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Run-out hazard assessment and drainage anti-sliding pile control of a rainfall-induced loess landslide

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Abstract: Rainfall-induced loess landslides in irrigated terrace areas can evolve from infiltration and pore-pressure buildup to rapid run-out toward river channels. Taking the Jiaojiaya No. 13 slope in the Heifangtai platform, Gansu Province, China, as a case study, this study first assessed untreated run-out hazard using Massflow and then evaluated the stabilization effects of conventional anti-sliding piles (CAP) and drainage anti-sliding piles (DASP) using SEEP/W and SLOPE/W in GeoStudio. Under natural conditions (NC), the calibrated Massflow model showed that about 12.0×10^4 m³ of unstable loess could travel 504.4 m and enter the adjacent river channel, indicating significant run-out and river-intrusion hazards. GeoStudio results showed that rainfall infiltration and post-rainfall moisture redistribution reduced the time-series factor of safety under NC to 0.701, while representative stability maps gave Fs values of 0.931, 1.057 and 1.638 for NC, CAP and DASP, respectively. CAP intercepted the main through-going slip surface but provided limited pore-pressure relief. In contrast, DASP combined mechanical resistance with drainage-pressure reduction, suppressed the through-going failure surface and shifted the reinforced slope to an overall stable state with a higher safety reserve. The potential low-reserve source zone decreased to about 0.86×10^4 m³, 92.8% lower than the untreated source volume. These results indicate that DASP mitigates landslide hazard mainly through source control by lowering pore-water pressure and preventing large-scale source formation.

Keywords: loess landslide; drainage anti-sliding pile; rainfall infiltration; Massflow; zoned factor of safety; hazard mitigation

1 Introduction

Loess is widely distributed across northwestern China and is characterized by a loose structure, well-developed pores, vertical joints and strong water sensitivity. Upon wetting, loess can undergo collapsibility, softening and shear-strength degradation, which provide the material basis for frequent landslide hazards on the Chinese Loess Plateau [1, 2]. With increasing agricultural irrigation, engineering disturbance and extreme rainfall, the internal hydrological conditions of loess slopes have changed markedly. Rainfall or irrigation infiltration reduces matric suction, increases pore-water pressure and raises groundwater levels, thereby becoming a major trigger for loess landslides [3, 4]. The Heifangtai platform in Yongjing County, Gansu Province, is a typical high-incidence area of loess landslides in China. Long-term irrigation has raised groundwater levels within the platform and induced numerous retrogressive, clustered and flow-like loess landslides, causing serious losses of life and property [5-7]. Previous studies have systematically examined landslide types, development rules, groundwater response, kinematic features and risk assessment in Heifangtai [8], showing that long-term irrigation, groundwater rise and water-induced loess softening are the key controls on landslide activity in this area [9, 10]. In addition, fissures and preferential pathways in loess can accelerate water migration to deeper layers, increase local pore-water pressure and weaken soils near potential slip surfaces. Therefore, post-rainfall seepage redistribution and delayed pore-pressure response may also affect slope stability [11, 12].

Recent research on rainfall-induced loess landslides has shifted from single stability evaluation toward integrated analyses of unsaturated seepage, preferential fissure infiltration, rainfall-pattern uncertainty, spatial variability of soil parameters and post-failure movement. Ma et al. [13] showed that stability assessment of rainfall-induced loess landslides is highly sensitive to hydraulic conductivity, shear-strength parameters and rainfall patterns when spatial variability is considered. Duan et al. [14] further linked extreme rainfall with creep effects in unsaturated loess slopes, emphasizing time-dependent strength degradation under sustained infiltration. Field infiltration studies have shown that rear-edge fissures and preferential pathways allow rainwater to bypass uniform shallow infiltration and rapidly reach deeper potential sliding zones [15]. Rainfall model tests also indicate that fissure propagation, wetting-front migration and localized saturation jointly control initiation positions and failure patterns [16]. For loess-palaeosol or loess-silty clay interbedded slopes, low-permeability layers can impede downward seepage, promote water retention in overlying loess and amplify delayed post-rainfall stability degradation [17]. Rainfall duration, rainfall intensity combinations and slope

gradient further affect wetting-front depth, pore-pressure response time and the rate of factor-of-safety reduction [18, 19].

For landslide mitigation, conventional anti-sliding piles mainly provide mechanical resistance through pile bending stiffness and the embedded segment. However, for water-sensitive loess slopes governed by rainfall infiltration and groundwater, rigid support alone cannot efficiently release elevated pore-water pressure within the slope. Drainage wells, horizontal drains and pile-drainage combined structures have shown that active drainage can lower groundwater levels, reduce pore-water pressure and increase effective normal stress along potential slip surfaces, making it an important supplement for hydraulically driven landslides [20]. Recently, drainage anti-sliding piles and upper-hollow drainage anti-slide piles have received growing attention. Their core concept is to combine pile resistance with side collection holes, internal vertical drainage channels and slope drainage systems that release pore-water pressure around the pile [21, 22]. Reviews and engineering studies on DASP indicate that its main advantage over CAP is the conversion of passive support into coupled support-drainage control. Nevertheless, most existing studies focus on structural force, drainage capacity or local stability improvement, whereas continuous analyses linking source-volume reduction to post-failure run-out mitigation remain limited [23, 24].

In summary, previous studies have clarified how rainfall infiltration, preferential fissure flow, low-permeability layer impedance and pore-pressure lag affect loess-slope stability, and have separately advanced drainage-support design and landslide run-out modelling. However, a process gap remains: run-out simulations commonly emphasize the hazard range after failure, whereas stabilization analyses often stop at the factor of safety and do not explain how a drainage-support measure changes the source conditions that control long-distance movement. This study therefore adopts a hazard-first evaluation logic. The untreated NC slope is first simulated with Massflow to quantify the potential run-out range and river-intrusion risk. SEEP/W and SLOPE/W are then used to compare NC, CAP and DASP in terms of pore-water pressure, critical slip-surface development, factor of safety and zoned safety reserve. The overall research framework is shown in Fig. 1. This structure separates the diagnosis of the natural landslide hazard from the evaluation of reinforced-slope stability, and clarifies the source-control mechanism by which DASP mitigates rainfall-induced loess landslide hazards.

