



A case study of a rainfall-induced landslide involving weak interlayer and its treatment using the siphon drainage method

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Abstract

Local collapse or even overall movement may occur due to excavation at the slope toe, especially when there is a weak interlayer in the stratum. This process frequently produces many tension cracks on the slope surface, increases the sensitivity of groundwater to rainfall and thus promotes the development of landslide. The Houpuacun landslide, which is located in Tonglu County, Zhejiang Province of China, is a typical case in which the weak interlayer and the tension crack play an important role in triggering the slope instability. In this study, the deformation process and the hydraulic characteristics of this landslide were analyzed based on monitoring of the slope displacement, rainfall and hydraulic head. The results show that the slope deformation has a strong correlation with rainfall and groundwater table. The large number of cracks on the slope surface provide favorable conditions for the infiltration of rainfall and that the hydraulic head rise rapidly under the action of rainfall. Because the mechanical strength of the weak interlayer greatly decreases when saturated, the slope is prone to failure under rainfall. Numerical simulations were carried out to compare the stability of the slope before and after rainfall. The results show that the factor of safety of the slope is close to one once the weak interlayer is immersed by groundwater. A new siphon drainage technique was employed to control the groundwater table and improve the stability of the slope, which has proven to be a practicable and efficient countermeasure for the case in hand.

Keywords Landslide · Weak interlayer · Displacement monitoring · Stability of slope · Siphon drainage

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Introduction

To meet the growing demands of infrastructure, an increasing number of mountainous construction projects require the cutting of slope in China (Sun et al. 2012). However, due to the intrinsic complexity of the geological structure and lithology, the excavation of slopes often involves a variety of adverse geological conditions such as weak interlayers (Wang et al. 2011). Normally, the strength of a weak interlayer is significantly lower than the upper and lower strata in the ground (Zhen et al. 2016), which means that the weak interlayer is usually the key structure controlling the stability of a slope (Pouya and Ghoreychi 2001). Therefore, the slope can easily experience a failure along the weak interlayer during excavations, and a landslide may occur (Huang et al. 2007; Huang et al. 2013).

The stability of slopes with a weak interlayer has been studied extensively (Al-homoud and Tubeileh 1998; Okubo 2004; Guzzetti et al. 2008; Nie et al. 2015; Tang et al. 2015). Many scholars focused on the physical and mechanical properties of the weak layer itself to study its formation mechanism

and its shear strength characteristics (Lu et al. 2012; Yu et al. 2016) by means of laboratory tests and field tests. Some others studied the failure process of a slope with a weak interlayer by performing numerical simulation and physical model tests (Li et al. 2016; Li and Ju 2016; Lin et al. 2017). However, a landslide's stability is usually affected by many factors. In addition to the weak interlayer, tension cracks also play an important role in triggering a landslide. For slopes with weak interlayers, the early deformation not only causes a potential sliding surface along the interlayer, but also forms many tension cracks on the slope surface. These tension cracks make the groundwater have a direct hydraulic connection with the rainfall, leading to the groundwater table in the slope rising rapidly under the action of heavy rainfall. The rapid recharge of groundwater from rainfall may aggravate the instability of slopes (Wang et al. 2010). Therefore, a landslide is more prone to occur along the weak interlayer because of these adverse effects of the tension cracks (Zhang et al. 2012).

The Houpucun landslide is a typical case of slope instability induced by the weak interlayer and the surface tension cracks. In this paper, the characteristics of cracks on the Houpucun landslide were studied through field investigation; the displacement of the slope and the time-varying hydraulic head with rainfall were analyzed using field monitoring. Based on the geological characteristics of the study area, a comprehensive analysis of the instability mechanism of the slope was carried out. The influence of the hydraulic head rose on the stability of the slope was investigated by numerical simulations. Furthermore, a new stabilization treatment method using the siphon drainage technique was adopted in the study area, and the effect and applicability of this treatment were discussed. The objective of this paper is to give some insights of failure mechanism of a typical rainfall-induced landslide and introduce a successful application of a siphon drainage method, which may provide a reference for stabilizing similar slopes.

Study area

Geological conditions

The Houpucun landslide is located in Tonglu County, Zhejiang Province of China, which is excavated due to the construction of an interchange ramp of Highway 208, as shown in Fig. 1. The peak elevation of the nearby Jiaoshan Mountain is approximately 166.8 m. The original gradient of the terrain is approximately 25 to 40° above the elevation of 100 m and is approximately 15 to 25° below 100 m. Because of the construction of the Highway 208, the slope is currently cut into approximately 30 to 40° at the toe.

The formation lithology in the slope area is mainly composed of carbonaceous shale of Permian Qixia Formation

(P_{1q}), conglomerates, tuffaceous siltstone and welded tuff of the Jurassic Laocun Formation (J_{3l}), and eluvial gravel interbedded with clay of Quaternary Holocene (Q₄). As revealed by borehole data, the conglomerates and tuffaceous siltstone in the study area are intercalated with weak layers. These weak layers are generally lenticular and discontinuous; most are approximately 0.1 to 4.0 m in thickness. The lengths of these layers are approximately 5 to 50 m. According to the drill core (Fig. 2a), the weak interlayer in conglomerate presents cataclastic state with some gravels (diameter of 0.5 to 2 cm), while original rock is black shale with purple tuffaceous siltstone and muddy cementation. The interlayer in tuffaceous sandstone is relatively thin, with fine particles and low strength (Fig. 2b). The results of laboratory tests show that the mechanical strength of the weak interlayer is very different between the saturated and natural state.

