



Study on stability of exit slope of Chenjiapo tunnel under condition of long-term rainfall

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Abstract

The exit slope of Chenjiapo Tunnel is located directly above the exit of Chenjiapo Tunnel on Enshi to Laifeng expressway. During the excavation of the exit of the right line of the tunnel, the left side of the front edge of the slope slips. Under the joint action of excavation and rainfall, a large landslide of $6.27 \times 10^4 \text{ m}^3$ and a huge unstable slope of $8.69 \times 10^5 \text{ m}^3$ are formed. The landslide body and unstable slope body not only cause the tunnel to be shut down, but also directly threaten the operation safety of the later expressway. Therefore, to study the stability change process of the exit slope of Chenjiapo tunnel under the condition of long-term rainfall, the finite element calculation of the slope is carried out by GeoStudio software. The results show that under the condition of long-term continuous rainfall, the safety factor of the slope decreases with the increased rainfall time, but the reduction rate gradually slows down, and finally tends to be stable. The safety factor of the slope is reduced from 1.187 in the natural state to 1.015, which indicates that the slope is still in a stable state under the condition of long-term continuous rainfall, but the safety reserve is not high, and it is easy to lose stability and damage due to the influence of external adverse factors. As the rainfall continues, the seepage line inside the slope is rising, and the saturated area of the soil at the toe of the slope is increasing. Until the slope begins to drain outwards, the seepage field inside the slope is basically stable. The maximum horizontal displacement of the slope increases with the increased rainfall time, but the increase rate gradually slows down until it tends to be stable. The maximum horizontal displacement of the slope occurred in the middle surface of the slope at the beginning of the rainfall, and gradually transferred to the toe of the slope within 7 days of the rainfall and continued until the end of the rainfall. At the end of the rainfall, the maximum horizontal displacement of the toe of the slope is 0.128 m, and the toe of the slope will be damaged first. At the beginning of the rainfall, the plastic zone of the slope is only scattered at the slope surface and the slope toe. And then as the rainfall continues, the distribution range of the plastic zone in the slope surface, the slope toe and the slide zone gradually widen, and the slope stability gradually decreases. The maximum horizontal displacement and plastic zone of the slope are concentrated at the toe of the slope, the slope presents obvious traction failure characteristics. According to the results of the field survey, there are small-scale gravel soil collapses and shear outlets at the front edge of the slope, and the survey results are consistent with the simulation results. It is suggested to set up perfect drainage engineering in the middle and back of the slope, and set anti-slide piles and drainage holes at the toe of the slope to reinforce the slope.

Keywords Chenjiapo tunnel · Slope stability · Long-term rainfall · Finite element method · Safety factor · Plastic zone

Introduction

Owing to the unique geographical and geological conditions, the slope stability problem is extremely serious in our country. China has a large amount of mountainous area, accounting for about 2/3 of the total land area. So there are a large number of natural slopes in China. At the same time, in the process of China's industrialization, we are faced with a large number of complex artificial slope problems due to plenty of infrastructure construction. Under the influence of

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rainfall, reservoir impoundment, earthquake and other factors, the slope tend to be unstable and landslide occurs easily. Among them, rainfall is the main factor to induce landslide (Dou and Wang 2017; Liu et al. 2019; Shi et al. 2020). Due to the infiltration of a large amount of rainwater, the saturation of the soil rises in the slope, the shear strength of the soil decreases, the stability of the slope decreases, and the landslide occurs finally (Zhou et al. 2014; Doumbouya et al. 2020). Because of its wide distribution and higher frequency of occurrence, rainfall landslides cause a lot of casualties and economic losses (Hou et al. 2013; Ye and Shi 2018). Therefore, the key to prevent landslide natural disasters is to study the process of slope instability under different rainfall conditions. Recently, because it has characteristics of intuitiveness, repeatability and easy extraction of data in the process of studying the influence of rainfall on slope stability, numerical simulation method has been used (Hou et al. 2016; Yang et al. 2017). In this way, fruitful research results are obtained.

The influence of rainstorm and heavy rainfall on slope stability is a hot topic. Based on the model test of rainfall slope, the influence of rainstorm on the stability of soil slope is explored (Lin et al. 2009). It is found that the phenomenon of slope erosion failure caused by heavy rainfall is obvious. When cumulative rainfall exceeds the threshold rainfall of landslide, heavy rain is easy to induce landslide. Besides, rainfall intensity and cumulative rainfall are taken as early warning factors to predict the landslide. By establishing the calculation model of slope stability under different depth wetting front, it is found that the inclined bedrock surface of the slope significantly changes the rainwater migration inside the shallow soil under the condition of heavy rainfall, which results in the double-fold linear development of the potential slip crack surface of the slope (Ma et al. 2015). A model based on a physical method to simulate the landslide process caused by rainstorm is put forward (Li et al. 2016), so the dynamic relationship between slope safety factor and cumulative rainfall is obtained. The feasibility of the model is verified by three typical landslide events during heavy rain in southwest, southeast and south-central of china. By analyzing the stability of the accumulation layer slope under the action of heavy rainfall, it is found that the size effect of the landslide in the process of rainwater infiltration is very obvious (Wang et al. 2016). The expansion rate of the landslide wetting front is significantly affected by the slope length. And in the early stage of heavy rainfall, the stability of the accumulation layer landslide decreases rapidly. Moreover, a landslide formed during heavy rain in India is studied (Dey and Sengupta 2018). It is found that heavy rain forms a higher water level near the slope, resulting in the increase of shallow saturated zone and positive pore water pressure. With the increase of rainfall intensity and rainfall time, the depth of the saturated zone increases rapidly. It is considered

that heavy rainfall is an important cause of shallow landslide in the red layer area (Wu et al. 2018). And by establishing a model of shallow landslide induced by rainfall based on physical method, it is found that the landslide failure process induced by heavy rainfall can be divided into three stages, the three stages are slope foot erosion, slope top tensile crack formation and shallow landslide. Based on the study of the landslide caused by typhoon “Megi” in 2016 in Kaohsiung City, Taiwan, it is found that most of the landslides are anti-dumping sandstone landslides with mudstone. Meanwhile, the instability failure mechanism of the landslide induced by rainstorm is revealed (Lin et al. 2019). Taking the expressway landslide caused by heavy rainfall in Vietnam as the research object, the reasons, failure mechanism and characteristics of the landslide are researched by the way of geological survey, unmanned aerial vehicle investigation and rainfall events investigation (Nguyen et al. 2020). It is found that rainstorm is the trigger factor of two landslides, while slope cutting is the main inducing factor of landslide.

