

Research Status of Coal Gangue Slope Stability and Integrated Protection

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Abstract

Coal gangue slopes are characterized by heterogeneity in particle size and lithology, a loose structure, water-induced softening and disintegration, and nutrient-poor ecological substrates. Their stability is jointly controlled by compaction, weathering, wet-dry cycles, slope geometry, filling or stripping sequence, rainfall infiltration, and the foundation-cover interface. This review summarizes the main advances in field investigation and testing, limit-equilibrium methods, FLAC3D, GeoStudio, PFC3D, and CFD-DEM coupling. The synthesis indicates that higher compaction and benched construction generally improve stability, whereas saturation and repeated wetting markedly reduce cohesion and friction angle; rainfall-induced failure commonly progresses through surface wetting, infiltration, local movement at the slope toe or benches, and eventual connection of deep or foundation-cover interface shear zones. Treatment has evolved from isolated retaining measures toward integrated slope reshaping, interception and drainage, structural support, substrate improvement, vegetation restoration, and monitoring. Current studies remain limited by single-project samples, insufficient long-term monitoring, limited consideration of spatial parameter variability, and incomplete coupling of hydro-mechanical-ecological processes. Future work should build standardized multiscale monitoring datasets, develop two-way coupling and probabilistic evaluation methods, and verify integrated treatment performance throughout the life cycle.

Keywords

Coal Gangue Slope; Rainfall Infiltration; Slope Stability; Numerical Modelling; Ecological Protection; Integrated Treatment

1. Introduction

Coal gangue slopes are man-made geomorphic bodies created by waste-rock dumping, mine-site backfilling, road construction, and the regrading of legacy gangue hills. Their engineering behavior differs from that of conventional soil or rock slopes because particle size, lithology, weathering, compaction, carbonaceous content, and placement history vary markedly within one mass. The same material may therefore behave as a coarse frictional fill when dry and dense, but as a

compressible, erodible, and strength-degraded aggregate after wetting. Recent Chinese studies have consequently moved from static safety-factor calculations toward coupled interpretations of material evolution, infiltration, progressive failure, and ecological rehabilitation [1-13].

The review covers gangue hills, high-fill slopes, gangue-filled subgrades and cut slopes, mine backfill slopes, and high accumulation slopes at ash yards. It addresses four interrelated questions: how material state controls strength; how rainfall and construction disturbance trigger instability; how different computational methods represent the failure process; and how structural support, drainage, and ecological measures perform in practice.

Table 1. Research methods and principal contributions

Source	Method / evidence	Principal contribution
[1] Liu, 2025	Field test; PFC; CFD-DEM; GeoStudio	Rainfall crack/force-chain mechanism; integrated-treatment verification.
[2] Zhang et al., 2025	Survey; Bishop; monitoring	Wall plus drainage; one-year displacement evidence.
[3] Song, 2025	Back-analysis; Bishop; M-P	Calibrated mixture parameters; slope angle dominates height.
[4] Shen, 2024	Field shear; wet-dry tests; SLOPE/W; SIGMA/W	Compaction, interface weakness, and cyclic degradation.
[5] Feng et al., 2023	Numerical excavation scenarios	Top-down stripping is safer than side stripping.
[6] Lin, 2023	Tests; FLAC3D-PFC3D coupling	Four-stage infiltration and progressive rainfall failure.
[7] Zhou and Fang, 2022	Microbial/polymer and erosion tests	Pure acrylic treatment improved cover and erosion resistance.
[8] Yuan et al., 2022	Engineering classification	Weathering-specific substrate and construction measures.
[9] Feng, 2022	Survey; tests; GeoStudio; LEM	Return-period rainfall, basal sliding, and residual risk.
[10] Yang et al., 2022	FLAC3D parametric study	Slope angle and fill height control settlement-stability trade-off.
[11] Yuan, 2022	BWM-CRITIC-TOPSIS; six sites	Fourteen-indicator ecological protection evaluation.
[12] Lin et al., 2021	Tests; FLAC3D rainfall model	Moisture-density effects and rainfall-induced slip migration.
[13] Liu et al., 2020	Expressway case study	Plant-substrate-selection and ecological construction workflow.

Note: M-P = Morgenstern-Price; LEM = limit-equilibrium method.

2. Engineering Characteristics and Failure Controls

The defining feature of coal gangue is heterogeneity across both particle and slope

scales. In a high-fill project, Shen [4] found that greater compaction increased cohesion and friction angle by 22.46% and 18.8%, respectively, while the gangue-mudstone interface remained weaker than the compacted fill. This interface contrast is important because a slope can satisfy bulk-material criteria yet remain vulnerable along the foundation contact. For a 5:3:2 coal-gangue, gravelly-soil, and cohesive-soil mixture, Song [3] used back-analysis to obtain $c = 10$ kPa and $\varphi = 27^\circ$, illustrating that calibrated field-equivalent parameters may differ materially from nominal laboratory values. The evidence supports treating strength as a state variable governed by gradation, density, interface condition, and moisture rather than as a single project-wide constant.

