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Research Article

Impact Analysis of Reservoir Water-level Fluctuation Speed on Reservoir Bank Building

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Abstract

Reservoir water-level fluctuation changes hydrogeological conditions and stress distribution status of reservoir bank slope and leads to settlement, bulging and horizontal sidesway of the building above it. Typical bank slope and building on the bank slope in the Chongqing section of the Three Gorges Reservoir Region in China were taken as study objects to explore influence laws of rising and falling speed of reservoir water on displacement and structural additional internal force of the reservoir bank building. Finite element software ABAQUS was employed to establish the 3D saturated–unsaturated seepage model and carry out the simulation calculation. Change laws of phreatic line in the bank slope, as well as structural additional internal force and foundation displacement of the reservoir bank building under different reservoir water-level fluctuation speeds, were compared. Results show that the height ratio of the phreatic line in the middle of the slope is 1.15 when descending speed of the reservoir water level is 4.2 m/d and 2.2 m/d. This phenomenon indicates that high descending speed of the reservoir water level denotes an increasingly intense seepage effect inside the bank slope. The displacement value of the reservoir bank building increases with the increase of the reservoir water-level fluctuation speed (within the same time period). When the ascending speed of the reservoir water level increases from 2.2 m/d to 4.2 m/d, the increase of axial force of structural column by 1.4 KN indicates that the structural additional internal force of the reservoir bank building elevates due to the increase of the reservoir water-level fluctuation speed. The obtained conclusions provide a significant reference for the safety evaluation of buildings on existing reservoir banks and building design on newly built reservoir banks.

Keywords: reservoir bank building, seepage field analysis, stress field analysis, saturated–unsaturated seepage, differential settlement

1. Introduction

Reservoir dams have been constructed on many rivers of various countries in recent decades to meet flood control, drought-relief and power generation needs. These reservoirs changed original hydrogeological conditions and stress distribution status on slopes at two banks of rivers and usually result in slope instability and structural damage of the upper building. The Three Gorges Reservoir Region in China is taken as an example, and the occurrence of large-scale landslides and collapses at approximately 2000 parts since its impounding has led to the collapse of many houses. The bank slope surface was exposed to loading and unloading actions of reservoir water pressure due to the reservoir water-level fluctuation, but soil body inside the bank slope generates seepage effect caused by water absorption and water loss; giving rises to the foundation deformation, settlement, bulging, and horizontal sidesway of the reservoir bank building; and causing structural failure. Therefore, an in-depth exploration of action and influence mechanisms of reservoir water-level fluctuation on the reservoir bank building is necessary, and the functional relation between the reservoir water-level fluctuation speed and building displacement on the reservoir bank must be determined.

The change of reservoir water level affects the stability of the bank slope and further result in the structural failure of the upper building because rock–soil mass on the bank slope is a medium with continuous pores and its physical and mechanical properties are influenced by water to a large extent [1]. When the reservoir water rises or falls, the underground water level and soil moisture content in the bank slope will change, resulting in the structural damage of the reservoir bank buildings due to the change of foundation stability and bearing capacity. Traditional studies first analyzed the influence of reservoir water-level fluctuation on the foundation of the bank slope and then obtained foundation displacement data, which were applied to the upper building to analyze their stress-strain laws. However, traditional methods neglected the constraint effect of the building foundation on the foundation soil. In addition, traditional studies particularly emphasized the analysis of influences of changes in rock－soil mechanical parameters of the bank slope on the upper building. However, the groundwater level inside the bank slope usually experiences considerable and high-frequency changes and thus resulted in frequent changes in the saturation state of the soil mass under the action of reservoir water-level fluctuation [2]. The rapid transformation of soil mass between saturated and unsaturated states due to water absorption and loss directly

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changed not only the matric suction of the soil mass but also generated seepage force. Seepage force is also an important factor that influences the foundation stability of the bank slope [3]. Therefore, the following limitations existed in traditional studies. First, only the influence of slope on the building foundation was considered but the constraint effect of the building foundation on the soil body was ignored in the aspect of pile-soil interaction. Second, only the influence of rock-soil body parameters was considered but influences of seepage effect and change of the matric suction were neglected in the aspect of soil-water interaction.

