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MPM Mathematical Modeling and Numerical Simulation for the Restart Mechanism of Retrogressive Loess Landslides

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Abstract. A two-dimensional MPM model of unsaturated two-phase hydro-mechanical coupling was established to address the restart problem of retrogressive loess landslides under irrigation infiltration conditions, with zoning parameters for the disturbed zone and stable zone as well as periodic irrigation conditions set. The results show that the pore pressure in the disturbed zone responds more rapidly, forming a continuous high pore pressure zone from 0.5 s to 25 s, with the first displacement penetration and shear localization occurring at 155 s and 162 s respectively; concentrated deformation reoccurs at the new rear edge and the landslide restarts at 625 s, 700 s and 900 s. The model well reveals the chain mechanism of "sliding-disturbance-seepage-resliding".

Keywords: Material Point Method, retrogressive loess landslides, restart mechanism, unsaturated seepage, numerical simulation

1. Introduction

Loess has typical engineering characteristics such as macroporosity, weak cementation, well-developed vertical joints and remarkable water sensitivity. Under the action of rainfall or irrigation infiltration, it is prone to structural damage, attenuation of matric suction and reduction of shear strength, thus inducing geological hazards like landslides and collapses [1]. For the high and steep slopes at the edge of loess tablelands, their instability process is often not a one-time overall failure, but more commonly presents the retrogressive evolution characteristics from local initiation and rear edge migration to multi-stage propagation. This evolutionary process essentially involves the coupling among unsaturated seepage, structural deterioration and large deformation response, which is a typical nonlinear problem of multi-field coupling. Therefore, it is necessary to carry out targeted research from the perspective of mathematical modeling and numerical simulation.

In the loess tableland areas of China, irrigation-induced landslides are one of the most representative water-induced disaster types. Taking the South Jingyang Tableland and Heifangtai Terrace as examples, long-term diversion irrigation has significantly changed the hydrogeological conditions of the tableland and slope mass, continuously recharging groundwater and enhancing the infiltration and seepage activities inside the slope mass, thus leading to frequent landslides at the tableland edge, which generally exhibit retrogressive characteristics such as re-failure of the rear wall of old landslides, continuous retreat of the rear edge and multi-stage chain propagation [2-6].

Existing studies have pointed out that the occurrence and development of loess landslides under irrigation conditions are not instantaneous instability triggered by a single external load, but a continuous evolutionary process jointly controlled by various factors such as groundwater level rise, preferential infiltration, local liquefaction and disturbance from previous sliding [3-6].

Regarding the formation mechanism of irrigation-induced loess landslides, existing studies have achieved important progress from the aspects of field investigation, laboratory tests, geophysical prospecting and numerical analysis. Relevant results show that the fractures and rear edge disturbed zone formed by previous sliding can provide new preferential infiltration channels for surface water, and under the condition of continuous infiltration, they promote the local formation of relatively high pore water pressure and stronger structural damage in the slope mass [3-5]. However, the existing research still lacks a systematic understanding of how "the previous disturbance evolves into a new high-permeability and low-strength weak zone and further controls the restart"; there is also a shortage of a quantitative framework that can uniformly explain the retrogressive chain instability process for the connections among the microstructural changes of loess, permeability evolution, pore pressure accumulation and macroscopic instability [5,6].

Aiming at the problems of large displacement and localization in landslide initiation and propagation, the Material Point Method (MPM) combines the advantages of Eulerian background grid and Lagrangian material point description, and has been widely used in the analysis of progressive slope failure and large deformation in recent years [7,8]. Compared with the traditional finite element method, MPM is more suitable for dealing with complex processes such as sliding surface penetration, block separation and post-failure movement; at the same time, after coupling with the seepage control equation, it can further simulate multi-field coupling responses such as unsaturated infiltration, pore pressure evolution and retrogressive instability [7,8]. Nevertheless, for irrigation-induced retrogressive loess landslides, few existing studies have integrated field understanding, zoning parameter characterization and restart mechanism analysis into a unified MPM calculation framework.

