



# Effects of Loess sinkholes Development on Loess Slope Stability Under Rainfall Infiltration Conditions

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**Abstract.** Loess sinkholes are one of the common diseases on loess slopes. To study the influence of loess sinkholes on the stability of loess slopes under rainfall conditions, indoor artificial rainfall simulation tests were carried out based on the rainfall similarity criterion. The corresponding laws of the influence of loess sinkholes on the rainfall infiltration of slopes and the impact on slope deformation were analyzed. The ABAQUS software was used to analyze the displacement development and stability of loess slopes with and without loess sinkholes under the same rainfall conditions.

**Keywords:** Sinkhole, Loess slope, Rainfall, slope stability

## 1 Introduction

Landslides represent one of the most significant geological hazards affecting loess slopes [1], causing substantial economic losses and posing serious threats to human lives in affected regions. Most landslides occur during or immediately after rainfall events, with precipitation being identified as a critical triggering factor [2]. As a unique geological feature in loess regions, sinkholes exacerbate severe soil erosion [3] and fundamentally alter rainwater infiltration pathways within slope structures during precipitation events [4]. This hydrological modification leads to increased water content and reduced shear strength in lower slope strata. When developed to critical dimensions under intense rainfall conditions, sinkholes may directly initiate or accelerate slope failure mechanisms [5], demonstrating that sinkhole evolution significantly impacts slope stability [6]. For slope stability analysis, this study employs the finite element strength reduction method [7], which enables comprehensive evaluation of stress-strain behavior in soil masses based on constitutive relationships, proving particularly suitable for slope stability assessments [8]. The strength reduction technique has gained widespread application in contemporary slope stability research [9].

Current investigations into loess sinkholes remain fragmented across various research priorities, failing to establish systematic connections between sinkhole development processes and critical engineering challenges such as slope instability or transportation infrastructure failures. In practical engineering contexts, however, sinkhole presence poses substantial risks to structural safety, potentially inducing slope

destabilization and roadbed collapse. This underscores the imperative for rigorous investigation into how sinkholes influence loess slope stability under rainfall conditions, particularly regarding their role in hydrological processes and mechanical degradation mechanisms.

## 2 Physical Model Test of Loess Slope under the Action of Rainfall

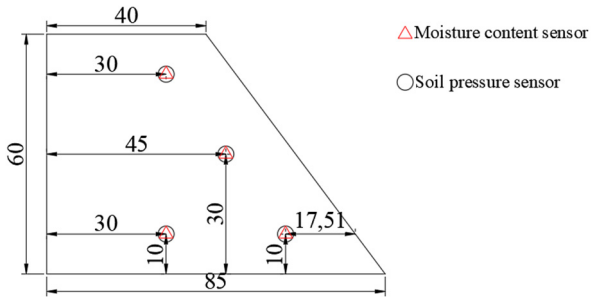
### 2.1 Indoor Model Setup

The soil samples in this experiment were sourced from the prototype slope. Indoor geotechnical test analysis revealed that they featured a good particle gradation, belonging to typical loess - like silty soil with a natural moisture content of around 12%, and the basic physical and mechanical parameters are presented in Table 1. Prior to model preparation, the soil materials retrieved from the field underwent sequential procedures of turning, sun - drying, and smashing, while large - diameter crushed stones, plant roots, and other debris were removed. Given the reduced moisture content of the pre - treated soil, the atomized spraying in combination with turning, mixing, and piling techniques were utilized to accurately adjust the moisture content to approximately 12%. In the filling process, the stratified compaction method was adopted, with the thickness of each loosely - laid layer strictly controlled at 10 cm. The quantity of soil samples needed for each layer was calculated based on the dry density of the filled soil, and these samples were evenly spread in the model box and tamped layer by layer to ensure a compaction degree of 0.85.

