Civil Engineering and Smart Structure Technology
W. Yao et al. (Eds.)

doi:10.3233/ATDE250198

Numerical Simulation of the Bank Slope Stability Associated with Reservoir Water Drawdown

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Abstract: After the construction of the Three Gorges Dam, geological hazards frequently occur, and landslides are the most widespread disasters in the reservoir area. The rapid landslide induced by rainfall is an important natural disaster in the Three Gorges Reservoir area. The rapid landslide induced by rainfall is an important natural disaster in the Three Gorges Reservoir area. Rainfall can cause changes in pore water pressure. To study the slope stability with the pore water pressure, Yangjialing landslide located in Three Gorges Reservoir area is performed using stress-seepage-slope stability coupled analysis after water drawdown. Meanwhile the phreatic line from the simulation results is compared with the analytical solution. Lower permeability and higher drawdown velocity will result in a higher pore water pressure and it is harmful to the slope stability. The zone with smaller permeability will spend longer time to change from saturated state to unsaturated state if the water level descends at the same speed. Through the research of this paper, the main factors of landslide are obtained, which lays a theoretical foundation for the prevention of landslide in the Three Gorges Reservoir area.

Keywords: Numerical calculation, water content, primary and secondary factors, slope stability, Yangjialing, three gorges reservoir area, Yangjialing landslide

1. Introduction

Rainfall-induced rapid landslides are an important natural hazard around the world, both as independent event and within large chains of cascading hazards due to their role in downstream debris flow hazards [1]. The investigations, published by Ministry of Land and Resource of China, revealed that most landslides in China were set off by prolonged rainfall or by short period of high intensity rainfall [2-4]. It also pointed out that more than 95% landslides were closely relevant to the rainfall or groundwater seepage [5].

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Specifically in reservoir region, the constantly verifying reservoir water level plays an essential role in landslides occurrence. Afte the Three Gorges Dam of China, which is across the Yangtze River, completed, the water level of the reservoir drops to 145m during the flood season, in the following months the dam stores water to 175m, and the water level drops again to 155m when entering the dry season every year [6]. The high frequency of water levels fluctuations, which is far greater than natural conditions, in the Three Gorges Dam reservoir region has led to several large scale landslides, such as Woshaxi landslide, Bazimen landslide, Tanjiawan landslide, Baijiabao landslide, Baishuihe landslide, Sanmendong landslide, and Heishiban landslide [7-10]. Some of them were the existing old landslides and began to reactivate in recent years.

As one of the most significant natural hazards, numerous researchers have conducted extensive studies on the slope stability assessment and the landslide susceptibility prediction. Some researchers consider spatial variability and seepage field fluctuation when analyze stability of reservoir landslides. In the study they exam pore water pressure calculations under rainfall and reservoir water level fluctuations to analyze landslides stability, and incorporate both water pressure and random fields into the computational framework, based on the consideration of the Mohr-Coulomb criterion, to ensure the computed landslide under steady state seepage [11]. Other researchers originate a radial degradation model, integrated with the conventional stationary Gaussian random field for rainfall-induced slope stability analysis to address two disadvantages finding in previous research that ignoring the non-uniform degradation effect of rainfall on soil parameters, and lack of study on the variation of transient failure probability throughout the duration of rainfall events [12,13]. Besides, a group of researchers incorporate the pore-water pressures from the three-dimensional water balance model, GEOtop, into the three-dimensional slope stability analysis, Scoops3D to explore the influence of subsurface flow in unsaturated soil under extreme rainfall conditions on regional slope stability. The results are also compared with those from two-dimensional seepage and slope stability analyses to provide an in-depth understanding of the effect of three-dimensional subsurface flow on the factor of safety of unsaturated slopes [14,15].

Additionally, there are a quantity of studies focusing on the early warning method of landslide disaster. For instance, a group of scholars propose a method, based on the normal distribution theory, integrating surface displacement and deep displacement random variables to enable timely scientific landslide warnings by estimating whether the random variables obeying the normal distribution, considering the non-linear and random nature of the displacement evolution in landslide and the varying sensitivity among monitoring points in landslide identification. Another crew of researchers have devised a method directly using rainfall records to predict a slope's potential instability. The method innovatively uses a slope's strength parameters and slope angle to develop the critical suction stress (tensile) or compressive pore water pressure profile where, at each depth within the slope, the effective stress reaches the failure state. Then conduct hydromechanical numerical modeling under various rainfall intensities to get the rainfall intensity-duration threshold curve of the slope, which provides pathway to forecast instability of natural slopes [16,17].

