Evaluation of loess-filled slope failure triggered by groundwater rise using a flume test

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ABSTRACT
Gully Stabilization and Highland Protection (GSHP) are useful in preventing gully erosion and have been widely utilized in the Loess Plateau of China. Groundwater rise is an important factor that can lead to loess-filled slope instability. A flume device was designed to study the process of water infiltration into a loess-filled slope and the subsequent failure process of the slope due to groundwater rise. The loess was uniformly infiltrated with water, resulting in preferential seepage via the development of cracks in the slope from settlement deformation. The pore-water pressure increased in the front of the slope and decreased at the back during slope failure, due to contraction in the slope toe and increased tensional at the back of the slope. The failure process of the slope can be divided into three stages, settlement deformation and collapse deformation with vertical displacement during slope settlement, and slope toe slide-flow or regressive failure with a primarily horizontal displacement in the direction of the slope’s free surface. The factors of suffusion erosion, saturated softening, and infiltration dynamics during water infiltration into the loess-filled slope promote slope failure according to experimental data and numerical simulations.

1. Introduction
Loess is a silt-sized dominated soil primarily distributed in semi-arid and arid areas and form three characteristic types of geomorphic structures: loess tablelands, loess ridges, and loess domes (Liu 1985). Loess tablelands are flat and the most valuable land resource for farming and living on the Loess Plateau (Liu 1985; Derbyshire 2001). However, with increasing human activity and extreme rainfall events resulting in gully erosion, the loess tableland has become fragmented (Lu et al. 2011; Qi et al. 2018; Juang et al. 2019). Among them, Dongzhuyuan in Qingyang, Gansu Province, known as ‘the largest loess tableland in the world’, has the thickest loess deposits and occupies the largest area of loess tableland in the world. Gully erosion caused by
urban construction and agricultural development has become increasingly problematic (Derbyshire et al. 2000; Wu and Cheng 2005). With the frequent occurrence of extreme climate events in northwest China and irrigation projects on the tableland, gullies around the loess tableland are constantly forming via erosion in the center of the loess tableland and separating it (Lu et al. 2011; Qi et al. 2018). The gullies tend to extend towards the center of the highland and cause the highland to become fragmented (Figure 1). The east-west width of this highland has decreased from 32.0 km in the Tang Dynasty to 17.5 km currently, while the east-west width at its narrowest is only 50 m (Shi 1987; Chen et al. 2009). Gully Stabilization and Highland Protection (GSHP) engineering is useful in preventing gully erosion and has been widely utilized in the Loess Plateau (Juang et al. 2019). For example, Qingyang in Gansu Province has implemented GSHP techniques to address the problem of retrogressive erosion in the loess tableland via ditch head landfill work on 14,035 gullies in the Dongzhuyuan tableland. According to the data from the Qingyang Water and Soil Conservation Administration, soil erosion in the Dongzhuyuan tableland has affected more than 96% of the total area, and approximately 66 million tons of silt are transported to the Yellow River each year. In some regions of the Dongzhuyuan tableland the highland has already collapsed (Xifeng Soil and water conservation Observation station of Yellow River Conservancy Commission of the Ministry of Water Resources 2005). In 2017, Qingyang completed the gully protection project with an investment of 152 million yuan. At the same time, the Management Committee of the middle and upper reaches of the Yellow River implemented plans to carry out GSHP for erosive gullies threatening the Loess Plateau over the next 20 years.