On this basis, the typical bank slope and upper building in the Chongqing section of the Three Gorges Reservoir Region in China were taken as a study object. The finite element software ABAQUS was used to establish the "bank slope–foundation–upper building" overall model on the basis of seepage–stress coupling theory to perform numerical simulation and calculation, followed by a detailed analysis of results. Change laws of the structural internal force of the reservoir bank building under different reservoir water-level fluctuation speeds were obtained, and the functional relation between the reservoir water-level fluctuation speed and building displacement on the reservoir bank was proposed.

2. State-of-art

Research on the influence of reservoir water-level fluctuation on the reservoir bank building, a complex problem that involves both seepage and structural damage, is still in the preliminary phase. Only a few scholars have concentrated on apparent phenomena, such as failure type of reservoir bank building and change laws of foundation bearing capacity. However, studies on influence and action mechanisms were limited. For instance, Huang L [4] investigated the reservoir bank building using multiple means, such as statistical analysis and field monitoring; the results showed that the rainfall or reservoir flood discharge results in high groundwater level fluctuation inside the bank slope, and diagonal cracks easily appeared on the exterior load-bearing wall perpendicular to the reservoir direction. Li [5] conducted a systematic test on the bearing capacity of pile foundation before and after soaking at the bank slope site in the Three Gorges Reservoir Region in China and found that the softening effect of water on soil mass seriously impacted the bearing capacity of the pile foundation of the reservoir bank building. The stability of bank slope directly influences the structural internal force and displacement of the reservoir bank building. Deng H F [6] explained the reasons for changes in the safety factor of the bank slope during the water level fluctuation process from the angle of mechanical mechanism to explore the influence mechanism of the reservoir water-level fluctuation on the stability of the bank slope. Zhou [7] used finite element software to analyze the impact of rainfall and slope engineering construction on the bank slope, and found that the construction of slope engineering provides a channel for the infiltration of rainfall to the slope. Cho M [8] studied the impact of rainfall on the slope through model tests and found that the failure of the slope often starts from the appearance of the infiltration surface on the slope. Choi [9] took the landslide disaster that occurred in Kaohsiung County, South Korea as an example, and analyzed the rainfall characteristics and landslide triggering factors in detail. Manchado [10] analyzed the relationship between landslide frequency and precipitation, and the results showed that there is a strong correlation between the number of shallow landslides and accumulated precipitation. Ernesto [11] used reference inclinometer measurement technology, electromagnetic induction technology and electrical resistivity tomography technology when studying the Gimigliano landslide in Calabria, southern Italy. Vladimir Greif [12] used ERS and ENVISAT sensors to measure the deformation of the landslide, which can accurately identify the displacement and boundary of the slope after sliding. Cojean [13] conducted statistics on reservoir bank landslides and found that landslides mainly occurred in the initial stage of reservoir impoundment. Sarada Prasad Pradhan [14] used the Phase2D finite element model to analyze the vulnerable road cutting slope and put forward reinforcement suggestions. Bayer [15] used SAR technology to monitor the slope deformation caused by tunnel excavation and summarized the influence law. Marot [16] proposed a numerical program that couples hydrodynamic conditions, sediment erosion and sedimentation, and calculations of bank slip in order to predict the impact of reservoir flood discharge on the stability of the upstream slope of immersion. Gallage [17] studied the influence of slope angle on slope stability during rainfall through model tests. The results showed that with the increase of slope angle, the slope was more likely to collapse suddenly during rainfall. Phuong Thao Thi Ngo [18] developed RNN and CNN algorithms to calculate the landslide-sensitive area in each province of Iran. Shoki [19] studied the relationship between flood peak discharge and landslide dam chain failure through flume experiments, and the results showed that the increase in downstream dam discharge is the main factor leading to chain dam failure.

The slope was deformed by the rise and fall of the reservoir water and the rainfall, which led to the structural failure of the superstructure due to the uneven settlement As for the uneven settlement damage of buildings, Jia [20] studied the cracking and failure laws of members of the frame structure under the two working conditions of side column settlement and middle column settlement through a three-span frame model test, and put forward the limit value of the non-uniform settlement of foundation. Abdallah [21] studied the influence of foundation settlement on masonry structure by numerical experiment design and statistical analysis method, the results showed that the effect of tensile strength of wall joints on the bond strength is dominant. Dpeduto [22] obtained the probability function of building damage under three different SRI parameters (i.e. uneven settlement, rotation and deflection ratio) by processing synthetic aperture radar (SAR) images. Bray [23] developed a simple program to estimate the shear-induced component of building settlement by analyzing the characteristics of building settlement. Dalgic [24] used two-stage numerical analysis method to simulate the settlement process of "foundation-mosque". The results showed that the greater the stiffness ratio of foundation soil to the superstructure, the lower the possibility of settlement. Saeidi [25] established an adaptive observation regression model of large building settlements based on In SAR mapping method. He W [26] established a finite element model of the building on a reservoir bank in Hunan, China to obtain the relationship between the reservoir water level and build displacement on the reservoir bank but ignored the pile-soil contact problem. Neglecting this problem is common in the research field. The staged separating-type calculation method typically used in the simulation calculation ignores the pile-soil interaction given that the fluid-solid coupling calculation is featured by high complexity and large calculated quantity. Many scholars have neglected the seepage force and matric suction in the soil mass in their deformation analysis of the bank slope.

