Slope Stability Analysis of a Coal Gangue Dump in Guizhou Province

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Abstract: Coal mining in China generates a large amount of coal gangue, making its disposal and stability assessment critically important. This study focuses on the Muzhushan coal gangue dump in Panjiazhuang Town, Xingren City, and establishes an "air–space–ground" integrated monitoring network to obtain key parameters. For the coal gangue slope, a stability evaluation model was developed by combining laboratory testing with numerical simulation, and multi-physical field coupling calculations and multi-condition comparative verifications were carried out on the FLAC^{3D} platform. The results indicate that the structure remains stable under self-weight conditions; however, heavy rainfall reduces the local safety margin by 47.6%, while seismic loading does not induce instability. The findings verify the applicability of the proposed methodology, provide a quantitative basis for graded management of coal gangue dump stability, and hold significant implications for the development of coal gangue waste disposal and ecological restoration.
***Keywords*:** coal gangue; solid waste disposal; stability evaluation; numerical simulation

1. Introduction

Coal gangue, as the main solid waste generated during coal mining and washing, has long been a central issue in the energy sector concerning its efficient and clean utilization. Statistics indicate that there are more than 6,000 existing coal gangue dumps in China, with a total stock exceeding 6 billion tons and an annual increase of about 500 million tons [1–2]. Coal gangue dumps exhibit engineering characteristics such as complex composition, loose structure, high porosity, and low shear strength. Under external loads such as rainfall, earthquakes, and freeze–thaw cycles, they are prone to geological hazards such as landslides and collapses, posing serious threats to the ecological environment of mining areas, infrastructure, and the safety of surrounding residents [3–4]. Therefore, stability analysis of coal gangue dumps and studies on treatment effectiveness constitute a critical scientific issue for ensuring the sustainable development of mining areas.

Traditional studies on coal gangue slope stability mainly rely on geological surveys, laboratory tests, and numerical simulations based on limit equilibrium theory. While these approaches can reveal the internal mechanical mechanisms of dumps, they present significant limitations in field-scale identification: (1) the coverage of manual surveys is limited, making it difficult to capture micro-geomorphological evolution over large slope areas; (2) single-point monitoring data lack spatial correlation, making it challenging to characterize the spatiotemporal distribution of deformation fields.In this study, long-term dynamic monitoring of coal gangue slopes is conducted using InSAR and high-precision remote sensing technologies. Based on high-resolution satellite imagery, UAV-based oblique photogrammetry, 3D laser scanning, and detailed geological surveys, a three-dimensional geological model of coal gangue slopes is constructed. Direct shear and consolidation tests are employed to analyze the physical and mechanical properties of coal gangue. Furthermore, soil mechanics, fluid mechanics, and three-dimensional numerical simulation methods are applied to establish a stability evaluation model for coal gangue dumps. By integrating the comprehensive index method with quantitative calculations, stability discrimination criteria and evaluation methods are developed under different geological conditions.

2. Project Overview

Based on the geological environment of coal gangue occurrence and its accumulation characteristics, a representative site was selected from among 1,119 untreated abandoned mines in the Nanpanjiang and Beipanjiang river basins of Guizhou Province, which are part of the Ecological Restoration Demonstration Project for Abandoned Mines (Figure 1). The coal mine is located approximately 26 km northeast of the main urban area of Xingren City and about 4.1 km northeast of the Panjiazhuang Town government. The coal gangue dump is situated on the southern slope of Muzhushan, lying to the south of the Xingren northwest ring road, east of Sigongzhai, and west of Qingjiao Group. The Qingxing Expressway and a county road pass along the western side of the mining area, providing highly convenient transportation access to the study site.