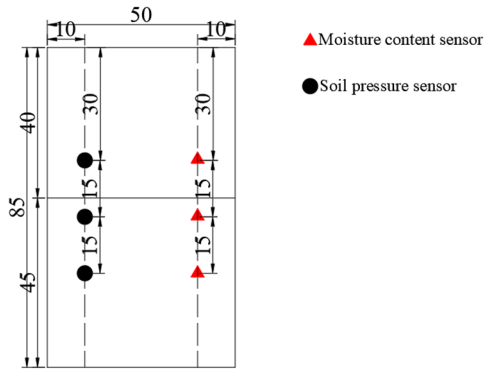
**Table 1.** Physical Parameter Indicators of Loess

natural dry density (g/cm <sup>3</sup> )	natural moisture content (%)	Maximum dry density (g/cm <sup>3</sup> )	Cohesion (kpa)	Internal friction angle (°)
1.47	12	1.65	24	30

Designed according to the similarity ratio theory, the indoor model of the slope has a length of 0.85 m, a height of 0.6 m, a width of 0.5 cm, and a slope gradient of 53°. The prototype rainfall intensity is 20 mm/h, and after calculation, the simulated rainfall intensity is 90 mm/h. The similarity relationship between the prototype and the indoor model is shown in Table 2. A total of two groups of tests are designed. One group is the test of a normal slope, and the other group is the test of a slope with a sinkhole. Both the diameter and the depth of the sinkhole are 10 cm, and its position is 10 cm away from the slope surface at the top of the slope. When filling the model, in order to ensure the uniformity and compactness of the soil, the method of layered filling and controlling the dry density is adopted, and each layer is 10 cm thick for filling. The on-site test photos and the monitoring schematic diagram are shown in Figure 1, and the monitoring points are all placed at the layering positions.



(a)



(b)



(c)

**Fig. 1.** (a) Side View of the Arrangement Position of the Sensors; (b) Top View of the Arrangement Position of the Sensors; (c) On-site Test Diagram

**Table 2.** Similarity Relationship between the Prototype and the Test

Parameters	Prototype	Experiment	scale
Length (m)	$l_p = 17$	$l_m = 0.85$	$C_l = l_p / l_m = 20$
Height (m)	$l_p = 12$	$l_m = 0.6$	$C_l = l_p / l_m = 20$
Rainfall Intensity (mm/h)	$q_p = 20$	$q_m = 90$	$C_q = q_p / q_m = 0.22$
Rainfall Duration (h)	$t_p = 4$	$t_m = 356$	$C_t = t_p / t_m = 89$

## 2.2 Analysis of Phenomena during the Test Process

The failure of the normal loess slope is manifested as progressive overall instability. In the initial stage of rainfall, rainwater infiltrates downward along the vertical joints and large pores, causing the shallow soil of the slope body to become saturated. The self-weight of the soil increases, and its shear strength decreases due to the loss of matric suction, which easily induces local slippage at the toe of the slope. With continuous rainfall, the saturated area expands deeper, and the pore water pressure increases, forming a potential slip surface. Eventually, the slope shows overall collapse in the shape of an arc or steps. Its failure process is relatively slow. The slip surface usually runs through the middle of the slope body to the toe of the slope, and the scale of the collapsed body is large, with obvious progressive characteristics.

For the loess slope with a sinkhole at the slope crest, the sinkhole forms a preferential seepage path, resulting in sudden and locally expanding failure. In the early stage of rainfall, rainwater rapidly infiltrates through the sinkhole, creating a concentrated seepage area at the bottom of the sinkhole. This scours the sinkhole walls and erodes the underlying soil, leading to collapses around the sinkhole. As seepage continues, water spreads deep into the slope along the preferential paths around the sinkhole, intensifying the damage to the soil structure. During this process, vertical cracks appear in the soil beneath the sinkhole due to hydraulic fracturing and connect with the seepage - softened area. Eventually, this triggers a local collapse centered around the sinkhole. The collapsed mass takes on an inverted - cone shape. Subsequently, the loss of support causes a chain reaction, leading to a stepped collapse from the slope crest to the middle of the slope. The failure surface is steep and irregular. As show in figure 2.