However, according to our field investigation, it was found that all projects suffered erosion damage within one year (Figure 2). In GSHP projects, the remodeled
Loess ditch is filled with rolling backfill, which destroys the original loess structure, and changes the circulation of groundwater and surface water, leading to groundwater rise (Yin et al. 2016a; Wang et al. 2018; Zhao et al. 2018). It is known that remolded loess is more likely to collapse and lose its strength with increasing water content. According to experiments, even the dry density of remolded loess is more than that of undisturbed loess, and after water infiltration, the strength of remolded loess sharply decreases and is prone to collapse (Yang et al. 2003; Wang et al. 2018). The existing gully head is often the groundwater discharge outlet in the tableland. Once filled, it will lead to a large amount of groundwater converging in the filled loess, causing the loess used in GSHP projects to soften, decreasing the filled loess stability. For example, in Dongxiang County of Gansu Province, the remolded loess-filled groundwater channel led to groundwater rise that infiltrated the filled loess, resulting in a landslide shortly after the project was completed in 2011, burying the county square and damaging residential buildings (Zhuang and Peng 2014). Similarly, a gully filled with remolded soil in Shichuan Town, Lanzhou, failed in 2015 due to water infiltration and groundwater rise, leading to a change in the debris flow and a landslide-mudflow chain disaster event (Zhang et al. 2019). The erosion phenomenon and groundwater rise have already appeared in the GSHP (Singh et al. 2010; Jin et al. 2019). GSHP projects continue to face failure risks due to erosion and rising groundwater. A comment article in the journal Nature, called for the implementation of relevant research projects as soon as possible to deal with the various new problems brought about by major engineering construction (Li et al. 2014).

Loess is a unique soil that is sensitive to water and prone to failure in excess water situations (Zhuang et al. 2017). It is very important to carry out studies on the characteristics of groundwater change in loess areas, especially groundwater change in loess-filled areas (Li et al. 2014). Most previous studies investigated filled projects have reported groundwater changes (Singh et al. 2010; Jin et al. 2019), simulation of the groundwater reconstruction process (Langevin and Guo 2006; Li et al. 2017), and
monitoring of the groundwater reconstruction path (Yu et al. 2014; Zhang et al. 2017). Filled engineering construction alters the original topography and geomorphic structure, which can block channels and water spring holes, thus changing groundwater seepage paths. Meanwhile, the infiltration rate of compacted fill soil is lower than that of undisturbed soil and the groundwater infiltrates into the filled soil, resulting in rising groundwater, geomorphic deformation, and instability. Yin et al. (2016a) predicted groundwater changes in large-scale fill projects using numerical simulation and determined that groundwater levels will likely rise in filled project bodies over the next 50 years. Some scholars have focused on the catastrophic effects of groundwater rise caused by filled engineering, such as pore-water pressure increase (Yin et al. 2016a; Jin et al. 2019), microstructural evolution of loess-filled areas when subjected to alkaline and saline environments (Hu et al. 2021; Wang et al. 2022), and geomorphic deformation due to rising groundwater in a filled body (Song et al. 2008). The large-scale filled projects in the Loess Plateau, such as GSHP, are likely to generate groundwater rise induced catastrophic landslide events similar to the Guangming landslide that occurred in Shenzhen on Dec. 20, 2015 (Yin et al. 2016b).

Although the implementation of the GSHP techniques can effectively alleviate gully erosion and soil erosion, groundwater rise can cause slope failure due to blocking the groundwater discharge and should be given more attention. To study the stability and failure mode of filled projects caused by groundwater rise we selected the Huoxiang gully of the Dongzhi tableland in Qingyang City, Gansu Province, which is the biggest loess tableland, as our study subject. A testing device was designed to study the process of water infiltration into the filled project and the failure mode of the filled project due to groundwater rise to elucidate the process and mechanisms of filled slope failure.

