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Research Article

The Coupling Effect of Rainfall and Reservoir Water Level Decline on the Baijiabao Landslide in the Three Gorges Reservoir Area, China

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Rainfall and reservoir level fluctuation are two of the main factors contributing to reservoir landslides. However, in China's Three Gorges Reservoir Area, when the reservoir water level fluctuates significantly, it comes at a time of abundant rainfall, which makes it difficult to distinguish which factor dominates the deformation of the landslide. This study focuses on how rainfall and reservoir water level decline affect the seepage and displacement field of Baijiabao landslide spatially and temporally during drawdown of reservoir water level in the Three Gorges Reservoir Area, thus exploring its movement mechanism. The monitoring data of the landslide in the past 10 years were analyzed, and the correlation between rainfall, reservoir water level decline, and landslide displacement was clarified. By the numerical simulation method, the deformation evolution mechanism of this landslide during drawdown of reservoir water level was revealed, respectively, under three conditions, namely, rainfall, reservoir water level decline, and coupling of the above two conditions. The results showed that the deformation of the Baijiabao landslide was the coupling effect of rainfall and reservoir water level decline, while the latter effect is more pronounced.

1. Introduction

In the Three Gorges Reservoir Area of China, there are about 664 landslides which are affected by the reservoir water level, and hydrodynamic conditions such as rainfall and reservoir water level variation have different degrees of impact on the stability of these landslides [1–5]. A key issue is about fluid-solid coupling when considering the effects of hydrodynamic conditions on the landslide in the Three Gorges Reservoir Area. Under the condition of rainfall infiltration and reservoir water level variation, the seepage field in the landslide is likely to change, resulting in redistribution of stress field, which will in turn affect the change of seepage field. It is a pore water pressure-stress interaction process.

In the study of soil mechanics, Terzaghi put forward the famous principle of effective stress and established the one-dimensional consolidation model. Afterwards, Rendulic proposed a quasi-3D consolidation equation based on the one-dimensional consolidation theory. On this basis, Biot [6] made some groundbreaking research results and established an improved theory of real 3D consolidation, serving as a theoretical basis for follow-up scholars to carry out researches on the theory of fluid-solid coupling. It had been widely used in landslide stability and deformation calculation through mutual influence mechanism between seepage, stress, and displacement fields, especially affected by rainfall and reservoir water level variation. Paronuzzi et al. [7] analyzed the 1963 Vajont landslide in detail to examine the influence of reservoir operations on Mt. Toc slope stability. Sun et al. [8] simulated the hydraulic-mechanic coupling process of Sanmendong landslide by software product ABAQUS and confirmed that the combined result of reservoir water level fluctuation and rainfall could primarily account for the increase of displacement of this landslide. Vallet et al. [9] studied the hydromechanical behavior and evolution of rainfall-induced landslides subjected to creep deformation. The previous researches are mainly based on the steady-state method, by calculating variables of the model under different reservoir water levels, so as to approximately simulate the dynamic process of reservoir water level variation. This obviously can not reflect the transient response of the seepage field and the stress field over time in the landslide. In this paper, taking Baijiabao landslide in Three Gorges Reservoir Area of China for example, we try to achieve the dynamic response of the seepage field, stress field, and displacement field in the landslide under complex dynamic hydraulic boundary conditions.

After the impoundment of the Three Gorges Dam, some ancient landslides have been revived, and new landslides generated. The Baijiabao landslide in Xiangxi River Basin is one of them [10]. The Baijiabao landslide is a typical landslide affected by the hydrodynamic conditions in the Three Gorges Reservoir Area. The monitoring data of the past 10 years show that the displacement-time curve of this landslide increases step by step from April to August every year, which is obviously affected by rainfall and reservoir water level decline. Based on the monitoring data of the landslide, many scholars have tried to study how rainfall, reservoir water level, and groundwater level influence the stability of the landslide. The results of Peng and Niu [11] show that rainfall and reservoir water level variation are the main factors causing seasonal deformation of the landslide. The key factors leading to the fluctuation of landslide displacement velocity are rainfall intensity and decline rate of reservoir water level. What is more, they have analyzed how the groundwater level in the Baijiabao landslide is influenced by factors such as rainfall and reservoir water level [12]. Using the model test method, Zhao et al. simulated the deformation of the landslide, respectively, under the conditions of rainfall and reservoir water level variation [13]. Cao et al. [14] used an extreme learning machine to predict the displacement of step-like landslides in relation to rainfall, reservoir water level, and groundwater level. Wu et al. [15] classified the monthly displacement of the Baijiabao landslide into three deformation phases using two-step cluster analysis: initial, constant, and rapid deformation phases. By analyzing the 10-year monitoring data of the Baijiabao landslide, Lu et al. [16] studied the dynamic deformation characteristics, deformation mechanism, and influence factors of the Baijiabao landslide and predicted the development trend of its dynamic deformation. The above results show that rainfall and reservoir water level decline are the important causes of the step-type deformation of the Baijiabao landslide every year. However, they are just based on the analysis of monitoring data, and further researches are still needed as to the mechanism underlying the coupling effect of rainfall and reservoir water level decline on the Baijiabao landslide, as well as which of rainfall and reservoir water level decline affects the landslide more significantly.

We investigated the deformation of the Baijiabao landslide and analyzed the monitoring data on its cumulative displacement in the past 10 years and its correlation with rainfall and reservoir water level variation. Based on the theory of fluid-solid coupling, the model of Baijiabao landslide under the hydrodynamic boundary conditions of rainfall and reservoir water level was established by means of finite element numerical simulation, which has been confirmed as an effective model to analyze the effects of complex dynamic hydraulic boundary conditions on landslides. The deformation evolution mechanism of this landslide during drawdown of reservoir water level was revealed, respectively, under three conditions, namely, rainfall, reservoir water level decline, and coupling of the above two conditions. It can also provide references for the movement mechanism of such landslides.

2. Theory of Fluid-Solid Coupling in Saturated-Unsaturated Soil

The changes of external hydrodynamic conditions, such as rainfall and reservoir level fluctuation, through the seepage, will cause pore water pressure variation in the porous soil. As a result, the effective stress is changed at the contact of the soil particles, leading to the deformation of the soil, which will in turn affect the seepage and pore water pressure. This is a fluid-solid coupling process in the porous soil. In addition, there is a phreatic surface inside the landslide, and the soil below it is saturated, while the soil above it is unsaturated. Under the condition of annual rainfall and reservoir level fluctuation, the soil in the area affected by the hydrodynamic conditions will be cyclically converted between saturated and unsaturated. Therefore, the theory of fluid-solid coupling in saturated-unsaturated soil can be a good solution to such problems.