(a)

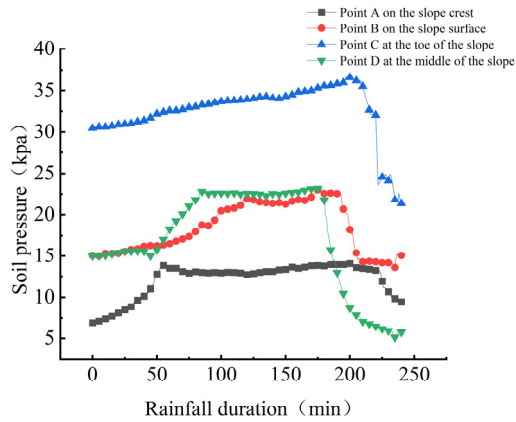


(b)

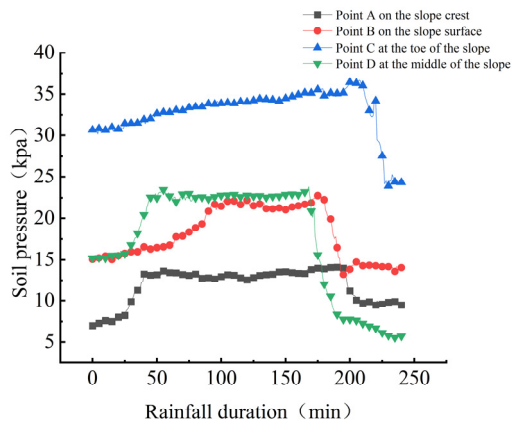
**Fig. 2.** (a) Process Diagram of the Simulation Test for the Normal Slope, (b) Process Diagram of the Simulation Test for the Slope with a Sinkhole

## 2.3 Analysis of Sensor Results

### 2.3.1 Soil Pressure Data Analysis



(a)



(b)

**Fig. 3.** (a) Soil Pressure Data Diagram of the Normal Slope, (b) Soil Pressure Data Diagram of the Slope with Loess sinkholes

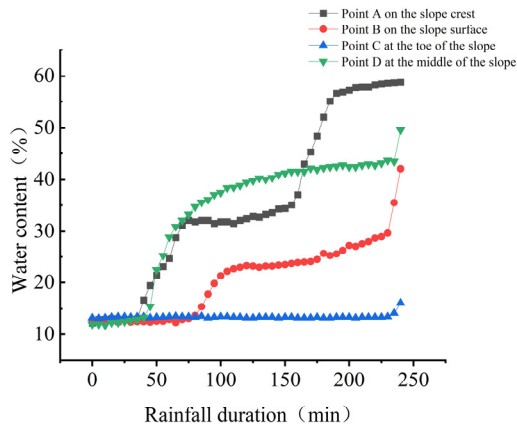
As show in figure 3. In the normal slope, the soil pressure at the monitoring point A on the slope crest increased significantly at the beginning of rainfall, and tended to be stable at around 55 minutes. At about 220 minutes, due to the sliding and collapse of the soil on the slope crest, the soil pressure dropped sharply. The soil pressure at the monitoring point B in the middle of the slope surface was stable at the beginning of rainfall, began to increase obviously at around 50 minutes, tended to be stable at around 80 minutes, and decreased significantly at around 180 minutes due to the rapid sliding

of the soil on the slope surface. The soil pressure at the monitoring point C at the toe of the slope remained basically unchanged within 70 minutes, continued to increase from 70 to 120 minutes, and decreased rapidly at around 190 minutes due to the large-scale sliding of the soil at the toe of the slope. The soil pressure at the monitoring point D at the rear edge of the slope body increased slowly from the beginning of rainfall with a small variation range, and decreased rapidly after 210 minutes due to the large-scale collapse of the whole slope.

