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Numerical Analysis of slope stability considering grading and seepage prevention

Fuyu Yan · Lianrong Wu · Xining Sun · Qiwu Shen · Qiaofeng Dong · Kun Wu · Xu Wang · Chengzhi Xia · Guangyin Lu

Abstract The normal operation of Yulangpei tailings reservoir is affected by landslide stability. In this paper, taking the main and side slopes near the dam bank of the Yulangpei ditch as an example, water-soil coupling theory is applied to comprehensively evaluate the reliability of the side slopes of the tailings reservoir. Grading and seepage prevention (GSP) measures and the suction of the substrate are considered, as well as the infiltration of different rainfall and reservoir water levels. We numerically simulate the typical three forms of side slopes under the coupling conditions and conduct a reliable and comprehensive evaluation of tailings reservoir side slopes. The study shows that under six reservoir water level changes, the factor of safety (FS) of the bank slope shows a hysteresis effect. According to nine rainfall infiltration conditions and during rainfall, the greater the rainfall intensity, the greater the weakening effect. When rainfall stops, the FS rebounds. After GSP measures, the initial stability of the bank slope under different conditions is improved, but the main slope is more sensitive to changes in rainfall and water levels.

Keywords: Grading, Seepage prevention, Unsaturated seepage, Reservoir water level, Heavy rain

1 Introduction

Reservoir landslide disasters are one of the most common geological hazards in tailings reservoirs (Jiao et al. 2014). During tailings reservoirs operation, long-term water level changes and heavy rainfall will often cause groundwater periodicity on the banks. This fluctuation will further affect the stability of the bank slope (Cojean and Cai 2011). These changes will also cause hydrological changes inside the slope body, which in turn will lead to changes in the saturation state of the landslide, as well as changes in the geomechanical and physical properties of the groundwater table, which will affect the stability of the bank slope (Fourniadis et al. 2007). Due to changes in reservoir water levels and heavy rainfall, landslides may occur in younger stable slopes, while ancient landslides may once again become active. For these reasons, the influence of water level changes and heavy rainfall is considered to be an important hazard factor for the stability of tailings bank slopes. Increasing evidence suggests that approximately 90% of slope instability is related to some extent by pore water pressure (PWP). Due to the periodic changes in reservoir water levels and rainfall, the landslide soil undergoes periodic soil-water effects, namely: (1) changes in water content (Acharya et al. 2015); (2) alternating wet and dry effects (Reid and Parkinson, 1984); (3) groundwater seepage (Take et al. 2015; Pender et al. 2016); and (4) hydrochemistry (Wei et al. 2012; Wen and He 2012). At present, the stability evaluation of the bank slope mainly shows a steady state, i.e., a single event corresponds to a single safety factor. Therefore, it is beneficial to study the stability of the bank slope by introducing time as a factor, so as to discuss any dynamic changes occurring in the bank slope safety over time. Traditional analysis of slope events is often a comparative analysis of excavation (Chen et al. 2018; Ran et al. 2019; Singh and Lan 2017; Kang et al. 2017), earthquakes (Zhou et al. 2019; Javdanian and Pradhan 2018; Gomberg 2018), seismic activity (Tang et al. 2014), rainfall (Vanwoert et al. 2005; Zhuang et al. 2018; Zhao et al. 2018; Fu 2017), reservoir water level (Mandal et al. 2019; Sun et al. 2015), and freeze-thaw change effects (Fan et al. 2014; Cheng et al. 2017). Comparative analysis performed both before and after GSP is relatively rare. However, reservoir water level changes and heavy rainfall comparative stability analysis on bank slopes, before and after GSP, has been conducted more often. Previous studies have typically

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yingagishi only considered steady-state saturated flow, and not the influence of matrix suction on landslide stability (Wei et al. 2008). The groundwater level is generally below the surface, while the PWP of the soil above the groundwater level is negative, i.e., suction occurs. This suction will increase the stability of the slope on unsaturated soils (Xiong et al. 2014). Kitamura and Sako (2010) reviewed studies of slope failure caused by rainfall over the past 50 years and emphasized the importance of unsaturated soil mechanics in elucidating the failure mechanism. In general, there are two physical mechanisms that cause soil suction stress, namely, the physical and chemical forces between particles, and capillary forces between particles. When the soil is near saturation, the suction stress is greatly reduced. This phenomenon may be the physical mechanism that instigates many shallow landslides under heavy rainfall conditions (Lu and Godt 2008). Existing research has not paid sufficient attention to the dynamic changes of soil pressure distribution (Tang et al. 2014), which is a common occurrence. Water-soil coupling is of great significance in landslide stability assessments.