2. Study location

The north-south strike of the Dongzhijiyuan loess tableland, located in the eastern part of the Gansu Province, is the ‘biggest loess plateau’. The loess of the Dongzhijiyuan tableland is almost 300 m deep. The upper layer is primarily composed of Malan loess, about 20–40 m thick, deposited in the late Pleistocene period (Q3). The geomorphology of the Dongzhijiyuan tableland belongs to the typical loess plateau tableland-gully, with a relatively flat surface and gullies that crisscross around the landscape. Since 2000, the headward erosion of gullies around the Dongzhijiyuan tableland has intensified because of population growth and increased human activities. The gully and soil erosion in the Dongzhijiyuan tableland is becoming increasingly serious and extends towards the center of the highland, causing the highland to be fragmented (Figure 1). Geohazards, such as landslides and collapses, occur frequently. Since the Tang Dynasty, the eroded area of the tableland has reached more than 599.6 km², with an average annual loss of about 0.46 km². According to investigations, the original Dongzhijiyuan tableland was divided into 11 pieces in the last 1300 years, with the largest at 946.25 km² and the smallest at 0.39 km² (Shi 1987; Chen et al. 2009).
To address gully erosion, Qingyang in Gansu Province has carried out a major project of ‘GSHP’ to solve the problem of retrogressive erosion in the loess tableland area via ditch head landfill work on 14,035 gullies in the Dongzhiyuan tableland, which is the most common location for GSHP filled soil failure research.

In this paper, the Huoxiang gully, which was filled via GSHP techniques in 2017 and finished in 2018, is taken as a case study. Huoxiang gully, located in the east of the Dongzhiyuan tableland, belongs to the Malian River basin. The gully erosion in the Huoxiang gully has become a substantial problem over the past 15 years due to water drainage from the city. The gully headward erosion is more than 30 m with an average annual headward erosion of more than 2 m since 2004, and cut erosion increased to 40 m. Continuous headward erosion poses a significant threat to the local population. According to the DEM (tandem with 5 m resolution) pre-filled and the design of the filled project, the maximum landfill depth is 80 m and the width is 300 m (Figure 3).

From the topographic map analysis and field investigation, it was determined that the altitude of the head of the Huoxiang gully is lower than that of the Dongzhiyuan tableland surface and the head of the gully is the groundwater outlet of the tableland before landfilling. The GSHP changed the circulation of groundwater and surface water, leading to groundwater rise. The groundwater infiltrates into the filled project and softens the filled loess, resulting in the project failure.

3. Materials and methods

3.1. Materials

A loess soil from the Huoxiang gully was used for this study. The soil has a mean particle size (D50) of 0.57 mm and a clay (<0.005 mm) and silt (0.005–0.075 mm) content of 18.75 and 72.67%, respectively. The experimental slope was constructed in layers and compacted to the specified density (dry density (1.52 g/cm³)) according to a standard of 5 cm for each layer. The experimental slope was constructed with a gradient of 40° according to the GSHP project in Huoxiang gully. The initial moisture...

Figure 3. The GSHP in the Huoxiang gully. Source: Author, base data from Google Earth.
content was determined by collecting and drying the soil samples before the experimental runs. In the experiment, the initial moisture content of the soil was measured to be about 12.20%. The strength of the specimen under different confining pressures was tested by an unsaturated soil stress-strain controlled triaxial apparatus. The physical characteristics of the soil in the test are similar to the filled project (Table 1).

### 3.2. Methods

The flume test measuring device consists of three parts: slope flume, rainfall operator, and data acquisition system. The slope flume is a three-dimensional experimental loess slope constructed in a $2 \, \text{m} \times 0.6 \, \text{m} \times 1.2 \, \text{m}$ (length $\times$ width $\times$ height) box with glass sidewalls and a metal frame (Figure 4). To accurately simulate the rising groundwater and infiltration into the filled project, the groundwater was recharged through the concentrated channel by locating the drainage plate and temporary water tank at the rear of the experimental model. The water in the temporary water tank was kept at a constant height of 40 cm. The drainage plate was set in five rows spaced at 20 mm, whereas the columns were spaced at intervals of 20 mm. The diameter of the drainage holes was 2.0 mm to ensure that the groundwater was able to infiltrate into the slope evenly.