Based on this, this paper takes the restart problem of retrogressive loess landslides as the research object and constructs a hydro-mechanical coupling MPM mathematical model for continuous infiltration conditions. Combined with the zoning characteristics of retrogressive instability of loess slopes, the parameters of the disturbed zone and stable zone are characterized to simulate the continuous evolutionary process of pore water pressure accumulation, deformation localization, rear edge migration and resliding. Furthermore, the chain mechanism of "previous disturbance-enhanced seepage-local instability-rear edge migration-restart" is revealed from the perspective of numerical simulation, providing a reference for the analysis of nonlinear multi-field coupling responses of loess slopes.

2. Model and parameters

2.1. Model generalization and coupling framework

To analyze the restart process of retrogressive loess landslides under continuous infiltration conditions, a two-dimensional slope numerical model was established in this paper. Considering that previous sliding will form a local area with structural damage and enhanced seepage sensitivity near the rear edge, the slope mass is divided into two material domains, namely the landslide disturbed zone and the stable zone, to characterize the influence of previous disturbance on the subsequent infiltration response and instability evolution. The model has a total length of 50 m, a height of 10 m and a slope angle of approximately 30°; triangular elements are adopted for the background grid with a characteristic size of 0.5 m, and 3 material points are arranged in each element, with a total of about 50,000 material points (Fig.1). This generalization method can well describe the evolutionary processes such as large deformation of the slope mass, sliding surface penetration and rear edge migration while ensuring calculation efficiency. This paper adopts the MPM calculation framework of unsaturated two-phase hydro-mechanical coupling, and solves the deformation of soil skeleton and migration of pore water synchronously under the continuum medium description to simulate the continuous evolutionary process of pore water pressure accumulation, deformation localization and landslide restart during irrigation infiltration. The solid skeleton is described by the Modified Cam-Clay Model, and the unsaturated hydraulic behavior is characterized by the soil-water characteristic curve and relative permeability function. This method combines the advantages of Eulerian background grid and Lagrangian material point description, and can well handle large deformation problems such as sliding surface penetration, block separation and post-failure movement [7,8].

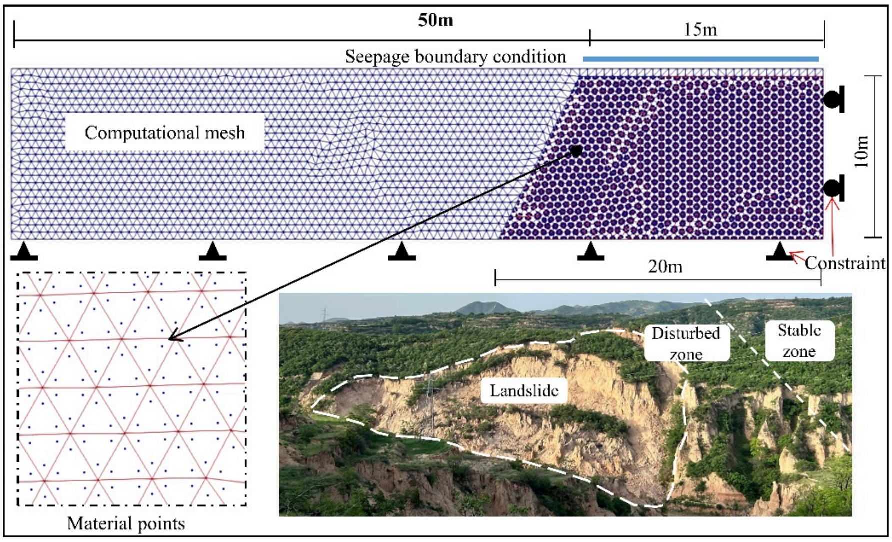

Figure 1. Geometric model and zoning of the numerical simulation

2.2. Boundary conditions and irrigation conditions

The infiltration flux boundary is applied on the top and slope surface of the model to simulate the hydraulic effect of continuous surface water recharge to the slope mass during irrigation; the bottom and side boundaries are set as impermeable boundaries to avoid the interference of lateral and bottom seepage loss on the results; the slope surface is set as a potential seepage surface to characterize the free drainage process that may occur after local saturation. The initial groundwater level is set 5 m below the slope toe, the initial pore water pressure is given according to hydrostatic distribution, and the initial matric suction is uniformly set to 50 kPa. To convert the irrigation activities in the study area into computable hydrological boundary conditions, the equivalent rainfall approach is adopted in this paper to uniformly characterize irrigation infiltration. According to the irrigation intensity data of the study area, the infiltration flux of the model is set to q=0.45 $\mathrm{mL \cdot min^{-1}}$, corresponding to an equivalent infiltration intensity of about 6.5 mm/d, which is continuously applied on the top and slope surface of the slope. To simulate the periodic irrigation process within a limited calculation time, the calculation sequence is compressed according to three irrigation-ceasing cycles in one year, divided into 6 stages, with odd stages as irrigation periods and even stages as ceasing periods; 300 steps are set for each stage with a time step of 0.5 s, totaling 1,800 steps and a total duration of 900 s. This setting aims to highlight the evolutionary characteristics of pore pressure accumulation, hysteretic dissipation and progressive landslide instability under the alternating action of irrigation and ceasing.