The study area belongs to a subtropical monsoon climate. The monsoons and typhoons have a significant impact on the weather, causing the main annual rainfall usually occur during the rainy season between April and September. The slope groundwater is dominated by phreatic water, which is mainly stored in bedrock fissure, the dissolution gap and fracture zone. Numerous springs are found pouring out after heavy rainfall.

Development of landslide

The construction of Highway 208 completed in December 2004, and the slope shape at that time is shown in the photo at the lower right corner of Fig. 1. At the beginning of 2005, the slope experienced creep deformation affected by rainfall. The sliding produced multiple tension cracks on the slope surface, and some cracks exhibited an increasing tendency. Some countermeasures, including cutting down the slope and building intercepting and drainage ditches, were then put in place. Unfortunately, in 2011, the slope was subjected to persistent rainfall and showed a tendency toward accelerated sliding and stability deterioration, producing local uplift on the leading edge and obvious tensile deformation on the trailing edge. In July of 2014, according to field observation, small scale toppling, faulting and fracturing occurred in the previously built retaining wall and intercepting ditch, as shown in Fig. 3a.

After several slip deformations, a series of tension cracks developed on the slope surface between the elevation of 50 m and 110 m, with lateral distribution in a range of 100 m. Field investigation shows that the total number of cracks on the slope surface reached 24, and these cracks are mostly between 20 and 40 m in length and approximately 0.3 to 2 m in width. Most of the cracks are vertical, and their shapes are mainly arc-shaped in the plane. The deepest crack is located in the front of the slope, at an elevation of about 70 m, and is a tensile crack of approximately 1 to 2 m in width with a maximum



Fig. 1 Location of study area

Fig. 1 Location of study area

visible depth of approximately 8 m. This crack cut off the overlying conglomerate, as shown in Fig. 3b.

Monitoring instrumentation

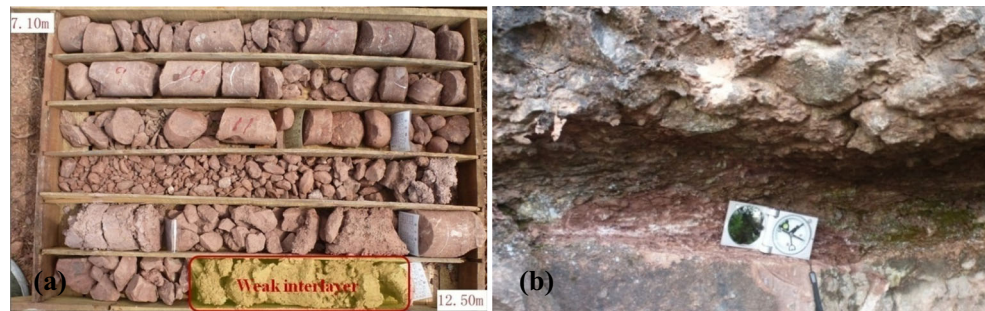
The deformation and failure of the slope usually occur after a period of abundant rainfall, which indicates that the landslide is

closely related to rainfall. To explore the failure mechanism of the landslide, the surface deformation, borehole hydraulic head and rainfall in the study area were monitored since February 2015.

Details of instruments

The instruments used in the monitoring system includes the GPS-based displacement measurement, the HOBO water

Fig. 2 The weak interlayer exposed by drill core and outcrops: **a** weak interlayer in the conglomerates and **b** tuffaceous siltstone



level data logger and an RG3-M rainfall gauge (www.onsetcomp.com). Figure 4 shows the topographic map of the study area and the detailed arrangement of the monitoring points on the slope. The total quantity of the GPS displacement monitoring points is eight. The surface displacement data in both the strike direction (dx) and the dip direction (dy) can be obtained via the static geodetic coordinate measurement. The hydraulic head in three boreholes is recorded automatically using the water level data logger. The rainfall data are collected by the automatic rainfall recorder.

Monitoring results and interpretation

Figure 5 shows the variation of monitored hydraulic head in BH3 and the corresponding rainfall data. The hydraulic head was expressed in terms of total head with the reference datum set at ground level of the borehole. As shown in Fig. 5, the rainfall is mainly distributed in mid of April to the end of August. The peak rainfall of a single day occurred on June 8th, reaching 91.5 mm. Afterwards, the rainfall decreased gradually from September to November. The groundwater in the study area was sensitive to rainfall. With a gradual increase in rainfall in February, the hydraulic head persistently rose from approximately -17 m and was maintained at approximately -14 m, and then it fluctuated rapidly along with the change in rainfall intensity. However, the hydraulic head was still able to maintain a high level despite the rainfall decrease at the end of August, which indicates that the groundwater in the study area has a

characteristic of rapid recharge from rainfall and poor discharge capacity.