The effect of water on soil mechanical properties and its role in slope stability has been extensively studied and confirmed [18,19]. However, because of complexity of the mechanism of water induced landslides, which involves an intricate mutual coupling of multiple factors, the key role of water on the landslides has still not been elucidated profoundly [20,21]. In this paper, single factor analysis method and multi-factor analysis method have been applied to quantitatively appraise a hypothetical homogeneous ideal slope by comparing the relative order of various sensitivity factors to identify the major and minor factors influencing slope stability. To study the landslide stability with water drawdown and the landslide stability with the pore water pressure, stress-seepage-slope stability coupled analysis (Midas GTS NX software) is used to simulate Yangjialing landslide, located in Three Gorges Reservoir region, after water drawdown. Meanwhile the saturation line from the simulation results is compared with the analytical solution. Via the results from the paper, it is capable of forming theoretical foundation for the prevention and control of landslides.

2. Numerical Modeling Methodology and Calculation Conditions

The example used in this paper is Yangjialing Landslide, which is located in the Three Gorges reservoir area (Figure 1) and National Road 209 go through this landslide. Seriously compromised the proper use of China National Highway 209. Yangjialing landslide include three small landslide body (Figure 2) and 1# Yangjialing landslide is considered here. 1# landslide has a height 119 m, longitudinal length 350 m and a width of 90-220 m, with an area of 4.2×104 m2, and a volume of 80×104 m3. The landslide body consists of crushed stone, stone and mudstone and the slip zone is sandy clay with breccia. The bedrock is composed of mud shale and mudstone quartz sandstone.

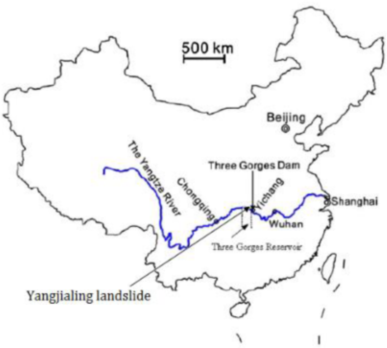


Figure 1. Location of the Yangjialing landslide.

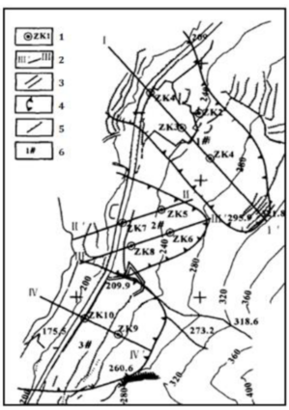


Figure 2. Geological map of the Yangjialing landslide: 1 drilling point, 2 profile number, 3 highway, 4 boundary of landslide, 5 reinforced scarp, 6 landslide number.

The Midas GTS NX software was used here to study the coupling analysis of stress-seepage-stability. A simplified two-dimensional model with a simplified geological stratum is established to represent the real Yangjialing landslide conditions, shown in Figure 3. The physical and mechanical parameters of the slip zone soil, coming from the statistical results of various groups of laboratory soil test, are shown in Table 1 [22]. The shear strength parameter is a function of water content. The slide body is assumed as homogeneous material and a time-dependent water head H is used to simulate the drawdown of water level. According to the actual situation of the Three Gorges reservoir, three lowering rate of water level are chosen, i.e., 0.2, 1.0 and 2.0 m/d. Transient seepage analysis is conduced to analyze the variation of water level due to the drawdown. The soil-water characteristic curve (SWCC) is necessary to depict the saturated- and unsaturated- permeability. Van Genuchten model is used in this paper.

$$\theta_w = \theta_r + \frac{\theta_s - \theta_r}{\left[1+(ah)^n\right]^m} \tag{1}$$

$$\frac{k_u}{k} = \frac{\left\{1-(ah)^{n-1}\left[1+(ah)^n\right]^{-m}\right\}^2}{\left[1+(ah)^n\right]^{m/2}} \tag{2}$$

Where: $\theta_w, \theta_s, \theta_r$: volume water content, saturated volume water content, residual volume water content respectively. k_u, k: the unsaturated- and saturated- permeability coefficient. a, n, m: experimental constants predicted from Curve Fitting of unsaturated experimental data.