2.1. Effective Stress Principal. An elementary volume, dV, consists of a volume of grains of solid material, dV_g, and a volume of voids, dV_v, which is either fully or partly saturated with a volume of fluid, dV_w. Saturation, S, is defined as the ratio of fluid volume to void volume:

$$S = \frac{dV_w}{dV_v}. \tag{1}$$

In ABAQUS program, tensile stress is positive, while compressive stress is negative, and liquid pressure u_w and gas pressure u_a are positive. Therefore, the expression of effective stress principle in ABAQUS is slightly different from conventional soil mechanics, as follows:

$$\overline{\sigma} = \sigma + \left(\chi u_w + \left(1 - \chi\right) u_a\right) \mathbf{I}, \tag{2}$$

where σ is total stress, $\overline{\sigma}$ is effective stress, and χ is an effective stress parameter. When the soil is fully saturated, $\chi = 1.0$, while when the soil is dry, $\chi = 0$. In ABAQUS/Standard, χ is taken as saturation. $\mathbf{I}$ is unit matrix.

2.2. Stress Equilibrium and Flow Continuity. Stress equilibrium for the solid phase of the material is expressed by writing the principle of virtual work for the volume under consideration in its current configuration at time t:

$$\begin{aligned}\int_V \sigma : \delta\varepsilon \, dV = \int_S t \cdot \delta v \, dS + \int_V f \cdot \delta v \, dV \\ + \int_V sn\rho_w g \cdot \delta v \, dV,\end{aligned} \tag{3}$$

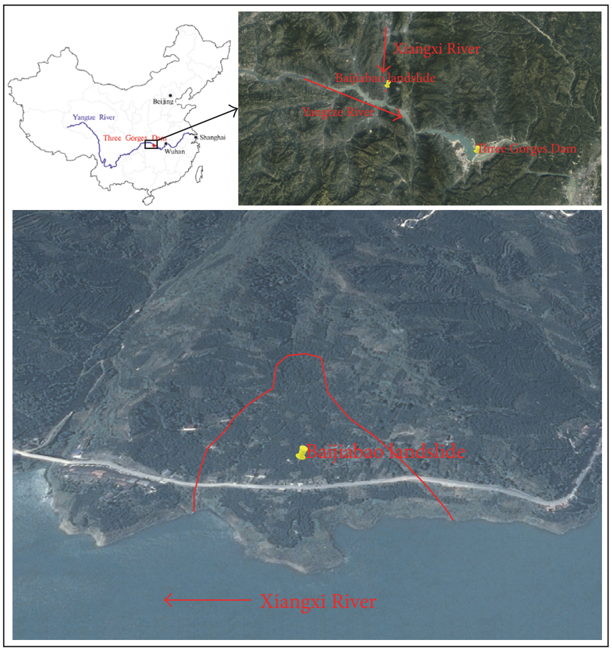


Figure 1: Location of the Baijiabao landslide in Guizhou Town, Zigui County, Hubei Province, central China.

where $\delta\varepsilon$ is the virtual rate of deformation; σ is the true effective stress; δv is a virtual velocity field; t are surface tractions per unit area; f are body forces (excluding fluid weight) per unit volume; s is the saturation; n is the porosity of the medium; ρ_w is the density of the fluid; and g is the gravitational acceleration.

In the continuity equation of the fluid, the rate of increase in fluid volume at a point is equal to the rate of volume of fluid flowing into the point within the time increment [17]:

$$\frac{d}{dt}\left(\int_V \frac{\rho_w}{\rho_w^0} sn\, dV\right) = -\int_S \frac{\rho_w}{\rho_w^0} sn\mathbf{n} \cdot v_w\, dS, \quad (4)$$

where v_w is the average velocity of the fluid relative to the solid phase and $\mathbf{n}$ is the outward normal to S. This equation has been normalized by ρ_w^0, the reference density of the fluid.

3. Engineering Background

3.1. Geological Conditions. The Baijiabao landslide is located in Guizhou Town, Zigui County, at a longitude of 110°45′33.4″E and latitude of 30°58′59.9″N, on the west side of the Xiangxi River, a major tributary to the Yangtze River; it is 2.5 km away from the estuary of the Xiangxi River and 29 km away from the Three Gorges Dam site (Figure 1). The front edge of the landslide is about 120 m in elevation, and the base of the trailing edge is 265 m. The left side of the landslide is bounded by the lower bedrock and the right side is a ridge. The landslide covers an area of 22×10^4 m^2, with a mean longitudinal dimension of 550 m and a width of 400 m. The mean depth of the sliding surface is about 45 m and the total volume of the Baijiabao landslide mass is about 990×10^4 m^3 (Figure 2).

The materials of the landslide are quaternary deposits that consist of gravel soil, the thickness of which is unevenly distributed in space. The slip surface is defined by the interface between bedrock and soil. The exposed bedrock stratums are mainly Jurassic Xiangxi formation, consisting of quartz sandstone and silty mudstones, with a dip direction of 250° and a dip angle of 30° (Figure 2). At present, there are 20 people living on the landslide, and Zixing road passes through the middle of the landslide. Once the landslide fails, the resulting disaster would be unimaginable.

3.2. Landslide Deformation. Cao et al. [14] had described in detail the deformation evolution of the Baijiabao landslide from June 2007 to July 2012, which showed that the Baijiabao landslide was apparently deforming in its entirety. In October 2015, we revisited this landslide and recorded its current deformation. There was a tension crack with a width of 2–10 cm at the trailing edge, which extended 200 m intermittently (Figure 3(a)). At the intersection between the north boundary of the landslide and Zixing Highway, the pavement was seriously damaged with cracking and subsiding (Figure 3(c)). A house near the north boundary of the landslide with an altitude of 210 m had been destroyed, as there were serious cracks in its walls (Figure 3(b)). The crack along the south boundary of the landslide was initially generated near the Zixing Highway and extended upward to the trailing edge and downward to the front of the landslide, causing subsidence and damage of the pavement of Zixing Highway, as shown in Figure 3(f). Near the south boundary of the landslide, the houses above Zixing Highway had serious ground deformation (Figure 3(e)), and some tensile failures could be observed in the rural road along the south boundary at the elevation of 230 m (Figure 3(d)). As described by local residents, during the annual rainy season and reservoir water level decline, the ground deformation of this landslide would be further exacerbated.

3.3. Ground Displacement Monitoring. Two monitoring profiles were distributed on the Baijiabao landslide. One was marked as A-A′ (Figures 2 and 3), which was consistent with the main slip direction of the landslide, arranged in the axial position of the landslide; the other was perpendicular to the slip direction and approximately paralleled to the road which crossed the landslide at about 200 m above sea level (Figure 3). There were four ground displacement monitoring points in the two monitoring sections, namely, ZG323, ZG324, ZG325, and ZG326 (Figure 3). Monitoring began in October 2006, and the monitoring data are shown in Figure 4.