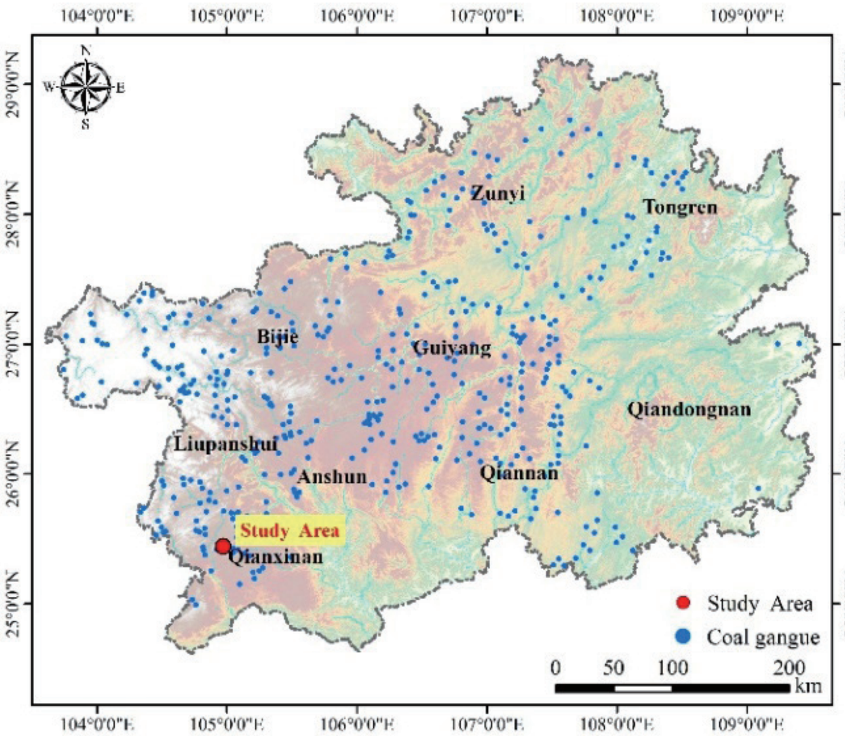

Figure 1. Distribution map of mines in the study area

The overburden in the study area consists of residual slope deposits (Q^{el+dl}), mainly silty clay and clay, with a thickness ranging from 0.5～2m. The bedrock belongs to the Upper Permian Longtan Formation (P_2l), composed of siltstone and argillaceous siltstone with locally interbedded coal seams. On the southwestern side of the site, a gangue-retaining dam has been constructed, with a height of 12 m, built using rubble concrete casting.

The current stacking of the coal gangue dump shows a north–south and east–west height difference, being higher in the north and east and lower in the south and west. The highest elevation, 1638.26 m, is located in the eastern part of the dump, while the lowest elevation, 1482.59 m, lies in a gully at the southwestern part, resulting in a total relief of 155.67 m. The waste is stacked in steps, with an average bench height of about 10 m and a local maximum of 15 m. The inter-bench slope angle is generally 30°, locally up to 36°, and the platform width typically ranges from 4～10m. Slopes of varying heights have formed in the southwestern, southern, southeastern, eastern, and central parts of the dump (Figure 2).

Figure 2. Current status of the gangue dump

3. Integrated "Air–Space–Ground" Coal Gangue Investigation System

Sentinel-1 data were used to analyze the historical deformation of the coal gangue dump. The swath width of Sentinel-1 in interferometric mode is 250 km × 250 km, with a spatial resolution of 30 m. Imaging was conducted using the TOPS mode to obtain high-quality and large-scale interferometric phase values. Sentinel-1 is a dual-satellite constellation; a single

Sentinel-1 satellite covers the globe every 12 days, while the two-satellite constellation shortens the revisit cycle to 6 days. In this study, a total of 31 Sentinel-1 scenes covering the study area were used, spanning the period from January 10, 2023, to April 6, 2024. As shown in Figure 3, the InSAR deformation location map identifies five distinct deformation zones based on the deformation value distribution.