Figure 6 shows the results of each GPS measuring point on the slope in which the displacements in the dx direction and dy direction are shown in Fig. 6a and b, respectively. Note that some monitoring points are destroyed due to the sliding of the slope. The monitoring results of the surviving points reveal that the sliding of the slope mainly occurred from May to August. Afterwards, the entire slope tended to be stable. The displacement in the dip direction (dy) is much larger than the strike direction (dx), which implies that the entire slope mainly slides towards the highway side. Generally, the slope shows a large displacement at the leading edge and a small displacement at the trailing edge, and the maximum monitoring displacement reaches nearly 2 m (see P02 in Fig. 6b). Moreover, the deformation of the slope distributes uneven on the surface. The main deformation area is near the cross section a-a', and the displacement of the slope in other positions is relatively uniform.

The monitoring data of rainfall, groundwater table and deformation show that the displacement of the slope has a strong correlation with the rainfall intensity and the groundwater table. Obviously, the sustained rainfall from May to August was the reason for inducing the landslide. Table 1 shows the hydraulic head values of each borehole during the monitoring period. It can be seen that after the sliding of the slope, the hydraulic heads in all boreholes are raised, and the change in the groundwater table at the

Fig. 3 **a** Local fracture on the concrete retaining wall; **b** characteristics of the deep tension crack



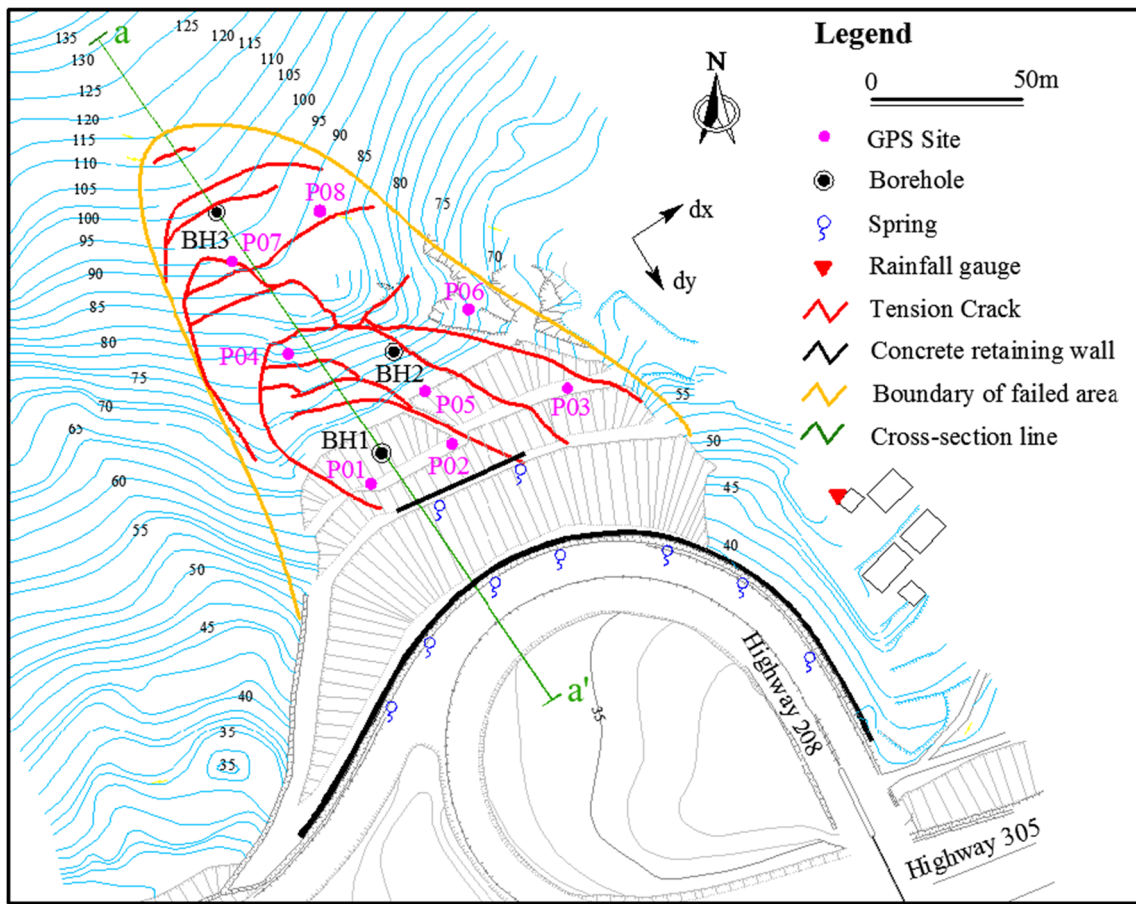


Fig. 4 Topographic map showing the extent of the study area and the position of measuring points on the slope

slope’s leading edge is higher than that at the trailing edge. However, after the failure of the slope, the groundwater table in BH1 has remained almost unchanged compared to the frequent fluctuations in BH3. These phenomena imply that the deformation of the slope makes the discharge channel of groundwater become partially blocked, resulting in a high level of the hydraulic head at the leading edge of the slope.