Time-dependent degradation adds a second layer of uncertainty. At 96% compaction, Shen [4] observed rapid deterioration during the first eight wet-dry cycles; after ten cycles, the friction-angle and cohesion degradation rates reached 19.2% and 58%, respectively. Failure surfaces evolved from interlocking, excavation-like rupture to smoother sliding. Strongly weathered gangue can be still more fragile: Zhou and Fang [7] reported an unconfined compressive strength of only 0.46 MPa and disintegration ratios of 35% after one wet-dry cycle and 100% after three. Conversely, weathering also improves the soil-like character of some material and can facilitate vegetation establishment, which is why Yuan et al. [8] recommend different substrate treatments for weakly, moderately, and strongly weathered gangue. Weathering is therefore not simply a monotonic loss of performance; it changes both geotechnical resistance and ecological treatability.

Geometry and construction activities determine how these weaknesses manifest. FLAC3D analyses of gangue-filled subgrades showed that increasing slope angle reduced settlement but also reduced the safety factor; increasing fill height enlarged settlement and lowered stability [10]. A 20 m fill produced calculated settlements of 11.46-39.76 cm, compared with less than 0.20 cm for a 1.5 m fill [10]. During resource recovery, side stripping increased displacement and shear stress, whereas top-down layered stripping reduced maximum displacement from 0.55 m to 0.023 m and toe shear stress from 150 kPa to 15 kPa [5]. Thus, slope design and operating sequence are not secondary boundary conditions: they actively redistribute confinement, self-weight, and toe resistance.

3. Rainfall Infiltration and Progressive Instability

Across the rainfall-focused studies, instability is consistently linked to rising saturation, loss of suction and contact strength, groundwater emergence near the toe, and migration of the critical shear zone from shallow cover toward deeper or basal surfaces. At the Baiguo ash-yard slope, natural and saturated triaxial parameters changed from $c = 7.86$ kPa and $\varphi = 31.44^\circ$ to $c = 5.39$ kPa and $\varphi = 15.18^\circ$; the measured permeability coefficient was 0.0146 cm/s [9]. Lin et al. [12] similarly found a natural-state safety factor of 1.395, followed by critical instability on the

sixth simulated rainfall day and full failure on the seventh. These results make toe drainage and the foundation-cover interface central to hazard assessment, not merely ancillary details.

The most detailed process models distinguish four infiltration stages: rapid wetting of the surface, downward percolation, progressive saturation, and a saturated phase [6]. Under 200 mm/d rainfall, Lin [6] simulated a stable response for less than two days, a critical state at two days, surface erosion and localized collapse at three days, and widespread failure at four days, when maximum particle displacement reached 9.9816 m. The Min'an case modeled by Liu [1] reached 2,657 contact cracks after five hours of rainfall and ultimately produced a maximum simulated displacement of 20.16 m before treatment. The two studies use different geometries, time scales, and coupling schemes, so their thresholds cannot be transferred directly; nevertheless, both show a transition from wetting to crack growth, local toe or bench movement, and system-wide progressive failure.

Failure morphology depends on topography and stratigraphy. Feng [9] identified a creep-slip and tension-cracking mode in a 70 m accumulation slope, with shallow upper-slope failure under observed rainfall and potential overall sliding along the foundation interface under 20- and 50-year rainfall scenarios. Lin [6] reproduced crest erosion, a rear scarp, and toe accumulation, while Liu [1] identified bench toes as the most sensitive locations because infiltration reduces force-chain continuity where overburden loading is concentrated. Together, these observations argue against a single circular-slip representation for all gangue slopes and favor mechanism-specific searches for shallow erosion, bench-toe initiation, and deep interface-controlled movement.

4. Stability Assessment and Numerical Modelling

The reviewed methods form a useful hierarchy. Simplified Bishop and Morgenstern-Price analyses remain efficient for screening and design. Song [3] found very similar safety factors from the two methods, but also showed that the assumed sliding-surface position can materially affect the Morgenstern-Price result. For a southern Sichuan fill slope, simplified Bishop analysis gave $F_s = 1.101$ under general conditions and $F_s = 1.012$ under ponding or heavy-rain conditions, shifting the assessment from basically stable to under-stable [2]. Parameter back-analysis, sensitivity checks, and explicit consideration of multiple potential surfaces are therefore essential when limit-equilibrium methods are used.

Continuum models add deformation, stress, and seepage fields. FLAC3D has been used to test slope-angle and height effects [10], rainfall-induced groundwater and plastic-zone evolution [12], and construction sequences [5]. GeoStudio enabled coupled seepage-stability evaluation of return-period storms and treatment schemes [9], while SLOPE/W and SIGMA/W compared direct and benched high-fill arrangements under compaction and wet-dry degradation [4]. These models are

well suited to scenario comparison, but their outputs remain conditional on constitutive laws, boundary conditions, and spatially representative parameters. Discrete and hybrid models attempt to resolve progressive fragmentation. Lin [6] calibrated PFC3D micromechanical parameters against laboratory tests, imported FLAC3D unsaturated-saturated seepage results, and represented continuous-discontinuous interaction during failure. Liu [1] used CFD-DEM to trace crack orientation, force-chain loss, and particle displacement. These approaches reveal mechanisms that a single safety factor cannot express, but both theses acknowledge limitations: idealized particle shapes, uncertain microscale calibration, omitted rainfall scour, sequential rather than fully simultaneous hydro-mechanical calculation, or one-way coupling. Numerical sophistication therefore does not remove the need for field validation; it raises the standard for calibration and uncertainty reporting.