From the start of monitoring to December 2015, the horizontal cumulative displacements of the monitoring points ZG323, ZG324, ZG325, and ZG326 of the Baijiabao landslide were 963.2 mm, 1118.1 mm, 1050.9 mm, and 1333.7 mm, respectively. The cumulative displacement curve showed a ladder-like increase trend, with leap increase from April to August every year and almost keeping unchanged in other months. Therefore, the landslide deformation mainly occurred in April to August, in which there was more rainfall compared with other months; what is more, it was

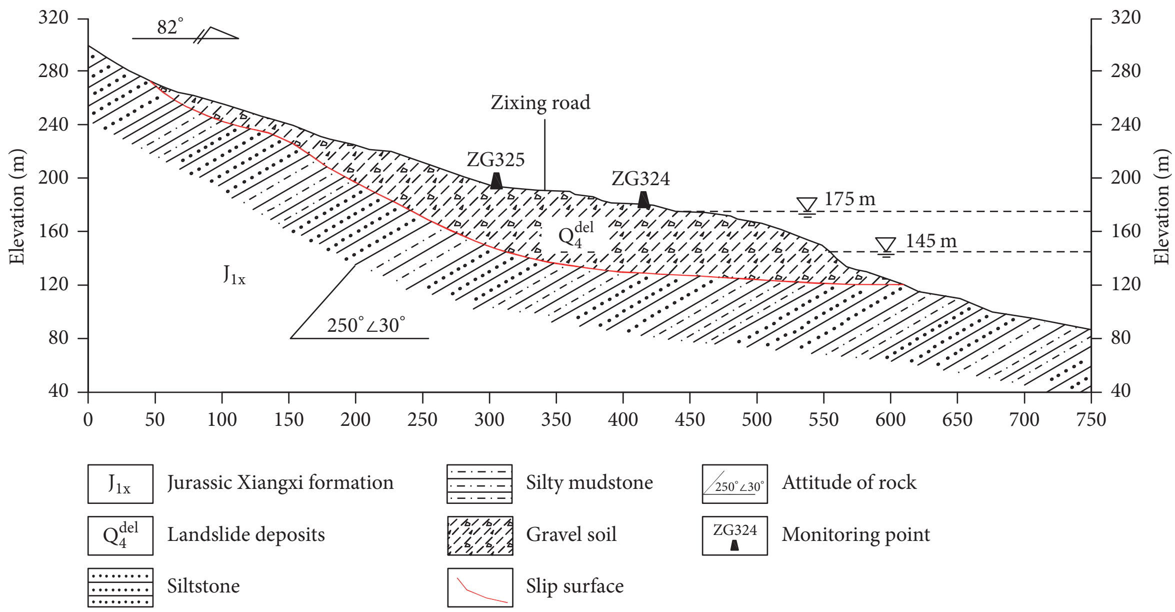


Figure 2: Geological cross-section (A-A′) of the Baijiabao landslide.

the period in which the Three Gorges Reservoir water level kept declining. Therefore, it is not difficult to find that displacement increase is significantly correlated with rainfall and reservoir water level decline. However, just as described above, further researches are still needed as to the mechanism underlying the coupling effect of rainfall and reservoir water level decline on the Baijiabao landslide, as well as which of rainfall and reservoir water level decline affects the landslide more significantly.

4. FE Model for Fluid-Solid Coupling

ABAQUS has capabilities for the treatment of single phase flow through porous media, including fully saturated flow, partially saturated flow, or a combination of the two which is adopted in this paper. Based on the theory of fluid-soil coupling in saturated-unsaturated soil, the finite element method was used to simulate the coupling effect of rainfall and reservoir water level decline on the Baijiabao landslide during drawdown of reservoir water level from December 1, 2014 (reservoir water level was 175 m), to August 18, 2015 (reservoir water level was 145 m). During this period, the mutation of field monitoring displacement of this landslide was most obvious.

4.1. Simulation Scheme. The coupling model of rainfall and reservoir water level of the Baijiabao landslide is shown in Figure 5. The model is composed of sliding mass, sliding zone, and sliding bed. The size of the model was determined completely according to the actual situation, in which the sliding zone was 0.5 m thick. To perform the stress-pore pressure-displacement analysis, a mesh consisting of 6225 eight-node pore fluid-stress, reduced-integration quadrilateral elements (CPE8RP) was used to discretize the materials. In the part of sliding mass and sliding zone, a more refined mesh was used considering its possible larger deformations and plastic behavior, with a constitutive model of Mohr-Coulomb failure criterion with linear elasticity before yielding, which can describe the transient response of soil under the influence of rainfall and reservoir water level decline, while in the sliding bed which is composed of bedrock that will not occur obvious deformation, a relatively coarse mesh was used, with the linear elasticity model applied. ZG324 and ZG325 are the ground displacement monitoring points, respectively, located at the elevation of 180 m and 194 m in the middle of the landslide, respectively.

For the boundary conditions, horizontal displacements at the left and right ends of the model were fixed, and horizontal and vertical displacements at the bottom of the model were also fixed. The boundary condition of constant water head of 243 m was applied on the left boundary of the model. On the right boundary, the boundary condition of reservoir water level was applied below the elevation of 175 m on the ground surface of the model, and the boundary condition of rainfall was applied above the elevation of 175 m. The rainfall boundary function is expressed as rainfall intensity, namely, unit circulation q (m/s). Due to the loose structure and localized cracks, the surface soil is characteristic of large infiltration rate, making it reasonable to postulate that rainfall would all infiltrate and the surface runoff would not occur. The drainage-only flow boundary condition which assumes that the flow rate of the pore fluid is proportional to the pore pressure when the pore pressure in the boundary is positive and the flow rate is limited to zero when the pore pressure is negative is assigned on the ground surface where no rainfall boundary conditions are imposed and above the reservoir level of any stages of the drawdown.

The initial stress field and seepage field of the model should be obtained before modeling the changes in rainfall and reservoir water level. Here, the stress state of the model with a reservoir water level of 175 m was taken as the initial condition for subsequent simulation. That is to say, under