The safety factor of the 1# landslide under natural condition is 1.0454 calculated by the limit equilibrium method [22]. Our safety factor is 1.05 under the same condition when the strength reduction method supplied by the Midas GTS NX is used. It means our model is useful for the following analysis.

Table 1. Main physical and chemical properties of soil

Parameters	Landslide Body	Bedrock
elastic modulus (kPa)	5840	5×10^6
Poisson ratio	0.3	0.25
Unit weight (kN/m3)	22.7	23
Saturated unit weight (kN/m3)	23.5	24
Cohesion (kPa)	$f_1(\theta)$	50
Angle of internal friction	$f_2(\theta)$	36
Initial void ratio	0.68	0.4
Saturated permeability (m/d)	0.05	8.64×10^{-4}
residual volume water content	0.1506	0.068
saturated volume water content	0.4771	0.503
a (1/m)	9.57	0.0067
n	1.2641	1.206
m	0.2089	0.171

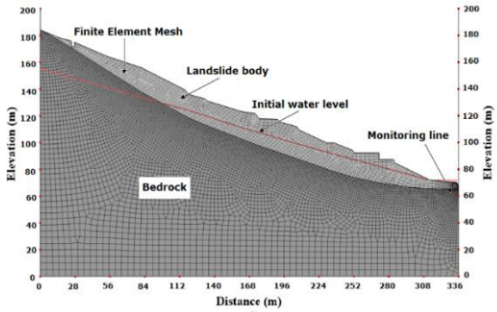


Figure 3. Numerical model of 1# Yangjialing landslide.

3. Influence Factors of Slope Stability with Water Drawdown

Figure 4 shows the evolution of the phreatic line in the slope during the decreasing of water level. When the reservoir water level drops rapidly from point B to point D, the seepage point of the slope C can not decrease synchronously with the reservoir water level due to the water in the slope is too late to drain if the permeability of the slope soil is small and the phreatic line at this time (called transient-state phreatic line) is still unstable and will change over a period of time, shown in Figure 4. With the water in the slope gradually discharges outward, the phreatic line tends to be stable (called steady-state phreatic line) and the seepage point of the slope C coincides with the reservoir water level D. The transient-state phreatic line have the greatest significance in analyzing the slope stability. So the phreatic line mentioned below refer to the transient-state phreatic line.

It's necessary to know the fluctuation of phreatic line during the process of water level drawdown in order to analyze the slope stability. Because the variation of water level is a function of time and the Boussinesq equation, which is often used to study the groundwater flows in the aquifer, is nonlinear, it is difficult to get the analytical solution of the Boussinesq equation with a moving boundary [23] transformed the Boussinesq equation into an advection-diffusion equation to address the moving boundary condition and then got an analytical solution on the basis of Laplace transformation [14]. The phreatic line obtained from the numerical simulation are compared with the analytical solution according to the Sun's results, shown in Figure 5 [24]. The two solutions are in a good agreement. It is proved that the numerical simulation method is correct, so the coupling relationship among the parameters affecting the landslide is further studied based on the numerical simulation.

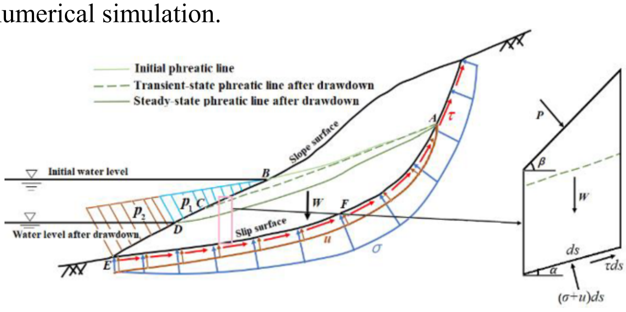


Figure 4. Sketch of a slope with water drawdown.