In this study, the main and side slopes of the Yulangpei Gully, near the dam bank, are taken as an example. Based on the Morgenstern-Price method, using the theories of water-soil coupling and unsaturated seepage under the infiltration of different rainfalls and reservoir water level changes, a numerical simulation of the bank slope stability was performed under the coupling conditions. In addition, the factor of safety (FS), saturation distribution, and displacement of the slope with time, before and after grading and seepage prevention (GSP), of the bank slope were obtained. Finally, we performed a comprehensive evaluation on the stability of the bank slope.

2 Method and Theory

2.1 Establishment of the control differential equation

This paper uses the SEEP/W module in Geo-studio to simulate seepage processes. In this study, the saturated-unsaturated seepage theory is used for numerical simulation, where rainfall infiltration is considered as a variable flow boundary in the unsaturated zone. According to the principle of mass conservation, the saturated-unsaturated seepage control differential equation is as follows (SEEP/W 2007):

$$[k_{ij}k_r(y)\frac{\partial}{\partial x_j} + k_{ij}k_r(h)] + S = [C(h) + \beta S_s]\frac{\partial h}{\partial t} \quad (1)$$

where h is the pressure head; $k_r(h)$ is the relative water permeability coefficient; $k_r(h)=1$ in the saturated region, and $k_r(h) \in [0,1]$ in the unsaturated region; k_{ij} is the saturated permeability tensor; S_s is the unit water storage coefficient; $C(h)$ is the water capacity; if in the positive pressure zone, $C(h)=0$; if in the negative pressure zone, $C(h)=\partial\theta/\partial h$; θ is the moisture content; β is the parameter for determining the saturated and unsaturated states; in the saturated region, $\beta=0$; in the unsaturated region, $\beta=1$; t is time; and S is the source exchange item.

2.2 Establishment of the unsaturated permeability coefficient

It can typically be expressed by the fitting equation in the Van Genuchten model (Genuchten 1980), which describes the water characteristic curve and unsaturated permeability coefficient:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + (p/a)^n]^m} \quad (2)$$

$$s = s_r + \frac{1 - s_r}{[1 + (p/a)^n]^m} \quad (3)$$

$$k_r = S^{1/2}[1 - (1 - S^{1/m})^m]^2 \quad (4)$$

$$k = k_w k_r = k_w S^{1/2}[1 - (1 - S^{1/m})^m]^2 \quad (5)$$

where θ is the corrected volumetric water content; θ_r is the residual volumetric water content; θ_s is the saturated volumetric water content; s is the corrected saturation; s_r is the residual saturation level; and a , n and m are the fitting parameters. According to the relationship between volume moisture content and saturation, Equation (3) can be obtained from Equation (2). According to the relationship of relative permeability and saturation, from Equation (4), Equation (5) can be obtained, where k_w is the saturated permeability coefficient, k_r is the relative permeability coefficient, and k is the adjusted coefficient of permeability.

2.3 Establishment of the finite element seepage equation

By applying the Galerkin method with a weighted margin to the governing equation, we can obtain the finite element format of the two-dimensional seepage equation:

$$\tau \int ([B]^T [C] [B]) dA \{H\} + \tau \int_A (\lambda \langle N \rangle^r \langle N \rangle) dA \{H\}, t = q \tau \int_L (\langle N \rangle^r) dL \quad (6)$$

where $[B]$ is the gradient matrix; $[C]$ is the element permeability coefficient matrix; $\{H\}$ is the node head vector; $\langle N \rangle$ is the interpolation function vector; q is the unit flow across the element boundary; τ is the element thickness; t is time; λ is the storage term; $m_w \gamma_w$ are equal to the transient downstream current; A is the summation sign on the element area; and L is the summation sign on the element boundary length.