2.3. Parameter setting and zoning assignment

Since this paper focuses on the numerical reproduction of the restart mechanism rather than parameter inversion or experimental identification, the model parameters adopt the commonly used value range in existing numerical studies of loess slopes, and representative assignment is carried out combined with the zoning characteristics of the restart problem of retrogressive landslides. To highlight the control effect of disturbance from previous sliding, the disturbed zone is set with a parameter combination of lower stiffness, lower strength and higher permeability compared with the stable zone. Among them, the elastic moduli of the disturbed zone and the stable zone are 12 MPa and 20 MPa respectively, the Poisson's ratios are 0.32 and 0.30 respectively, and the saturated permeability coefficients are 8×10^{-6} m/s and 3×10^{-6} m/s respectively; for the parameters of the soil-water characteristic curve, α and n of the disturbed zone are 0.012 kPa^{-1} and 1.60 respectively, while those of the stable zone are 0.009 kPa^{-1} and 1.45 respectively. To reflect the weakening effect induced by infiltration, the shear strength parameters of the two zones are given according to the saturated state: the cohesion and internal friction angle of the disturbed zone are 17.02 kPa and 11.25° respectively, and those of the stable zone are 21.81 kPa and 12.12° respectively. This zoning assignment makes the disturbed zone more likely to form pore pressure concentration and local instability under continuous infiltration, thus providing a parameter basis for analyzing the chain evolution of "disturbance-seepage-resliding".

3. Result analysis

3.1. Evolution characteristics of pore water pressure

Under the boundary conditions and irrigation conditions described in Chapter 2, the pore water pressure of the slope mass shows obvious stage characteristics and zoning differences. As shown in Fig.2, during the first irrigation period (0–150 s), at the initial simulation time of 0.5 s, the pore water pressure response first appears in the slope top area, and water infiltrates preferentially along vertical preferential channels and accumulates rapidly in the landslide disturbed zone. With the infiltration advancing to 10 s, the pore water in the upper part of the disturbed zone moves downward rapidly along the macropore network, and the pore pressure rise begins to appear in the slope toe area, indicating that the rear edge disturbed zone has become a preferential infiltration and water accumulation area. At 25 s, the pore water pressure in the disturbed zone is basically connected up and down, forming a continuous high pore pressure zone, the effective stress of the soil mass is significantly weakened, and the overall strength decreases rapidly. In contrast, due to the relatively dense pore structure, the stable zone has slow infiltration progress and relatively intact soil structure, with only limited pore pressure response in the shallow layer; at the same time, part of the infiltrated water recharges the disturbed zone laterally from the stable zone along interlayer interfaces or fractures, further aggravating the hydraulic accumulation in the disturbed zone.