In many areas with humid climate and abundant rainfall, there is a long period of continuous light rain, which may also induce landslides. Therefore, it is necessary to study the slope stability under the condition of long-term continuous rainfall. The failure process of a highway slope under the condition of long-term continuous rainfall is studied by numerical simulation method (Cui et al. 2007). It is found that the loss of suction in slope soil caused by long rainfall is the main factor of slope failure. The slope stability under long-term small intensity rainfall is analyzed (Liu et al. 2012). The soil moisture content is introduced into the strength reduction method, and the expression of slope safety factor under the condition of long-term small intensity rainfall is established. The change law of slope safety factor during rainfall is obtained, which provides the reference for slope instability prediction under long-term small intensity rainfall. The study of a high-filled slope shows that in the process of 118 days' weak rainfall, the unsaturated zone of the surface soil of the slope appears because the rainfall intensity is less than the permeability coefficient of the soil. At the same time, the slope stability continuously decreases, but the reduction extent is smaller (Tian et al. 2014). Under the condition of extreme long rain, the seepage and stability analysis of soft rock slope on Rucheng-Chenzhou Expressway shows that the slope stability decreases with the increasing of rainfall time. The slope stability continuously decreases within one day after the end of rainfall, then the slope stability gradually rises. But the slope stability decreases again due to rock softening (Jiang et al. 2014). By simulating the effect of rainfall lasting for 30 days, the unsaturated behavior of expansive soil under external hydraulic load is studied. Moreover, the volume change of expansive soil during hydraulic suction and saturation process under different sections were studied as well (Mohammed et al.

2020). The results show that with the increase of initial soil suction and rainfall duration, soil uplift will be aggravated, which will affect the overall stability of the ground. By analyzing the scale of 172 rainfalls induced landslides in Taiwan from 2006 to 2012, it is found that the increase of groundwater level caused by long rainfall is the main factor to induce large landslide (Chen et al. 2017). The field investigation, deformation monitoring and numerical simulation analysis of a large landslide that occurred in Fuquan, Guizhou Province in 2014 are finished. It is found that the rise of groundwater level caused by continuous rainfall is the decisive factor of landslide formation (Lin et al. 2018). Additionally, the joint action of excavation and continuous rainfall is the inducing factor of landslide formation. The bedding landslide occurred under the continuous rainfall is studied in Libo County, Guizhou Province in 2017. It is found that the bedding characteristics of weak intercalation and rock strata, the influence of steep slope and slope excavation are the objective factors of landslide formation (Zhao et al. 2019). And the effect of continuous rainfall is the main trigger factor of landslide formation.

It is full of rainfall in the area of Chenjiapo tunnel exit slope. And the annual rainfall time is long and rainfall types are mostly small and moderate rain. At present, under the combined action of rainfall and excavation, the left side of the slope front has slipped downward. Under the condition of long-term continuous rainfall, external factors such as excavation disturbance and slag stacking may cause the slope to be unstable as a whole, which poses a threat to the tunnel construction and the operation safety of the expressway in the later stage. Therefore, taking the exit slope of Chenjiapo tunnel as an example, the change process of slope stability under the condition of long-term continuous rainfall and the mechanism of slope instability induced by rainfall are analyzed by GeoStudio software, and the research results can provide a reference for the prevention and control of landslide.

Engineering situation of Chenjiapo tunnel exit slope

The exit slope of Chenjiapo Tunnel is located in Xuanen County, Hubei Province. The slope is directly above the exit of Chenjiapo Tunnel on Enshi-Laifeng Expressway. During the excavation of the tunnel at the exit of the right line of the tunnel, the left side of the slope front slips downward, and the sliding landslide and unstable slope are formed under the action of rainfall and excavation. Belonging to the middle and low mountain area of structural denudation and erosion, the mountain structure of the whole slope area is the geological structure of hidden fault. The overburden layer on the slope is mainly

composed of Quaternary Holocene residual slope layer gravel soil and landslide accumulation layer silty clay, and the underlying rock layer is mainly Silurian Middle Series Shamao Formation siltstone. The surface water in the slope area is mainly gully water, and the flow rate changes strongly responsive to the seasonal variation. Groundwater is mainly pore water developed in the overburden, which is greatly affected by atmospheric precipitation. The slope is located in Qinjiaping Village, whose climate belongs to a subtropical monsoon humid climate. Qinjiaping Village has the characteristics of less cold winter, no summer heat, wet all year round, abundant rainfall. Frequent rainstorm, continuous rainfall, high-intensity rainfall and sudden rainfall and so on in spring and summer are the main factors inducing landslide. At present, the landslide has caused a serious threat to the safety of tunnel construction, and the tunnel construction can only be suspended. The unstable slope directly threatens the operation safety of the expressway in the later period and may cause the loss of people's lives and property. The engineering geological map of the slope is shown in Fig. 1 and the longitudinal section 2–2' is shown in Fig. 2.

The sliding landslide presents an irregular fan shape on the plane, its width is about 120 m, its longitudinal length is about 70 m and the volume of the landslide is about $6.27 \times 10^4 \text{ m}^3$, which belongs to the large-type landslide. The overburden layer on the left side of the sliding landslide is thinner and the right overburden layer is thicker. The back and front edge elevation of the slope are 756.0 m, 722.0 m respectively. The relative height difference is about 34 m. The landslide is mainly composed of silty clay mixed with gravels. The thickness of the landslide body is about 8.3–30.3 m. The thickness of the landslide body is thicker, the gravel content is higher, and the composition of gravel is mainly siltstone. The composition of the sliding zone is mainly silty clay mixed with gravels in some parts, which is yellow to grayish brown. It is in soft plastic condition and has lower strength when exposed to water. The composition of the sliding bed is mainly the underlying bedrock and the overburden which is still in a stable state. The underlying bedrock is siltstone.

The elevation of the trailing edge of the potential landslide area of the unstable slope is about 822.5 m. The elevation of the front is about 722.0 m. The relative height difference is about 100 m. The average thickness of the sliding body is about 20.8 m, the width is about 200 m, the longitudinal length is about 300 m, and the volume is about $8.69 \times 10^5 \text{ m}^3$. The sliding body is mainly gravel soil, local solitary stone, about 8.7–30.3 m thick. It has the characteristics of larger thickness and uneven distribution. The sliding zone is a silty clay layer between the overburden and the bedrock. It is gray-brown and in a soft plastic condition. And its strength