In the axisymmetric analysis, the equivalent element thickness is the hoop distance at the radius R , which is relative to the axis of symmetry. The complete hoop distance is multiplied by 2π . Due to the fact that SEEP / W in Geo-studio is derived for a 1-radian surface, the equivalent thickness is R . The finite element equation in the case of axisymmetric is as follows:

$$\tau \int ([B]^T [C] [B] R) dA \{H\} + \tau \int_A (\lambda \langle N \rangle^r \langle N \rangle R) dA \{H\}, t = q \tau \int_L (\langle N \rangle^r) dL \quad (7)$$

It is important to note that, unlike the thickness τ in the two-dimensional analysis, the distance of radial R in a unit is not a constant, and that the radial R changes within the integrand. The finite element seepage equation can be expressed in the following simplified form:

$$[K] \{H\} + [M] \{H\}, t = \{Q\} \quad (8)$$

where $[K]$ is the element feature matrix; $[M]$ is the element mass matrix; and $\{Q\}$ is the flow vector applied on the element. The above equation is a general-purpose finite element equation used for transient seepage analysis in Geo-studio SEEP / W.

2.4 Establishment of the factor of safety for unsaturated soil and rock

SLOPE/W uses the Morgenstern–Price method, based on limit equilibrium theory to calculate the FS. The modified method strictly satisfies the force balance and torque balance and is highly accurate. The expression is shown below:

$$F_s = \frac{\sum_{i=1}^{n_s} \frac{c'_i b_i + (W_i + P_i \cos \beta_i - u_a b_i) \tan \phi'_i + (u_a - u_w) b_i \tan \phi_b}{[1 + (\tan \phi'_i \tan a_i) / F_s] \cos a_i}}{\sum_{i=1}^{n_s} W_i \sin a_i - r_i P_i} \quad (9)$$

where c'_i is the cohesive strength for every soil slice; i is the soil slice number; W_i is the weight of each soil slice; P_i is the water pressure; β_i is the angle of the bottom of the soil slice; b_i is the length of each soil slice; ϕ'_i is the frictional strength for each soil slice; r_i is the radius of the sliding arc; and F_s is the FS.

2.5 Establishment of the numerical calculation model

As shown in Fig. 1, the bank slope of the Pulang copper mine tailings bank is located to the northeast of Diqing Tibetan Autonomous Prefecture, in northwestern Yunnan Province, China. The Pulang copper mine is one of the largest underground copper mines in the country. The bank slope selected by the geological model is the bank slope near the rockfill dam of the Yulangpei tailings reservoir, as shown in Fig. 1c. The coordinate system of the numerical calculation model was selected as follows: The X (538 m) direction of the main slope is perpendicular to the surface runoff, and the Y (242 m) direction runs vertically upwards, as shown in Fig. 2a. The X (328 m) direction of the side slope is almost parallel to the surface runoff, while the Y (196 m) direction runs vertically upwards, as shown in Fig. 2c. The sizes of the slope and model after grading and seepage prevention (GSP) remain unchanged. The height of the main slope grading is about 165 m, and the length is about 290 m, as shown in Fig. 2b. The height and length of the side slope grading are roughly 135 and 240 m, respectively, as shown in Fig. 2d. In the numerical simulation, there are 59 monitoring points on the main slope and 66 monitoring points on the side slope. The thickness of the geomembrane is only 0.5-2 mm, and the actual permeability coefficient value is 10-13cm/s. To simulate the geomembrane, according to the equivalent principle of seepage, the total volume of seepage flow is constant, therefore, the equivalent permeability coefficient k' and the equivalent thickness t can be expressed as:

$$k' = \frac{t}{\delta} k = Mk \quad (10)$$

According to the research of Cen et al. (2012), when the equivalent thickness is 1000 mm (1m), the equivalent permeability coefficient is 10-13 cm/s, and the numerical simulation effect is optimized. For the HDPE geomembrane, the height and length of the impervious layer on the main slope are 125 and 220 m, respectively, as shown in Fig. 2c. The height and length of the impervious layer on the side slope are 75 and 130 m, respectively, as shown in Fig. 2d.

Fig. 1 *a* Location of the study site in northwestern Yunnan Province, China. *b* Google Earth image of the study site. *c* Topographical map of the bank slope near the dam

Fig. 2 Numerical simulation calculation model. *a* Grid model of the main slope before GSP. *b* Grid model of the main slope after GSP. *c* Grid model of the side slope before GSP. *d* Grid model of the side slope after GSP

2.6 Calculation parameters

The rock and soil constitutive model follows the Mohr-Coulomb model, and the FS is calculated using the Morgenstern-Price method. As shown in Table 1, the parameters for ascertaining the rock and soil layers of the bank slope are based on quality surveys and laboratory test data. Combined with the VG model parameter sensitivity analysis and literature (Chen et al. 2020), the parameters of the water retention curve of the rock mass can be attained by referring to Table 2. The relationship between the volumetric water content, permeability coefficient, and matrix suction in the soil-water characteristic curve is determined by geological survey data and Equations (2) - (5), as shown in Fig. 3.