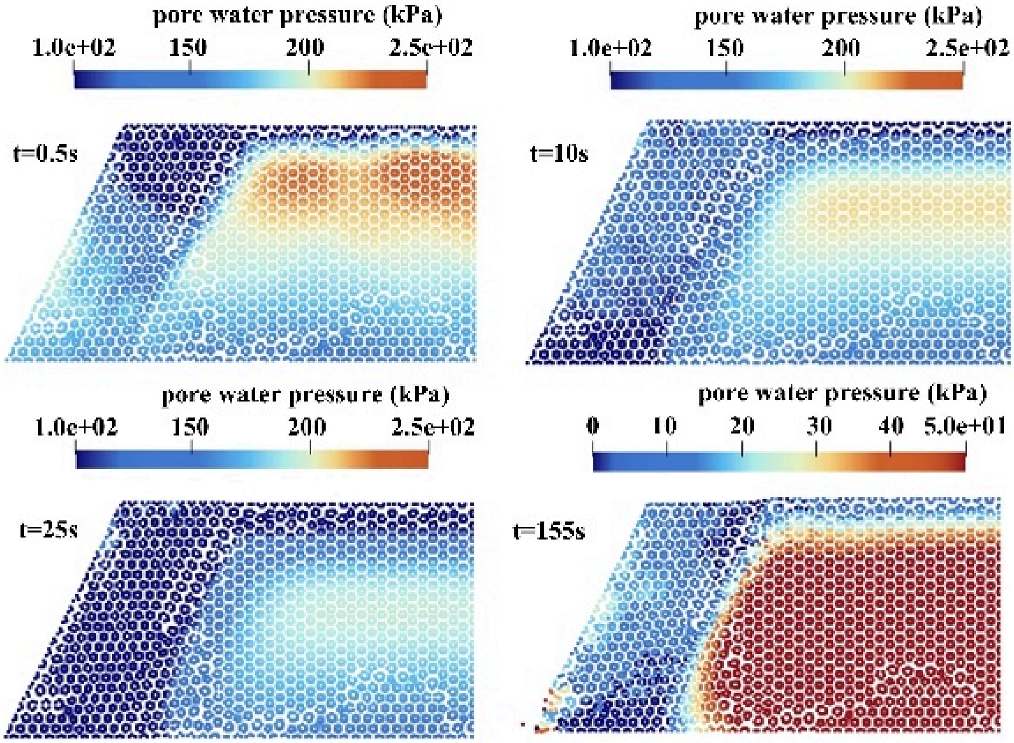

Figure 2. Evolution of pore water pressure at different times

During the first ceasing period (150–300 s), the high pore water pressure accumulated at the slope toe does not dissipate immediately, but continues to infiltrate upward in the reverse direction, forming a hydraulic redistribution process dominated by the high pore pressure zone at the bottom. This paper emphasizes that the hysteretic dissipation of pore pressure after irrigation ceasing will still promote the further deterioration of soil strength and make the landslide hysteresis effect begin to appear. That is to say, the high pore pressure formed during the irrigation period will not recover rapidly with the stop of the external infiltration boundary, but will continue to adjust inside the slope mass and maintain an unfavorable effective stress state. It can be seen that the first irrigation-ceasing process has completed the entire pore pressure evolution chain of "slope top infiltration-disturbed zone water accumulation-slope toe pressure rise-redistribution after irrigation ceasing", laying a hydraulic foundation for the subsequent localized deformation and landslide initiation.

3.2. Deformation localization and initial sliding

The continuous accumulation of pore pressure further drives the development of shear localization inside the slope mass (Fig.3). According to the description in this paper, during the first ceasing period, at 162 s, an obvious shear localization zone first appears in the upper middle part of the landslide disturbed zone, characterized by the continuous concentration of high deviatoric strain values, marking the initial formation of the potential sliding surface. This indicates that the structural damage zone caused by previous sliding is prone to strain localization under continuous hydraulic action, becoming the weak part of the initial sliding. At the same time, the results of the displacement field show that the displacement penetration zone formed by the initial sliding appears at 155 s, and its spatial position corresponds to the continuous displacement concentration zone extending from the slope toe of the disturbed zone to the inside of the slope mass, indicating that the slope mass has entered the sliding penetration stage from the previous progressive deformation. Correlating the displacement penetration at 155 s with the shear localization at 162 s, it can be seen that the initial sliding is not an instantaneous occurrence, but a continuous evolutionary process experiencing pore pressure accumulation, slope toe displacement concentration, shear zone formation and sliding surface penetration.