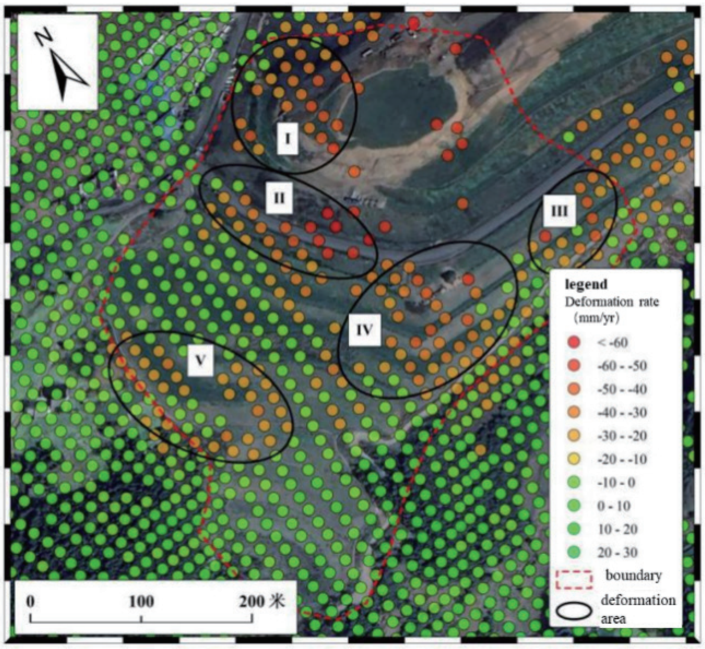

Figure 3. Schematic diagram of deformation area locations

Using UAV-based oblique photogrammetry, a high-precision digital elevation model (DEM) was established. The aerial survey covered an area of 633,404.9 m², with a forward overlap of 85% and a side overlap of no less than 75%. Considering factors such as the project area, elevation differences and slope gradients, and external signal interference, six flight lines and three capture angles (-90°, -45°, and 0°) were planned for the UAV survey to comprehensively obtain structural surface images of the hazardous rock zones. A total of 1,383 high-resolution digital photographs were acquired, with a ground sampling distance of 0.1 m. The ContextCapture software was further used for 3D reality modeling, reconstructing the true scenes of the site.

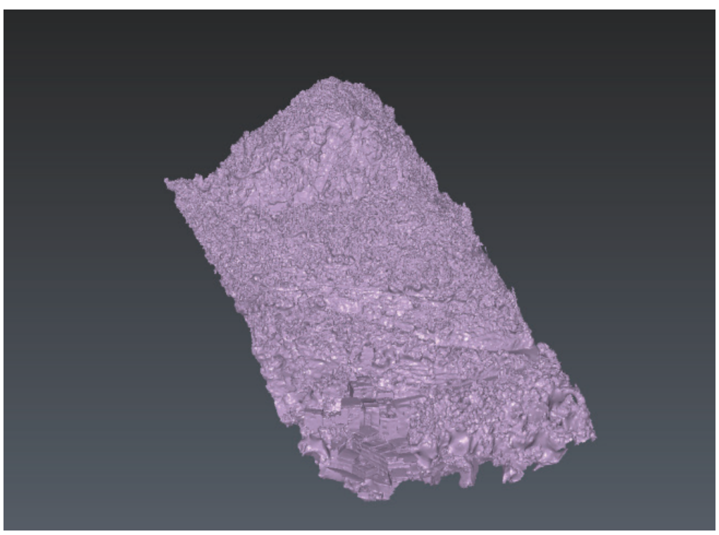

Figure 4. Point cloud of the 3D model

Through geophysical and physical surveys combined with field sampling, key parameters of the dump were obtained, including particle size distribution (0.1–50 mm), shear strength (C = 15–35 kPa, φ = 25–32°), and permeability coefficient ($1 \times 10^{-5} \sim 5 \times 10^{-4}$ cm/s) (Figure 4).