Triggering mechanism and numerical simulation

Based on the results of the field investigation, the monitoring data and the geological conditions in the study area, the failure of the Houpuacun landslide during the monitoring period is mainly caused by the following two reasons: (1) the weak interlayer in the conglomerates and tuffaceous siltstone and

Fig. 5 Variation of the monitored hydraulic head in BH3 and rainfall data

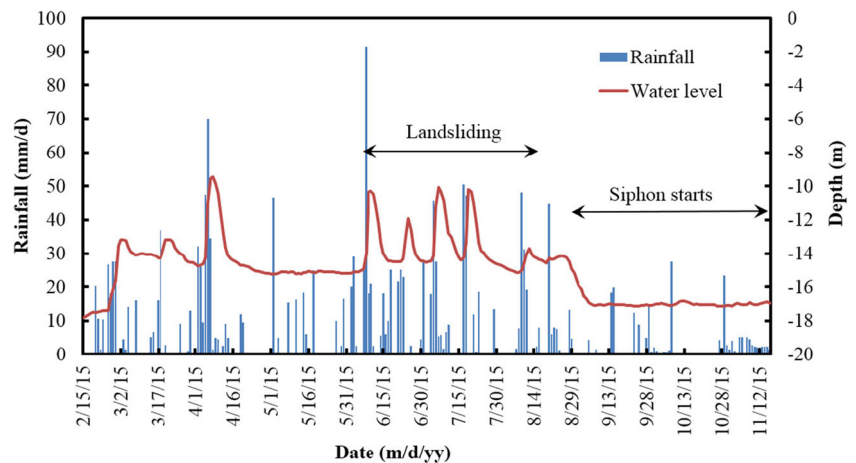
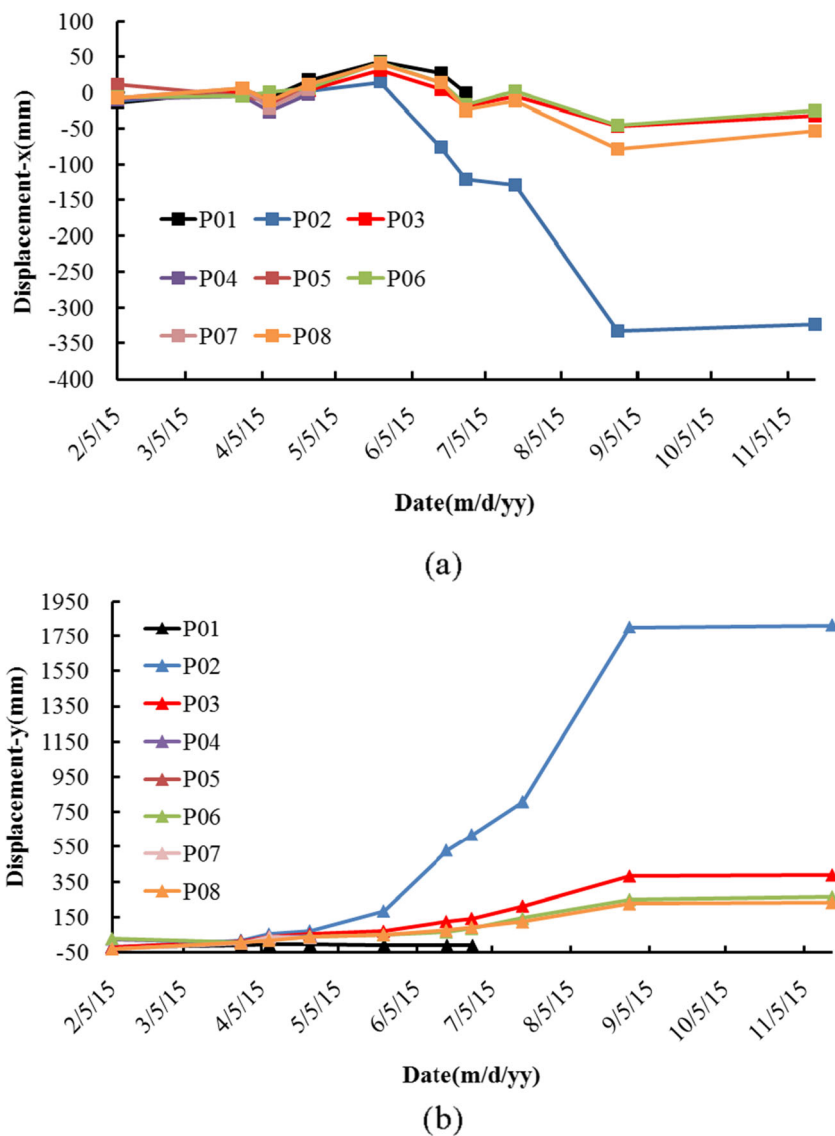


Fig. 6 Monitoring results of GPS sites: **a** displacement in the strike direction (dx) and **b** the dip direction (dy) of the slope



(2) the wide distribution of tension cracks on the slope surface. Among them, the weak interlayer is the internal factor of the landslide. A large number of vertical tension cracks provide favorable conditions for rainfall infiltration, which is an external factor inducing the slope deformation. The lithological profile of the main deformation area of the slope (i.e., the cross section a-a' in Fig. 4) is shown in Fig. 7, in which the weak interlayer in the slope basically formed a potential sliding zone and the dense distribution of tension cracks can be seen.

Because of the low mechanical strength of the weak interlayer, early excavation induced initial slip of the slope, forming a surface of rupture along the interlayer, which created favorable conditions for recurrent sliding of a landslide during the monitoring period. The large number of tension cracks caused the study area to have good water permeability and increase the sensitivity of groundwater to rainfall. Moreover, limited by the discharge capacity of the leading

edge, the groundwater table rose rapidly under the action of rainfall, but remained at a high level. The mechanical properties of the weak interlayer in the slope are quite different before and after saturation. Laboratory tests show that the cohesion and internal friction angle of weak interlayer are 25 kPa and 18° at natural state, while they are only 10 kPa and 11° at saturated state. Therefore, when the weak layer was immersed by groundwater, the slope stability decreases.