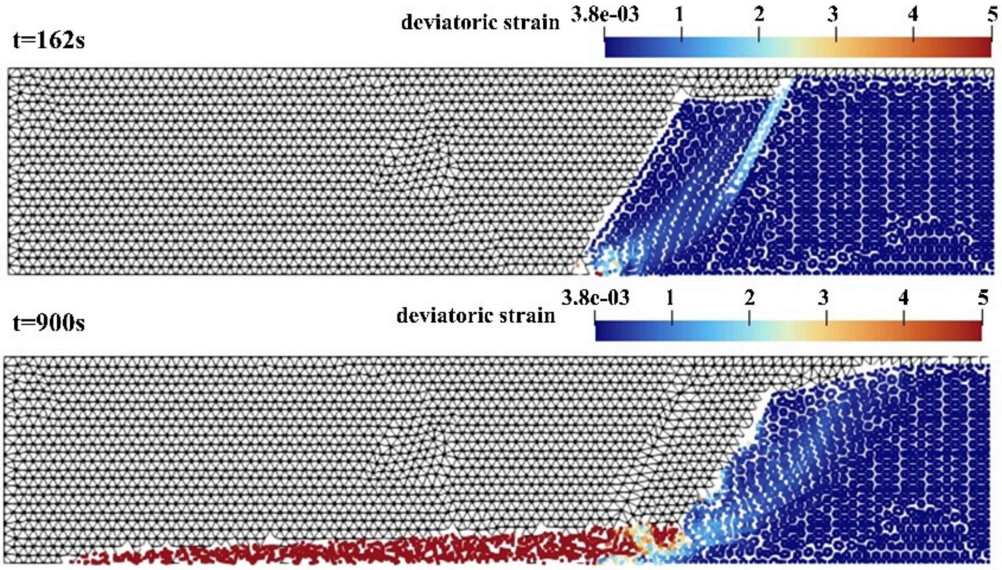

Figure 3. Distribution of deviatoric strain at different times

3.3. Rear edge migration and resliding

After the initial sliding, the landslide rear wall is exposed and gradually transformed into a new disturbed zone, and the instability control position of the slope mass begins to migrate to the rear edge. The key time points given in this paper show that in the middle of the third irrigation period at 625 s, a highly continuous displacement concentration zone appears again at the slope toe of the new disturbed zone, and its morphology is similar to the displacement response at the slope toe of the disturbed zone before the initial sliding, indicating that the new rear edge has possessed the mechanical conditions for re-instability under continuous infiltration. At 700 s in the third ceasing period, the displacement concentration zone further expands upward and penetrates, forming a second long-scale displacement concentration zone, and the sliding range expands significantly toward the rear edge. Compared with the displacement penetration zone formed by the initial sliding (155 s), the spatial position of the displacement penetration zone at 700 s has moved significantly backward, and the sliding volume of the two times is equivalent, which well reflects the kinematic characteristics of step-by-step retreat and chain instability of retrogressive landslides.

