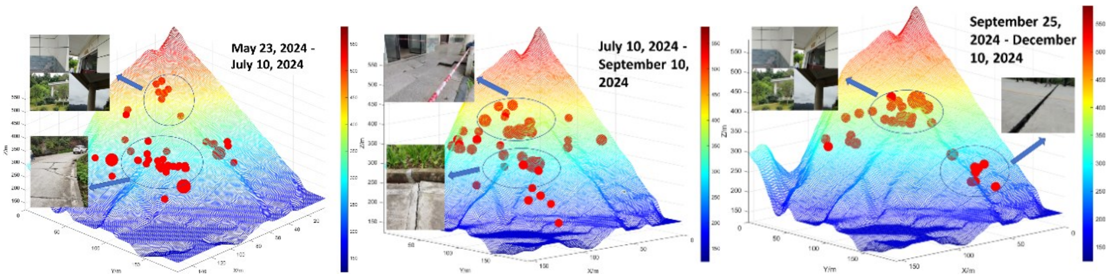

Fig. 4. Earthquake source location (May–December)

Microseismic monitoring at Jiuxianping landslide (May–December 2024) further reveals significant reservoir water-level influence on event distribution: during the water-level decline phase (May–July), 76 events clustered in the middle-rear section showing spatial coupling with road cracks; during rapid drawdown (July–September), 38 high-energy events triggered ground collapse in the central Lingyuan area, highlighting water saturation-unloading coupling effects; while the gradual water-level rise period (September–December) witnessed 42 events migrating toward the rear section, reflecting pore-water-pressure-dominated mechanisms. Crucially, the spatiotemporal evolution of seismic sources demonstrates strong consistency with landslide deformation fields, confirming microseismic technology's effectiveness in identifying failure mechanisms of reservoir bank landslides.

Discussion

Microseismic data faces multiple challenges in slope stability analysis: Firstly, characteristics like amplitude and frequency are significantly influenced by geological conditions, landslide types, and external interference, requiring complex interpretation with specialized expertise. Secondly, while microseismic monitoring can indirectly reflect rock mass damage, it cannot directly provide key mechanical parameters (e.g., shear strength, friction angle) for stability assessment, and localized damage poorly represents overall stability. Thirdly, landslide evolution is driven by external factors like water level changes and rainfall; microseismic data captures instantaneous micro-changes but struggles to quantify temporal dynamic effects and complex mechanical coupling processes. Therefore, sole reliance on microseismic signals is insufficient for accurate stability evaluation, necessitating comprehensive analysis with multi-source data including geological surveys and mechanical parameter testing.

Conclusion

Addressing the need for rock landslide prevention, this study utilized microseismic monitoring to investigate weak signal denoising, source location, and stability analysis. Key conclusions are:

1) Proposed a CEEMDAN-SSA denoising method based on energy entropy: CEEMDAN decomposes signals to remove low-frequency noise by optimizing IMF components, followed by SSA-based secondary filtering. Simulations show a 10.19 dB SNR improvement and 74.24% RMSE reduction. This method outperforms traditional EMD and wavelet thresholding

in high-frequency noise suppression while preserving signal features, enabling precise location of weak rupture events.

2) Developed an artificial bee colony (ABC) microseismic location model: Using a layered velocity model, elevation matrix, and cosine similarity objective function for source inversion. Simulation tests achieved < 1 m location error within 100 iterations, surpassing conventional linear inversion. Field validation at Jiuxianping landslide showed high consistency between located sources and actual deformation (left boundary displacement, road cracks, and cemetery subsidence).

3) Revealed the mechanism linking microseismicity to slope stability: Microseismic events are triggered by rainfall but show no significant energy correlation. High-energy events originate from deep rock fracturing. Displacement mutation zones spatially coincided with source locations, with abrupt displacement phases accompanied by large-scale microseismicity. An innovative LURR early-warning method using amplitude-frequency parameters was developed: Ratios > 1.0 indicate accelerating damage, while significantly higher values signal instability risk. This method identifies hazards earlier than traditional displacement tangent angle approaches.

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