The forces distributing diagrammatic sketch of slide body is shown in Figure 4. u, σ, and τ are the pore water pressure, the normal stress and the shear stress on the slip surface, respectively. W is the weight force; Force P is the hydrostatic force on the slope surface. The hydrostatic force P1 acting on the BD section of the slope surface at the initial state will disappear suddenly when the water level decrease from B to D. In slice method the safety factor at initial state is

$$Fs=\frac{\text{anti-sliding force}}{\text{sliding force}}=\frac{\sum\left\{c_i^{'}l_i+\left[(W_i\cos\alpha_i+P_i\cos\beta_i+P_i\sin\beta_i)-u_il_i\right]\tan\varphi_i^{'}\right\}}{\sum\left[(W_i+P_i\cos\beta_i)\sin\alpha_i-P_i\sin\beta_i\cos\alpha_i)\right]} \tag{3}$$

After the drawdown of water level, the safety factor is

$$Fs=\frac{\sum\left\{c_i^{'}l_i+(W_i\cos\alpha_i-u_il_i)\tan\varphi_i^{'}\right\}}{\sum W_i\sin\alpha_i} \tag{4}$$

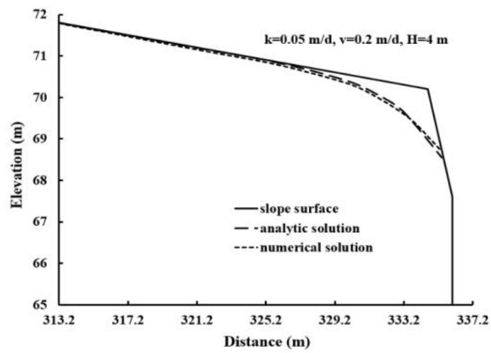


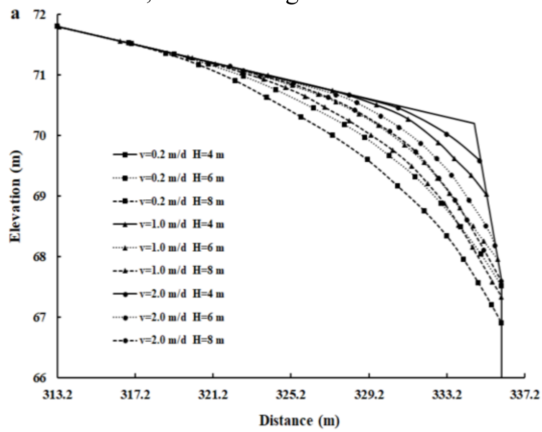
Figure 5. Phreatic line comparison between analytic solution and numerical solution.

In order to study the change of slope stability, the increase rate of safety factor β is defined as follows:

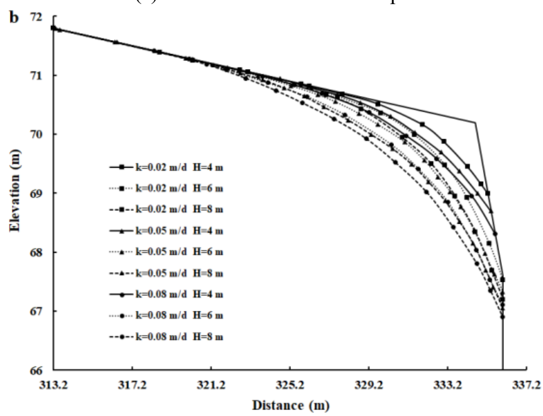
$$\beta=\frac{F_{st}-F_{s0}}{F_{s0}}\times 100\% \tag{5}$$

Where F_{s0} is the initial safety factor before the drawdown of water level; F_{st} is the safety factor after the drawdown of water level for each case.