These studies have shown that the reservoir water-level fluctuation generates a large impact on the stability of the bank slope and deformation of the upper building; however, their analysis methods have certain limitations given that such approaches fail to consider not only the constraint effect of the building foundation on soil but also the seepage force and matric suction in the soil mass. The change in the reservoir water level resulted in the deformation of bank slope and lead to the deformation of the building foundation in practical engineering. Meanwhile, the foundation generated a constraint effect on the slope and reduced the actual deformation of the slope while a complex interaction exists between the two.

Therefore, a 3D fluid-solid coupling model based on the seepage–stress coupling principle is proposed in this study to solve the limitations of existing studies. Through the comparative analysis of the calculation resulted in various working conditions, this study explored the stress change law and displacement change law of the bank slope building foundation under the effect of reservoir water rise and fall.

The remainder of this study is organized as follows. The basic theory and profile of the finite element model are presented in Section Three. The calculation results under multiple working conditions are analyzed in Section Four. Finally, the conclusions of the study are summarized in Section Five.

3. Methodology

3.1 Seepage control equation and constitutive relation

The seepage of both saturated and unsaturated soil laws generally followed Darcy's law (Equation 1), which stated that the seepage flow Q of pore water was directly proportional to both cross-sectional area A of the seepage surface and total head loss ΔH but the seepage discharge was inversely proportional to the length L of seepage path. A large seepage coefficient k indicated a large seepage discharge in the pore water within the unit time.

$$Q = kA\frac{\Delta H}{L} \tag{1}$$

According to seepage–stress coupling theory, an interaction existed between soil and water. On the one hand, infiltration of reservoir water changed the saturation of the soil mass and matric suction. On the other hand, the soil saturation and matric suction determined the soil permeability coefficient and water suction force of the soil mass and reversely influenced the infiltration of reservoir water. Hence, controllability of changes in soil permeability coefficient with the saturation and saturation realized the seepage–stress coupling. This study was based on the geological investigation and geotechnical test in engineering. The permeability coefficient and moisture absorption curves were calculated by combining the empirical formula proposed by Cho.[27] as follows:

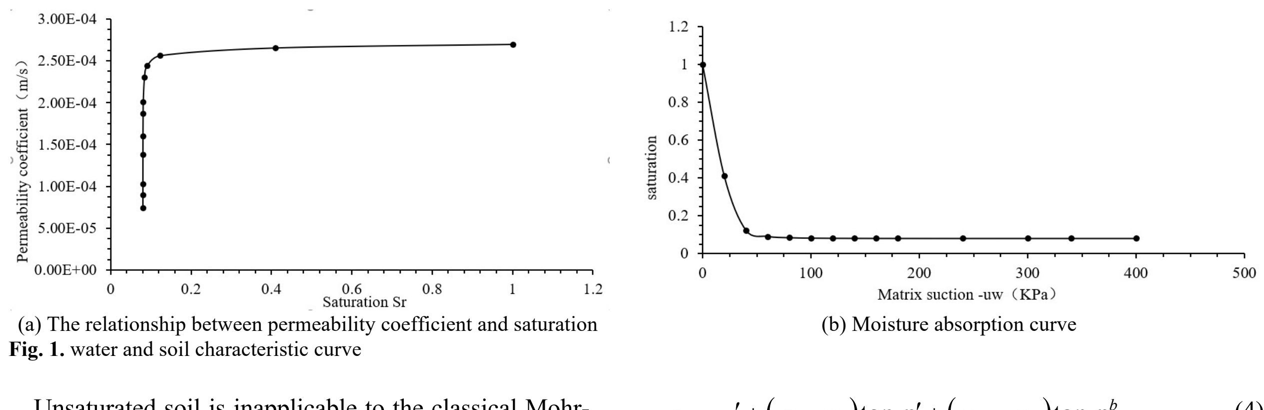
$$K_w = a_w K_{ws} / \left[a_w + \left(b_w \times (\mu_a - \mu_w)\right)^{c_w}\right] \tag{2}$$