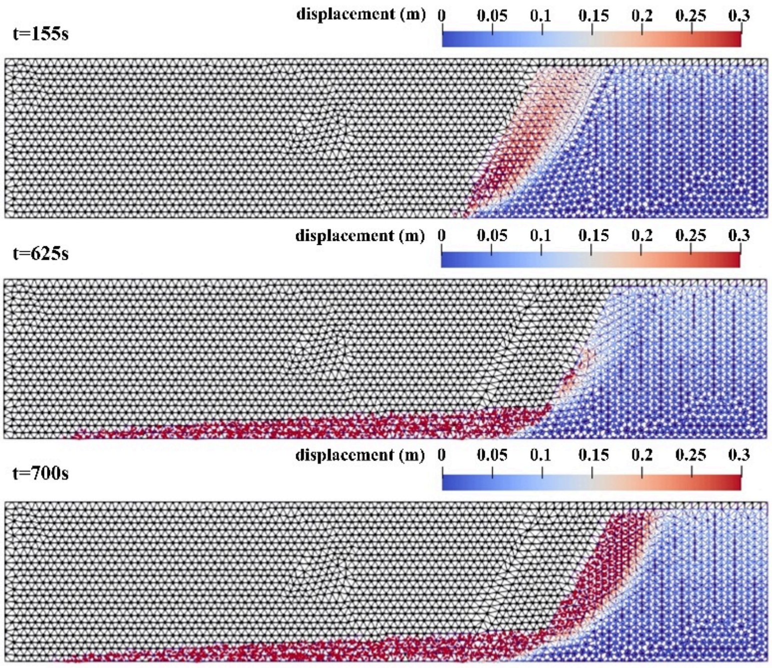

Figure 4. Distribution of displacement at different times

In addition to the displacement response, the deviatoric strain field also records the re-localization process after the rear edge migration (Fig.4). This paper points out that as the simulation enters the later stage, at 900 s, an obvious shear localization zone appears again in the newly formed disturbed zone. Compared with the first shear zone appearing at 162 s, the position of the shear zone at 900 s has moved significantly toward the rear edge of the slope mass, the sliding surface depth is relatively shallow, but the degree of deviatoric strain concentration is still significant, indicating that the new disturbed zone has possessed the mechanical conditions for re-instability. The evolution of the shear zone from 162 s to 900 s and the evolution of the displacement penetration from 155 s to 700 s jointly reveal that the landslide follows the retrogressive development path of "slope toe localization-slope mass penetration-rear edge migration-resliding". In other words, a single sliding does not terminate the instability process, but forms a new disturbed zone, which continues to trigger new localization and resliding in the subsequent irrigation-ceasing cycles.

4. Discussion

4.1. Control effect of the disturbed zone on retrogressive restart

The numerical simulation results show that the landslide disturbed zone is the core control unit in the process of retrogressive restart. Compared with the stable zone, the disturbed zone exhibits faster pore pressure response, earlier displacement concentration and more obvious shear localization characteristics under irrigation infiltration conditions, which indicates that the structural damage formed by previous sliding is not a "residual result" after one-time failure, but a direct control condition for subsequent re-instability. It can be seen from the results in Chapter 3 that the pore pressure first appears at the slope top and the upper part of the disturbed zone at 0.5 s, an obvious downward infiltration channel is formed in the upper part of the disturbed zone at 10 s, and the high pore pressure zone is basically connected at 25 s; correspondingly, the first displacement penetration zone appears at 155 s, and an obvious shear localization zone is formed at 162 s, indicating that the disturbed zone has experienced a continuous evolution of "preferential infiltration-pore pressure accumulation-displacement concentration-localization penetration". In other words, the disturbed zone has both hydraulic weakness and mechanical weakness, and their coupling effect determines that the initial sliding is preferentially initiated from this zone.

This understanding is in good agreement with existing field studies. Based on the 2D/3D resistivity tomography results of Heifangtai Terrace, Zeng et al. pointed out that the conventional infiltration depth in thick loess is limited, but fractures, sinkholes and existing landslide deposits can form rapid water-conducting channels and cause water accumulation at the slope toe of landslides and existing landslide sites, thus inducing new slope mass instability; they also clearly pointed out that previous landslides will change the subsequent hydrological processes of the slope mass and may continuously trigger new slope mass failure at the existing landslide sites [9]. This is highly consistent with the law of "preferential water accumulation in the disturbed zone, hysteretic dissipation of pore pressure after irrigation ceasing and continuous instability in subsequent stages" obtained from the simulation in this paper. For the retrogressive loess landslides on the South Jingyang Tableland, the rear edge disturbed zone caused by previous sliding can be understood as a local area with highly connected pores, high seepage sensitivity and low strength reserve. Under the background of periodic irrigation, it will continuously amplify the hydro-mechanical coupling effect and ultimately control the temporal and spatial positions of the restart.

4.2. Chain evolution mechanism of the multi-stage sliding process

From the perspective of the whole process, the simulation results of this paper clearly reveal the chain evolution mechanism of retrogressive loess landslides, namely "irrigation infiltration-pore pressure accumulation-initial sliding-rear edge re-disturbance-resliding". Among them, the key stage before the initial sliding is the formation of the high pore pressure zone and shear localization zone; the key stage after the initial sliding is the rapid deterioration of the new rear edge. Specifically, after the first sliding occurs, a new free face is formed on the landslide rear wall, the stress of the soil mass at the rear edge is redistributed under the action of unloading, and at the same time, the subsequent irrigation water continues to infiltrate along fractures and highly connected pore channels, making the newly exposed rear edge gradually transform from a relatively intact zone into a new disturbed zone. A continuous displacement concentration zone appears again at the slope toe of the new disturbed zone at 625 s, a second long-scale displacement concentration zone is formed at 700 s, and an obvious shear localization zone appears again in the new rear edge at 900 s, indicating that the landslide control position has migrated from the original disturbed zone to the interior of the tableland. It can be seen that retrogressive landslides are not a simple superposition of several independent sliding events, but a continuous chain process in which a single sliding continuously "creates" new weak zones and promotes the occurrence of the next sliding under continuous infiltration conditions.