Fig. 1 Engineering geological map of the slope

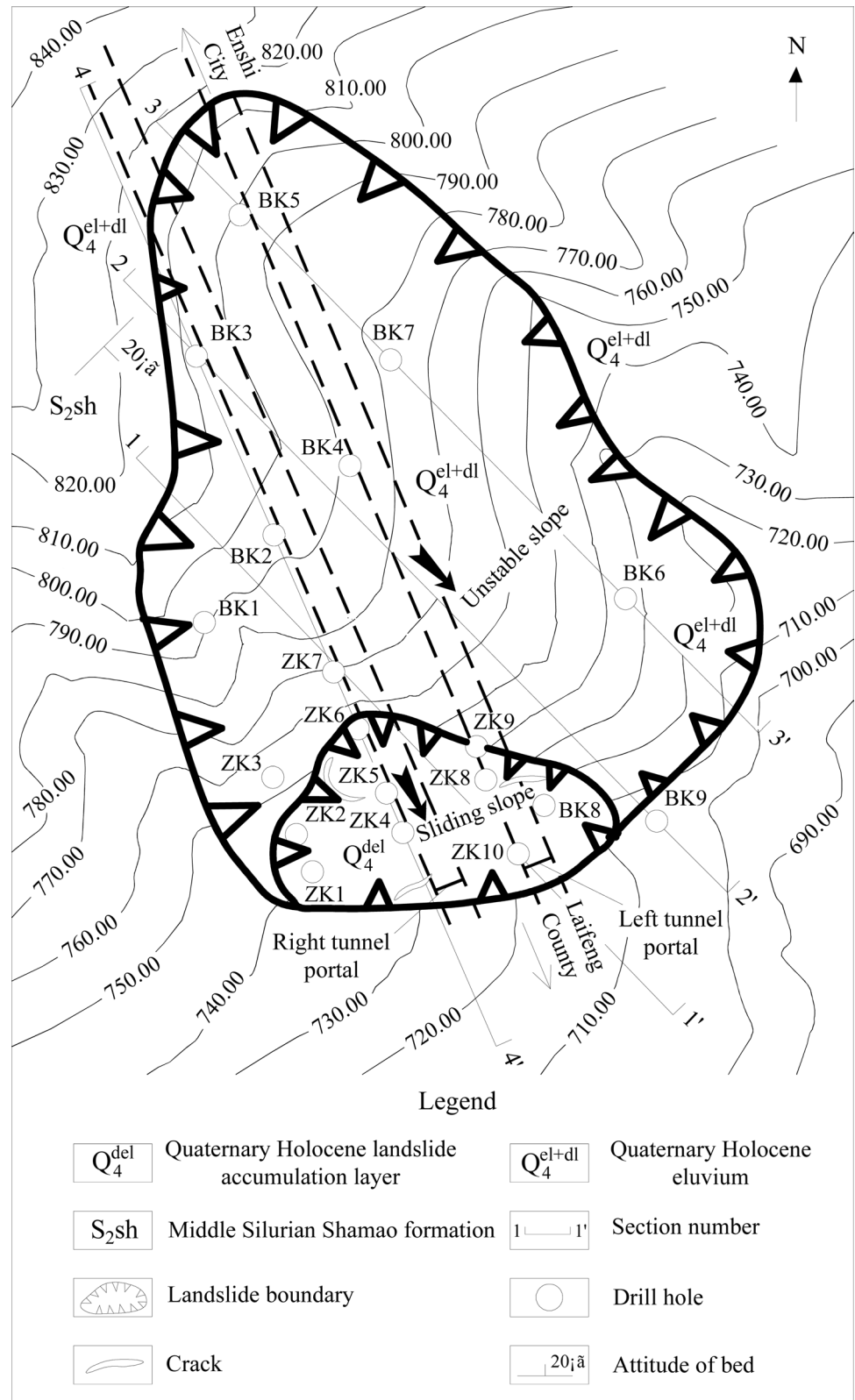
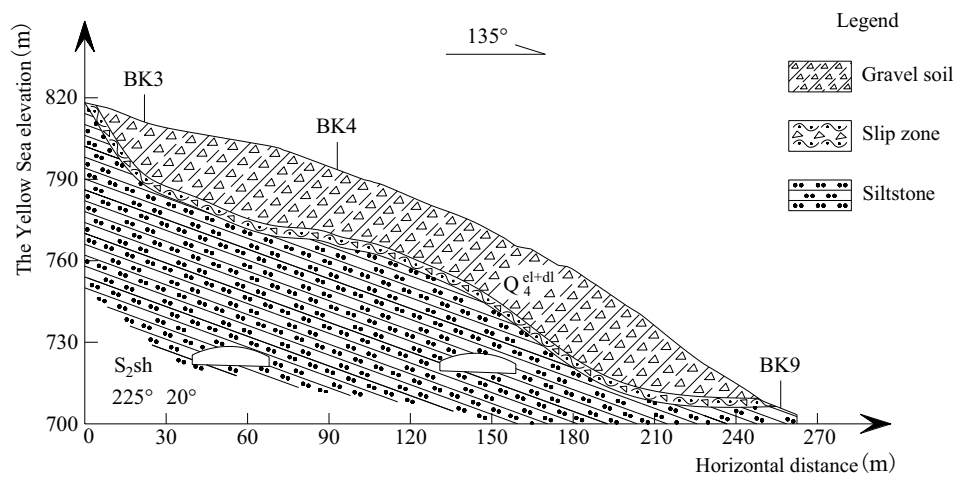


Fig. 2 2–2' longitudinal section of the slope



becomes lower when exposed to water. The sliding bed is mainly underlying bedrock and partly a stable gravel soil layer. The bedrock is siltstone.

Model establishment and selection of calculation conditions

At present, the left side of the front edge of the exit slope in Chenjiapo Tunnel has slid downward, which forms a sliding landslide. To further study the stability of the unstable slope, the longitudinal section of the slope shown in Fig. 2 is introduced into the SEEP/W module of the GeoStudio software. The slope calculation model

is established as shown in Fig. 3. There are 2218 computing nodes and 2097 computing units in the model. In the SEEP/W module, the groundwater level is defined at the interface of rock and soil. The rainfall boundary condition is applied on the slope surface. According to Darcy’s law of unsaturated soil seepage, the finite element equation of unsaturated soil seepage flow is established. The changes of the seepage field of the slope during rainfall infiltration are obtained by the finite element calculation method. The stability of slope is calculated by Morgenstern-Price method in the SLOPE/W module. The change laws of the safety factor of the slope during rainfall is obtained. The Morgenstern-Price method is a limited equilibrium analysis method of slope, which takes into account the shear