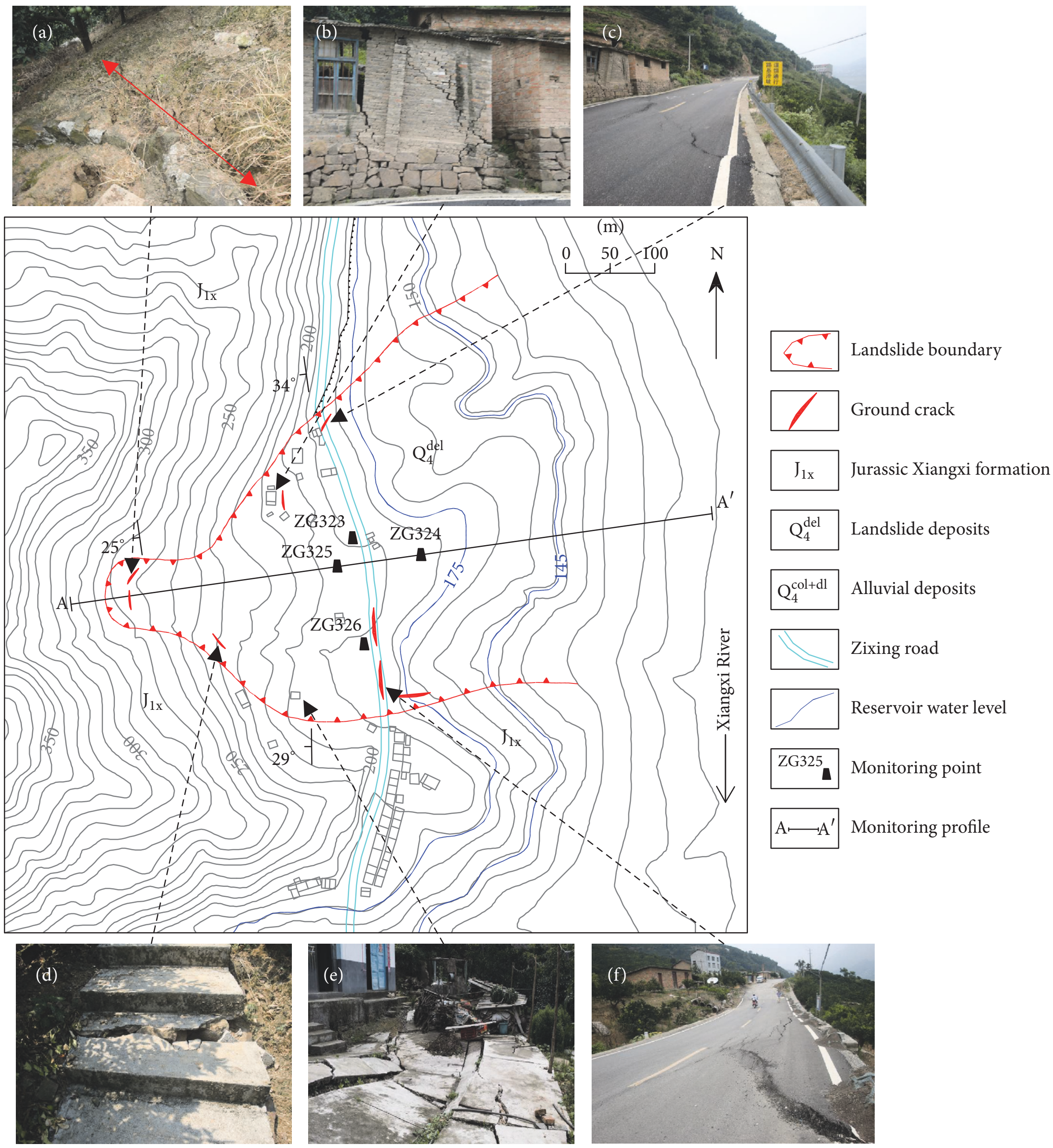


FIGURE 3: Geological plan of Baijiabao landslide, with the locations of deformations and monitoring points.

the self-gravity of the model, the constant water head of 243 m was supplied on the left boundary, and the constant total water head of 175 m was applied on the right boundary below the elevation of 175 m; in this way, the initial stress field and the seepage field were calculated. Next, taking the above results as the initial conditions, the following three conditions were simulated:

(1) Only consider the effect of rainfall. The boundary condition of rainfall was applied above the elevation of 175 m on the ground surface of the model. The rainfall process from December 1, 2014, to August 18, 2015, is shown in Figure 6. The total pore water head of 175 m was kept unchanged below the elevation of 175 m.

(2) Only consider the effect of reservoir water level decline. The boundary condition of reservoir water level variation was applied below the elevation of 175 m on the ground surface of the model. The process of reservoir water level variation from December 1, 2014, to August 18, 2015, is shown in Figure 6. The surface above the reservoir level of any stages of the drawdown is the drainage-only flow boundary.

(3) Consider the coupling effect of rainfall and reservoir water level decline. The boundary condition of rainfall

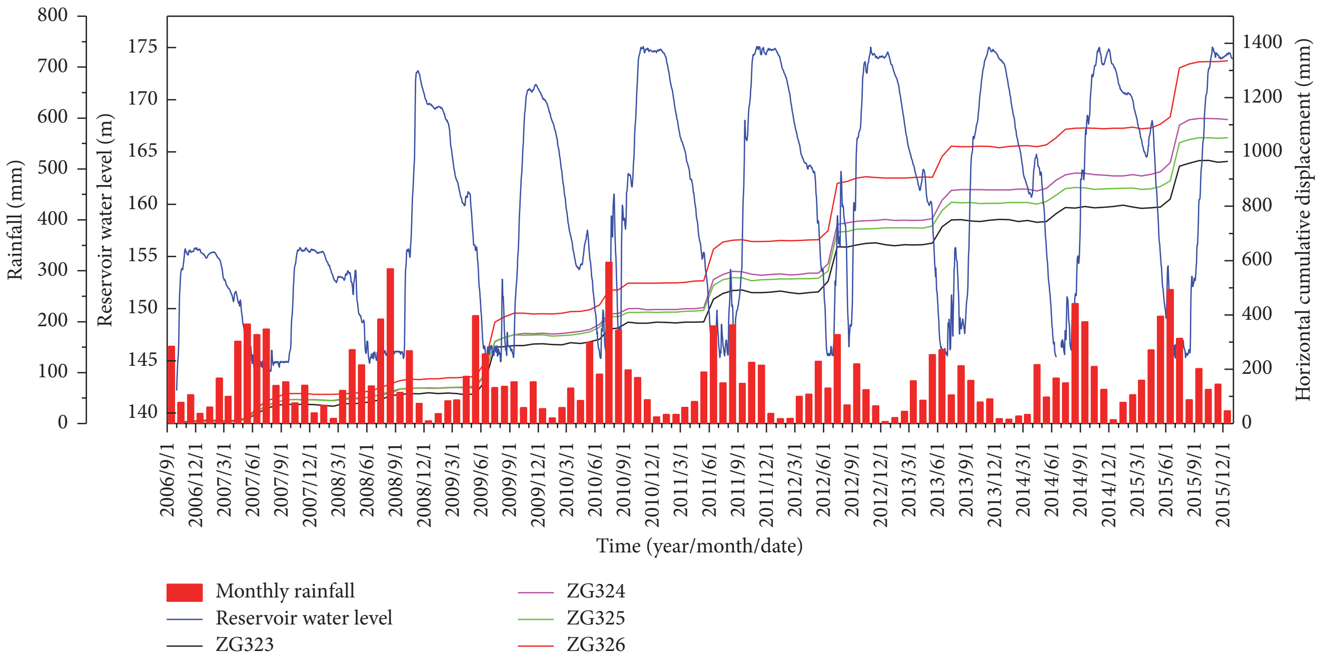


Figure 4: Monitoring curve of horizontal cumulative displacement at the ground of the landslide, with the monthly rainfall and reservoir water level.