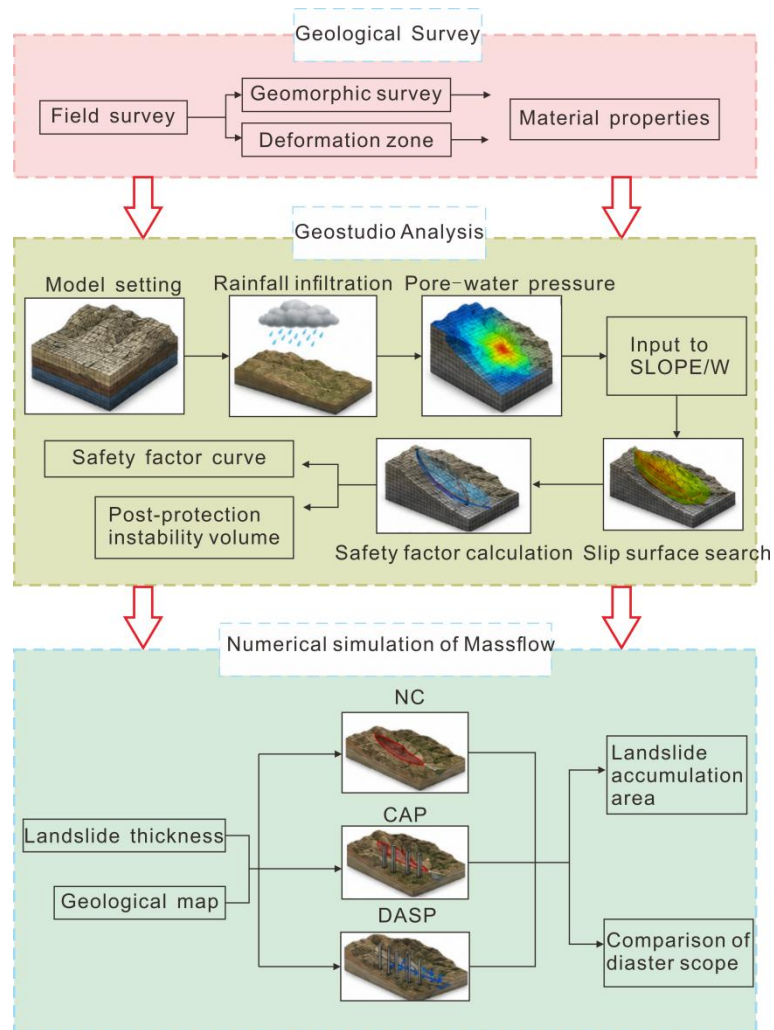


Fig. 1 Research framework

2 Study area

The study area is located in the Heifangtai irrigation district of Yanguoxia Town, Yongjing County, Gansu Province, upstream of the confluence between the Huangshui River and the Yellow River. It belongs to a typical fourth-order terrace of the Yellow River. The platform covers approximately 13.7-14.0 km², has a generally flat surface that inclines from west to east, and has elevations of 1664-1864 m. Steep marginal slopes around the platform provide favorable free-face topography for landslide initiation (Fig. 2). Since the 1960s, reservoir resettlement and long-term Yellow River irrigation have caused persistent infiltration of irrigation water and substantial groundwater rise within the platform. Because loess loses strength rapidly after wetting, clustered and flow-like landslides have frequently occurred along the platform margins, threatening riverside infrastructure, farmland and local

97 residents.

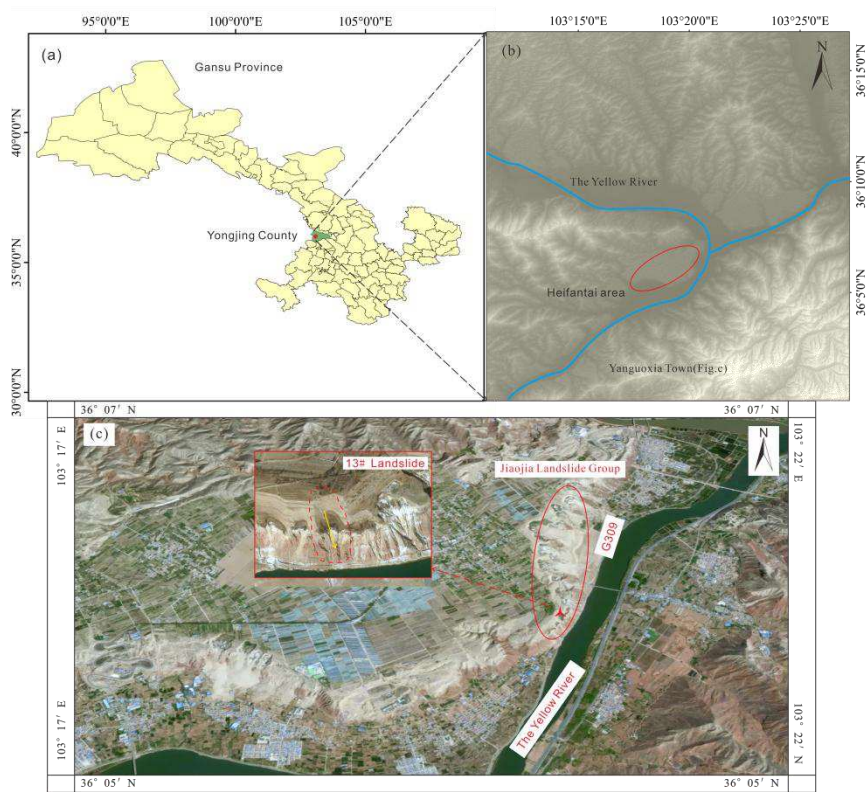


Fig. 2 Overview of the study area

The Heifangtai platform mainly consists of four stratigraphic units from top to bottom. The upper layer is Upper Pleistocene Malan loess (Q_3^{eol}), 26-48 m thick, with a loose structure and well-developed vertical fissures that serve as major channels for rapid rainfall and irrigation infiltration. Beneath it lies Middle Pleistocene alluvial-diluvial silty clay (Q_2^{al}), 3-19 m thick, which is dense and weakly permeable. This layer slows groundwater flow and forms a transient or perennial phreatic zone within the overlying loess. A 1-6 m thick gravel layer (Q_2^{al}) with high permeability occurs below the silty clay, and the basal bedrock is sandy mudstone of the Lower Cretaceous Hekou Group ($K1hk3$), with bedding dips of 125-220 degrees. Under this geological configuration, rapid infiltration through Malan loess fissures and long-term irrigation-induced wetting can easily saturate and soften loess above the interfaces, creating a typical rainfall-irrigation coupled failure mechanism in Heifangtai.

To define the engineering geological conditions and provide a basis for numerical model simplification, an engineering geological section of the Jiaojiayatou No. 13 slope was established using field section data, lithology and groundwater information (Fig. 3). The section shows thick Malan loess in the upper slope, well-developed vertical fissures, landslide deposits in the middle-lower slope, and silty clay,

gravel and sandy mudstone at the base. The potential slip surface mainly extends through the loess and landslide deposits toward the slope toe and converges near the silty clay and gravel layers, indicating that weak interfaces and groundwater accumulation zones jointly control the failure boundary.

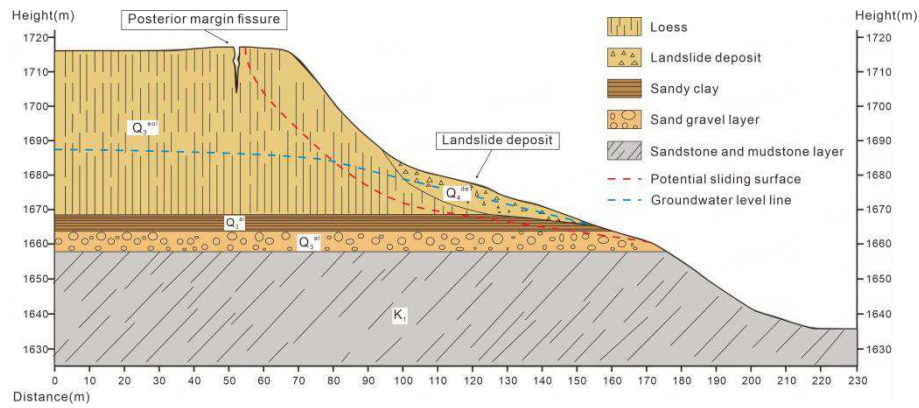


Fig. 3 Engineering geological section of the Jiaojiaya No. 13 slope

Hydrogeologically, groundwater in the study area is mainly recharged by long-term irrigation and rainfall infiltration. Vertical fissures in the loess provide preferential pathways for downward water migration. Infiltrated water gradually accumulates near the lower loess and silty clay layers to form a saturated zone, and then discharges along the top of the silty clay layer, through the gravel layer and toward the free face at the slope toe (Fig. 4). Because of the impedance of the weakly permeable layer and toe-controlled discharge, elevated pore-water pressure and reduced effective stress can develop near the potential sliding zone. This provides an important hydrogeological basis for high-position initiation and long run-out of the Jiaojiayatou landslide under rainfall or irrigation.