The data acquisition system is composed of nine EC-5 volumetric water content sensors, each with an accuracy of $\pm 2\%$, nine MKM pore-water pressure sensors, and a displacement sensor with an accuracy of $\pm 0.1 \, \text{mm}$ were installed at specific depths during slope construction. The sensors were each connected to two Em50 data loggers and calibrated before each experiment. To monitor the internal movement of the slope, a displacement monitoring system was set up inside the soil slope. The system consists of a hollow sphere with a 2 cm diameter and a weight of 10 g, which was buried 5 cm inside the slope and connected to the displacement sensor at the upper end through a wire strand with a diameter of 0.5 mm. A counterweight was applied at the lower end to ensure the force balance of the sphere in the initial state and reduce the relative movement between the sphere and the surrounding soil. The other sensors were placed in the middle of the slope and are divided into two rows, with an interval of 20 cm between the two rows. The sensors were separated by 10 cm, and the bottom layer of the sensor was 20 cm away from the slope bottom (Figure 4).

Surface deformation was monitored using a 3D laser scanner with 1 mm precision and high-resolution topographic data was obtained by repeatedly scanning the experimental slope surface every 30 min during each experiment. Polyworks software was used to process the data and quantitatively describe slope deformation and failure characteristics. The registration of multi-phase scan data adopts a point-to-point
method, and mark points are pasted on the scanned object. After the image is imported into the software, the registration is carried out through the mark points.

4. Results

4.1. The groundwater infiltration process

During the initial infiltration stages, the groundwater diffuses from the back of the slope towards the surface of the slope. With rising groundwater, the height of water entering the slope was consistent with the rising height of groundwater without forming preferential seepage. In this process, the water softens the soil and causes deformation of the slope with infiltration into the slope. Cracks appeared in the slope due to deformation, resulting in the groundwater forming preferential seepage along the cracks and rapidly entering the soil. Figure 5 shows the change in water content of the slope vs time at different positions. The water content at the back of the experimental slope increased immediately with increasing groundwater levels, and, later, the water content at the front of the experimental slope showed a relative increase. The water content of the upper region increases slowly due to the groundwater rise. Subsequently, the groundwater infiltrated from the back of the slope and seeped out from the toe slope. The water transfer path formed and the slope failure occurred at 316 mins. The water content near the slope toe at 20 cm responded to the failure and rapidly increased, demonstrating that the slip surface is near this area. The hydrostatic pressure near the sliding surface increased during failure, resulting in an increased water content, which indicates that the shear contraction is within the sliding surface.

During the test, groundwater seeped out from the middle of the slope surface and then spread to the slope toe; however, the slope remained stable even when the middle of the slope was saturated. Upon groundwater seepage from the slope toe, the slope began to fail via a retrogressive sliding process (Figure 6). This phenomenon shows that the slope would not fail due to saturated soil in any area of the slope and will fail due to the key part of the slope saturation (Yin et al. 2016b). The stress distribution of the slope was uneven and concentrated at the slope toe, resulting in this
The slope toe failed first, causing the upper part to fail and resulted in a regressive landslide. This phenomenon is consistent with that observed at Heifangtai, most landslides at Heifangtai fail following groundwater seepage out from the slope toe (Peng et al. 2018). The slope toe fails first, causing the upper part to fail, forming a regressive landslide. The results show that the key blocks have a substantial influence on slope stability.

4.2. Pore-water pressure changes

The experimental slope body also responded to groundwater rise, including increased water content and pore-water pressure, and deformation when groundwater infiltrates into the experimental slope.

Groundwater infiltrated from the back to the front of the experimental slope resulting in pore-water pressure at the back of the slope increasing sharply with the increasing groundwater level. Meanwhile, the pore-water pressure at the front of the experimental slope did not fluctuate because the water was not infiltrating into this area (Figure 7). The pore-water pressure of the soil at different heights at the back of the slope responded differently to groundwater rise. The pore-water pressure of the soil below the height of the groundwater level increased immediately and sharply as the groundwater rose and infiltrated the soil, while the pore-water pressure of the soil above the height of the groundwater level increased gradually. The experimental slope settlement deformation due to groundwater infiltration caused visible cracks on the slope.