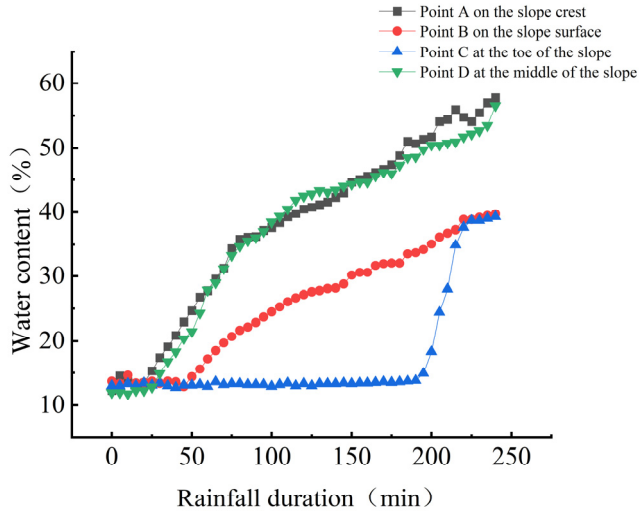
For the slope with a sinkhole, the variation trend of the soil pressure at the monitoring point A on the slope crest was similar to that of the normal slope, but the time when the slope crest began to slide and collapse was advanced by 20 minutes, and the soil pressure dropped at around 200 minutes. The soil pressure at the monitoring point B in the middle of the slope surface also remained stable first, then increased and then became stable again. The time when the soil on the slope surface began to slide was advanced by 10 minutes, and the soil pressure decreased significantly at around 170 minutes. The variation process of the soil pressure at the monitoring point C at the toe of the slope was similar to that of the normal slope. The time when the soil at the toe of the slope began to slide in large quantities was advanced by 10 minutes, and the soil pressure decreased rapidly at around 180 minutes. The variation of the soil pressure at the monitoring point D at the rear edge of the slope body was basically consistent with that of the normal slope. Because the influence of rainfall infiltration on the rear edge of the slope in the depth direction was small, it increased slowly at the beginning of rainfall, and decreased rapidly after 210 minutes due to the overall collapse of the slope.

In conclusion, compared with the normal loess slope, the time when the soil at the slope crest, the middle of the slope surface and the toe of the slope begins to slide is advanced for the loess slope with a sinkhole, indicating that the existence of the sinkhole has a significant impact on the stability of the loess slope, and it is more likely to cause slope instability under the condition of rainfall infiltration.

### 2.3.2 Water Content Data Analysis



(a)



(b)

**Fig. 4.** (a) Water Content Data Diagram of the Normal Slope, (b) Water Content Data Diagram of the Slope with Loess sinkholes

As show in figure 4. In the initial state, the slope soil is unsaturated soil with a water content of about 12%. As the rainfall duration increases and the rainwater continuously infiltrates, the water content within the slope body will change significantly.

It can be seen from the figure that in the normal slope, the water content at the slope crest of measuring point A and the slope surface of measuring point B first began to increase rapidly at around 50 minutes. However, in the slope with loess sinkholes, the water content at the slope crest of measuring point A and the slope surface of measuring point B started to increase rapidly at around 30 minutes. This is because in the early stage of rainfall, rainwater accumulates in the loess sinkholes and infiltrates into the slope body.

It can be observed from the figure that the time of the change in water content at the slope toe of measuring point C in the slope with loess sinkholes is advanced significantly. In a normal slope, it takes a relatively long time for rainwater to infiltrate from the slope crest to the vicinity of the slope toe. In the slope with loess sinkholes, rainwater can flow directly to the lower soil through the channels formed after the destruction of the loess sinkholes, and the rainwater accumulates more quickly at the slope toe.

The earlier change in the water content at observation point D in the slope with loess sinkholes is caused by the earlier collapse of the slope.