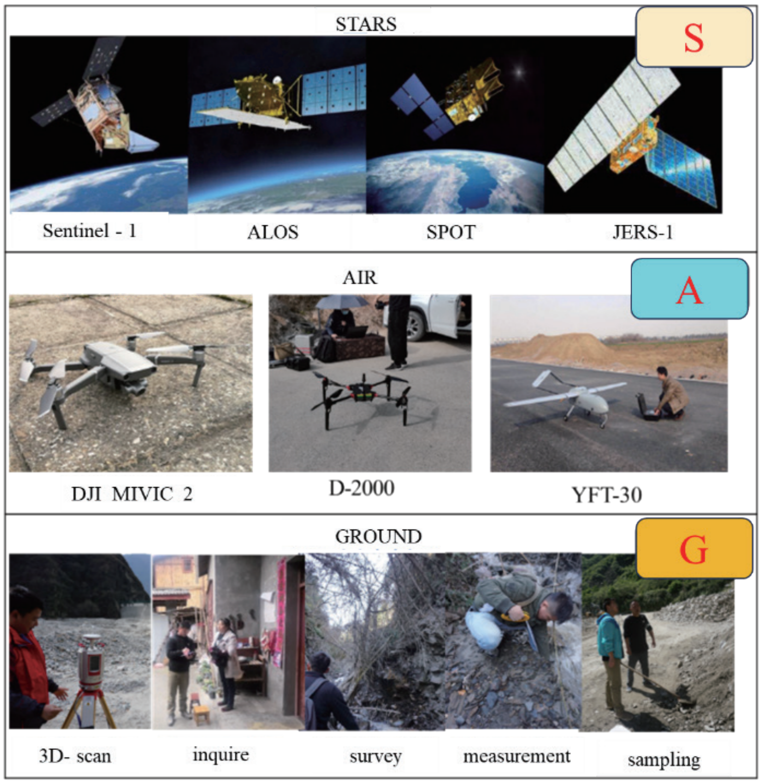

Figure 5. Multi-source data coupling survey scheme for coal gangue

A multi-source data coupled investigation scheme for the coal gangue dump slope was implemented to establish an integrated "Air–Space–Ground" monitoring network (Figure 5).

4. Construction of the Coal Gangue Stability Evaluation Model

The stability evaluation of coal gangue stored in open-air dumps requires the establishment of differentiated model systems based on storage configurations. From a mechanical mechanism perspective, three typical scenarios can be identified: for dump slopes, methods similar to those used in open-pit mine slope stability evaluation are applied, focusing on the structural characteristics of the slope; for tailings deposits, post-failure material transport models need to be constructed to study the critical initiation conditions of particles under gravity; for flat-layered dumps, bearing stability is assessed through settlement prediction. Based on the geological conditions and dump characteristics of the study area, this research mainly focuses on the first scenario.

The mechanical properties of coal gangue dump slopes exhibit significant spatial variability. Studies show that the dry density parameter displays a gradient distribution along the depth direction, which has a decisive influence on the spatial heterogeneity of strength indices [5–6]. A combined approach of laboratory testing and numerical simulation was adopted. Direct shear tests were first conducted to establish quantitative relationships between shear strength parameters, moisture content, and compaction density. Simultaneously, staged consolidation tests were performed to reveal the evolution of dry density under different confining pressures [7–8]. Based on the experimental data, a constitutive model was constructed and implemented in the FLAC3D three-dimensional numerical platform for multi-condition simulation. The study focused on investigating the influence of sensitive factors, such as water level variations and slope morphology, on the factor of safety [9–10]. This research framework provides theoretical support for analyzing instability mechanisms of high dumps and developing prevention and control technologies.

4.1 Construction of the Computational Model and Parameter Calibration

A three-dimensional numerical model was developed for the Muzhushan coal gangue dump in Panjiazhuang Town, Xingren, Guizhou Province (Figure 6). The model profile from top to bottom includes four typical geological units: the artificially stacked layer, siltstone interbeds, the coal seam base, and the argillaceous siltstone bearing layer. The parameter system was determined through a combination of laboratory testing and engineering analogy. Shear strength indices were further calibrated using direct shear test data from field samples, resulting in a multi-phase parameter matrix covering both natural and saturated states (Table 1).The natural unit weight of coal gangue is 19 kN/m³, which increases to 20 kN/m³ after saturation by rainfall. The internal friction angle decreases from 35° to 28°, indicating a pronounced water-sensitive characteristic.

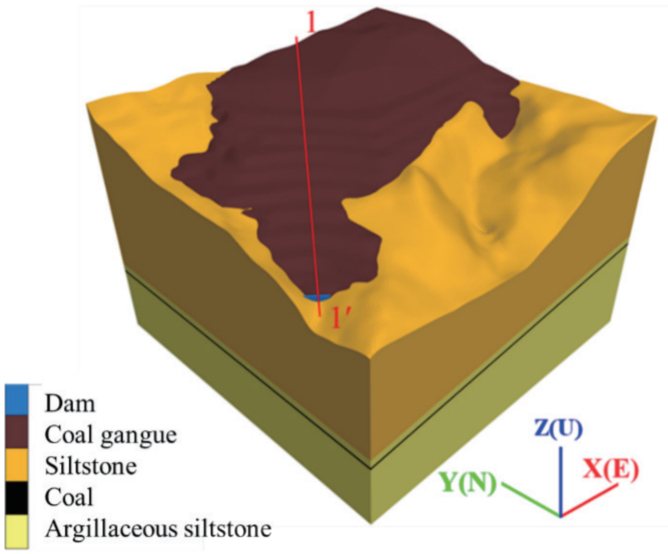

Figure 6. 3D numerical simulation model

Table 1. Summary of Model Parameter Values

Material	Unit Weight (kN/m³)	Bulk Modulus (GPa)	Cohesion (kPa)	Internal Friction Angle (°)
	Natural / Saturated	Natural / Saturated	Natural / Saturated	Natural / Saturated
Coal Gangue	19/20	2	0/0	35/28
Siltstone	24/24.5	22	40/33	37/35
Coal Seam	16/17.5	3.5	12/10	23/21
Argillaceous Siltstone	23.5/24	18	35/32	30/26
Dam Body	24	20	1000/950	45/43