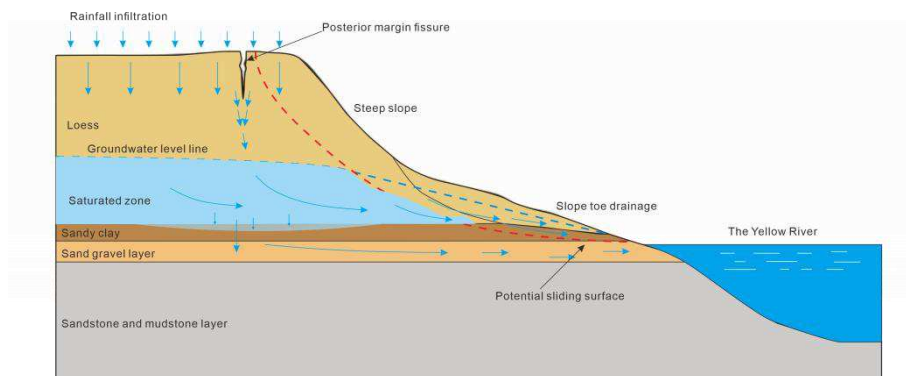


Fig. 4 Conceptual model of groundwater occurrence, runoff and discharge in the Jiaojiaya No. 13 slope

The numerical analysis was organized in two stages. First, the untreated NC slope was used to diagnose the potential run-out hazard and river-intrusion consequence. Second, NC, CAP and DASP were compared in GeoStudio to evaluate stability control after pile installation. CAP represents

mechanical interception of the main through-going slip surface, whereas DASP combines mechanical support with drainage-pressure relief. The outside optimized drainage anti-sliding pile arrangement (D-DASP) is discussed only as a conceptual extension and is not included in the main numerical comparison.

3 Natural run-out hazard assessment based on Massflow

3.1 Massflow parameter setting and validation

UAV photogrammetry was used to obtain topographic information for the Jiaojiayatou No. 13 landslide and adjacent areas, and a three-dimensional terrain model was constructed as the base topography for Massflow simulations. Massflow was used in this stage to evaluate the possible run-out process of the untreated slope, rather than to simulate failure after engineering treatment. The initial source area was defined from the field-interpreted through-going failure boundary and constrained by previous Massflow applications, kinematic simulations, centrifuge model tests and disaster records for loess landslides in Heifangtai [25-29]. The Coulomb model was selected because it is suitable for landslides and collapsed deposits dominated by solid granular motion. Input parameters included landslide density, cohesion, internal friction angle, pore-water pressure coefficient and gravitational acceleration. These parameters describe equivalent motion resistance during the post-failure movement stage and were constrained by back-analysis of historical run-out distance, deposition area and morphology. The high-speed Jiaojiayatou landslide event of 7 February 2012 was used for Massflow parameter back-analysis. The historical landslide volume was approximately $12 \times 10^4 \text{ m}^3$, and most of the sliding mass entered the Bapanxia reservoir area, blocking the Yanlan highway and generating reservoir waves. The back-analysis used source volume, river entry, deposition extent and maximum run-out distance as the main constraints, with effective deposition volume as a mass-conservation check. Because Massflow did not include significant erosion entrainment, final volume variations among parameter combinations were limited; parameter selection was therefore mainly based on run-out distance, deposition area and river-entry behavior. A stepwise trial method was used. First, the pore-water pressure coefficient was fixed at 0.4, and cohesion was tested between 0 and 7 kPa to reflect the substantial reduction in cohesion after loess wetting. A cohesion value that reproduced the

historical deposition range was then selected. Next, with cohesion near 5 kPa, the pore-water pressure coefficient was adjusted in increments of 0.1 to compare run-out extent, effective deposition area, maximum thickness and river-entry behavior. Selected back-analysis results are listed in Table 1, and final input parameters are listed in Table 2.

Table 1 Back-analysis results for Massflow parameters (selected cases)

Case	c (kPa)	lambda	Effective area (H> 0.1m) /10 ⁴ m ²	deposition volume (H>0.1m)/ 10 ⁴ m ³	Maximum thickness (m)	Deposition position
1	4	0.4	7.46	11.82	5.22	Farthest deposit reached the river margin
2	5	0.4	7.00	11.81	5.34	Farthest deposit reached the river margin
3	5	0.5	7.51	11.81	5.18	River intrusion
4	5	0.6	8.13	11.80	4.87	River intrusion
5	5	0.7	8.77	11.79	4.62	River intrusion

Table 2 Basic input parameters for the Massflow numerical simulation

Parameter	ρ (kg m ⁻³)	c (kPa)	φ (degrees)	λ	g (m s ⁻²)
Value	1400	5.0	17.2	0.7	9.8

The back-analysis showed that the farthest deposits in cases 1 and 2 reached only the river margin, whereas cases 3, 4 and 5 reproduced river-entry behavior. Considering both river entry and final deposition thickness and morphology, the parameter combination in case 5 ($\rho=1400$ kg/m³, $c=5.0$ kPa, $\varphi=17.2$ degrees and $\lambda=0.7$) was selected for the untreated NC run-out simulation. This combination reproduced the historical source volume of approximately 12×10^4 m³, long run-out and river-entry deposition. The internal friction angle $\varphi=17.2$ degrees is consistent with the loess value used in GeoStudio, but in Massflow it acts as an equivalent friction parameter during the motion stage; its rationality is mainly constrained by historical landslide back-analysis.

3.2 Run-out hazard under natural conditions

An untreated NC initial source volume of approximately 12×10^4 m³ was adopted for the run-out simulation. This volume corresponds to the field-interpreted through-going failure zone of the

Jiaojiayatou No. 13 slope and is consistent with the scale of historical loess landslides in the Heifangtai platform. To clarify the run-out characteristics and hazard range without engineering treatment, the NC process was simulated at four typical time nodes: $t = 10, 20, 30$ and 40 s (Fig. 5). The results indicate high mobility and severe hazard potential. After failure, gravity drove the sliding mass rapidly downslope. At $t = 10$ s, the rear source area showed clear shear thinning, whereas the front advanced rapidly with increasing kinetic energy; the central source area still retained a high-thickness zone of $12.0\text{--}15.0$ m, but the front had already stretched into a tongue-shaped pattern. During 10-20 s, the landslide entered a high-speed shearing stage. Controlled by the steep-to-gentle terrain transition, source materials were continuously supplied downslope, and the high-thickness core moved rapidly. Because of the large source volume under NC, the front crossed the middle-lower buffer platform and reached the free face at the slope base, entering the river area at $t = 20$ s. During 20-40 s, kinetic energy was gradually consumed by terrain-controlled friction and front expansion nearly stopped. By $t = 40$ s, the landslide had almost stopped. The final deposit was a long tongue-shaped body, with an effective deposition volume of approximately $11.83 \times 10^4 \text{ m}^3$ and a maximum run-out distance of 504.4 m. The front formed a distinct deposition zone along the riverbank after entering the main river channel, indicating significant river-intrusion risk under untreated conditions.