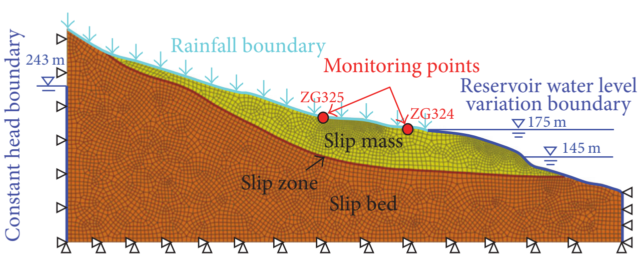


Figure 5: The finite element model of the landslide, with mesh and boundary conditions.

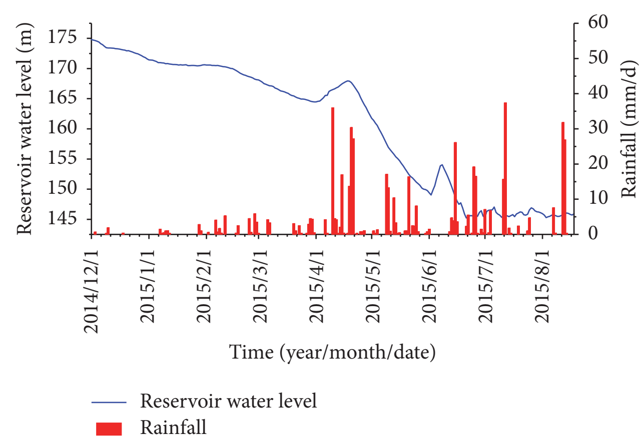


Figure 6: Process of rainfall and reservoir water level variation from December 1, 2014, to August 18, 2015.

was applied above the elevation of 175 m on the ground surface of the model, while the boundary condition of reservoir water level variation was applied below the elevation of 175 m, while surface below 175 m but above the reservoir level of any stages of the drawdown is applied to the drainage-only flow boundary condition.

4.2. Model Parameters. The hydraulic conductivity function (HCF) and soil-water characteristic curve (SWCC) are important for fluid-solid coupling analysis of saturated-unsaturated soil. The relationship between the permeability coefficient and the matrix suction of materials in the model can be expressed as [18, 19]

$$K_w = \frac{a_w K_{ws}}{\left[a_w + \left(b_w \times (u_a - u_w)\right)^{c_w}\right]}, \tag{5}$$

where K_{ws} is the permeability coefficient of saturated soil, whose values obtained from field and laboratory tests are shown in Table 1; u_a and u_w are, respectively, the air pressure and water pressure in the soil; and a_w, b_w, and c_w are material coefficients.

The relationship between the saturation and the matrix suction of materials in the model can be expressed as [18, 19]

$$S_r = S_i + \frac{(S_n - S_i)\, a_s}{\left[a_s + \left(b_s \times (u_a - u_w)\right)^{c_s}\right]}, \tag{6}$$

where S_r is the saturation; S_i is the residual saturation; S_n is the maximum saturation, whose value is set as 1; a_s, b_s, and c_s are material coefficients.

According to the material type of the slip mass (mainly composed of gravel soil), slip zone (mainly composed of clay),

Table 1: Permeability parameters of the Baijiabao landslide model.

Materials	Saturated permeability coefficient (m/s)	Saturated volume water content	Residual volume water content	a_w	b_w	c_w	a_s	b_s	c_s
Slip mass	$3E-6$	0.6	0.08	500	0.026	1.5	1	$7.49E-5$	1.45
Slip zone	$5E-7$	0.4	0.1	1000	0.01	1.48	1.12	$1.64E-5$	1.22
Slip bed	$1E-7$	0.2	0.04	$2.79E-5$	$2.22E-4$	6.14	0.16	$4.68E-4$	2.77

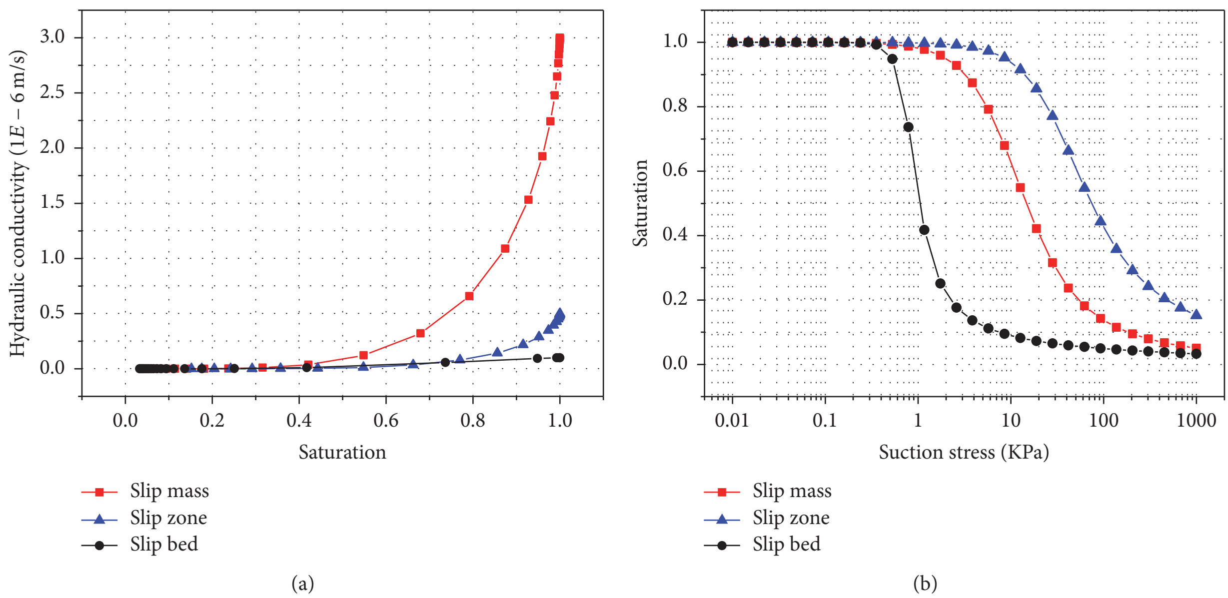


Figure 7: (a) Hydraulic conductivity function (HCF); (b) soil-water characteristic curve (SWCC).

slip bed (mainly composed of siltstone and silty mudstone), and the particle grading characteristics, the sample functions of HCF and SWCC provided in the GeoStudio software of Canada are modified to obtain the estimated curves, respectively, which are then fitted by (5) and (6) to obtain the final HCF and SWCC (Figure 7) applied in the FE model. The parameters related to HCF and SWCC are shown in Table 1.

The mechanical parameters of each material in the model were obtained through triaxial compression test, which are shown in Table 2.