Table 1 Calculation parameters of slope

Materials	Elastic modulus (MPa)	Poisson ratio	Unit weight (kN/m ³)	Cohesion (kPa)	Friction angle (°)
Gravel soil	261.6	0.4	20.5	15	32
Strongly weathered Carbonaceous slate	2644.9	0.38	22.4	93.6	33.3
Moderately weathered Carbonaceous slate	5561	0.35	26.5	120	35
Silty clay soil	179.8	0.42	18.5	35	15
Breccia.	222.7	0.42	20	15	30

Table 2 Unsaturated parameter values

Materials	SWCC Parameters			Hydraulic Conduction Coefficient		
	a/kPa	m	n	θ_s	θ_r	kx (m/s)
Gravel soil	100	0.5	2	0.346	0.005	3.14×10^{-3}
Strongly weathered carbonaceous slate	10	0.31	1.45	0.242	0.001	8.08×10^{-5}
Moderately weathered carbonaceous slate	10	0.31	1.45	0.021	0.001	2.47×10^{-6}
Silty clay soil	100	0.145	1.17	0.476	0.001	6.51×10^{-6}
Breccia	100	0.5	2	0.39	0.005	1.28×10^{-2}
HDPE geomembrane						1×10^{-15}

Fig. 3 Water retention and hydraulic conductivity curves for different layers of the slope used in numerical analysis

2.7 Establishment of model boundary conditions

Based on hydrogeological data, the initial water level at the far bank of the main slope is maintained at approximately 210 m, and the near-shore groundwater head is roughly 30 m. The initial water level at the side

slope is fixed at roughly 150 m. The near-shore end groundwater head is approximately 40 m high, allowing the model to seep naturally for 600 days, and therefore the seepage-to-matrix suction is stable. The simulation time is 120 days. The numerical simulation considers three dynamic boundary conditions and their time-varying properties, which are defined as the three following operating conditions:

Condition 1: Different reservoir water level height and assorted rising and falling rate combinations. It is assumed that the rising and falling water levels are linear, while the water level changes are generalized into three relative modes. Two water level heights are considered, and category 1 is fast rising and slow falling (water levels 1 and 4); category 2 is moderate rising and falling (water levels 2 and 5); category 3 is slow rising and fast falling (water level 3 and 6). There are six cases in each category, as shown in Fig. 4.

Condition 2: Rainfall infiltration boundary. 9 consecutive rainfall intensities are simulated over 5 days: 1 mm/h, 3 mm/h, 5 mm/h, 7 mm/h, 9 mm/h, 11 mm/h, 13 mm/h, 15 mm/h, and 17 mm/h. After the rain stopped, the stability simulation of the bank slope seepage condition without rainfall continued for 5 days.

Condition 3: According to the real-time rainfall and monitored reservoir water level from 24:00 on March 1, 2019, to 24:00 on July 27, 2019, the influence of real rainfall and reservoir water level coupling on bank slope stability can be simulated, as shown in Fig. 5.

Fig. 4 Main and side slope reservoir water level changes. **a** Main slope water level changes. **b** Side slope water level changes

Fig. 5 Main and side slope reservoir water level changes and rainfall. **a** Main slope water level changes and rainfall. **b** Side slope water level changes and rainfall

3. Results and Discussion

3.1 Analysis of condition 1

Figs. 6 and 7 show the calculation results for the factor of safety of the bank slope under working condition 1. For the different reservoir water level fluctuation modes, when the increase is small, whether the reservoir water level rises or falls, the valley of the safety factor (VFS) appears only once. Therefore, there is no factor of

safety peak (PFS). When the increase is large, the VFS appears twice during the rise and fall of the reservoir water level, thus a PFS is present. The PFS of the three water level modes increases with the water level rising faster and higher.