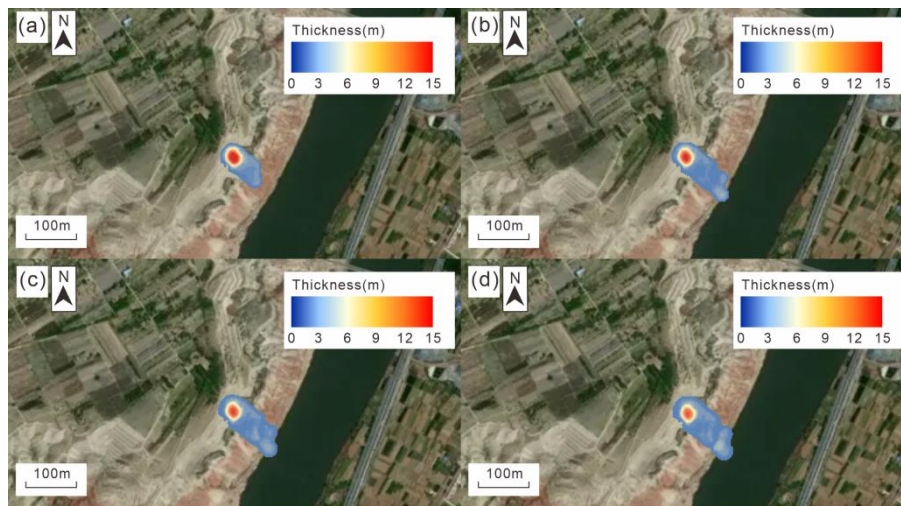


Fig. 5 Predicted accumulation-thickness evolution during landslide movement under NC based on Massflow: (a) 10 s; (b) 20 s; (c) 30 s; and (d) 40 s

4 Stability-control simulation based on GeoStudio

4.1 Numerical model construction

After the untreated run-out hazard had been identified, GeoStudio was used to evaluate whether pile reinforcement could prevent development of the large source area responsible for long-distance movement. The model geometry, stratigraphic structure and initial groundwater level were determined from the engineering geological section and the conceptual model of groundwater occurrence, runoff and discharge for the Jiaojiayatou No. 13 slope (Figs. 3 and 4). The physical-mechanical parameters, soil-water characteristic curves (SWCCs) and hydraulic conductivity functions were selected by integrating engineering investigation data and previous studies in the Heifangtai area. A two-dimensional numerical model was established using SEEP/W and SLOPE/W in GeoStudio. From top to bottom, the model materials were loess, silty clay, gravel and sandy mudstone. The model had a total height of approximately 93.5 m and a total length of 230 m. To represent preferential infiltration through a rear-edge fissure, a 5 m deep and 0.2 m wide fissure was placed at the model top. The mechanical and hydraulic parameters of each soil layer were mainly determined from the field investigation report of the Jiaojiayatou No. 13 slope (Table 3). An unsaturated seepage model was established in SEEP/W using the Van Genuchten estimation method, based on saturated water content, residual water content and soil type. The SWCCs and unsaturated hydraulic conductivity functions of the soil layers are shown in Fig. 6.

Table 3 Physico-mechanical and hydraulic parameters of soil layers in the loess slope

Soil layer	Unit weight (kN/m ³)	Elastic modulus (MPa)	Poisson's ratio	Porosity	Vertical hydraulic conductivity (m d ⁻¹)	Horizontal hydraulic conductivity (m d ⁻¹)	Cohesion (kPa)	Friction angle (degrees)	Suction friction angle (degrees)
Loess	15.0	46	0.35	0.52	0.12	2.4×10^{-2}	19.2	17.2	15.6
Silty clay	19.5	90	0.30	0.30	2.4×10^{-4}	2.0×10^{-4}	60.0	22.0	-
Gravel layer	20.0	140	0.3	0.40	2.0	2.0	-	-	-
Sandy mudstone	22.0	200	0.3	0.10	1.0×10^{-5}	1.0×10^{-5}	-	-	-

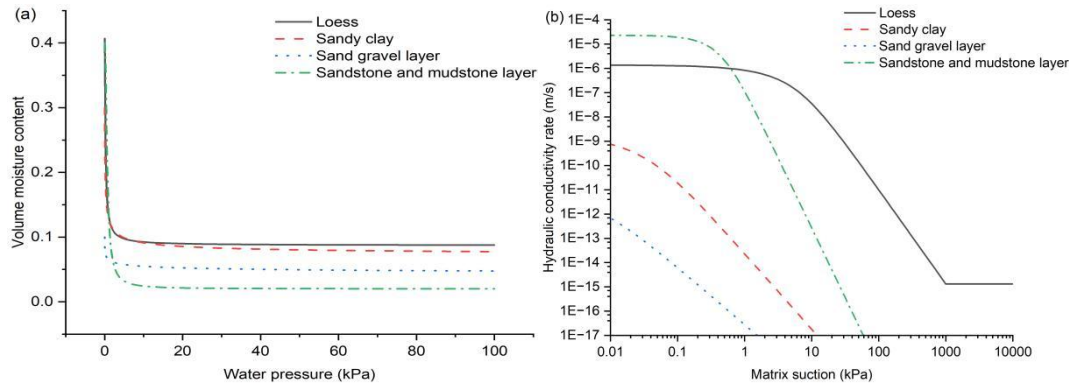


Fig. 6 Hydraulic properties of the four soil layers: (a) soil-water characteristic curves (SWCCs) showing volumetric water content as a function of matric suction; and (b) unsaturated hydraulic conductivity functions as a function of matric suction

4.2 Stability comparison under different conditions

The model boundary conditions are shown in Fig. 7. Historical daily rainfall records for Yongjing County were first examined to constrain the regional plausibility of the rainfall setting. Three high-rainfall events with clear monthly contrasts were selected, namely 24 July 2020 (84.4 mm), 15 July 2021 (61.8 mm) and 17 July 2024 (72.6 mm), and their antecedent and post-peak rainfall processes are summarized in Fig. 8. On this basis, the SEEP/W analysis generalized the rainfall input into a 48 h rainfall-response scenario, consisting of rainfall loading during 0-20 h and post-rainfall moisture redistribution during 20-48 h. Segmented rainfall-flux boundaries were applied to the slope surface and the rear-edge fissure to represent short-duration intense rainfall and preferential fissure infiltration. A constant-head boundary was assigned to the fissure to represent water filling and preferential infiltration during rainfall. Lateral boundaries below the initial groundwater level were set as constant-head boundaries to approximate lateral groundwater recharge and discharge. Lateral boundaries above the initial groundwater level were set as no-flow boundaries, and the model base was set as a no-flow boundary according to the weak permeability of the underlying sandy mudstone. A zero-pressure boundary was assigned at the slope toe to represent free drainage. Other external boundaries were treated as natural boundaries. This boundary-condition scheme therefore links the observed heavy-rainfall background with a generalized seepage-stability simulation, and can represent continued internal moisture redistribution and toe discharge after short-duration intense rainfall.