During the process of reservoir water level drawdown, the slope stability is mainly affected by drawdown speed, soil permeability coefficient. Figure 6 shows the phreatic line for different drawdown speed and permeability when the drawdown height is 4, 6 and 8 m respectively. Figure 6(a) illustrates the numerical process of phreatic line with different drawdown speed 0.2, 1.0, 2.0 m/d when the permeability is 0.05 m/d. Results shows that the lower the rate of decline, the greater reduction degree of water level, if the water level drops the same height. Figure 6(b) depicts the phreatic line under different permeability 0.02, 0.05, 0.08 m/d when the drawdown speed is 1.0 m/d. The reduction degree of water level is larger as the permeability increase when the water level drops with a same velocity and a same height, shown in Figure 6(b). Figure 7 reveals the changes of safety factors for different drawdown speed and permeability. The negative increase rate of safety factor means the safety factor decrease with the water level drawdown. With the drawdown of water level, the increase rate of safety factor drops sharply and then becomes stable, shown in Figure 6.



(a) with different drawdown speed



(b) with different permeability

Figure 6. The transient-state phreatic line.

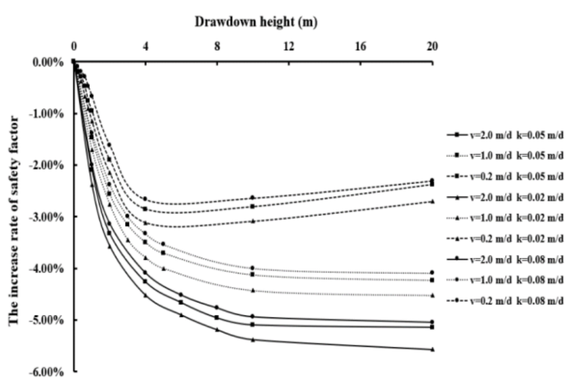


Figure 7. Comparison of safety factor during the decrease of water level with different drawdown speed and permeability.

At the early stage of water drawdown, the water cannot be discharged from the slope body timely due to the small permeability of slide body. So the phreatic line drops slowly for the larger drawdown speed when the drawdown height is same, shown in Figure 6(a). Simultaneously the water pressure, which originally acts on the side of the slope body to prevent the slope sliding, disappears after the water level has declined. Therefore the safety factor decreases rapidly at the early stage of water drawdown, and then with the water level continue to decrease, the safety factor still decline but the decrease rate slows down, shown in Figure 7. Larger permeability means more water can be discharged from the landslide body timely with the decline of water level. So the phreatic line drops sharply for the larger permeability when the drawdown height is same, shown in Figure 6(b). Accordingly the decrease rate of safety factor with smaller permeability is higher than that with higher permeability. If the water level declines at a lower speed and is closer to the soil's permeability coefficient, the safety factor of the slope will increase, shown in Figure 7. Then the probability of slope landslide is smaller.

4. Analysis of Slope Stability and Pore Water Pressure with Water Drawdown

Lower permeability and higher drawdown velocity means the water cannot be discharged from the slope body immediately. This will result in a higher pore water pressure and it is harmful to the slope stability.

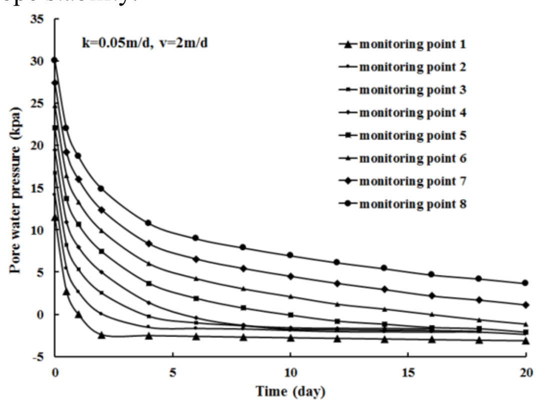


Figure 8. Variation of pore water pressure at each monitoring point with time: The permeability is 0.05m/d, water level decrease rate is 2.0m/d.

In order to study the variation of pore water pressure, a monitoring line is set up at the toe of slope. The monitoring point is established every 30 cm on the monitoring profile. From top to bottom, the point is followed by 1, 2, 3… Figure 8 depicts the variation of pore water pressure on the monitoring profile. Positive pore water pressure means that the monitoring points are in the saturation zone. Conversely, the negative pore water pressure means that the observation point is in the unsaturated zone. With the decrease of water level, the zone of the observation point located is gradually changed from the saturation state to the unsaturated state. The pore water pressure changes from positive to negative. The monitoring point 1 is located on the surface of the slope and its pore water pressure firstly turned from positive to negative with the water drawdown. Then the pore water pressure of the following points is also gradually turned from positive to negative.