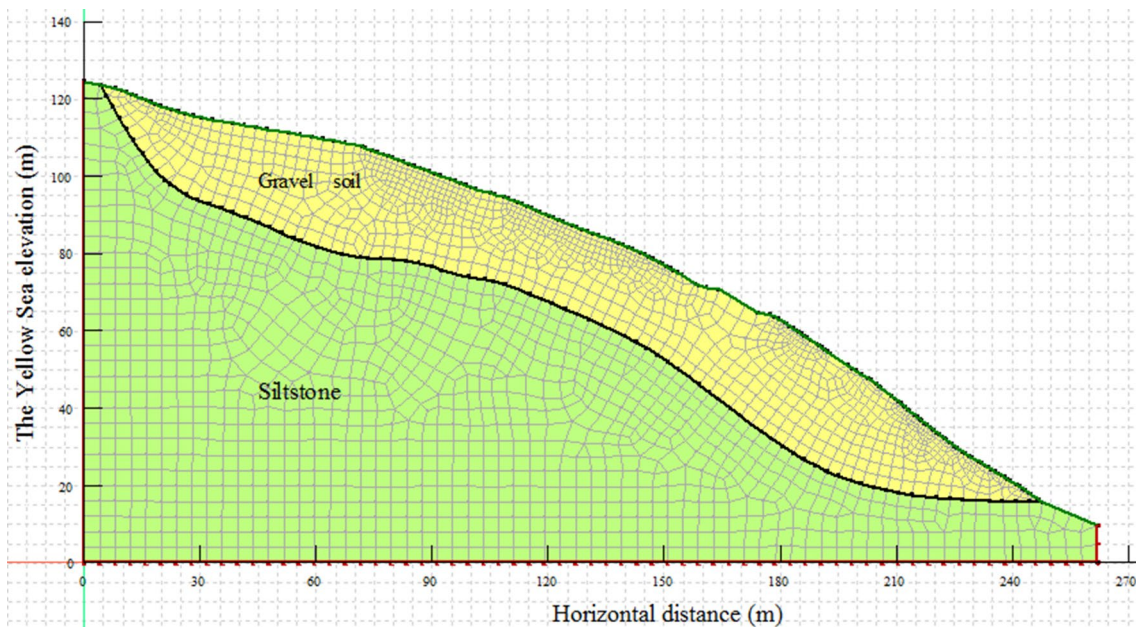


Fig. 3 Calculation model of 2–2' profile

stress and normal stress. Compared with other methods, a smaller safety factor will be obtained by Morgenstern-Price method. Therefore, the calculation results will be more safe and reliable. In SIGMA/W module, horizontal and vertical constraints are applied to the bottom of the slope, while only horizontal constraints are applied to both sides of the slope. Then the way of seepage-stress coupling analysis is used. Through the finite element method, the change of displacement field and plastic zone of the slope in the rainfall process are obtained.

According to the results of engineering geological survey and laboratory tests, the overburden layer of slope 2–2' section is gravel soil of Quaternary Holocene residual slope deposit. The underlying bedrock is the siltstone of the Middle Silurian Shamao Formation. Groundwater level line is located at the interface of rock and soil. The physical and mechanical parameters are shown in Table 1.

According to the rainfall data shown by the Hydrology and Water Resources Survey Bureau of Enshi Autonomous Prefecture in Hubei Province, a statistical map of monthly average rainfall and monthly rainfall days in Xuanen County from June 2015 to December 2018 is drawn, which is shown in Fig. 4. It can be seen from Fig. 4 that within the statistical rainfall time, Xuanen County has the highest monthly rainfall of 388.4 mm in June 2016. There are 24 rainy days in Xuanen County in June 2016. That is, the daily rainfall is about 16.2 mm. In addition, Xuanen County has the most monthly rainfall days in January 2016, August 2017, January 2018, and June 2018, all of which are 28 days. Therefore, to study the stability change process of the slope at the exit of the Chenjiapo tunnel under long-term continuous rainfall, the most unfavorable conditions are selected. Namely, the rainfall intensity is 17 mm/day and the rainfall time is 28 days.

Calculated results and analysis

The analysis of slope stability

It can be seen from Fig. 5 that the slope safety factor decreases gradually with the increasing of rainfall time under the condition of long-term continuous rainfall. Under natural condition, the safety factor of the slope is 1.187, which is in a stable state. The slope safety factor is reduced

to 1.095, 1.034, 1.017 and 1.015 respectively at the 7th, 14th, 21st and 28th day of rainfall. Although the slope is still stable, the safety reserve is not high at the end of rainfall. It is already in a critical instability state. In the 1st, 2nd, 3rd and 4th weeks of rainfall, the slope safety factor decreased by 7.8%, 5.6%, 1.6% and 0.2%, respectively. That is, the slope stability decreases faster within the first two weeks of rainfall, and then decreases gradually with the increasing of rainfall time, until it tends to be stable.

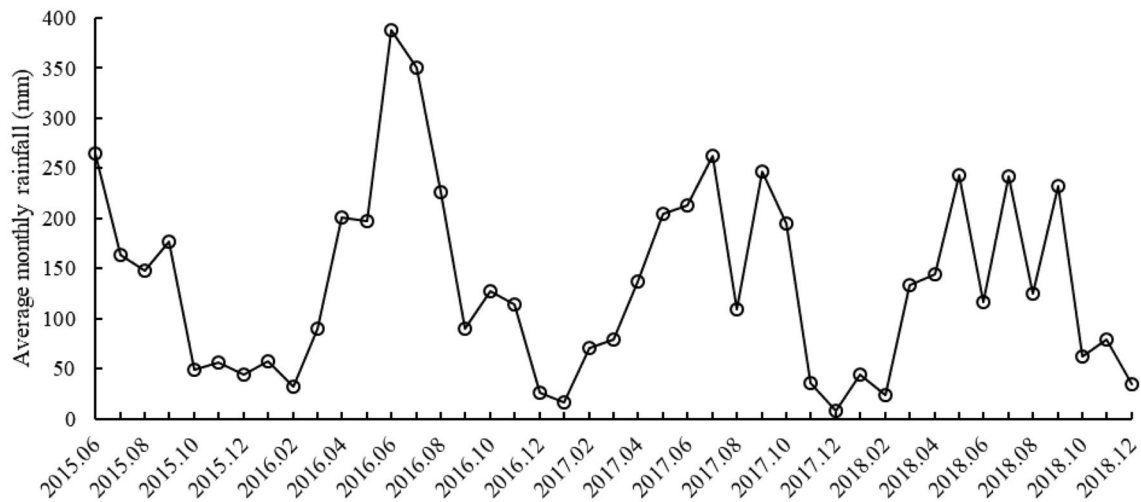
The surface soil of the exit slope of Chenjiapo tunnel is mainly gravel soil with high content of gravel and better permeability. At the beginning of the rain, rainwater quickly seep down. Although the rain intensity is smaller, the long rainfall still makes a large amount of rainwater infiltrate into the slope, which leads to the rise of the saturation line inside the slope. Part of soil in the slope changes from an unsaturated state to a saturated state. The shear strength of soil decreases, so does the slope stability. After a long period of rainfall, the amount of rainwater infiltrated into the slope has exceeded the absorption capacity of the slope. The slope begins to drain outwards and the reduction rate of slope stability begins to decrease. The slope stability tends to be stable until the infiltration of rainwater and the water discharge of the slope reach a new balance. After 28 days of rainfall, the slope safety factor decreased from 1.187 in the natural state to 1.015 and gradually becomes stable. It is showed that long-term continuous rainfall will not cause instability and damage to the slope, but it is enough to threaten the slope stability. If there are any external factors that affect the slope adversely during rainfall, it is very likely that the whole slope will be unstable and destroyed.