Groundwater infiltrated to the front of the slope caused the pore-water pressure to rise with continuous groundwater infiltration. The groundwater infiltrated into the front of the slope after about 190 mins. The pore-water pressure of the soil at the bottom of the experimental slope gradually increased with groundwater infiltration, and the pore-water pressure of the upper soil did not change.

Groundwater seeped out from the saturated experimental slope toe due to continuous groundwater infiltration. The pore-water pressure sharply increased, resulting in a decrease in the effective stress of the soil and the slide-flow occurred from the toe of the slope, resulting in experimental slope instability and failure as a regressive landslide process. The pore-water pressure in the front of the slope body sharply increased, especially the pore-water pressure near the sliding surface, which substantially increased. However, the change in pore-water pressure at the back of the slope sharply decreased and the pore-water pressure at the front of the slope increased during the failure.
Figure 6. Water infiltration process. Source: Author.
process (Figure 7). Both resulted in slope failure the change in pore-water pressure indicates shear contraction characteristics in the slope toe. This resulted in a sharp increase in pore-water pressure of the slope toe, while the back of the slope showed a state of tensional stress, resulting in sharply decreasing pore-water pressure.

4.3. The failure processes

During the test, the deformation process of the experimental slope can be divided into three stages as follows:

1. Settlement deformation. The groundwater gradually infiltrates into the experimental slope with rising groundwater. The water content of the soil increases due to water infiltration, resulting in decreased loess strength. Meanwhile, the water infiltration into the loess leads to suffusion erosion, which causes loess collapsibility, a volume decrease, and settlement. Settlement cracks at different depths are induced due to the differential settlement and suffusion erosion in the slope body. The settlement cracks gradually extend in length and width with continuous groundwater infiltration (Figure 8a).

2. Collapse deformation. The settlement cracks continue to expand and form a curtain with cracks, due to continuing suffusion erosion, and the soil of the upper layer collapses due to gravity. The internal soil collapse of the slope causes the surface of the slope to deform and induces cracks on the surface. The cracks extend and connect, leading to preferential seepage routes in the slope which are potential sliding surfaces (Figure 8b).

3. Slope toe slide-flow and failure. The groundwater infiltrates to the slope toe and seeps out. The soil at the toe of the slope is saturated, and the effective stress decreases resulting in the sliding and flowing of the loess. Then the slope toe forms a free surface resulting in the upper part of the slope failing from a decrease in support from the lower soil mass and, finally, the slope fail causes a regressive landslide (Figure 8c).

In the first and second stages, the deformation is the vertical displacement of slope settlement, and in the third stage, the deformation is primarily the horizontal displacement with the direction to the free surface of the slope body.
5. Discussion

The land-filled gully created via GSHP is typically the discharge outlet of groundwater and urban sewage outfall. The seepage of the groundwater enters the filled slope from the back, which is different from the mechanism of the rising groundwater in a reservoir or caused by irrigation. In this process, groundwater infiltrates into the filled slope and produces a variety of effects on the slope, including suffusion erosion, saturation softening, and altered infiltration dynamics.

5.1. Suffusion erosion

The process of suffusion erosion is different from that of surface erosion (Kenney and Lau 1985; Chapuis 1992; Bendahmane et al. 2008; Zhuang et al. 2021). Scholtes et al. (2010) observed that suffusion can change the soil state change ‘dense’ to ‘loose’ via fine particle size migration with water outflow. Additionally, local mechanical and hydraulic variations due to fine particle migration influence the stability of the soil slope. Furthermore, fine particle migration reduces the total volume and has a potential for collapse of the soil matrix due to reduced soil strength (Richards and Reddy 2007; Chang and Zhang 2013; Zhuang et al. 2021).

To perform suffusion erosion tests of the remodeled loess, a suffusion permeameter was used to simulate water infiltration into the loess according to Zhuang et al. (2021). After the 30 days of infiltration, the settlement of the loess sample reached 1.2 cm (sample height is 12 cm) and the total amount of soil particles carried out by the seepage water was 0.57 g. The clay content accounts for 19.57% ($d < 0.005$ mm), the silt content accounts for 75.31% ($0.075 > d > 0.005$ mm), and the sand content...
accounts for 5.12% (0.075–2 mm) of the fine particles carried out by the seepage water (Figure 9).