Table 2 The time that pore water pressure change from positive to negative at each monitoring point

Case Number	**Time that Pore Water Pressure Change from Positive to Negative**	**Monitoring Point Number**					
		1	2	3	4	5	6
1. v=2.0m/d, k=0.08m/d	time (d)	1	2	4	5	8	20
	Pore water pressure (kPa)	-0.080	-0.055	-0.824	-0.504	-0.584	-1.812
2. v=2.0m/d, k=0.05m/d	time (d)	2	3	4	6	20	20
	Pore water pressure (kPa)	-1.031	-0.721	-0.089	-0.124	-2.390	-1.162
3. v=2.0m/d, k=0.02m/d	time (d)	2	4	8	20	20	
	Pore water pressure (kPa)	-0.502	-0.452	-0.275	-1.716	-0.177	
4. v=1.0m/d, k=0.05m/d	time (d)	3	4	6	8	20	20
	Pore water pressure (kPa)	-0.736	-0.135	-0.137	-0.093	-1.97	-0.546
5. v=0.2m/d, k=0.05m/d	time (d)	7					
	Pore water pressure (kPa)	-0.177					

The time point of the monitoring point from the positive pore water pressure to the negative pore water pressure with different water drawdown velocity and permeability is shown in Table 2. Since the time steps of the numerical simulation is calculated in days, the pore water pressure in the table is not exactly zero. The pore water pressure not shown in the table indicates that the monitoring point is still in a saturated state during the monitoring time. If the water level descends at the same speed, the smaller the permeability, the longer time the zone changes from saturated state to unsaturated state. Take the monitoring point 4 as an example, it takes 5 days for the water pressure changed from positive to negative when the permeability is 0.08 m/d. If the permeability is 0.05 m/d, the time is 6 days. When the permeability is reduced to 0.02 m/d, it will take 20 days. It is obviously that the larger water drawdown velocity, it need shorter time for the water pressure changed from positive to negative with the same permeability. The rate of slope instability increased.

5. Conclusions

Through the research of this paper, we can get the following conclusions:

(1) Aiming to the Yangjialing landslide located in Three Gorges Reservoir area, we perform the stability analysis owing to the water drawdown using Midas GTS NX software. The phreatic line obtained from the numerical simulation are compared with the analytical solution according to the Sun's results. The two solutions are in a good agreement. The location of phreatic line is related to the permeability, water drawdown speed and the duration time of water drawdown. Larger permeability means more water can be discharged from the landslide body at the same time and the phreatic line declines greatly. If the water level drops the same height, the lower the rate of decline, the greater reduction degree of water level.

(2) The safety factor decrease with the water level drawdown and is affected by permeability, drawdown rate. With the drawdown of water level, the safety factor decreases rapidly at the early stage of water drawdown, then with the water level continue to decrease, the safety factor still decline but the decrease rate slows down. However if the water level declines at a lower speed and is closer to the soil's permeability coefficient, the safety factor of the slope will increase. Lower permeability and higher drawdown velocity means the water cannot be discharged from the slope body immediately. This will result in a higher pore water pressure and it is harmful to the slope stability.

(3) The variation of pore water pressure on the monitoring profile which is located at the toe of slope are studied. With the decrease of water level, the monitoring zone gradually changed from the saturation state to the unsaturated state and the pore water pressure changes from positive to negative accordingly. The pore water pressure of the monitoring point located on the surface of the slope firstly turned from positive to negative with the water drawdown. The zone with smaller permeability will spend longer time to change from saturated state to unsaturated state if the water level descends at the same speed.

Through this paper, the quantitative evaluation of primary and secondary factors affecting slope stability is obtained, which lays a theoretical foundation for the prevention and control of landslide in the Three Gorges Reservoir area. There are many factors that affect the slope stability, such as contour, tensile zone, height, angle, lithology, support and so on. In the future, we can systematically study the influence of each factor and establish the evaluation system to provide a more comprehensive basis for landslide early warning.

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