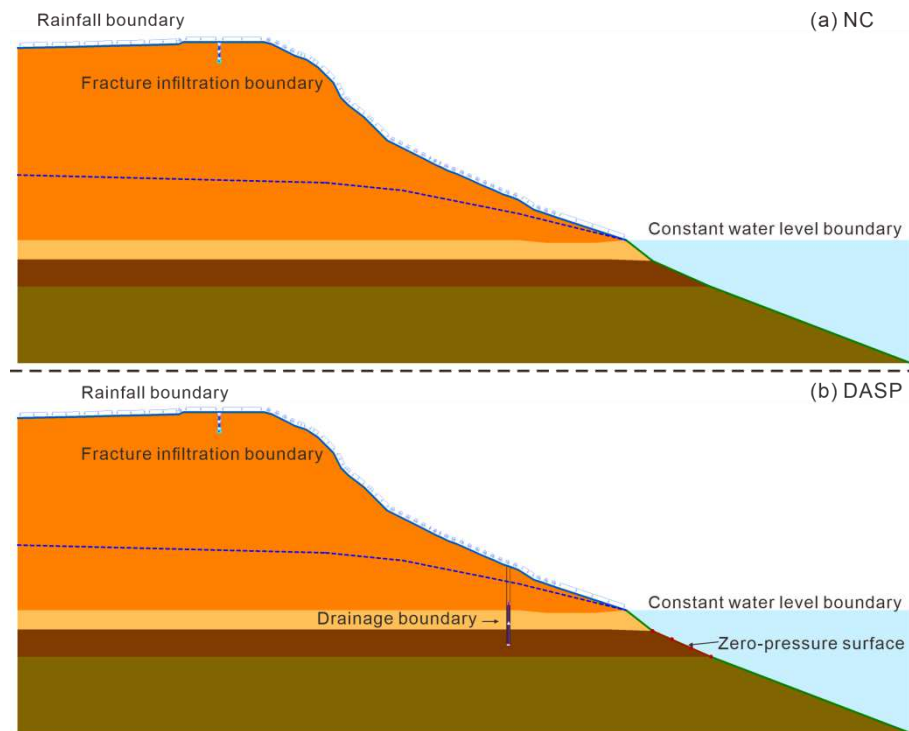


Fig. 7 Schematic seepage boundary conditions under (a) NC, including rainfall infiltration, fissure infiltration and constant-head boundaries; and (b) DASP, including equivalent drainage boundaries and free-outflow conditions

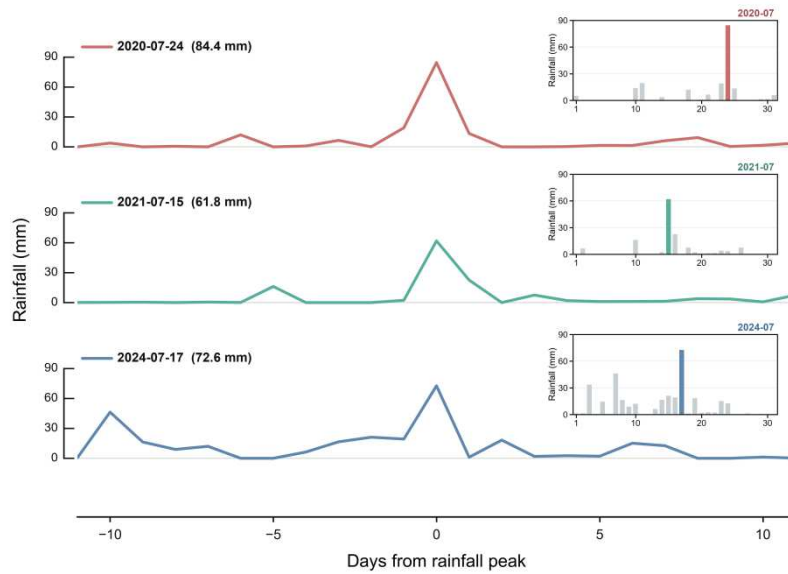


Fig. 8 Historical heavy-rainfall events used to constrain the representative rainfall scenario for GeoStudio analysis. The stacked curves show daily rainfall before and after the rainfall peaks on 24 July 2020, 15 July 2021 and 17 July 2024, and the embedded bar charts show daily rainfall distributions for the corresponding months in Yongjing County, Gansu Province

The seepage results (Fig. 9) show clear temporal evolution of the pore-water pressure field within 48 h. At the early stage of rainfall, shallow parts of the slope were still dominated by negative pore-water pressure, indicating that matric suction had not been fully dissipated and that infiltration was concentrated near the slope surface and the rear-edge fissure. As rainfall continued, the shallow negative-pressure zone gradually contracted and local pressure contours extended downward, indicating a persistent influence of rainfall infiltration on the seepage field. During the middle to late rainfall stage, pore-water pressure changes became more evident near the rear-edge fissure, where contours bent locally and extended to deeper layers, suggesting the development of a relatively concentrated infiltration pathway. At approximately $t = 21$ h, about 1 h after rainfall had stopped, the shallow pore-pressure field had already changed markedly from the initial state: the negative-pressure zone further decreased and pore-water pressure near the potential sliding zone increased. After rainfall cessation, the water that had entered the slope did not dissipate immediately; instead, it continued to migrate downward and toward the slope toe under gravity and unsaturated suction gradients. Therefore, at $t = 30, 39$ and 48 h, the internal pore-pressure field still showed delayed adjustment. Overall, the contours indicate reduction of negative pore pressure, local pressure increase

and post-rainfall migration, whose stability effects are evaluated using the factor of safety and potential slip-surface evolution.

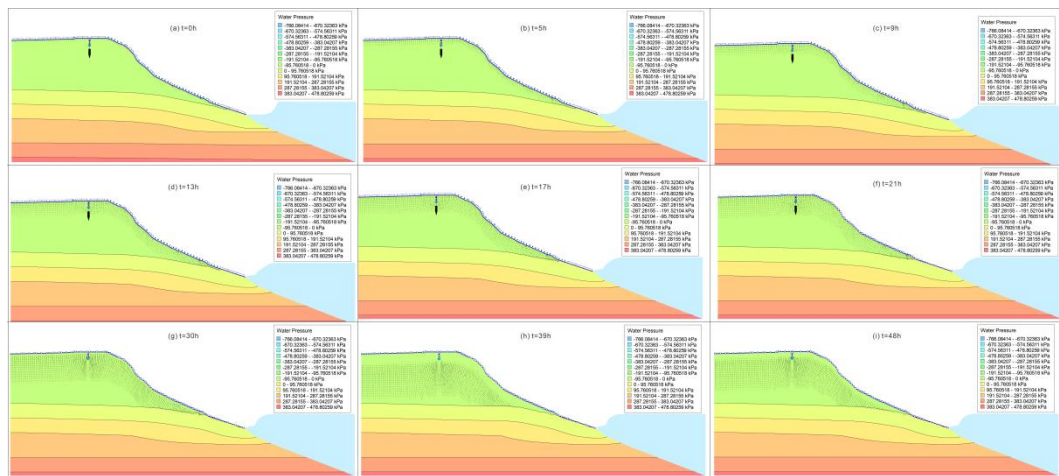


Fig. 9 Distribution of pore-water pressure in the loess slope during and after rainfall: (a) $t = 0$ h; (b) $t = 5$ h; (c) $t = 9$ h; (d) $t = 13$ h; (e) $t = 17$ h; (f) $t = 21$ h; (g) $t = 30$ h; (h) $t = 39$ h; and (i) $t = 48$ h