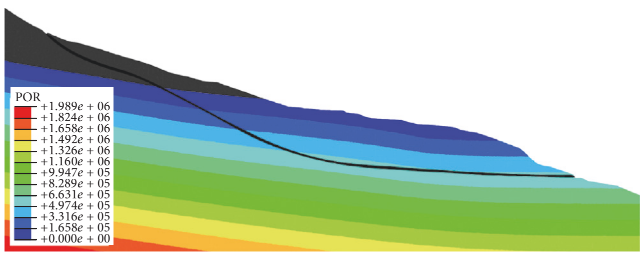
5. Simulation Results

The fluid-solid coupling model of the Baijiabao landslide was built based on the finite element method to investigate the characteristic of change in seepage field in the Baijiabao landslide caused by rainfall and reservoir water level decline during drawdown of reservoir water level from December 1, 2014, to August 18, 2015, as well as the rule of change in stress field and displacement field caused by the change in seepage field. Figure 8 shows the distribution of pore water pressure in the landslide under different boundary conditions at the last day of the simulation. The black part is the area of negative pore water pressure. Figures 8(a), 8(b), and 8(c) are the pore water pressures, respectively, under the influence of rainfall, reservoir water level decline, and coupling of the above two conditions. Through comparison between Figure 8(a) and Figure 8(b), it can be seen that the groundwater level in the landslide obviously rises when only the influence of rainfall is considered, while in the case that only the boundary condition of reservoir water level decline is applied, the groundwater level drops obviously, and the pore water pressure decreases in the section; what is more, the groundwater gradient increases. Comparing with the condition that only reservoir water level decline is considered (Figure 8(b)), the groundwater level slightly rises, especially in the elevation range of 175 to 200 m under the coupling effect of rainfall and reservoir water level decline (Figure 8(c)). Namely, when the groundwater level is closer to the surface, the soil can become saturated more easily under the influence of rainfall.

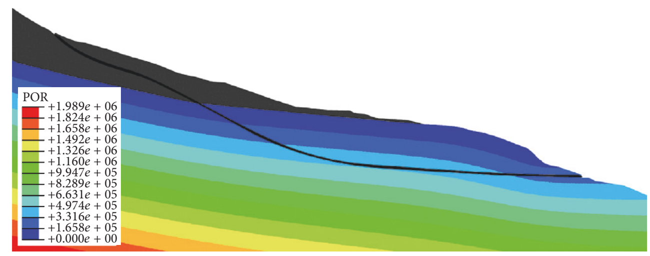
In order to better show the variation characteristics of pore water pressure internal landslide under different conditions, the pore water pressure increment is contoured after the whole process is provided as Figure 9. The results show that the pore water pressure in the whole landslide body has increased under the condition of rainfall only and reduced in different extent under the condition of reservoir level decline only. When considering the couple effect of above conditions, the pore pressure in the first part of landslide increases due to rainfall, while in the second part it decreases for the result of reservoir level drawdown. During the decline of the reservoir water level, the gradient of pore water pressure near the area of reservoir level variation (175~145 m) varied

Table 2: Physicomechanical parameters of the Baijiabao landslide model.

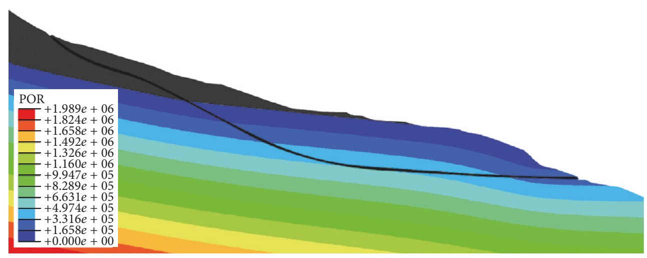
Materials	Dry density (kg/m^3)	Elastic modulus (MPa)	Poisson ratio	Cohesion (KPa)	Friction angle (°)
Slip mass	1800	10	0.3	35	25
Slip zone	1600	1	0.35	80	18
Slip bed	2600	1000	0.2	—	—



(a) Only rainfall considered



(b) Only reservoir water level decline considered



(c) The coupling of rainfall and reservoir water level decline

Figure 8: The distribution of pore water pressure under different boundary conditions (unit, Pa).

greatly, which indicated that there is significant hydrodynamic pressure in this part due to the drawdown of reservoir level.

Figure 10 shows the fluid velocity vector in the Baijiabao landslide considering the coupling effect of rainfall and reservoir water level decline, respectively, at the first day, the 120th day, and the last day of the whole modeling process which lasted 260 days. The results showed that the velocity of pore water was very slow in the initial state of the model (Figure 10(a)), but the flow direction in the middle and rear of the landslide was consistent with the direction of the landslide movement. The flow velocity was not obvious in the front of the landslide due to the effect of reservoir water pressure which achieved equilibrium with the groundwater pressure within the landslide, while the groundwater near the reservoir water surface flows obviously up to the intersection of reservoir water surface and landslide ground surface, due to the disappearance of hydrostatic pressure from external reservoir water. After 120 days (Figure 10(b)), the flow velocity outside the slope increased significantly in the zone where reservoir water level declined. At the last day (Figure 10(c)), the groundwater velocity in the front of the landslide significantly increased, and at the back of the landslide near the infiltration line, the pore water velocity also showed a certain degree of increase due to the influence of rainfall. In the process of rainfall and reservoir water level decline, the ground water in the landslide discharged outwards, which result in the variation of pore water pressure.

According to the fluid-solid coupling theory, the seepage field, stress field, and displacement field influence each other. Once the pore water pressure on the node in the landslide changes, the effective stress on the node changes, thus resulting in displacement. When the pore water pressure increases, the soil shows swelling deformation, while when it decreases, it shows consolidation deformation, whose direction is determined by the stress characteristics on the node. The variation characteristics of seepage field have been analyzed under the dynamic hydraulic boundary conditions above; in the following, the influence of seepage field variation on the displacement field will be further analyzed.

Figure 11 shows the displacement of the landslide at the last day of the simulation. Figures 11(a), 11(b), and 11(c) show the displacement, respectively, under the influence of rainfall, reservoir water level decline, and coupling of the above two conditions. When only rainfall is considered, the deformation of the landslide is relatively small, mainly concentrated in the middle of the landslide within the elevation range of 175 to 230 m (Figure 11(a)). According to the pore water change in the first contour of Figure 9 and based on the effective stress principle, it is not difficult to deduce that the rainfall leads to the increment of saturation and pore water pressure in the soil and thus results in swelling deformation in the shallow part of the landslide. Under the influence of reservoir water level decline, the middle and the front of the landslide are obviously deformed (Figure 11(b)). Deformation is mainly distributed below the elevation of 220 m, and along the sliding