The fine particles that migrated out by suffusion were mainly clay and silt particles. The migration of fine particles changed the soil skeleton and increased the porosity and infiltration rate of the sample. Soil tested after oven drying of the soil column revealed that the dry density of the soil sample column decreased from 1.47 to 1.42 g/cm³ and the void ratio increased from 0.85 to 0.93 after 30 days of water infiltration.

Loss of particles due to internal erosion can reduce the soil volume and lead to the potential collapse or settlement of the soil skeleton (Crosta and di Prisco 1999; Moffat et al. 2011; Chang and Zhang 2013; Fan et al. 2017). This phenomenon of infiltration settlement is prevalent in Heifangtai (Zhuang et al. 2021). The suffusion erosion occurring with groundwater infiltrating into the filled slope causes the migration of fine particles. The migration of fine particles will change the structure of the filled slope contributing to collapsed settlement, which is similar to the experimental phenomenon.

5.2. Saturation softening

Since loess is highly sensitive to water, the strength of the loess will sharply decrease with increasing water content (Zhuang et al. 2015; Peng et al. 2018). Loess structural strength is high with low soil water content. However, the strength decreases significantly and subsidence deformation occurs as the water content increases (Zhuang et al. 2017; Zhang and Wang 2018; Zhang et al. 2019). A large number of laboratory tests have shown that the formation of preferential seepage channels is common and loess is reshaped loess at the saturation depth (Zhang et al. 2009; Singh et al. 2010; Zhuang and Peng 2014; Yin et al. 2016a, 2016b; Zhang et al. 2017; Zhao et al. 2018; Zhuang and Peng 2014). Groundwater continues to enter the loess along this saturated zone resulting in fine particle and salt migration via internal erosion (Zhuang et al. 2021). The skeleton and the strength of the saturated zone of the loess gradually decrease due to the migration of fine particles and salts, resulting in a softening zone, which provides a potential sliding surface for the loess-filled slope.
For this study, remodeled loess samples, with an approximate volume of 30 cm × 30 cm × 30 cm, were retrieved from a filled slope in Qingyang. A subsample of 100 mm height and 50 mm diameter was extracted for subsequent tests. The shear stress is defined by \( \sigma_1' \) (the maximum effective principal stress) and \( \sigma_3' \) (the minimum effective principal stress), and the effective stress path is defined by \( (\sigma_1'+2\times\sigma_3')/3 \). The samples used in the triaxial test were wetted to saturation with distilled water and assisted by CO₂ until the pore pressure coefficient (BD) (Sassa 1985) exceeded 95%. The samples were then compressed under undrained conditions following the strain-controlled method. The confining pressures were 100, 200, and 300 kPa, and the shear velocity was fixed at 0.07 mm/min.

Figure 10 shows pore-water pressure graphed against axial strain. At all three normal stress levels, the pore pressures generated attained values up to the normal stress when the axial strain reached 15%. After this, steady-state resistance was observed. The path of effective stress indicated that the effective stress decreased with shear strain, and the final points were less than 40 kPa (Figure 10b), indicating that cohesive strength was completely lost. This enabled liquefaction in the presence of saturation shearing.

The loess strength decreases, especially while the strength of loess at the slope toe decreases, and the slope fails in the sequence of slope toe sliding. Meanwhile, the phenomenon of shear contraction can be observed via the triaxial test and is attributed as the reason for the sharp increase of pore-water pressure during sliding of the slope. The sharp increase in pore-water pressure leads to further decreases in loess strength, which promotes slope failure.