Numerical simulation

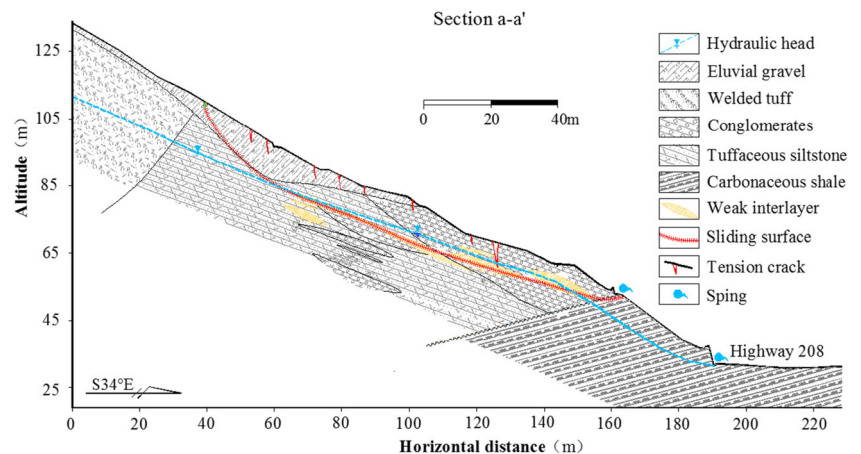
To quantitatively evaluate the influence of the weak interlayer and the tension crack on the slope stability, a series of numerical simulations are carried out. The numerical model is developed using the finite element code Phase2 (www.roscience.com), which is 220 m in length and 170 m in height, as shown in Fig. 8a. The model is discretized by

Table 1 Variation of the hydraulic head with time in three monitored boreholes

Date	BH3 (m)	BH2 (m)	BH1 (m)
2014.12.10	-16.78	-12.1	-8.1
2015.01.15	-17.7	-11.31	-7.96
2015.03.30	-14.5	-10.3	
2015.04.09	-10.04	-9.54	
2015.04.24	-15.20	-10.74	
2015.06.13	failure of slope		-3.7
2015.06.17	-14.3		<-4.0
2015.06.19	-14.5		-3.85
2015.06.22	-14.5	-9.75	-3.8
2015.06.26	-12.45	-9.2	-3.84
2015.06.27	-13.48	-9.31	-3.9
2015.08.27	-14.34		<-4

six nodes triangular element, and the total nodes and the elements are 11,809 and 5751, respectively. The soil model used in this paper is an elastic-perfectly-plastic model of a fixed yield surface defined by the Mohr-Coulomb failure criterion. The physical and mechanical parameters of strata are listed in Table 2, according to the geological exploration and laboratory test. The location and depth of tension cracks in the model are according to the field investigations. The tension cracks are simulated by joint elements, and the joint strength parameters are set to depend on the materials. The groundwater table is modeled as hydrostatic pressure to account for the influence of the groundwater level fluctuation under different rainfall conditions. For simplicity, the rainwater infiltration on the slope surface and groundwater seepage at the landslide shear outlets are not considered during the numerical simulations. Different groundwater levels under different rainfall scenarios are simplified and only modeled as hydraulic boundary conditions. The factor of safety (F_s) of the slope is computed by the shear strength reduction technique.

Fig. 7 The lithological profile of Houpuacun landslide (cross section a-a' in Fig. 4)



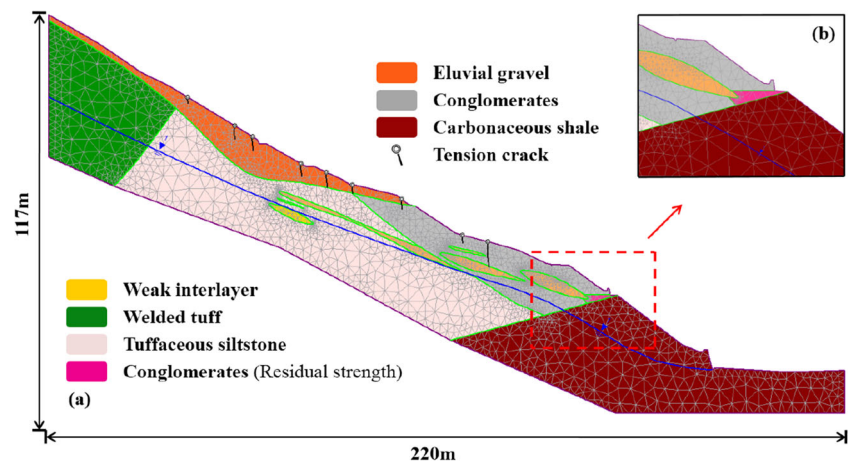
Taking into account the early deformation and sliding failure of the landslide, the strength parameters of rock mass near the shear outlet are set as residual strength values. Some scholars proposed estimation methods of the residual strength and the deformation parameters of rock mass (Cai et al. 2007; Peng et al. 2014). In these studies, the residual cohesion of the rock mass was usually set to zero. Therefore, in this numerical simulation, a part of the conglomerate, near the landslide shear outlets, is set to only provide a friction angle for its shear strength (Fig. 8b).