The rise and fall of the bank slope FS is associated with the rising water level speed and height. When the water level rising height is larger, and the water level rises faster, the FS keeps increasing. This is because the pore water pressure growth rate in the slope is less than that of the reservoir water pressure on the main slope (Wu et al., 2017). This results in reverse pressure on the foot of the slope, and the difficulty of the slope body from saturation to saturation will gradually increase. The negative pressure zone decelerates, resulting in the bank slope FS increasing. The FS is also related to the decline rate of the reservoir water level. The faster the reservoir water level decreases, the faster the FS decreases. This is because the decline in the slope water level lags behind the decline in the reservoir water level. In addition, the pore water pressure decrease rate on the slope is less than the decrease rate of the water pressure on the main slope. Consequently, excess pore water pressure and hydrodynamic pressure are generated outside the inclined slope. The FS exhibits a lag effect with the water level change, that is, the FS corresponding to the highest water level is not the minimum value, yet the lag reaches a minimum after a certain period (Zhang et al., 2014). This lag effect is further strengthened by the faster increase of water level, a slower decline, and a greater increase in water level. The water level 1 lag effect in mode 1 is the most apparent, and the water level 6 lag effect in mode 3 is the weakest. For the various reservoir water level fluctuation modes, during the water level rise of the reservoir main slope, the VFS appeared last in mode 3 (water levels 3 and 6), and first in mode 1 (water levels 1 and 4), as shown in Fig. 6.

Following GSP, the stability of the bank slope improved, and the FS change law remained basically the same as before GSP. Furthermore, the side slope lag effect was enhanced, but that of the main slope was weakened. The main slope VFS appeared later. The side slope FS was clearly improved, yet the main slope FS increase was not significant. The main slope PFS decreased, and that of the side slope increased significantly.

Fig.6 Variation of the FS of the main slope with time under different reservoir water level modes. **a** Main slope before GSP. **b** Main slope after GSP

Fig. 7 Variation of the side slope FS with time with different reservoir water level modes. **a** Side slope before GSP. **b** Side slope after GSP

Figs. 8 and 9 show the progressive results of the slope body saturation and horizontal displacement at water

level 1. Initially, the saturation above the water level surface is inversely proportional to the elevation, namely the further away from the water level surface the rock and soil body is, the less saturated it will be. At this time, the horizontal displacement of the slope is zero. After 20 days of rising water level, the infiltration line in the slope increases the slope internal saturation, and the rate of increase in the water level becomes greater than the slope infiltration rate. This causes the saturation curve to become "concave". The soil shear strength is low, and the horizontal displacement is large under the soil-water coupling. After 60 days, the water level drops. As the infiltration line in the slope decreases, the slope saturation decreases, and the slope seeps outwards, which in turn generates dynamic water pressure and excess pore water pressure. Consequently, the slope horizontal displacement further increases. After another 40 days, the water level drops again. Although the water level has returned to normal, the soil was rich in water and the saturation is still higher than its initial state. At this time, the displacement increases slowly. After grading, the initial slope unsaturated area decreases. Compared with pre-grading, the slope saturation and horizontal displacement are more sensitive to water level changes, the horizontal displacement area increases, and the maximum displacement area approaches the foot of the slope.

Fig. 8 Variation of the saturation of the main slope with time. **a, b, c, d:** Main slope before GSP; **e, f, g, h:** Main slope after GSP

Fig.9 Variation of the horizontal displacement of the main slope with time. **a, b, c, d:** Main slope before GSP. **e, f, g, h:** Main slope after GSP

3.2 Analysis of condition 2

Figs. 10-11 show the calculated result of the bank slope FS in condition 2. The stronger the rainfall intensity was, the more obvious the weakening effect is. After the rainfall ended, the FS rebounded. Following a heavy rainfall period, the slope FS, before GSP, decreased twice. The first drop was during rainfall. Under short-term and high-intensity rainfall, a strong outward tilting water pressure was generated inside the slope, which caused the slope stability to decrease (Zhang et al. 2014). The second drop occurred after the rain stopped. The mine drainage lagged behind, and a large amount of water was stored in the slope. After the rainfall ceased, the drainage increased, the slope continued to seep and produced a strong outward water pressure, causing a decrease in the slope stability.

According to Article 5.3.1 of the Technical Specification for Construction Slope Engineering (GB50330-2013), the stability coefficient of the bank slope is 1.3, as shown in Fig. 10b. After GSP, the initial and final factors of safety of the main slope were enhanced. The sensitivity to rainfall was also improved, but during rainfall, with an intensity greater than 7 mm/h, the FS was less than 1.3, indicating that the main slope seepage protection was poor. After GSP, the initial and final side slopes safety coefficients were significantly improved. When rainfall intensity was no greater than 9 mm/h, the sensitivity to rainfall was reduced. When the rainfall intensity exceeded 13 mm/h, the FS was lower than previously, but remained in a stable state, as shown

in Fig. 11b. Considering that the record for single-day maximum rainfall intensity in the Prang area is 8 mm/h, the side slope GSP can be considered safe and reliable.