5.3. Infiltration dynamics

There is a different level of seepage water in the process of groundwater infiltrating to the front of the slope due to the rise in groundwater resulting in seepage pressure in the experimental slope. To study the change in seepage pressure of the experimental slope during groundwater rising, a two-dimensional slope with 40° was established using a sigma/W module based on the experimental results. The shape and soil parameters of the simulation slope are the same as that of the experimental slope protected by a flat slope in the physical model experiment (Table 2). The lower boundary of the simulation slope was set as the impermeable boundary (unit flow is...
Table 2. The parameters of the simulation slope. Source: Author.

| Elastic Modulus (MPa) | Poisson ratio | Weight (kN/m³) | Cohesive (kPa) | Internal friction angle (°) | Permeability coefficient (m/s) | Saturated water content (%) | Residual water content (%) |
|-----------------------|---------------|----------------|----------------|-----------------------------|-------------------------------|----------------------------|--------------------------|
| 60                    | 0.3           | 18             | 30             | 18                          | 5e-6                          | 32                         | 12                       |

Figure 11 shows the water pressure distribution at different times. In the early stage of the test, the water pressure of the slope developed via diffusion. The soil mass at the place of groundwater infiltration changed first, and the water pressure gradually rose and tended to stabilize. The variation area of water pressure extended

Figure 12. Displacement of the slope. Source: Author.

zero), the left boundary was set with a constant head of 50 cm, and the other boundary was set as the default boundary. The simulation process lasted for seven hours.

Figure 11 shows the water pressure distribution at different times. In the early stage of the test, the water pressure of the slope developed via diffusion. The soil mass at the place of groundwater infiltration changed first, and the water pressure gradually rose and tended to stabilize. The variation area of water pressure extended
from the back edge of the slope to the front edge of the slope. The water pressure of the slope shows obvious stratification in the horizontal direction, and the water infiltration pressure along the back edge of the slope gradually decreased towards the front of the slope. The data reveal a water pressure gradient from the back of the slope to the front of the slope. The water pressure gradient increases the probability of slope instability and promotes slope failure.

The displacement of the slope in the horizontal direction increased gradually from the top of the slope to the toe slope, and the maximum displacement area was located near the toe slope, which is consistent with the model test results. In the vertical direction, the displacement at the top of the slope was greater than that at the bottom (Figure 12). This deformation is caused by the collapsibility and settlement of the slope due to internal erosion.

6. Conclusion

The Gully Stabilization and Highland Protection (GSHP) project has been widely used in the Loess Plateau and has proven to be an effective means to alleviate gully erosion in the Dongzhiyuan tableland. Although the implementation of GSHP can effectively alleviate gully erosion, the design and implementation of a GSHP project should be based upon scientific study of the erosion characteristics of the gully. Loess has special characteristics of macro-pores, vertical joints, loose texture, and water sensitivity, which makes it prone to erosion, especially for remolded loess. The GSHP project used remolded loess to fill in the gully which led to groundwater rise. Otherwise, the implementation of this project would not be able to alleviate the gully erosion; rather, it might lead to various engineering disasters and ecological problems. From the experiment conducted in this study, the processes of a loess-filled slope failure triggered by groundwater rise were studied and the following conclusions were drawn:

1. With rising groundwater, the groundwater initially infiltrates the filled slope uniformly. Then deformation and cracks appear in the slope due to preferential seepage. This process is accompanied by suffusion erosion, migration of fine particles, structural damage, collapsible settlement, and crack formation.
2. The soil at the toe slope reaches saturation when the groundwater flows out the foot slope. Flow-slip phenomenon occurs first, leading to regressive failure of the fill slope. The failure process of the experimental slope can be divided into three stages: settlement deformation, collapse deformation, and slope toe slide-flow and regressive failure.
3. The groundwater rises and infiltrates into the loess-filled slope resulting in suffusion erosion, saturation softening, and hydrodynamic pressure.

Therefore, the loess-filled slope should be well-drained and the groundwater outflow should be designed to prevent groundwater from infiltrating into the loess-filled slope.
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Data availability statement

The data that support the findings of this study are available from the corresponding author, Jianqi Zhuang, upon reasonable request.

Disclosure statement

No potential conflict of interest was reported by the authors.

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