Three scenarios are considered to evaluate the slope stability under different hydraulic heads. Among them, scenario 1 represents the groundwater table is below the weak interlayer, simulating the hydraulic characteristics of the slope in the dry season. Another two situations including the partial immersion (scenario 2) and the complete immersion (scenario 3) of the weak interlayer are also computed to consider the dynamic process of the groundwater table in the rainy season. The peak value of the groundwater table in scenario 3 (complete immersion) is obtained from the monitoring data.

Results and analysis

Figure 9 shows the total displacement distribution and the factor of safety (F_s) of the slope in the mentioned three scenarios. It can be seen that the slope remains stable when the groundwater table is lower than the interlayer, and the $F_s = 1.18$ in scenario 1. However, the slope is approaching the critical state of equilibrium when the groundwater table is gradually raised due to the infiltration of rainfall, the computed $F_s = 1.07$ in scenario 2 and $F_s = 0.98$ in scenario 3, indicating that the slope cannot maintain stability. From the results of displacement distribution, the main displacement occurs at the trailing edge of the slope in scenario 1, and with the rise of water level the main displacement gradually moves toward the leading edge. When the landslide occurs (scenario 3), the displacement near the shear outlet is the largest, and the

Fig. 8 **a** Model of the numerical simulation (Scenario 1); **b** a part of conglomerate is set as residual strength values



displacement gradually decreases from the leading edge to the trailing edge of the slope. This trend is consistent with the field monitoring results.

Note that although the first two scenarios (scenario 1 and scenario 2) and the last two scenarios (scenario 2 and scenario 3) have nearly the same groundwater table difference, the decrease of the factor of safety is larger between the first two scenarios. This is because the weak interlayer mechanical properties under the natural and saturated state are quite different. The softening effect of the rise of the groundwater table to the interlayer has a large influence on the stability of the slope. The numerical modeling results show that for the slope in hand, ensuring the groundwater table under the interlayer is significant to the slope stability.

Stabilization treatment using siphon drainage method

The analysis shows that the effective control of the groundwater table is the key to guarantee the stability of the slope. If the groundwater can be discharged quickly under rainfall, a landslide might be avoided. At present, most of the drainage methods used in engineering are of the gravity type,

which not only presents low drainage efficiency, but also is prone to be blocked (Shang et al. 2015). To this end, we have developed a new siphon drainage method to enhance the slope stability. Compared with other drainage methods, siphon drainage has powerful water delivery capacity and the flow velocity can be automatically controlled by changing water levels during the siphon process (Cai et al. 2014). This siphon drainage method needs no power and can realize persistent, real-time drainage and control the groundwater table at a low level.

The traditional siphon method has been applied in some slope drainage projects (Cambiaghi and Schuster 1989; Gress 1992; Govi 1999; Bomont 2008) and has achieved good results. However, in the cases when the siphon borehole is vertically arranged, because the highest siphon head is 10 m and the intermittent drainage may produce air accumulated at the siphon top, which limits the drainage depth and restricts its application for practical landslide drainage. Moreover, some drainage process requires some auxiliary equipment to achieve its continuous drainage, which needs manual maintenance and management. The newly developed siphon drainage method, taking advantage of inclined boreholes drilled into the deep slope and keeping the difference between the groundwater level control point height

Table 2 Physical and mechanical parameters of strata

Name of stratum	Unit weight (kN/m ³)	Cohesion (kPa)	Internal friction angle (°)	Young's modulus (MPa)	Poisson's ratio
Eluvial gravel	21.0	30	23	20	0.3
Conglomerates (weakly weathered)	26.5	150	31	5000	0.25
Conglomerates (Residual strength)	26.5	0	31	5000	0.25
Carbonaceous shale (weakly weathered)	27.0	200	30	7000	0.22
Weak interlayer (saturated)	21.5	10	11	5	0.3
Weak interlayer (natural)	21.5	25	18	5	0.3
Welded tuff (weakly weathered)	27.5	800	43	9000	0.15
Tuffaceous siltstone (weakly weathered)	26.5	180	34	5000	0.23

Fig. 9 Horizontal displacement distribution and the factor of safety (F_s) of the slope in three scenarios: **a** scenario 1 represents the water table is lower than the interlayer, **b** scenario 2 represents the partial immersion of the interlayer, **c** scenario 3 represents the complete immersion of the interlayer