Because this study evaluates the integrated control effect of DASP on the slope seepage field and stability state, rather than the structural optimization of a single pile, DASP was represented in the model in an equivalent manner. Its anti-sliding effect was represented by pile elements that provide mechanical constraint, whereas its drainage effect was represented by free-outflow boundaries with zero pore pressure on both sides of the pile to reduce pore-water pressure around the pile and near the potential sliding zone. Studies of drainage anti-sliding piles and upper-hollow drainage anti-slide piles have shown that side collection holes and internal drainage channels can collect groundwater around the pile and discharge it through the pile body, thereby reducing groundwater level, pore-water pressure and landslide thrust. Based on this physical process, the pressure-relief effect of the pile drainage system at the slope scale was generalized as a free-outflow boundary. Both pile types were 20.0 m long and embedded 3.0 m into the basal gravel layer. To enhance internal drainage, DASP was configured as a split structure: the upper pile segment was treated as weakly permeable to collect groundwater from the slope and pile surroundings, while the lower segment was treated as impermeable to prevent direct leakage to the deep layer. A vertical drainage hole inside the pile connected the upper and lower parts and discharged collected water along the pile channel (Fig. 10). Based on the SEEP/W analysis, three conditions were then constructed for SLOPE/W analysis: NC, CAP and DASP.

The equivalent zero pore-pressure/free-outflow boundary was not intended to resolve local

three-dimensional flow inside individual drainage holes. Instead, it expresses the pore-pressure release caused by DASP at the scale of a two-dimensional slope section. In seepage analysis, a free-outflow boundary has the same physical meaning as a seepage-face boundary: once groundwater reaches a drainable boundary, pore pressure no longer accumulates and boundary head is controlled by the drainage outlet. Such boundaries are commonly used to represent natural outflow near slope faces, drainage holes or drainage wells in saturated and unsaturated seepage simulations [30]. For section-scale analysis aimed at overall slope stability and source-volume control, and in the absence of measured single-pile discharge, clogging ratio or filter-material permeability, the free-outflow boundary is a mechanism-oriented representation under effective drainage conditions. This treatment highlights the main distinction between CAP and DASP: CAP provides mainly mechanical support, whereas DASP provides both mechanical support and pore-pressure release. Thus, the results should be interpreted as an evaluation of stability and source control under unobstructed drainage channels and effective outlets, not as a detailed design check of pile drainage capacity.

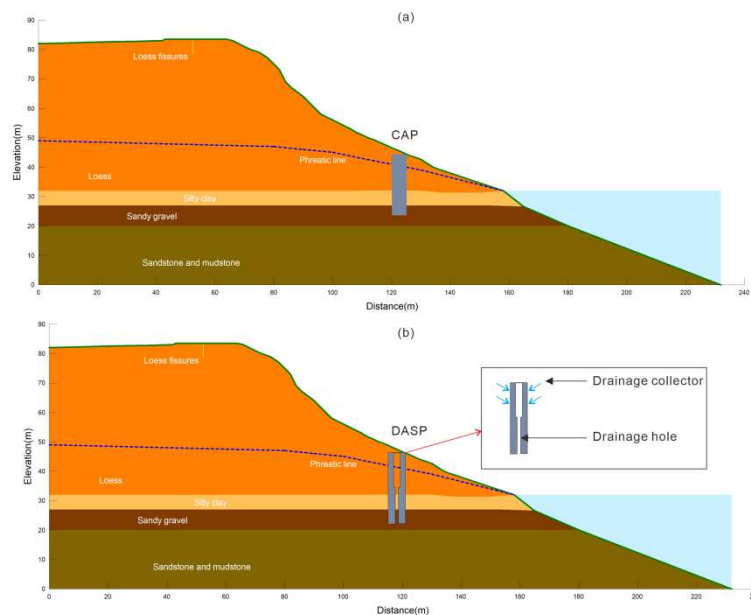


Fig. 10 Structural layout of anti-sliding pile measures: (a) conventional anti-sliding pile (CAP); and (b) drainage anti-sliding pile (DASP) with an internal drainage structure

The simulation results (Fig. 11) show distinct mechanical responses and stability states under different measures. Under NC, rainfall infiltration rapidly dissipated matric suction in shallow soil and reduced shear strength. The most critical slip surface remained a deep circular surface, and the representative factor of safety was $F_s = 0.931$, indicating that the untreated slope was still in an unstable or

near-critical state. After CAP was installed in the middle slope, the main through-going slip surface was mechanically intercepted and the representative F_s increased to 1.057. This indicates that the principal sliding path had been stabilized by pile resistance, although the safety reserve remained limited because CAP did not provide pore-pressure relief. Under DASP, the representative F_s increased markedly to 1.638, and the critical slip surface no longer developed as a continuous deep failure path. The colored zones in the reinforced cases should therefore be interpreted as zoned factor-of-safety distributions, namely the spatial redistribution of stability reserve, rather than as evidence that the reinforced slope would still undergo a large-scale landslide. Compared with CAP, DASP further reduced the low-reserve area and shifted most of the reinforced slope to high F_s ranges by combining mechanical resistance with drainage-pressure reduction. This interpretation is consistent with numerical simulations of an arched micropile group in the Tizicao high-position landslide and optimized pile-position analyses, which show that pile support improves overall factor of safety while local load-transfer and deformation zones may still control the spatial distribution of stability reserve [31, 32]. Overall, Fig. 11 indicates that DASP converts the slope from a near-critical through-going failure mode to an overall stable state with a substantially enhanced safety reserve.

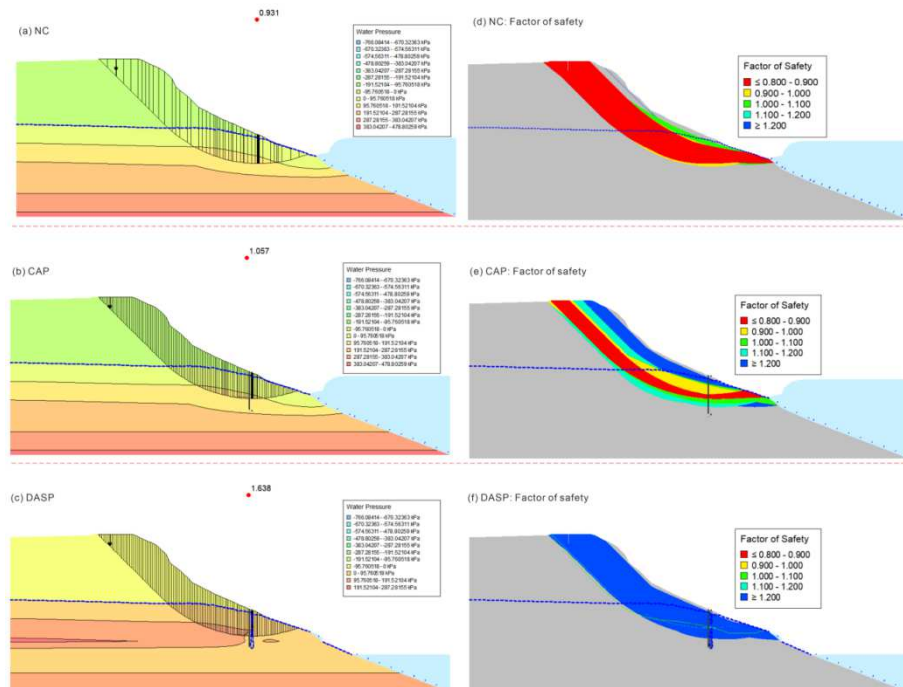


Fig. 11 Stability analysis under NC, CAP and DASP conditions: (a-c) critical slip surfaces and F_s values (0.931, 1.057 and 1.638, respectively); and (d-f) zoned factor-of-safety maps