Fig. 10 Variation of the main slope FS with time under different reservoir water level modes. **a** Main slope before GSP. **b** Main slope after GSP

Fig. 11 Variation of the FS of the side slope with time under the different reservoir water level modes. **a** Side slope before GSP. **b** Side slope after GSP.

Figs. 12 and 13 show the progressive results of the saturation and horizontal displacement of the main slope under the rainfall intensity of 17 mm/h. After 5 days of heavy rainfall, the saturation of the slope surface increased sharply, and the horizontal displacement increased significantly. After 3 days without rain, the surface water infiltrated the slope, the slope surface saturation decreased, and the horizontal displacement also gradually decreased. After 5 days with no rain, the surface water continued to seep into the slope, and both the saturation zone and the horizontal displacement slowly increased. After grading and seepage, the main slope impervious layer slowed the water outflow and seepage of the slope, and the middle and lower parts of the slope drew close to saturation. The horizontal displacement area instigated by heavy rainfall increased.

Fig. 12 Variation of the main slope saturation with time under a rainfall intensity of 17 mm/h. **a, b, c, d**: Main slope before GSP. **e, f, g, h**: Main slope after GSP

Fig. 13 Variation of the main slope horizontal displacement with time under a rainfall intensity of 17 mm/h. **a, b, c, d**: Main slope before GSP. **e, f, g, h**: Main slope after GSP

3.3 Analysis of condition 3

Fig. 14 shows the change of PWP at 59 monitoring points of the main slope and 66 monitoring points of the side slope with time. The smaller the monitoring point value, the higher the altitude. For the monitoring points above the highest point of the reservoir water level, the PWP is affected by changes in the reservoir water level. As the distance from the monitoring point to the highest water level point increases, the PWP gradually becomes smaller eventually reaching a fixed value. At monitoring points below the highest reservoir water level, the PWP is consistent with the changes in the reservoir water level. Furthermore, the closer the monitoring point is to the bottom of the slope, the greater the change in PWP will be. After GSP, a negative pressure zone appeared in the middle of the main slope, and the negative pressure zone increased in the lower and middle sides of the side slope, which is indicated by the red dotted area.

Fig. 15 shows the calculated results of the main slope FS and displacement over time. It can be seen that two stages exist in the change of the FS from March 1 to July 27. The overall change trend is a small decline, followed by a sharp rise. This is correlated with the increased rainfall intensity in the rainy season, more concentrated rainfall, faster water level elevation, and greater water level increase. The displacement is the total displacement of each monitoring point, which increases steadily. When the rainfall intensity is greater and the water level rises faster, then the displacement growth rate increases. After GSP, the overall FS is increased by about 3%, and the total displacement is reduced by about 87%. Fig. 15a shows the FS and displacement of the side slope of working condition 3 with time. From March 1 to July 27, the safety factor was negatively correlated with the change in total displacement. The overall trend is an initial slight rise, followed by a sharp rise. This is related to the increased rainfall intensity during the rainy season, as well as more concentrated rainfall, faster water level elevation, and greater water level increases. After GSP, the overall safety factor of the side slope increased by approximately 41%, and the total displacement decreased by about 66%. When the rainfall intensity was greater than 4 mm/h the bank slope total displacement increased significantly.

Fig. 14 Variation in the PWP of monitoring points on the main and side slopes with time in condition 3. **a** At the 59 monitoring points on the main slope. **b** At the 59 monitoring points on the main slope after GSP. **c** At the 66 monitoring points on the side slope. **d** At the 66 monitoring points on the side slope after GSP

Fig. 15 Variation of the FS and displacement with time in condition 3. **a** Main slope. **b** Main slope after GSP. **c** Side slope. **d** Side slope after GSP

4 Conclusions

In this paper, the slope stability considering grading and seepage prevention in the Yulangpei Gully is investigated. Under three common hydraulic boundary conditions, SEEP / W is applied to analyze the finite element unsaturated seepage on the bank slope, while SLOPE / W software implements the Morgenstern-Price method to analyze the bank slope stability by solving the FS. Finally, SIGMA / W software is used to investigate the horizontal displacement, based on the soil-water coupling theory. The following results were achieved:

1. Under the combined working conditions of two reservoir water levels and three different rising and falling speeds, it is shown that the SF of the bank slope exhibits a hysteresis effect with the change of water level. This hysteresis effect increases with faster and higher water level increases, and slower water level declines. Meanwhile, the PFS of the three water level modes increases when the water level rises faster and higher.