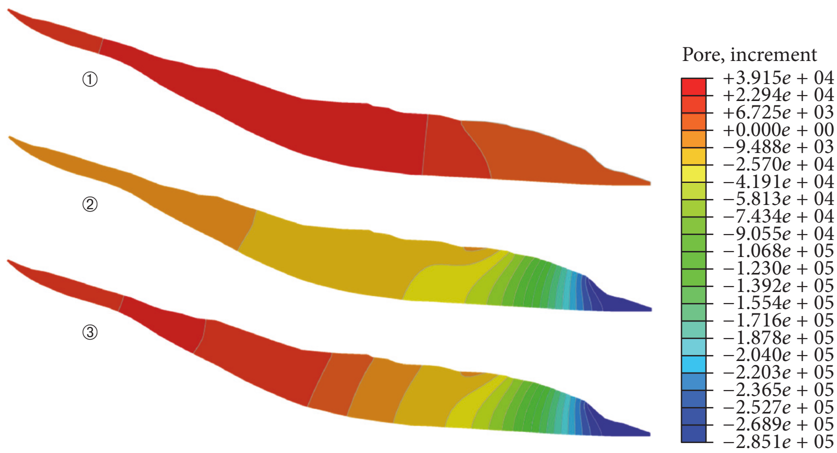
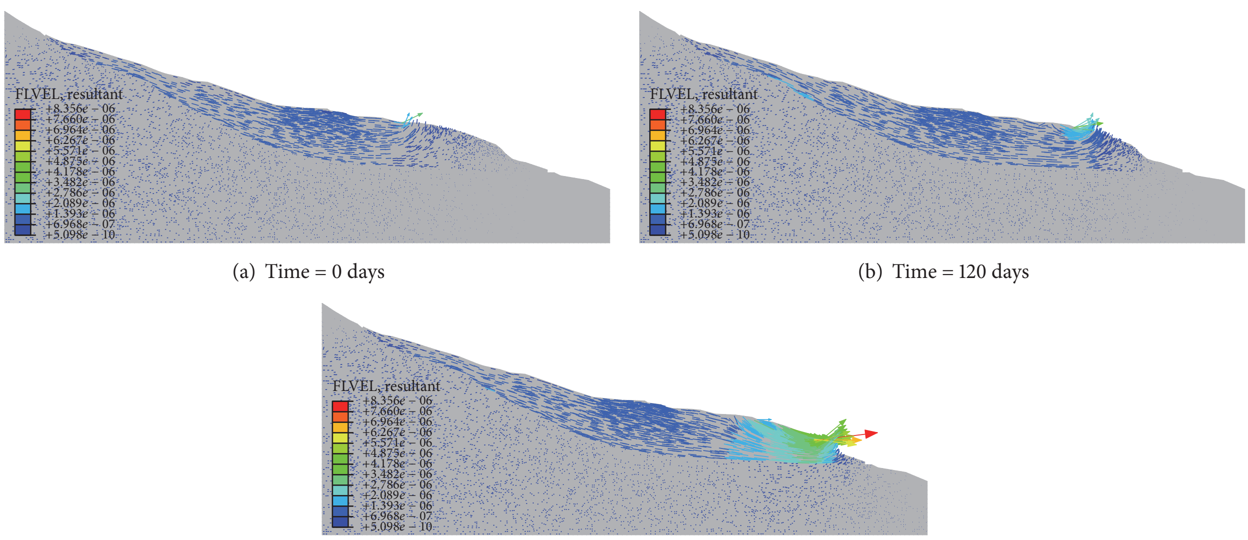


FIGURE 9: Pore water pressure increment under different boundary conditions: ① only rainfall considered; ② only reservoir water level decline considered; ③ the coupling of rainfall and reservoir water level decline (unit, Pa).



(a) Time = 0 days

(b) Time = 120 days

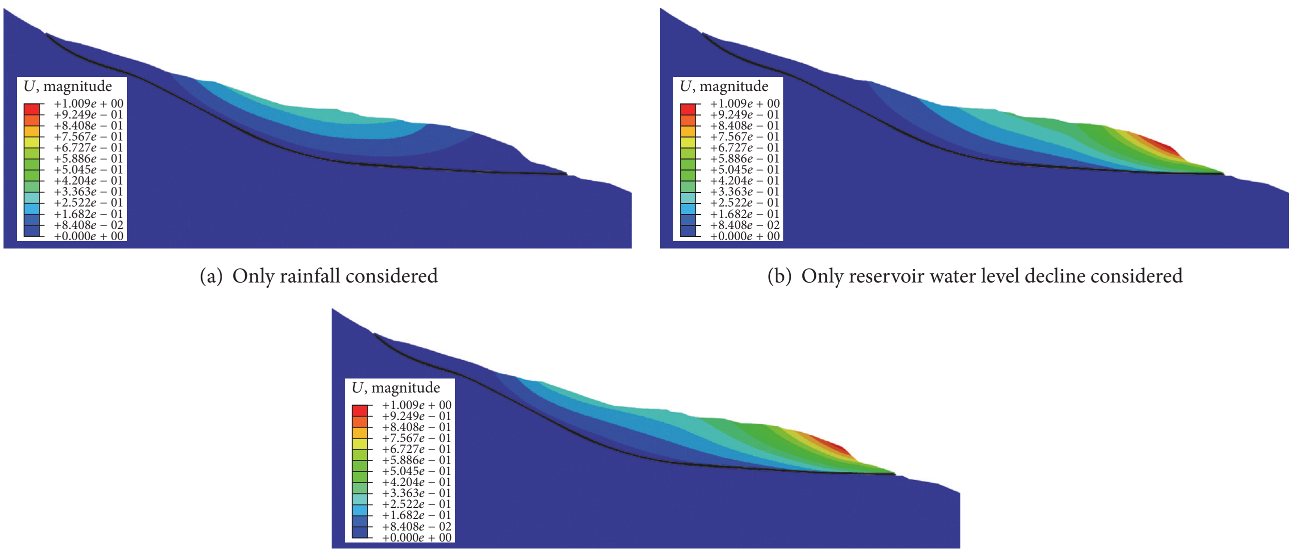
(c) Time = 260 days

FIGURE 10: Pore water effective velocity over time under the coupling effect of rainfall and reservoir water level variation (unit, m·s^{-1}).

direction, the deformation amplitude increases progressively, while in the longitudinal section of the profile, the displacement decreases with depth. The decline of the reservoir water level leads to the reduction of the pore water pressure in the landslide, which resulted in consolidation in the soil. Under the coupling effect of rainfall and reservoir water level decline, the displacement distribution is shown in Figure 11(c). The range from the leading edge of the landslide to the elevation of 230 m has been obviously deformed. According to previous analysis of pore water pressure, the area above elevation of 190 m mainly showed soil swelling deformation affected by the rainfall, while the area below elevation of 190 m showed soil consolidation, whose directions are mainly downward and outward of the slope, respectively.

In order to further study the deformation evolution mechanism of the Baijiabao landslide under external hydrodynamic conditions and verify the validity of the model, two points on the ground surface of the model were monitored. The monitoring points were, respectively, at the elevation of 180 m and 194 m, corresponding to the field monitoring points ZG324 and ZG325, respectively. Figure 12 shows the simulation results of horizontal cumulative displacement at the monitoring points ZG324 and ZG325, from December 1, 2014, to August 18, 2015 (lasting for 260 days), respectively, under the influence of rainfall, reservoir water level decline, and the coupling of above two factors. In this figure, the simulation results are compared with the field measured results.