### 3 Analysis of the Safety and Stability of Normal Slopes and Slopes with Loess sinkholes Based on ABAQUS Finite Element Simulation

#### 3.1 Establishment of the Slope Model

The slope in the study area is a loess slope located beside the G59 Expressway in Fangshan County, Lüliang City. According to the actual terrain, the ABAQUS finite element software is used to establish a three-dimensional meshing model as shown in the figure. The loess slope model has a height of 17 m, among which the height of the slope is 12 m. The model has a length of 22 m, and the length at the bottom of the slope is 17 m. The slope gradient is  $53^\circ$ .

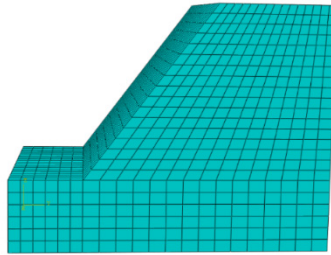


Fig. 5. Mesh Generation Diagram of the Finite Element Model of the Loess Slope

According to the on-site geotechnical investigation report and the results of indoor geotechnical tests after sampling, the physical and mechanical parameters are shown in Table 3. The slope height and gradient of the loess slope model with loess sinkholes are consistent with those of the normal model. Through field investigation, it is found that the distribution of loess sinkholes at the crest of the loess slope is more extensive than that on the middle slope surface, and the slope surface of the loess slope is greatly affected by human engineering activities, which has a relatively small impact on the slope stability.

Therefore, the main position of the loess sinkholes simulated in the loess slope model is located 1 m away from the slope surface at the slope crest. The size of the loess sinkholes is a diameter of 2 m and a depth of 2 m. Since the cross-sectional shapes of the loess sinkholes in the loess slope are diverse, in order to facilitate the modeling and simulation, the loess sinkholes in this section are simplified and replaced by cylinders for simulation.

Table 3. Physical and Mechanical Parameters of the Simulated Slope Soil

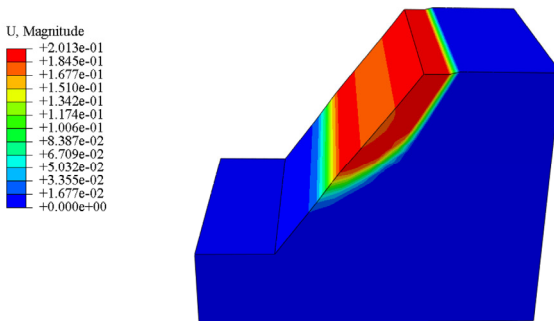
Elastic modulus (kPa)	Dry density (kg/m <sup>3</sup> )	Cohesion (kpa)	Internal friction angle (°)	Poisson's ratio	Saturated hydraulic conductivity (m/h)
28000	1650	24	30	0.3	0.018

After multiple attempts, it was found that the normal slope experienced a relatively large displacement when it rained continuously at a rate of 20 mm/h for 255 hours. Therefore, a loess slope model with a simulated rainfall duration of 260 hours was established. Due to the long rainfall duration, the time interval of rainfall for calculating the safety factor was set to 24 hours.

The slope safety factors of the normal loess slope and the loess slope with loess sinkholes under the condition of heavy rainfall at a rate of 20 mm/h were calculated respectively. After the calculations at the slope toe and the slope crest, the slope crest was selected as the characteristic point of the safety factor.

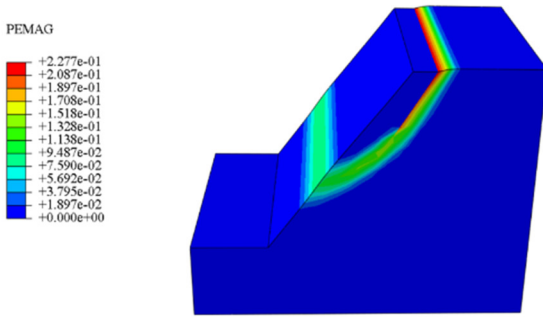
### 3.2 Analysis of the Simulation Results of the Normal Slope