2. Under 9 types of rainfall infiltration conditions, it can be seen that during rainfall, the greater the rainfall intensity is, the more obvious the weakening effect is. Furthermore, the FS increases following the cessation of rainfall.

3. Under the condition that real rainfall infiltration and reservoir water fluctuation are coupled from 1 to July 27, 2019, the pore water pressure is affected by the change in reservoir water level. The pore water pressure gradually decreases as the distance between the monitoring point and the highest water level point increases. The pore water pressure changes with the reservoir water level, and the closer the monitoring point is to the bottom of the slope, the greater the change in the pore water pressure. The displacement increases with rainfall intensity and concentration, and the groundwater level rises faster, increasing significantly.

4. Based on the safety factor evaluation and the corresponding saturation and displacement changes under the three working conditions, the effect of GSP on the main slope is evaluated. The slope saturation sensitivity and horizontal displacement to changes in water level and rainfall increase. When the rainfall intensity is greater than 7 mm/h, after GSP, the main slope safety factor is lower than the stability coefficient of 1.3, and the bank slope is deemed to be in an unstable state.

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Author contributions FY wrote the original manuscript; XC and GL provided overall ideas and analyzed the results; LW, QS and QD provided the data; XS, KW and XW revised the manuscript.

Data Availability The data used to support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

- Acharya KP, Bhandary NP, Dahal RK et al (2015) Numerical analysis on influence of principal parameters of topography on hillslope instability in a small catchment. *Environ Earth Sci* 73(9):5643-5656.
- Calgary AB Canada (2010) GEO-SLOPE International Ltd. Seepage Modeling with SEEP/W 2007: 1–207
- Cen WJ, Wang M, Yang ZX (2012) Partial saturated seepage properties of (composite) geomembrane earthrock dams. *Advances in Science and Technology of Water Resources* 32(03):6-9. (In Chinese)
- Chen JD, Ge XR, Song DQ et al (2018) Deformation and mechanical characteristics of bedding rock slope in tunnel excavation. *journal of water resources and architectural engineering* 16(06):149-154. (In Chinese)
- Chen YF, Yu H, Ma H et al (2020) Inverse modeling of saturated-unsaturated flow in site-scale fractured rocks using the continuum approach: A case study at Baihetan dam site, Southwest China. *J Hydrol* 584: 124693-124693.
- Cheng YT, Li P, Xu GC et al (2017) Effect of soil erodibility on nitrogen and phosphorus loss under condition of freeze-thaw. *Transactions of the Chinese Society of Agricultural Engineering* 33(24): 141-149.
- Cojean R and Căi Y (2011) Analysis and Modeling of Slope Stability in the Three-Gorges Dam Reservoir (China)——The Case of Huangtupo Landslide. *J Mt Sci-Engl* 8(2):166-175. (In Chinese)
- Fan HM, Huang DH, Zhou LL et al (2014) Effects of Seasonal Freeze-thaw Action on Phosphorus Loss of Slope in Black Soil. *J Soil Water Conserv* 28(1):152-151.