4.2 Multi-Physical Field Coupled Computational System

A three-stage progressive analysis was conducted on the FLAC^{3D} platform. Boundary constraints were applied to the model: on the front, back, left, and right boundaries, unidirectional velocity constraints were imposed to simulate a semi-infinite spatial domain, while the bottom boundary was constrained in all three directions. The gravitational field was simulated by incrementally applying gravity and calculating stability.The factor of safety was determined using the strength reduction method. The basic principle of this method is to divide the material strength parameters by a numerical factor K and apply them in the calculations. The value of K is gradually increased, reducing the strength parameters of the geotechnical material until instability occurs. The corresponding value of K at failure is taken as the factor of safety. The parameter reduction is iteratively performed according to the following formula:

$$C_i = \frac{c}{K} \tag{1}$$

$$\tan\varphi_i = \frac{\tan\varphi}{K} \tag{2}$$

(1) Self-Weight Stress Field Simulation: Based on the Mohr–Coulomb criterion, the strength reduction method was

applied iteratively to determine the limit equilibrium state. Cohesion c and internal friction angle φ were continuously adjusted according to Equations (1) and (2). When a through-going plastic zone appeared in the computational domain, the corresponding reduction factor Fs was taken as the factor of safety. Under the initial condition, the minimum Fs=1.92 (Figure 7), which satisfies the requirements of the GB/T 37573-2019 standard.

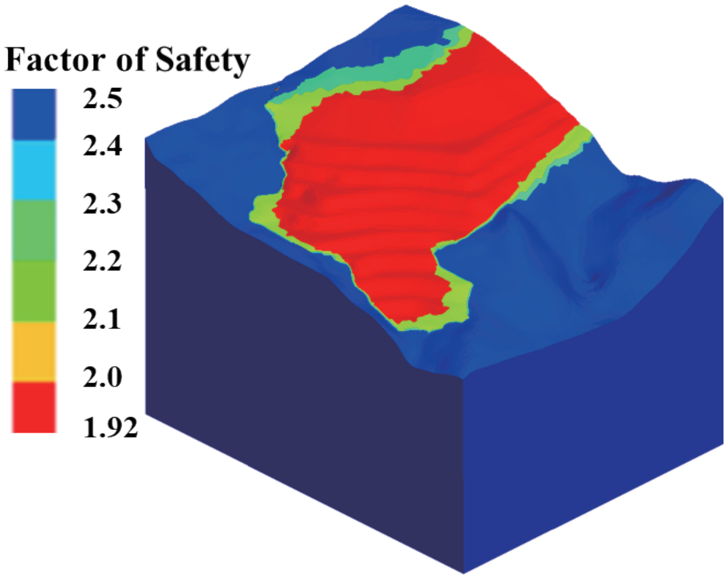

Figure 7. Safety factor contour of coal gangue slope stability

(2) Unsaturated Seepage–Mechanical Coupling: The improved Darcy's law (Equation 3) was introduced to simulate the rainfall infiltration process. The variable z_pp was employed to dynamically track pore water pressure distribution, with real-time updates to the permeability tensor Kil. Key steps included: defining a liquid tensile strength threshold, establishing a saturation storage unit, and constructing the nonlinear relationship $kr(s)=s^2(3-2s)$. Under extreme rainfall conditions, an unstable zone with Fs<1 emerged along the southwestern slope (elevation 1570–1610 m) (Figure 8).