The analysis of seepage field of the slope

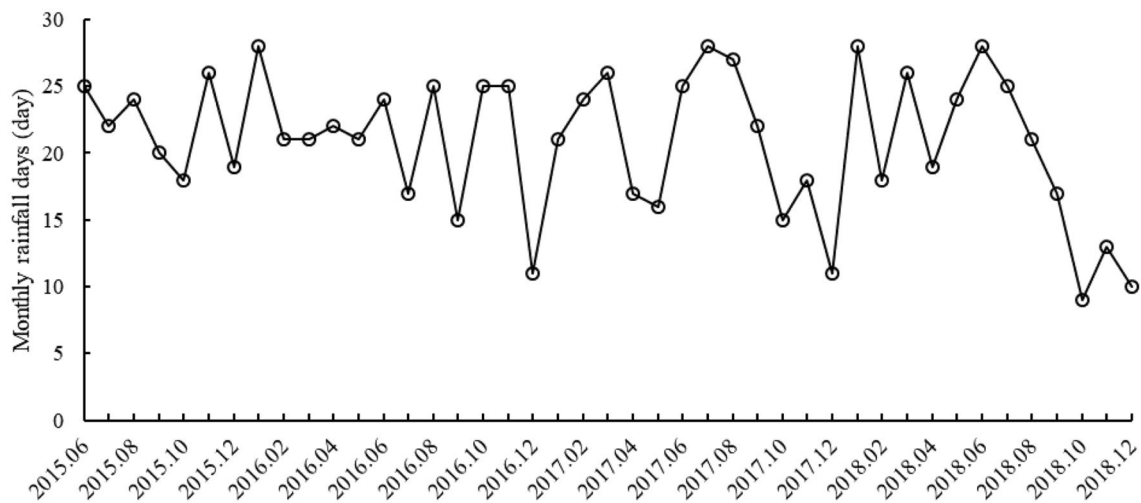
It can be seen from Fig. 6 that in the process of long-term continuous rainfall, the saturation line inside the slope is rising continuously. The saturated area of soil at the foot of the slope is increasing continuously as well. Because the soil in the upper part of the slope is gravel soil with strong permeability and rainfall intensity is far less than the permeability coefficient of the soil, rainwater will directly penetrate into the slope, resulting in the rise of the saturation line in the slope. However, due to the low rainfall intensity, the infiltration amount of rainwater is less as well. Therefore, on the first day and third day of rainfall, the saturation line of

Table 1 Physical and mechanical parameters of slope strata

Strata	Saturated bulk density/ γ_{sat} (kN/m ³)	Cohesion/ c (kPa)	Internal friction angle/ φ (°)	Saturated permeability coefficient/ k_{sat} (m/day)	Saturated moisture content/ w_{sat}	Poisson's ratio/ ν
Gravel soil	21.8	13.4	26.8	0.663	0.25	0.20
Siltstone	25.6	2030.0	41.3	0.102	0.22	0.17



(a) Average monthly rainfall



(b) Monthly rainfall days

Fig. 4 Rainfall statistics of Xuanen County from June 2015 to December 2018. **a** Average monthly rainfall. **b** Monthly rainfall days

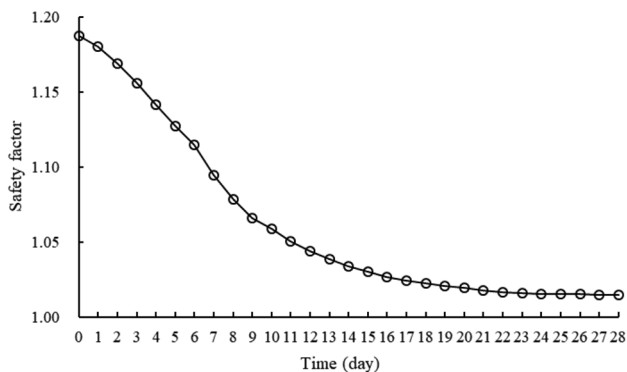


Fig. 5 Change trend of safety factor with the increasing of rainfall time

the slope increases very little. On the fifth day of rainfall, the water in the slope began to transfer to the foot of the slope. The soil at the foot of the slope reached saturation first. After that, with the increasing of continuous rainfall and infiltration of rainwater, the saturation line inside the slope continues to rise. Meanwhile, the moisture in the slope continues to transfer to the foot of the slope, which leads to the larger and larger saturation area at the foot of the slope. After 14 days of rainfall, the amount of rainwater infiltrated into the slope has exceeded the absorption capacity of the slope. The slope begins to drain outward and the saturation line inside the slope basically stops rising. However, during the drainage process, the water inside the slope continues to transfer to the slope foot, resulting in the further increase of the saturated area at the slope foot. After 21 days of rainfall,

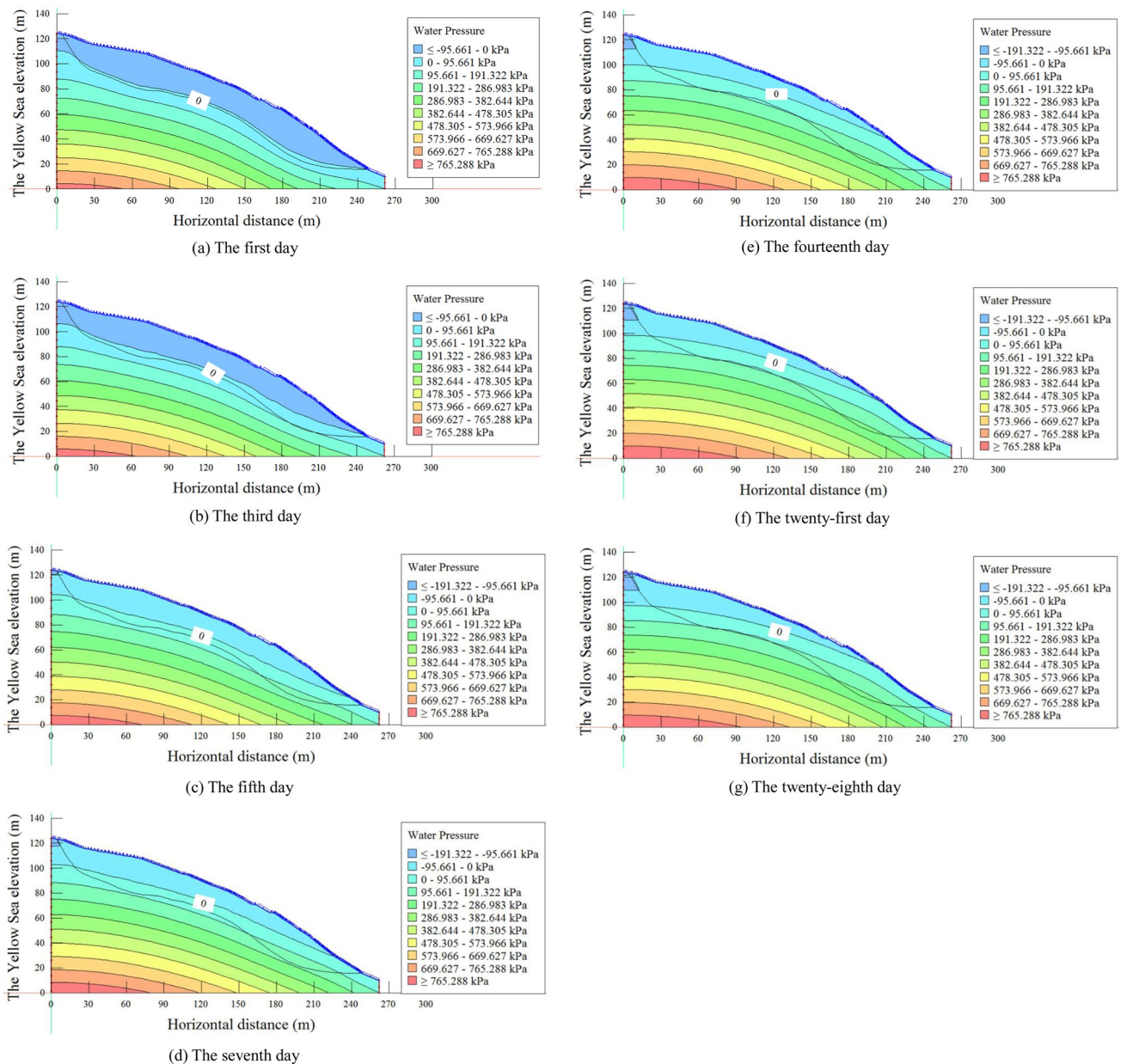


Fig. 6 Change trend of slope seepage field. **a** The first day. **b** The third day. **c** The fifth day. **d** The seventh day. **e** The fourteenth day. **f** The twenty-first day. **g** The twenty-eighth day

the infiltration amount of rainwater and the water discharge of the slope are basically balanced. And the seepage field inside the slope is basically stable. Until the end of rainfall, the seepage field of the slope is basically unchanged.