The simulation results (Figure 12) of final horizontal cumulative displacement at the points ZG324 and ZG325 are, respectively, 0.250 m and 0.164 m under the coupling effect of rainfall and reservoir water level decline, which are close to the field measured values (0.206 m and 0.181 m, resp.). As to the displacement increase process, it can be divided

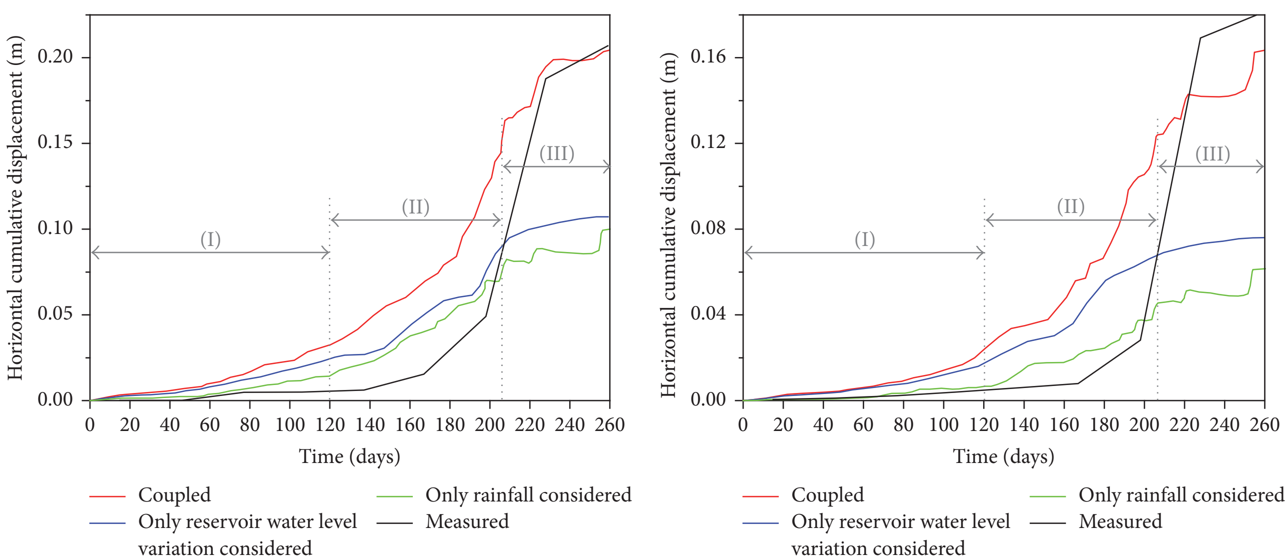


(a) Only rainfall considered

(b) Only reservoir water level decline considered

(c) The coupling of rainfall and reservoir water level decline

FIGURE 11: The displacement under different boundary conditions (unit, m).



(a) Monitoring point ZG324

(b) Monitoring point ZG325

FIGURE 12: The horizontal cumulative displacement at the points ZG324 and ZG325 from December 7, 2014, to August 18, 2015.

into three stages taking the monitoring point ZG324 as an example (Figure 12(a)). Stage I is from the 0th to the 120th day. At this stage, the horizontal cumulative displacement had little increased. During this period, the rainfall was small and the reservoir water level was in the slow decline stage, coupled with the hysteresis effect that groundwater variation lags behind reservoir level; as a result, the change in seepage field in the landslide was not obvious, and there is no major change in displacement field. Stage II is from the 120th to the 205th day. The coupling effect of rainfall and reservoir water level decline was obvious at this stage. During this period, the rainfall increased significantly, and the decline rate of reservoir water level increased (Figure 6). Under the coupling effect, the horizontal displacement of the reservoir showed a trend of accelerated increase. From the curve, the influence of reservoir water level decline on the horizontal displacement at this stage was more obvious than the influence of rainfall. Stage III is from the 205th to the 260th day. During this period, the reservoir water level kept fluctuating around 145 m, while the rainfall continued (Figure 6). In the first 20 days of this stage, the horizontal displacement continued the trend of accelerated increase due to the hysteresis effect of seepage field at Stage II. After that, the trend of increase slowed down, but there was still some increase under the influence of rainfall. Therefore, the increase of horizontal displacement at this stage was more obviously affected by rainfall.

6. Conclusions

This study focuses on how rainfall and reservoir water level decline affect the seepage and displacement field of Baijiabao landslide in spatially and temporally during drawdown of reservoir water level in the Three Gorges Reservoir Area, thus exploring its movement mechanism, so as to provide references for such landslides. Based on the theory of fluid-solid coupling, the numerical model of the Baijiabao landslide under the hydrodynamic boundary conditions of rainfall and reservoir water level decline was established by the finite element method. The deformation evolution mechanism of this landslide during drawdown of reservoir water level from December 2014 to August 2015 was revealed, respectively, under the conditions of rainfall, reservoir water level decline, and coupling of the above two conditions. The following conclusions have been made.

(1) The finite element model of seepage and stress coupling for Baijiabao landslide, can achieve the dynamic response of the seepage field, stress field and displacement field in the landslide under complex dynamic hydraulic boundary conditions. What is more, the results are consistent with the actual situation, which indicates that the model applies to analyze the effects of complex dynamic hydraulic boundary conditions on landslides.

(2) Reservoir level decline is the main cause of the deformation of the Baijiabao landslide. It leads to reduction of pore pressure in the middle and front part of the landslide, resulting in soil consolidation, whose directions are mainly downward and outward of the slope, respectively. Rainfall leads to the increment of saturation and pore water pressure in the soil, and thus results in swelling deformation in the shallow part of the landslide within the elevation range of 175 to 230 m. When considering the coupling effect of above two conditions, the spatial deformation characteristics of the landslide are almost in accordance with the field deformation, so the deformation of the landslide is the result of the combined effect of rainfall and reservoir water level decline.

(3) Rainfall and reservoir water level decline have different effects on landslide deformation at different stages. Taking into account the coupling effect of rainfall and reservoir water level decline, the deformation process of the Baijiabao landslide during drawdown of reservoir water level, which lasted 260 days, can be divided into three stages. Stage I is from the 0th to the 120th day. During this stage, the displacement had no significant increase. Stage II is from the 120th to the 205th day. During this period, the rainfall increased significantly, and the decline rate of reservoir water level increased. Under the coupling effect of the two factors, the displacement showed a trend of accelerated increase. What is more, the influence of reservoir water level decline on the horizontal displacement at this stage was more obvious than the influence of rainfall. Stage III is from the 205th to the 260th day. During this period, the reservoir water level kept fluctuating around 145 m, while the rainfall still continued. In the early period of this stage, the horizontal displacement continued the trend of accelerated increase due to the hysteresis effect of seepage field that groundwater variation lags behind reservoir level. After that, the trend of increase slowed down, but there was still some increase under the influence of rainfall. Therefore, the increase of horizontal displacement at this stage was more obviously affected by rainfall.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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