The ABAQUS numerical simulation software was used to calculate the slope displacements, plastic strains, and safety factors of the normal slope and the aforementioned slope with loess sinkholes under two working conditions, respectively. The slope displacement nephogram of the normal slope under the condition of continuous rainfall with a rainfall intensity of 20 mm/h is shown in Figure 5. As the rainfall duration increases continuously, the slope displacement keeps increasing. Until after 255 hours of rainfall, the maximum slope displacement reaches 20 cm. After that, the maximum slope displacement starts to increase rapidly, and at this time, the slope begins to lose stability.



**Fig. 6.** Slope Displacement Nephogram of the Normal Slope When It Loses Stability after 255 Hours of Rainfall Duration

The plastic strain nephogram of the normal slope is shown in Figure 6. With the increase of the rainfall duration, the plastic zone first appears at the slope toe after the rainfall duration reaches 200 hours. After that, the area of the plastic zone at the slope toe keeps increasing as the rainfall duration progresses. When the rainfall duration reaches 250 hours, the plastic zone begins to increase rapidly, and the plastic strain keeps increasing. Until after the rainfall duration reaches 255 hours, a continuous plastic through zone is generated in the slope. According to the judgment basis of the plastic zone through, at this time, the loess slope begins to lose stability.



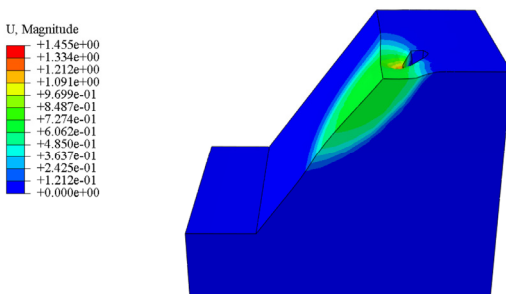
**Fig. 7.** Plastic Strain Nephogram of the Normal Slope When It Loses Stability after 255 Hours of Rainfall Duration

**3.3 Analysis of the Simulation Results of the Slope with Loess sinkholes**

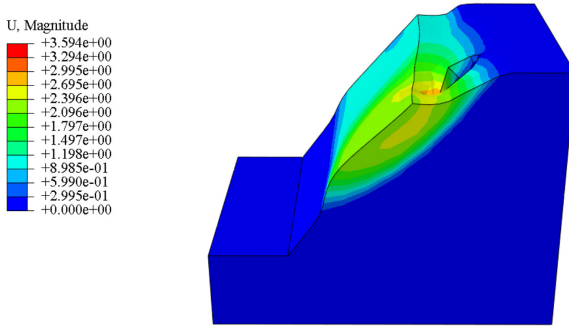
The displacement nephogram of the slope with loess sinkholes under the rainfall condition of 20 mm/h is shown in Figure 7. Before the rainfall duration reaches 250 hours, the maximum displacement of the slope mainly occurs on the slope surface, and the pattern is basically consistent with that of the slope without loess sinkholes. However, the displacements are all larger than those of the normal slope during the same period. When observing the slope with loess sinkholes, there are obvious differences in displacements at different positions, and the maximum displacement on the slope surface is more biased towards the side with loess sinkholes.

After the rainfall duration exceeds 250 hours, relatively large displacements first occur in the soil around the loess sinkholes. This is because the loess sinkholes have changed the original structure of the soil, causing stress concentration in the soil around the holes, which makes it a weak point in the slope stability. The loess sinkholes have damaged the integrity of the soil and weakened the mutual restraint and supporting capacity among the soil particles, making the soil more prone to deformation and movement.

After the rainfall duration reaches 252 hours, the entire slope begins to experience landslides, and the side with loess sinkholes obviously moves to a greater extent.