The analysis of the displacement field of the slope

It can be seen from Fig. 7 that under long-term continuous rainfall conditions, the maximum horizontal displacement of the slope shows the opposite trend to the change of the safety factor with the increasing of rainfall time. The maximum

horizontal displacement of the slope on the 7th, 14th, 21st, and 28th day of the rainfall is 0.070 m, 0.107 m, 0.122 m and 0.128 m, respectively. That is, the maximum horizontal displacement of the slope gradually increases with the increasing of the rainfall time. At the 1st, 2nd, 3rd, and 4th week of rainfall, the maximum horizontal displacement of the slope increases by 0.070 m, 0.037 m, 0.015 m and 0.006 m, respectively, compared with the previous week. Although the maximum horizontal displacement of the slope is increasing, with the increasing of rainfall time, the increase rate becomes smaller and smaller and gradually

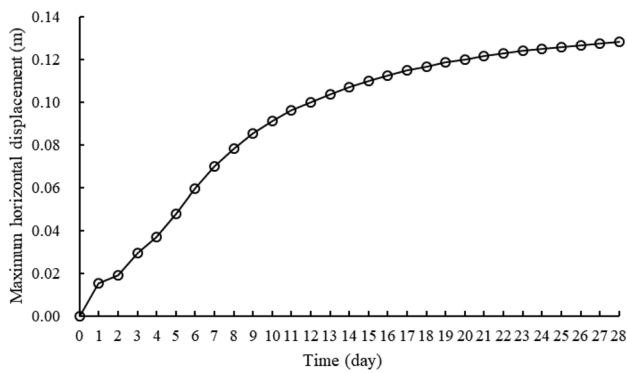


Fig. 7 Change trend of maximum horizontal displacement with the increasing of rainfall time

tends to be stable. Although the maximum horizontal displacement of the slope reached 0.128 m after 28 days of rainfall, the rainfall only causes a wide crack in the local slope and does not lead to large-scale instability of the slope as a whole.

As is shown in Fig. 8, on the first day of rainfall, the maximum horizontal displacement of the slope occurs on the surface of the middle of the slope. With the increasing of rainfall time, the maximum horizontal displacement of the slope gradually transfers to the foot of the slope. On the 7th day of rainfall, the maximum horizontal displacement occurs at the foot of the slope. After that, the maximum horizontal displacement of the slope increases gradually at the 14th, 21st and 28th day of rainfall, but the distribution law of the horizontal displacement is roughly the same. On the whole, the horizontal displacement of the slope mainly occurs in the upper soil and gradually increases from the slope inside to the slope surface. At the beginning of rainfall, the maximum horizontal displacement occurs in the middle surface of the slope. Then, with the increasing of rainfall time, the maximum horizontal displacement occurs at the foot of the slope on the 7th day of rainfall, and until the end of the rainfall. Therefore, in the process of 28 days of rainfall, the horizontal displacement of the slope at the foot of the slope increases gradually, resulting in cracks and local damage at the foot of the slope, which leads to the gradual decrease of the slope stability. However, it does not cause the overall failure of the slope. At this time, if the cracks at the bottom of the slope continue to develop due to unfavorable external factors, then resulting in the complete destruction of the bottom of the slope, it is very likely that the whole slope will become unstable.

The analysis of the plastic zone of the slope

Plastic zone is an important index to judge whether the slope is unstable or not (Pei et al. 2010). With the continuous

infiltration of rainwater, the soil inside the slope absorbs water and becomes soft. Meanwhile, the soil saturation increases, the shear strength decreases and the plastic deformation of soil increases as well. When the plastic zone is completely through the slope, a sliding zone is formed, the slope is unstable and destroyed. It can be seen from Fig. 9 that within the first 7 days of rainfall, due to the smaller rain intensity and less rainwater infiltration, the plastic zone inside the slope is only scattered at the slope surface and the foot of the slope. Although the stability of the slope is reduced, it is still in a stable state. After that, with the increasing of rainfall time, a large amount of rainwater infiltrated into the slope. The plastic zone of slope continues to develop, and is distributed in the surface, foot and slip zone of the slope in large quantities. Especially at the end of rainfall, the plastic zone of the slope has basically been through at the slip zone. Though the slope is still not unstable, it is in a critical limitation state. In addition, the distribution range of slope plastic area at the foot of the slope is obviously more than that of other parts. It indicates that if the slope is unstable, the failure must begin at the foot of the slope, which will lead to the failure of the whole slope. The slope presents obvious traction failure characteristics.

As is shown in Fig. 10, in the course of the investigation, it is found that there are small-scale gravel collapse and shear exit in the front edge of the slope, which indicates that local small-scale failure has occurred in the front edge of the slope, but its damage scale is not large enough to cause the overall instability of the slope. According to the numerical simulation results, under the condition of long-term continuous rainfall, the horizontal displacement and plastic zone distribution range of the slope in the front are obviously larger than that of other parts of the slope, which indicates that the stability of slope front soil is worse than that of other parts. The survey results well confirm the simulation results that this part of the soil will be destroyed at first. When the failure scale of the soil in the front edge of the slope reaches a certain level, the instability of the whole slope may be induced under the influence of self-weight and rainfall.