5. Integrated Stabilization and Ecological Protection

The treatment literature converges on a layered strategy: reshape the slope and manage water first, provide structural resistance where consequences are high, then establish a durable ecological cover. Zhang et al. [2] selected an anti-slide retaining wall plus interception and drainage ditches for a 25-40 m fill slope. One year after completion, the maximum cumulative horizontal and vertical displacements were 6.2 mm and 3.9 mm, with low average rates, supporting short-term effectiveness. Liu [1] simulated an integrated treatment that reduced maximum displacement to 0.04 m; treated safety factors were 1.869 in the natural condition and 1.5887 after five hours of rainfall. Feng [9], however, found that an existing scheme could keep overall stability while leaving local instability under 20- and 50-year rainfall, demonstrating that system-level acceptance should not conceal residual hot spots. Ecological protection must be matched to weathering state and substrate limitations. Yuan et al. [8] proposed polymer solidification and guest-soil spraying for weakly weathered material, microbial water-retaining treatment with anchoring and mesh for moderately weathered material, and skeletal frames with vegetation bags for strongly weathered slopes. Zhou and Fang [7] showed that a compound microbial solution plus pure acrylic polymer outperformed a styrene-acrylic alternative; at 400 L/h test rainfall, erosion loss was reduced by 75% relative to untreated gangue, and a one-year field inspection found good cover with little visible runoff erosion. Liu et al. [13] similarly emphasized plant selection, substrate thickness, anchoring, mesh, spray seeding, and maintenance for the Longlang Expressway, and reported that gangue content around 35% in mixed soil favored vegetation in the cited project context.

The emerging emphasis is not only construction but performance evaluation. Yuan [11] built a 14-indicator system spanning soil reinforcement, substrate quality, and ecological function, and combined subjective and objective weights in a

BWM-CRITIC-TOPSIS model. Application to six expressway slopes broadly agreed with field conditions and supported polymer and microbial improvement measures. This framework is a valuable step toward auditable acceptance, but early-stage vegetation scores cannot establish long-term geotechnical reliability. Ecological cover should be monitored as a living engineering layer whose root reinforcement, coverage, infiltration, nutrient status, and erosion resistance evolve with time.

6. Research Gaps and Priorities

Three evidence gaps recur. First, most studies are single-site cases and many depend primarily on simulations; long-duration monitoring that captures rainfall, pore pressure, displacement, settlement, erosion, and vegetation succession is sparse. The strong agreement between observed deformation and calibrated models in several studies is encouraging, but general design thresholds cannot be inferred from a small, geographically concentrated corpus. Second, parameter variability is usually compressed into deterministic values even though gradation, density, weathering, interfaces, and saturation are spatially heterogeneous. Probabilistic characterization and reliability-based design should complement single-value safety factors.

Third, hydro-mechanical-ecological processes are commonly separated. Future models should implement two-way fluid-particle coupling, realistic irregular particles, dynamic erosion and drainage boundaries, and parameter updating from monitoring. Field trials should compare untreated, structurally stabilized, ecologically treated, and integrated sections under consistent instrumentation. Reporting should include calibration data, sensitivity ranges, failure criteria, mesh or particle dependence, and uncertainty intervals so that results can be reproduced and transferred.

A practical research agenda is therefore to build standardized multi-scale datasets: laboratory strength and disintegration tests across moisture and weathering states; in-situ interface and compaction measurements; event-scale rainfall, suction, pore-pressure, and displacement records; and multi-year ecological performance. Linking these data to staged models would support early warning, maintenance thresholds, and life-cycle optimization. The central question should shift from whether a slope is stable in one modeled condition to how its margin of safety evolves under weathering, repeated wetting, operational disturbance, and treatment aging.

7. Conclusions

Coal gangue slope stability is governed by coupled material state, geometry, water, interfaces, and operations. Compaction and benching generally improve performance, whereas saturation, wet-dry cycling, excessive height or steepness, toe disturbance, and poorly drained interfaces promote progressive failure.

Limit-equilibrium methods remain valuable for transparent screening; continuum, discrete, and coupled methods clarify seepage, deformation, cracking, and force-chain evolution when calibrated against tests and field evidence. The most defensible treatment strategy combines grading, drainage, selective structural support, weathering-specific substrate improvement, ecological cover, and monitoring. The next advance will come less from a single more complex model than from long-term, standardized field data that allow models and treatment performance to be updated through the slope life cycle.

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