- Fourniadis IG, Liu JG, Mason PJ (2007) Regional assessment of landslide impact in the Three Gorges area, China, using ASTER data: Wushan-Zigui. *Landslides* 4(3):267-278.
- Fu XT (2017) Characteristics of flow pattern and sediment transport processes on loessal soil slope in western Shanxi Province. *J HydraulEng* 48(6):738-747.
- Genuchten V M (1980) A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils *Soil Sci Soc Am J* 44(5):892-898.
- Gomberg, J (2018) Cascadia Onshore-Offshore Site-Response, Submarine Sediment Mobilization, and Earthquake Recurrence. *Journal of Geophysical Research: Solid Earth* 123(2):1381-1404. (In Chinese)
- Javdanian H, Pradhan B (2018) Assessment of earthquake-induced slope deformation of earth dams using soft computing techniques. *Landslides* 16(1):91-103.
- Jiao YY, Zhang HQ, Tang HM et al (2014) Simulating the process of reservoir-impoundment-induced landslide using the extended DDA method. *Eng Geol* 182:37-48.
- Kang ZJ, Tan Y, Deng G et al (2017) Impact of Soil Reinforcement in Passive Zone on the Deformation Behaviors of Deep Excavation. *journal of yangtze river scientific research institute* 34(06):119-123.
- Kitamura R, Sako K (2010) Contribution of "Soils and Foundations" to Studies on Rainfall-Induced Slope Failure. *Soils Found* 50(6):955-964.
- Lu N, Godt J (2008) Infinite Slope Stability Under Steady Unsaturated Seepage Conditions. *Water Resour Res* 44(11): 63-75.
- Mandal AK, Li XP, Shrestha R (2019) Influence of Water Level Rise on the Bank of Reservoir on Slope Stability: A Case Study of Dagangshan Hydropower Project. *Geotechnical and Geological Engineering* 37(6):5187-5198.
- Pender MJ, Orense RP, Wotherspoon LM et al (2016) Effect of permeability on the cyclic generation and dissipation of pore pressures in saturated gravel layers. *Géotechnique* 66(4):313-322.
- Ran T, Liu DA, Mei SH et al (2019) Intelligent feedback analysis on a deep excavation for the gravity anchorage foundation of a super suspension bridge. *Chinese J Rock Mech Eng* 38:2898–2912. (In Chinese)
- Reid I, Parkinson RJ (1984) The wetting and drying of a grazed and ungrazed clay soil. *Journal of Soil Science* 35(4):607-614.
- Shi J, Lan JK (2017) Predicting the impact of riverbed excavation on the buried depth of groundwater table and capillary water zone in the river banks-taking Xinfeng hydropower station as an example. *IOP Conf Ser Earth Environ Sci* 69(1): 012019-012019.
- Singh J, Banka H, Verma AK (2018) Analysis of slope stability and detection of critical failure surface using gravitational search algorithm. *Proc 4th IEEE Int Conf Recent Adv Inf Technol RAIT* 2018 1–6.
- Sun GH, Zheng H, Tang HM et al (2015) Huangtupo landslide stability under water level fluctuations of the Three Gorges reservoir. *Landslides* 13(5):1167-1179.
- Take WA, Beddoe RA, Davoodi-Bilesavar R et al (2015) Effect of antecedent groundwater conditions on the triggering of static liquefaction landslides. *Landslides* 12(3):469-479.
- Tang HM, Hu XL, Xu C et al (2014) A novel approach for determining landslide pushing force based on landslide-pile interactions. *Eng Geol* 182:15-24.
- Vanwoert ND, Rowe DB, Andresen JA et al (2005) Green Roof Stormwater Retention: Effects of Roof Surface, Slope, and Media Depth. *J Environ Qual* 34(3):1036-1044.
- Wei J, Deng J, Tham L et al (2008) Unsaturated seepage analysis for a reservoir landslide during impounding. *Landslides Eng Slopes from Past to Futur* 999–1004.
- Wei ZA, Yin GZ, Wang J G et al (2012) Stability analysis and supporting system design of a high-steep cut soil slope on an ancient landslide during highway construction of Tehran–Chalus. *Environ Earth Sci* 67(6):1651-1662.
- Wen BP, He L (2012) Influence of lixiviation by irrigation water on residual shear strength of weathered red mudstone in Northwest China: Implication for its role in landslides' reactivation. *Eng Geol* 151:56-63.
- Wu YP, Miao FS, Li LW et al (2017) Time-varying reliability analysis of Huangtupo Riverside No.2 Landslide in the Three Gorges Reservoir based on water-soil coupling. *Eng Geol* 226:267-276.
- Xiong YL, Bao XH, Ye B et al (2014) Soil – water – air fully coupling finite element analysis of slope failure in unsaturated ground. *Soils Found* 54(3):377-395.
- Zhang D, Jian WB, Ye Q et al (2014) A time-varying analytic model of tailings slope and its application. *Yantu Lixue/Rock and Soil Mechanics* 35(3):835-840.
- Zhao LS, Hou R, Wu FQ et al (2018) Effect of soil surface roughness on infiltration water, ponding and runoff on tilled soils under rainfall simulation experiments. *Soil and Tillage Research* 179:47-53.
- Zhou Z, Wang XQ, Wei YF et al (2019) Simulation study of the void space gas effect on slope instability triggered by an earthquake. *J Mt Sci-Engl* 16(6):1300-1317.
- Zhuang XH, Wang W, Ma YY et al (2018) Spatial distribution of sheet flow velocity along slope under simulated rainfall conditions. *Geoderma* 321:1-7.