(a)

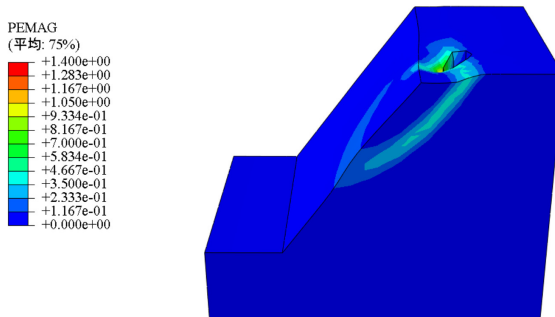


(b)

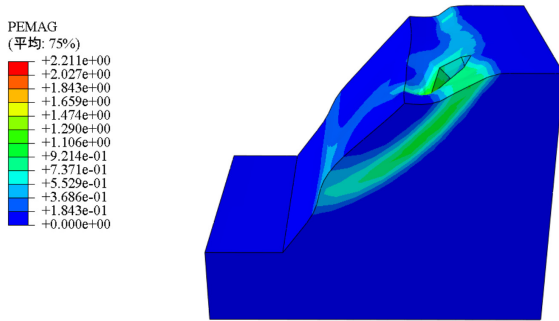
**Fig. 8.** (a) Displacement Nephogram of the Slope with Loess sinkholes after 250 Hours of Rainfall , (b) Displacement Nephogram of the Slope with Loess sinkholes When It Begins to Lose Stability after 252 Hours of Rainfall

The plastic strain nephogram of the slope with loess sinkholes is shown in Figure 8. After the rainfall duration reaches 248 hours under the condition of a rainfall intensity of 20 mm/h, plastic strains with relatively high strain values appear around the loess sinkholes. This is because the presence of the loess sinkholes has changed the stress state of the surrounding soil, and the stress distribution of the soil near the hole walls has become uneven, resulting in local stress concentration, which causes the soil to enter the plastic deformation stage in advance.

As the rainfall simulation continues, the development of plastic strain shows a radial expansion trend outward with the loess sinkholes as the center. When the rainfall duration reaches 252 hours, a continuous area of plastic strain in the slope appears, and the time when the entire slope loses stability is significantly earlier compared to that of the normal slope.



(a)

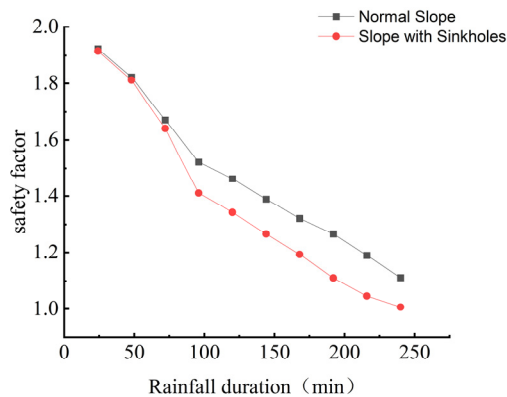


(b)

**Fig. 9.** (a) Plastic Strain Nephogram of the Slope with Loess sinkholes after 250 Hours of Rainfall, (b) Plastic Strain Nephogram of the Slope with Loess sinkholes When It Begins to Lose Stability after 252 Hours of Rainfall

### 3.4 Analysis of Safety Factor

Using the strength reduction method in the ABAQUS finite element software, the broken line diagrams of the safety factors with a rainfall time interval of 24 hours for the normal loess slope and the loess slope with loess sinkholes were obtained, as shown in Figure 9.



**Fig. 10.** Curve Diagram of Safety Factor

As can be seen from the above figure 10, under the condition that the rainfall intensity is both 20 mm/h, with the increase of rainfall time, the safety factor of the slope shows a continuously decreasing trend. At the beginning, the safety factor decreases significantly with the continuation of rainfall, and then the decreasing rate gradually slows down. The safety factor of the slope with loess sinkholes starts to decrease significantly compared with that of the normal slope after 72 hours of rainfall

duration. The safety factor of the slope with loess sinkholes decreases at a faster rate, and the slope of the curve decline is steeper, indicating that the presence of loess sinkholes makes the slope more prone to instability under the influence of rainfall.