Analysis and discussion

Different from the condition of short-term heavy rainfall, the change process of slope stability under long-term rainfall is relatively slower, and the length of rainfall time will significantly affect the stability of the slope (Greco et al. 2021). The influence of rainfall on slope stability can be divided into two stages: rainfall infiltration replenishment stage and slope instability accumulation stage. In the early stage of the rain, the rainfall infiltration is slow because of low rainfall intensity. At this time, the shear strength of the soil body at the slope slip zone is continuously reduced due to the increase of the groundwater level, and the sliding resistance

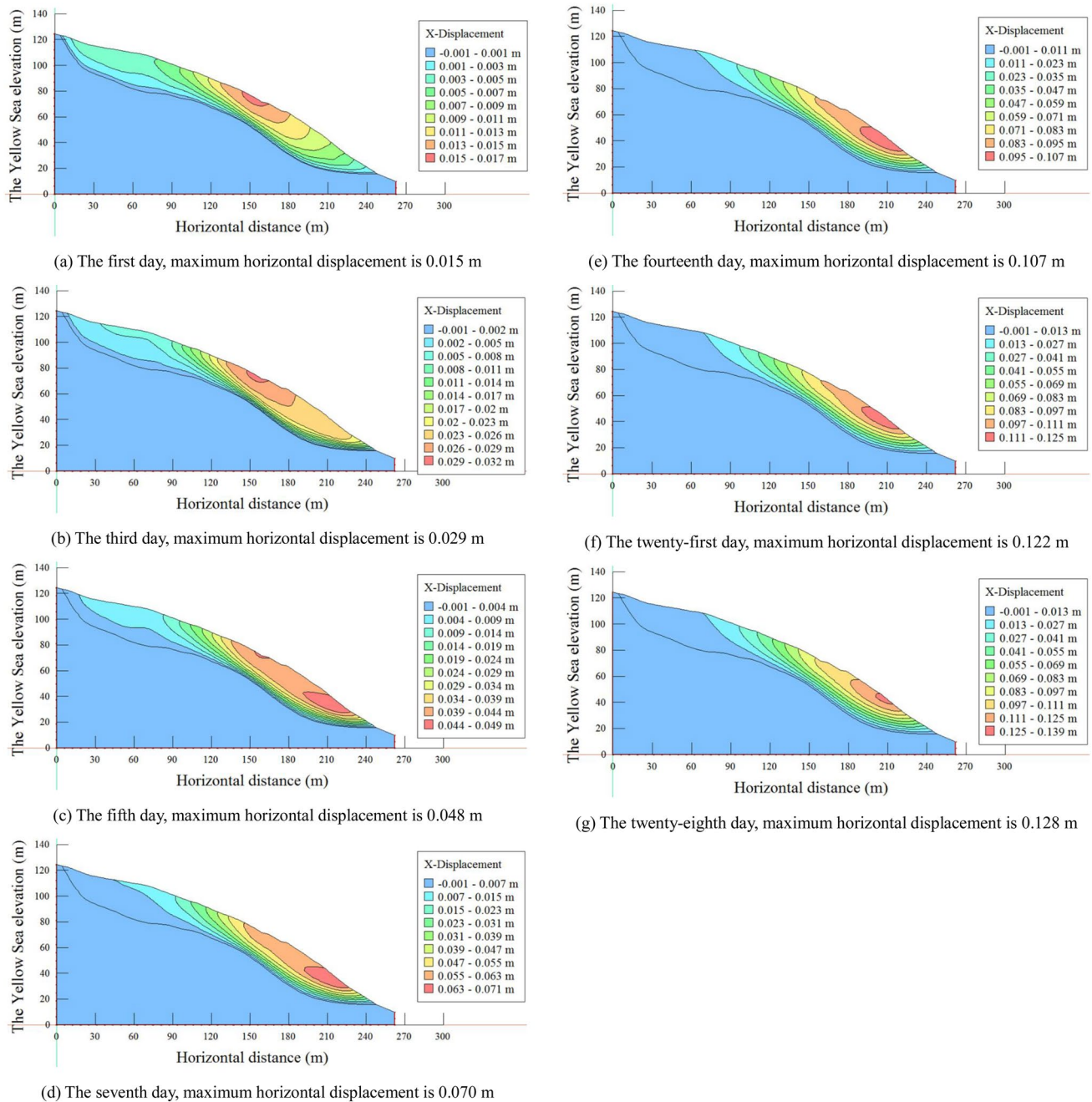


Fig. 8 Maximum horizontal displacement diagram of the slope. **a** The first day, maximum horizontal displacement is 0.015 m. **b** The third day, maximum horizontal displacement is 0.029 m. **c** The fifth day, maximum horizontal displacement is 0.048 m. **d** The seventh

day, maximum horizontal displacement is 0.070 m. **e** The fourteenth day, maximum horizontal displacement is 0.107 m. **f** The twenty-first day, maximum horizontal displacement is 0.122 m. **g** The twenty-eighth day, maximum horizontal displacement is 0.128 m

decreases. During the gradual infiltration of rain, the water absorption capacity of soil in the upper slope and the sliding force increased, and the slope stability decreases. In the middle and late period of rainfall, the water in the slope continuously gathers at the foot of the slope, and the infiltration line at the bottom of the slope increases significantly. At this time, the saturation of the soil at the front edge of the slope

begins to increase. The closer it is to the foot of the slope, the larger the increase of pore water pressure and the lower the shear strength. The anti-sliding ability of the soil at the front edge of the slope is weakened, and the slope stability is further reduced. It is studied that when the rainfall intensity kept constant, the saturation line at the bottom of the slope increases significantly and the negative pore-water pressure

decreases with the increase of rainfall duration (An et al. 2019). It is found that under the condition of continuous rainfall, the saturation line of slope is not only determined by the total rainfall under continuous rainfall but also related to the initial water distribution (Greco et al. 2021). Under the long-term rainfall, the different water distribution characteristics also have different effects on landslide development. Meanwhile, the drainage capacity of the slip zone between soil layer and bedrock interface determines the possibility of slope failure. However, it is found that the infiltration of rainwater has a limited impact on the groundwater level lines under the pavement during continuous rainfall (He et al. 2014). During the rainfall process, the pore water pressure and volume water content of slope surface in a certain depth gradually increase. After the rain stopped, pore water pressure and volume water content will gradually return to the initial state in the slope. At the slope of Chenjiapo tunnel exit, long-term continuous rainfall can stimulate larger pore water pressure though accumulated rainfall is lower, which leads to the increase of pore water pressure in the deeper soil and the rise of infiltration line in slope. These phenomena may lead to landslides, and the scale of potential landslides is also larger. As the rainfall continues, the water content in the slope gradually rises and tends to be a certain value, and then the soil internal water content rises from top to bottom. When rainfall infiltrates into the bottom of the soil, the groundwater level gradually rises to the slope surface from bottom to top, resulting in the saturation of the slope. Due to the increasing water content of soil in the slope, rainwater that can not penetrate further forms surface runoff on the slope. This runoff water flows downward by gravity and seeps to the bottom of the unsaturated slope, accelerating the saturation of the lower slope and increasing the possibility of landslide.

Due to continuous rainfall, the water content and gravity of landslide increase, leading to the decrease of mechanical properties of soil as well as the slope stability. The seepage effect under the long-term rainfall increases the water content and pore water pressure in the sliding area, resulting in the softening and expansion of the cracks in the sliding area and the decrease of soil strength. In this process, the connectivity of the potential slip zone gradually increases and the tensile deformation at the rear edge of the slope gradually rises. Tension cracks appeared at the rear edge of the slope, which expanded further as time goes on, and may lead to a further landslide.