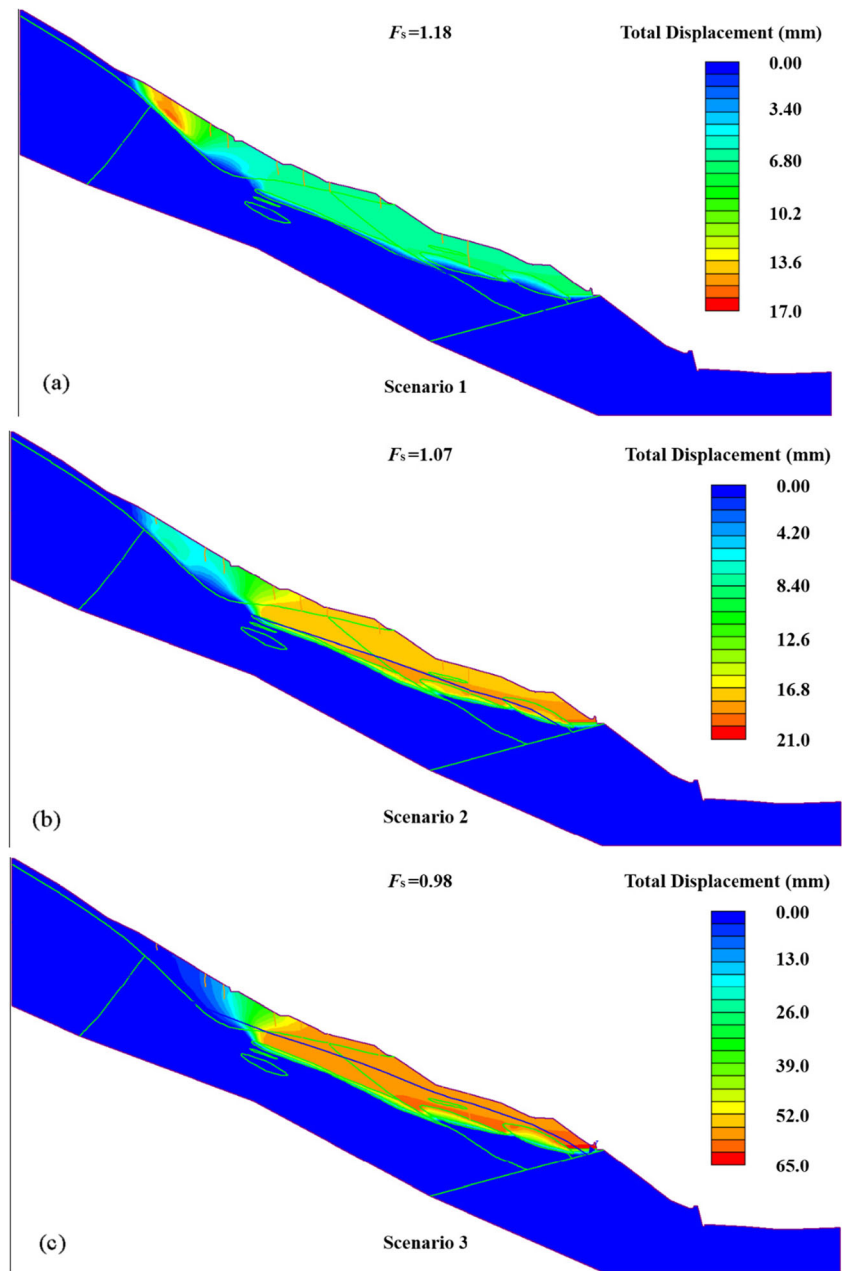


Fig. 10 a Location of the siphon drainage hole in the Houpuacun landslide (a-a'); **b** tectonic diagram of a drainage pipe, permeable pipe and water storage pipe

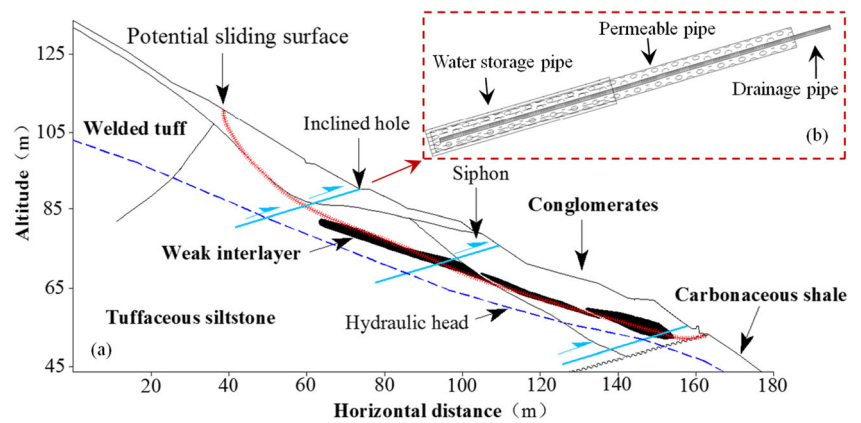
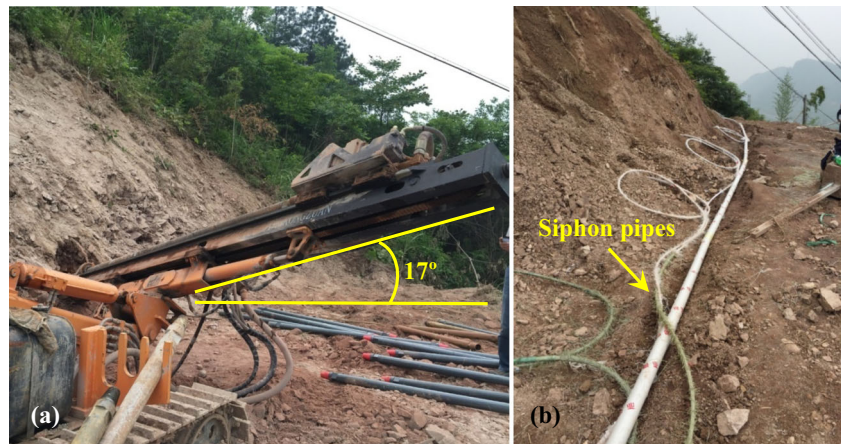


Fig. 11 **a** Construction of the drainage borehole using the drilling rig; **b** siphon drainage pipes buried under the slope surface



and the orifice height less than 10 m, can realize the landslide deep groundwater descending requirements. In addition, by controlling the siphon drainage pipe diameter (i.e., 4 mm used in the Houpucun landslide) and choosing a reasonable location for the drain outlet, the siphon pipes form a stable slug flow that can prevent air accumulation (Cai et al. 2014; Cai et al. 2015; Shang et al. 2015). This innovative drainage method achieved the goal of long-term persistent drainage without power and maintenance, and has been successfully applied in the treatment of many rainfall-sensitive landslides, and the maximum decline depth of groundwater level in a landslide is 7.5 m (Shang et al. 2015).