Slope stability differed markedly among the three support conditions. In the representative stability

maps (Fig. 11), F_s increased from 0.931 under NC to 1.057 under CAP and 1.638 under DASP, showing a progressive improvement from a near-critical untreated state to a mechanically stabilized state and then to a drainage-reinforced stable state. During the 0-20 h rainfall period shown in the time-series analysis (Fig. 12), F_s decreased in all cases because rainfall infiltration reduced matric suction. During the post-rainfall period (20-48 h), F_s continued to decrease because of delayed moisture redistribution. NC had the lowest stability, with the time-series F_s decreasing to 0.701 and showing high sensitivity to seepage-field changes. CAP increased the time-series F_s from 1.32 to 1.044 through mechanical resistance, but because it could not reduce high pore-water pressure within the slope, its post-rainfall decline trend remained nearly parallel to that of NC. DASP produced the most favorable response: the free-outflow boundaries around the pile reduced pore-water pressure near the potential sliding zone, slowed stability degradation, and kept the reinforced slope in an overall stable state. In this sense, the main contribution of DASP is not the simulation of a smaller post-treatment landslide, but prevention of the through-going source area that supplied the hazardous NC run-out.

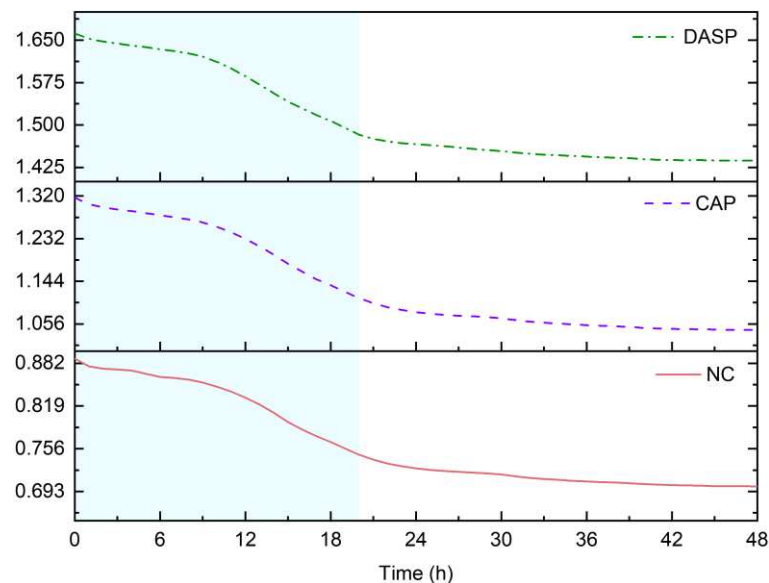


Fig. 12 Variation in factor of safety under different stabilization measures during and after rainfall. The blue shaded area indicates the rainfall period

To characterize the time-dependent stability response during rainfall and post-rainfall seepage, the rate of safety-factor change, dF_s/dt , was introduced. A negative value indicates a decrease in F_s with time, and a larger absolute value indicates faster stability degradation. This index identifies critical periods of rapid F_s decline and compares the sensitivity of different protection conditions to rainfall infiltration. Fig.

13 shows the dynamic evolution of dF_s/dt over 48 h for NC, CAP and DASP. Throughout the period, the rates remained negative. During the 0-20 h rainfall stage, their absolute values showed a double-peak pattern. From 0 to 5 h, the absolute values first increased rapidly and then briefly decreased, forming the first secondary peak near 3-4 h. After 9-10 h, all three curves dropped sharply again, with peak absolute rates around 14-15 h.

Before rainfall stopped at 20 h, CAP showed the deepest trough, approximately -0.018, followed by NC at approximately -0.013. The DASP trough was approximately -0.015, and its curve from 10 to 20 h remained clearly above that of CAP. After rainfall stopped, the rates in all three conditions quickly approached zero and showed weak, gradually attenuating oscillations during 24-48 h, finally approaching zero at 48 h.

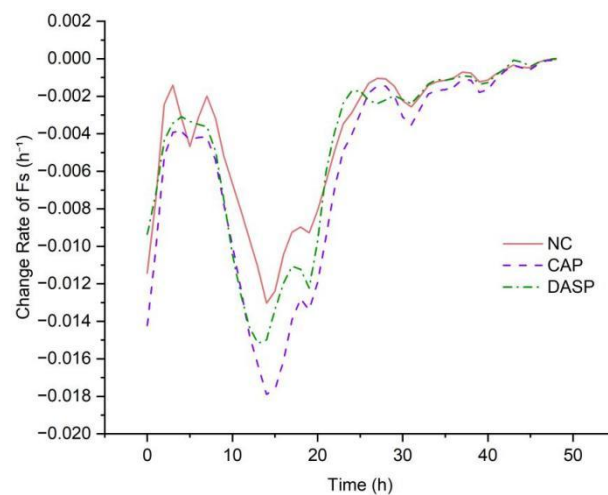


Fig. 13 Rate of change in factor of safety under NC, CAP and DASP conditions during the 48 h rainfall-response simulation

At approximately 14 h, CAP had the largest absolute decrease rate of F_s , followed by DASP, whereas NC showed a smaller rate. This is because NC had already entered a low safety-reserve state during the early to middle rainfall stage; strength degradation along the potential sliding zone had nearly developed, and subsequent F_s reduction gradually converged. CAP provided mechanical support, but pore-water pressure around the pile continued to accumulate, causing rapid effective-stress loss in the later rainfall stage. DASP reduced the growth rate of pore-water pressure near the potential sliding zone through pile-side collection and drainage holes, resulting in a smaller post-rainfall stability degradation than CAP.

5 Discussion: application of drainage anti-sliding technology in

loess slopes

The front-positioned Massflow simulation establishes the consequence baseline for the untreated slope: once the through-going NC source is released, the large volume of wet loess can evolve into a long tongue-shaped run-out and enter the river channel. The GeoStudio results then explain how this hazard chain can be controlled before large-scale movement begins. CAP improves stability mainly by mechanical interception, but elevated pore-water pressure may still reduce the safety reserve during and after rainfall. DASP acts one step earlier in the hazard chain by lowering pore-water pressure around the piles and near the potential sliding zone, restoring effective stress and suppressing the formation of the deep through-going source. Therefore, the mitigation mechanism identified here is source-control based. DASP reduces the material supply required for long-distance movement, rather than merely blocking an already moving landslide mass.