From the perspective of numerical methods, the key for this paper to completely reproduce this process lies in the adaptability of MPM to large deformation and multi-field coupling problems. In a 2024 review, Zheng et al. pointed out that MPM has become an important method for dealing with large-deformation hydro-mechanical coupling problems in two-phase porous geomaterials in recent years, and its advantage lies in its ability to simultaneously handle large solid displacement, pore fluid migration and the continuous evolution of free surfaces/slip interfaces, which is especially applicable to the processes of progressive slope failure, local zone development and subsequent movement [10]. This evaluation is highly consistent with the simulation object of this paper: if only small-deformation analysis or a single limit equilibrium framework is adopted, it is difficult to connect these key nodes such as 155 s, 162 s, 625 s, 700 s and 900 s into the same evolution chain; while under the coupled MPM framework, pore pressure rise, displacement penetration, shear zone migration and rear edge retreat can be uniformly incorporated into the same calculation system, thus explaining the restart mechanism of retrogressive loess landslides on the South Jingyang Tableland more effectively.

4.3. Model significance and limitations

It should be noted that the focus of this paper is to reveal the restart mechanism rather than to make an accurate prediction of a single landslide. Therefore, a certain degree of idealized expression is still adopted in the model in terms of geometric generalization, parameter selection and boundary condition treatment. For example, this paper adopts a two-dimensional slope model to characterize the rear edge profile of retrogressive landslides, the irrigation process is uniformly applied through the equivalent infiltration flux, and the parameters adopt zoning representative values rather than field inversion values. These treatments help to highlight the control effect of the differences between the disturbed zone and the stable zone on the restart process, but also mean that the simulation results are more suitable for mechanism explanation rather than quantitative prediction in the strict sense.

Nevertheless, the model in this paper still has clear application significance. First, it transforms "previous disturbance" from empirical judgment into computable zoning conditions, and reproduces the causal chain among pore pressure evolution, displacement concentration, shear localization and rear edge migration in the same framework; second, it provides a basis for understanding the key points of prevention and control of irrigation-induced retrogressive loess landslides, that is, the governance object should not be limited to the already sliding zone itself, but special attention should be paid to the water control and disturbance reduction of the new disturbed zone at the rear edge; third, the model provides a basis for the subsequent introduction of more refined 3D terrain, parameter inversion and monitoring data coupling. For a short conference paper, the value of this paper mainly lies in proving that even in a relatively simplified numerical framework, the core mechanism of "step-by-step retreat of the rear edge" of retrogressive loess landslides can be well explained as long as the evolution of the disturbed zone and the action of periodic infiltration are explicitly considered.

5. Conclusions

(1) Based on the MPM calculation framework of unsaturated two-phase hydro-mechanical coupling, a two-dimensional numerical model of loess slopes considering the zoning characteristics of the disturbed zone and stable zone was established in this paper, and periodic irrigation infiltration, pore water pressure evolution and large deformation response of the slope mass were uniformly incorporated into the same analysis system. The model can well characterize the continuous evolutionary characteristics of multi-field coupling, localization development and rear edge migration in the restart process of retrogressive loess landslides.

(2) The numerical results show that the disturbed zone formed by previous sliding exhibits faster pore pressure response and earlier deformation concentration under continuous irrigation. The pore pressure first appears at the slope top and the upper part of the disturbed zone at 0.5 s, an obvious downward infiltration channel is formed at 10 s, and the high pore pressure zone is basically connected at 25 s; subsequently, the first displacement penetration zone appears at 155 s, and an obvious shear localization zone is formed at 162 s, indicating that the initial sliding has experienced

a progressive development process of "preferential infiltration-pore pressure accumulation-displacement concentration-sliding surface penetration".

(3) After the initial sliding, a new free face is formed on the landslide rear wall, which gradually transforms into a new disturbed zone under the action of subsequent infiltration. A continuous displacement concentration zone appears again at the slope toe of the new rear edge at 625 s, a second displacement penetration zone is formed at 700 s, and an obvious shear localization zone appears again in the new rear edge at 900 s, indicating that the landslide control position continuously migrates backward. The simulation well reproduces the chain evolution mechanism of "sliding-disturbance-seepage-resliding" and reveals the internal dynamic process of step-by-step retreat of irrigation-induced retrogressive loess landslides.

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