Conclusions

The deformation and failure of the slope at the exit of Chenjiapo tunnel are related to lithology, landform and rainfall. The higher permeability and weak interlayer in the slope

are the material basis of landslide. The fluctuation of slope surface provides favorable landform conditions for rain accumulation and landslide movement. Especially, long-term continuous rainfall increases the pore water pressure of landslide and reduces the mechanical strength of weak interlayer, which is the main reason of landslide. The slope stability at the exit of Chenjiapo tunnel is calculated and analyzed under the condition of long-term rainfall by GeoStudio numerical simulation software. Through the comprehensive analysis of seepage field, displacement field and stress field, the instability mechanism of slope induced by rainfall is explored. The results are shown as following:

(1) Under the condition of long-term continuous rainfall, the slope safety factor decreases continuously with the increasing of rainfall time, but the decreasing rate becomes smaller gradually until it becomes stable. At the end of rainfall, the safety factor of the slope decreased from 1.187 in the natural state to 1.015. Although the slope is still in a stable state, the safety reserve is not high, and the overall instability is easy to occur due to the influence of other unfavorable factors.

(2) In the course of long-term continuous rainfall, the saturation line inside the slope is rising and the saturated area of soil at the slip zone is increasing. The internal moisture of the slope transfers to the foot of the slope, which leads to the sustained increase of the saturated area of the soil at the foot of the slope with the increasing of rainfall time. However, in the later stage of rainfall, because the amount of rain water infiltrated into the slope has exceeded the absorption capacity of the slope, the slope begins to drain outwards. The seepage field of the slope is basically stable.

(3) Under the condition of long-term continuous rainfall, the maximum horizontal displacement of the slope increases continuously with the increasing of rainfall time, but the increasing rate reduces gradually and finally tends to be stable. The maximum horizontal displacement of the slope appears at the middle surface of the slope at the beginning of the rainfall. On the 7th day of rainfall, the maximum horizontal displacement transfers to the foot of the slope. At the end of rainfall, the maximum horizontal displacement at the foot of the slope is 0.128 m, and local failure occur first at the foot of the slope.

(4) In the long-term continuous rainfall process, with the increasing of rainfall time, the plastic zone of the slope gradually widens at the slip zone, slope foot and slope surface. Additionally, the slope stability gradually decreases. At the end of rainfall, the plastic zone of the slope is basically through at the slip zone, and the slope stability is in a critical state.

(5) It can be got from the results of a numerical simulation that in the process of long-term continuous rainfall, the slope foot is damaged first and then affects the overall stability of the slope. It can be seen from the filed investigation

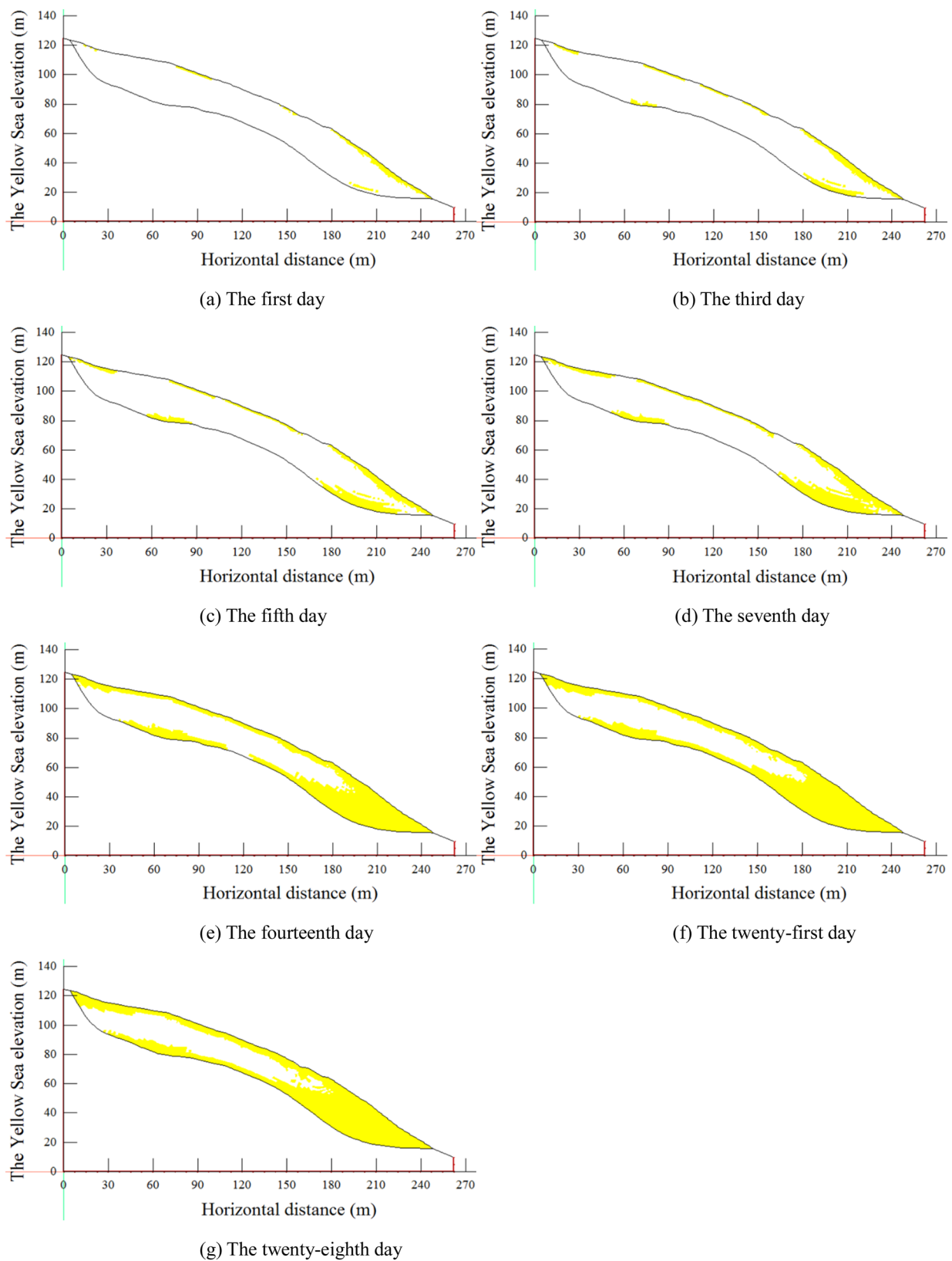


Fig. 9 Variation process of plastic zone of the slope. **a** The first day. **b** The third day. **c** The fifth day. **d** The seventh day. **e** The fourteenth day. **f** The twenty-first day. **g** The twenty-eighth day



(a) Small-scale gravel soil collapse

(b) Shear outlet

Fig. 10 Small-scale gravel soil collapse and shear outlet in front of the slope. **a** Small-scale gravel soil collapse. **b** Shear outlet

that small-scale gravel soil collapses and shear outlets are formed at the front edge of the slope. The simulation results are consistent with the filed investigation results. Although the slope is not unstable at the end of rainfall, it is already in a critical state. Therefore, it is recommended to set up a complete drainage project in the middle and rear of the slope, arrange a row of anti-slide piles at the foot of the slope for reinforcement, and add drainage holes at the foot of the slope to drain the water in the slope, so as to prevent the whole slope from sliding.

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