The coupled SEEP/W-SLOPE/W results further show that F_s did not immediately stop decreasing after short-duration intense rainfall ended. The reason is that rainfall cessation does not mean that internal seepage has ended. During 0-20 h, infiltration mainly reduced shallow negative pore-water pressure and increased local pore pressure near the rear-edge fissure. During 20-30 h, surface water and previously infiltrated water continued to redistribute downward along vertical fissures, preferential pathways and the top of the weakly permeable layer, allowing the pore-pressure response to reach deeper potential sliding zones. During 30-48 h, internal pore-pressure gradients gradually weakened, but high water content could persist near the weakly permeable silty clay boundary, causing delayed stability degradation. Field monitoring and model tests have similarly shown strong spatiotemporal heterogeneity in rainfall-induced loess landslides, with wetting-front and pore-pressure responses continuing after rainfall and stronger lag effects often occurring near the toe and middle-lower slope [33-35]. For CAP, high pore-water pressure around piles during intense rainfall may weaken pile-soil interaction and reduce subgrade reaction [36]. DASP, however, lowers the local phreatic line around piles through active drainage and restores effective normal stress along the slip surface [37, 38]. Its engineering performance is therefore jointly affected by rainfall intensity, rainfall duration, antecedent water content, stratigraphic permeability and fissure connectivity.

For slopes with high groundwater levels, strong fissure infiltration or significant pore-pressure response between piles, a double-row or staged drainage anti-sliding pile concept (D-DASP) may be

adopted. In this concept, front and rear pile rows jointly share landslide thrust and form multi-level drainage pathways. The safety-island concept used here should be understood as an engineering zoning concept rather than a claim that no deformation occurs anywhere in the slope: the protected main body remains stable, while a limited front or marginal zone may retain a lower relative safety reserve without propagating into whole-slope instability. Constructing this stable buffer outside the landslide zone is consistent with the pile-position interpretation noted above, in which pile location and parameter configuration directly affect stabilization performance. Complementary measures such as fissure filling, surface anti-seepage treatment and toe drainage may further reduce infiltration into the potential sliding zone, especially where surface runoff can rapidly enter open cracks [39]. This zoning idea is also consistent with previous work emphasizing coupled support and drainage in DASP [40]. However, pile spacing, drain spacing, hole diameter, inclination, filter gradation and anti-clogging capacity should be optimized according to hydraulic conductivity, design rainfall and allowable groundwater drawdown. The present conclusions are mainly applicable to water-sensitive loess slopes and colluvial slopes with a clearly defined potential sliding zone. For rock slopes, strongly three-dimensional convergent-flow slopes or slopes subjected to long-term vibration, the coupled drainage-support effect of DASP should be re-evaluated using site monitoring and dedicated models. Future optimization should further consider the hydraulic coupling between the filling/filter material inside the drainage pile and the basal gravel layer. In DASP, the filling medium controls not only the water-collection capacity of the pile body but also whether the idealized free-outflow boundary used in the present model can be achieved in engineering practice. If the filler permeability is too low, pore-water pressure around the pile may not be released efficiently; if it is too high but lacks proper retention capacity, fine particles from loess may migrate into the drainage channel and reduce long-term discharge capacity. Numerical work on upper-hollow drainage anti-slide piles has shown that the stabilizing effect of drainage-type piles is sensitive to permeability conditions [41], and recent analyses of horizontal drains further indicate that groundwater drawdown and phreatic-line lowering are transient and spatially localized processes controlled by drain geometry, hydraulic conductivity and boundary connection [42]. For the Jiaojiaya No. 13 slope, the gravel layer may serve as a lateral drainage corridor if it is hydraulically connected with the pile drainage channel. Under this condition, water collected by the pile could be discharged into the high-permeability gravel layer, lowering the local phreatic line near the pile rows and reducing the hydraulic gradient toward the potential sliding

zone. Therefore, future design should test the sensitivity of water-level drawdown to filler permeability, gradation, porosity, hydraulic contact with the gravel layer and outlet elevation. The permeability of granular drainage media is strongly related to grain-size distribution, effective diameter and grading coefficient [43], whereas fine-particle clogging can reduce filter permeability and drainage capacity over time [44]. Thus, the DASP drainage boundary adopted in this study should be regarded as an effective-drainage scenario, and subsequent engineering design should be supported by filter-material tests, anti-clogging evaluation and long-term monitoring of groundwater levels around the pile-gravel drainage system.

6 Conclusions

This study first assessed the untreated run-out hazard of the Jiaojiaya No. 13 loess slope using Massflow, and then evaluated the stability-control effects of CAP and DASP using SEEP/W and SLOPE/W. The main conclusions are as follows.

1. Rainfall infiltration in the loess slope showed three stages. During the first 20 h of rainfall, infiltration was limited by the high matric suction of unsaturated loess. During 20-30 h after rainfall cessation, surface water provided a continued hydraulic head and drove the wetting front downward. During 30-48 h, infiltration rate decreased substantially as the slope approached a new seepage equilibrium. This staged behavior identifies a critical post-rainfall window during which slope stability may continue to deteriorate even after surface rainfall has stopped.

2. In the time-series stability analysis under the simulated rainfall event, F_s under NC decreased to 0.701, indicating deep-seated instability risk. CAP increased F_s to 1.044 through mechanical resistance. However, CAP could not dissipate elevated pore-water pressure within the slope, and its post-rainfall F_s decay trend was nearly parallel to that under NC; therefore, neither NC nor CAP reached the target safety threshold in the post-rainfall response.

3. DASP suppressed the formation of a through-going slip surface through the combined action of mechanical resistance and internal drainage. In the representative stability map, F_s reached 1.638 under DASP, much higher than NC (0.931) and CAP (1.057). The continuous low-reserve source zone was reduced to a limited local zone, and the overall slope changed from near-critical through-going instability to an overall stable state with substantially enhanced safety reserve. The drainage structure

locally lowered the phreatic line, restored effective normal stress along the potential slip surface and slowed rainfall-induced stability degradation.

4. Massflow simulations of the untreated NC slope showed that approximately $12.0 \times 10^4 \text{ m}^3$ of unstable material could move over a maximum distance of 504.4 m, with an effective deposition volume of approximately $11.83 \times 10^4 \text{ m}^3$. The sliding mass entered the adjacent river channel, indicating significant river-intrusion risk and confirming the need for source-area stabilization before failure.

5. DASP improved slope stability through coupled drainage-pressure reduction and mechanical resistance. Its hazard mitigation effect should be understood mainly as prevention of the large through-going source area identified under NC. For water-sensitive loess slopes controlled by rainfall infiltration and groundwater, mitigation design should therefore consider both factor-of-safety improvement and source-volume control.

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Author contributions

L.W. and W.W. conceived the study. L.W. performed the numerical modelling and drafted the manuscript. F.G., X.F., R.L., J.L. and K.Y. contributed to data collection, interpretation and manuscript revision. All authors reviewed and approved the manuscript.

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Data availability

The data used in this study are available from the corresponding author upon reasonable request, subject to project and institutional restrictions.

Declarations

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