## 4 Conclusions

Two rainfall-induced landslide model tests were carried out indoors using the rainfall similarity criterion. The failure processes of rainfall-induced shallow landslides, as well as the variation processes of earth pressure and moisture content, were compared between the normal slope and the slope with loess sinkholes. The ABAQUS numerical simulation software was used to conduct a stability analysis of the normal loess slope and the loess slope with loess sinkholes. The main conclusions are as follows:

(1)The indoor model tests show that under the same rainfall intensity, for the slope with loess sinkholes, a small - scale collapse will occur around the loess sinkholes in the early stage of rainfall, and the overall landslide time will be advanced. The time when the moisture content increases at the top, surface, toe, and inside of the slope with loess sinkholes is earlier than that of the normal slope. The earlier increase in moisture content at the top, surface, and toe of the slope is due to the fact that the presence of loess sinkholes accelerates the infiltration rate of rainwater in the early stage of rainfall. The earlier increase in moisture content inside the slope is because the slope collapses earlier.

(2)displacements, and a small-scale shallow landslide will occur. The time when the loess slope with loess sinkholes starts to lose stability will also be advanced.By comparing the variation laws of the safety factors of the two slopes with the rainfall time, it is found that the safety factor of the slope with loess sinkholes begins to decrease significantly compared with that of the normal slope after 72 hours. After that, the safety factor of the slope decreases at a faster rate, and the slope of the curve decline is steeper, indicating that the presence of loess sinkholes makes the slope more prone to instability under the influence of rainfall.

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## References

1. Li Y, Mo P. A unified landslide classification system for loess slopes: A critical review. *Geomorphology*. 2019, 340: 67-83. <https://doi.org/10.1016/j.geomorph.2019.04.020>
2. Guo Z, Huang Q, Liu Y, et al. Model experimental study on the failure mechanisms of a loess-bedrock fill slope induced by rainfall. *Eng Geol*. 2023, 313: 106979. <https://doi.org/10.1016/j.enggeo.2022.106979>

3. Peng J, Sun P, Igwe O. Loess caves, a special kind of geo-hazard on loess plateau, northwestern China. *Eng Geol.* 2018, 236: 79-88. <https://doi.org/10.1016/j.enggeo.2017.08.012>
4. Ren J, Gong W, Xue C, et al. Formation and evolution of a loess sinkhole in the southern Chinese Loess Plateau. *Catena.* 2023, 233: 107519. <https://doi.org/10.1016/j.catena.2023.107519>
5. Sun P, Wang H, Wang G, et al. Field model experiments and numerical analysis of rainfall-induced shallow loess landslides. *Eng Geol.* 2021, 295: 106411. <https://doi.org/10.1016/j.enggeo.2021.106411>
6. Quan X, He J, Cai Q, et al. Soil erosion and deposition characteristics of slope surfaces for two loess soils using indoor simulated rainfall experiment. *Soil Till Res*, 2020, 204: 104714. <https://doi.org/10.1016/j.still.2020.104714>
7. Wu L Z, Zhou Y, Sun P, et al. Laboratory characterization of rainfall-induced loess slope failure. *Catena.* 2017, 150: 1-8. <https://doi.org/10.1016/j.catena.2016.11.002>
8. Shu H, Ma J, Guo J, et al. Effects of rainfall on surface environment and morphological characteristics in the Loess Plateau. *Environ Sci and Pollut R.* 2020, 27: 37455-37467. <https://doi.org/10.1007/s11356-020-10365-3>
9. Ma J, Yao Y, Wei Z, et al. Stability analysis of a loess landslide considering rainfall patterns and spatial variability of soil. *Comput Geotech.* 2024, 167: 106059. <https://doi.org/10.1016/j.compgeo.2023.106059>

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