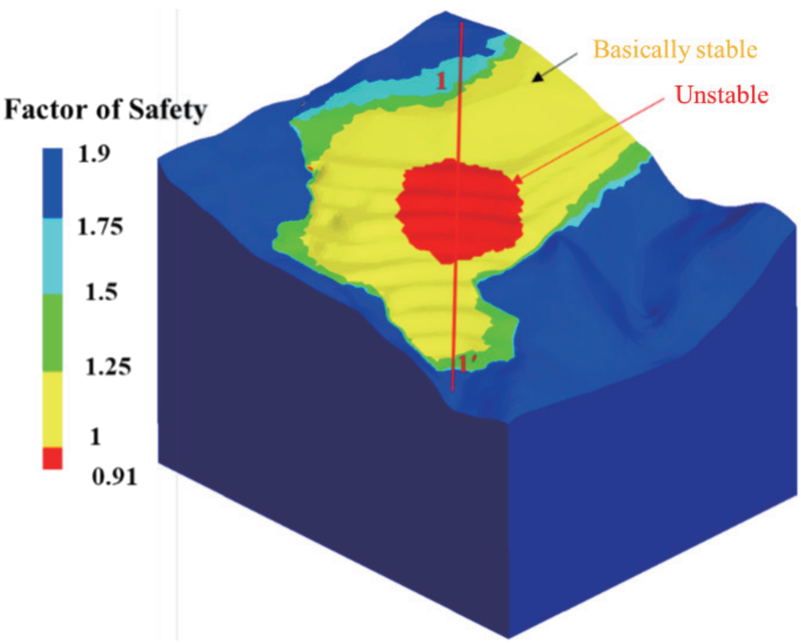

Figure 8. Safety factor contour of coal gangue slope stability under heavy rainfall conditions

(3) Seismic Dynamic Response Analysis: According to GB 18306-2015, a characteristic period of 0.4 s and a peak ground acceleration of 0.05 g were adopted. The motion equations were solved using the explicit difference method, with mesh boundary conditions treated via the lumped-mass model. Dynamic strength reduction analysis indicated a minimum Fs=1.63(Figure 9), suggesting that the overall structure remained within the elastic deformation stage [15–16].

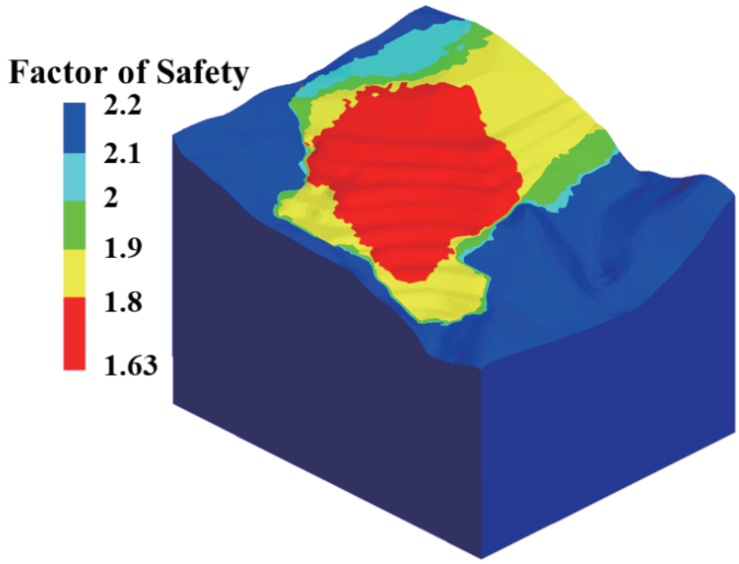

Figure 9. Safety factor contour of coal gangue slope stability under seismic conditions

4.3 Multi-Condition Comparative Verification

The study reveals differentiated impacts of environmental loads on stability: under self-weight conditions, the overall structural integrity remains intact; rainstorm-induced seepage softening effects reduce local safety margins by 47.6%; seismic loading, while causing stress redistribution, does not trigger a critical state. These findings validate the engineering applicability of the stratified modeling approach and the multi-field coupling algorithm, providing a quantitative basis for graded stability control of coal gangue dumps under special geological conditions.

5. Conclusion

This study focuses on a coal gangue slope in Guizhou Province and establishes a comprehensive monitoring system to acquire multi-source parameters for stability assessment. An evaluation model was developed by integrating laboratory tests and numerical simulations, followed by multi-physical field coupling and multi-condition comparative analyses, which clarified the influence of different environmental loads on slope stability. Nevertheless, current research on coal gangue still faces challenges such as the lack of classification standards and incomplete stability evaluation systems [17–18]. Future work should further improve classification and assessment frameworks, enhance the efficiency of solid waste disposal and ecological restoration [7–8,12], and strengthen studies on coal gangue resource utilization [11,13]. This would contribute to sustainable development in coal gangue waste management and ecological remediation [19–20], providing more effective solutions to address the environmental and safety issues caused by coal gangue.

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