Construction techniques

For the Houpucun landslide, based on the investigation of the catchment area, the rainfall intensity, groundwater level and its descending requirement in the study area, three rows of inclined boreholes for siphon drainage are created along the slope at elevations of 55 m, 75 m and 90 m, respectively, as shown in Fig. 10a. The total number of siphon boreholes is 80,

among which 20 are at 55 m elevation and spacing 5 m, 40 are at 75 m elevation and spacing 3 m, and 20 are at 90 m elevation and spacing 3 m. The siphon drainage pipe, permeable pipe and water storage pipe are arranged in the specified form and placed into the borehole, as shown in Fig. 10b. The depth of the siphon drainage borehole is 40 m, and the downward drilling angle is 17° (Fig. 11a). After the construction of the siphon system is completed, the drainage pipes are buried under the slope surface (Fig. 11b). Four drainage pipes with diameter 4 mm are arranged in each siphon hole, and a high pressure sprayer is used for reverse water injection to start the siphon. All of the siphon pipes are pulled down along the slope surface from the orifice to the concrete retaining wall near Highway 208, and the groundwater is discharged into a water collecting pool.

Treatment effect

Figure 12a shows the groundwater drained by the siphon pipes, and Fig. 12b shows the water collecting pool at the foot of the Houpucun landslide in which a triangular weir is used to

Fig. 12 **a** Groundwater drained by siphon pipes; **b** water collecting pool at the foot of the Houpucun landslide



monitor the total water yield. Because of the powerful water delivery capacity of the siphon, the actual drainage efficiency depends on the velocity of groundwater infiltrating into the borehole. The fractured rock mass and the tension cracks on the slope surface in the study area provide convenient conditions for the infiltration; thus, the rainfall can be quickly discharged through the siphon drainage pipes. From the monitoring data, the flow is relatively stable and can reach about 13 m³/day currently. Therefore, the hydraulic head also returns to a deep position. According to the monitored data, the groundwater level in BH3 drops to approximately -17 m, which is about -14 m before drainage. The displacement monitoring data indicate that the slope restores stability after the siphon drainage works. These results demonstrate that the siphon drainage method effectively achieved the desired stability goal for the case in hand.

Furthermore, an alternative treatment method to stabilize the Houpucun landslide using the large diameter anti-slide piles was also designed by contractor for comparison. By contrast, the cost and the construction time of the siphon drainage method is only 1/9 and 1/3, respectively, that of the anti-slide pile.

Conclusions

In this study, the hydrological and displacement responses of the Houpucun landslide induced by tension cracks and weak interlayer were studied by field investigation and monitoring. The mechanism of the landslide was discussed, and the slope stability under different hydraulic heads were analyzed by numerical simulations. Finally, a treatment using the new siphon drainage method was applied to control the groundwater table. The following conclusions can be drawn from this case study:

- (1) Early excavation induced the initial slip of the slope along the weak interlayer, a series of tension cracks were developed on the slope surface. The slope shows high rainfall sensitivity, and the hydraulic head rises rapidly under the action of rainfall. The monitoring data indicate that the displacement of the slope has a strong correlation with the rainfall intensity and groundwater table. During the maximum rainfall that occurred from May to August in 2015, the slope produced a persistent deformation.
- (2) A numerical model was developed using the finite element method. Three scenarios were calculated to simulate the slope stability under different hydraulic heads. The factors of safety (F_s) of the slope with respect to three scenarios were computed by the shear strength reduction technique. The results show that when the groundwater table completely immerse the weak interlayer, the safety factor of slope is less than one due to the decrease in the interlayer strength.
- (3) The results from the present study indicate that the tension crack plays an important role in determining the landslide occurrence under heavy rainfall, especially when there is a weak interlayer in the slope. The recurrence of the landslide might be avoided if it was given enough attention before excavation; thus, the tension cracks should be paid more attention during the survey and design of the engineering works, not only during the construction.
- (4) According to the characteristics of the slope, a new siphon drainage method was adopted to control the groundwater table and enhance the slope stability. Using inclined borehole drilling into the slope, the groundwater table could be controlled below the weak interlayer. From the monitoring data, the daily drainage of groundwater can reach approximately 13 m³. The groundwater table also return to a deep position, and the slope is restored stability. For the Houpucun case in hand, the siphon drainage method has been illustrated as an efficient landslide treatment method of low cost and rapid construction; however, it should be noted that this method is only applicable to control landslides mainly caused by groundwater rise. For landslide with different failure mechanism, some other slope stabilization method such as anti-slide piles may still be required.

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