where K_w and K_s are permeability coefficients of unsaturated and saturated soil mass (Table. 1), respectively; μ_a and μ_w are air and water pressure values in soil respectively; and a_w, b_w, and c_w are material coefficients equal to 1000, 0.01, and 1.7 respectively.

$$S_r = S_i + (S_n - S_i) a_s / \left[a_s + \left(b_s \times (u_a - u_w)\right)^{c_s}\right] \tag{3}$$

S_r is the saturation; S_i is the residual saturation; S_n is the maximum saturation; and a_s, b_s, and c_s are material parameters equal to 1,5×$10^{-5}$and 3.5, respectively.

A shrink film that existed on the air/water interface in the unsaturated soil jointly acts on pore air and water pressures. The difference value between pore air and water pressures is the matric suction. The matric suction is related to the soil saturation and controlled by the moisture adsorption curve, which is calculated using Equation 3 and shown in Fig. 1.



(a) The relationship between permeability coefficient and saturation

(b) Moisture absorption curve

Fig. 1. water and soil characteristic curve

Unsaturated soil is inapplicable to the classical Mohr-Coulomb strength criterion because it bears the effect of the matric suction. Therefore, Fredlund proposed the following strength formula applicable to unsaturated soil with the normal shear stress and matric suction as variables:

$$\tau_f = c' + (\sigma - \mu_a)\tan\varphi' + (\mu_a - \mu_w)\tan\varphi^b \tag{4}$$

where τ_f is the shear strength; c' and φ' are the effective cohesion and internal friction angle, respectively; $\mu_a$and μ_w are air and porewater pressures, respectively; and φ^b is the increase rate of unsaturated shear strength with the matric suction $\mu_a - \mu_w$. μ_a and φ^b approach 0 and φ', respectively, when the soil mass is saturated with water. Equation [4] is then transformed into the shear strength formula of saturated soil on the basis of the definition of effective stress, as follows:

$$\tau_f = c' + \sigma \tan \varphi' \tag{5}$$

The total cohesion can be expressed as follows when both matric suction $\mu_a - \mu_w$ and effective nominal stress are assumed equal to 0:

$$\tau_f = c' + (\mu_a - \mu_w) \tan \varphi^b \tag{6}$$

If $\xi = c'c \tan \varphi'$, then Equation (5) can be transformed into the following form:

$$\tau_f = \bar{\sigma} \tan \varphi' \tag{7}$$

where $\bar{\sigma} = \sigma' + \xi$; σ' has meaning ditto; and ξ is the generalized suction. The following equation is further derived as

$$\xi = c'c \tan \varphi' + (\mu_a - \mu_w) \tan \varphi^b c \tan \varphi' \tag{8}$$

Equation (8) shows that the generalized suction is mainly composed of the following parts: (1) $c'c \tan \varphi'$, which is the cementing power between soil particles, and the true bonding power between soil frameworks under the matric suction is ignored and (2) $(\mu_a - \mu_w) \tan \varphi^b c \tan \varphi'$, which is the capillary acting force generated by the matric suction $\mu_a - \mu_w$ in the soil mass on the bank slope.

3.2 Finite element calculation

The seepage–stress coupling analysis was conducted using the finite element software ABAQUS. First, the rock–soil body on the slope was divided into three layers, namely, plain fill, gravelly soil, and sandstone, according to survey data. Parameters of each rock–soil layer are listed in Table 1. The slope profile map in the geological survey report was stretched to establish the 3D slope model. Meanwhile, the upper building was built according to the structural design drawing. Members, such as stairways and infilled walls, were omitted in the construction of the upper building to simplify the calculation and improve the model convergence. The ground floor plan of the building and the overall model are shown in Fig. 2 and Fig. 3, respectively. The stress transfer and deformation coordination were realized between the building foundation and slope via "contact pairs."

Table 1. material parameters

Materials	Volume weight (KN·m-3)	Effective angle of internal friction Φ'/°	Effective elasticity modulus E'/MPa	Effective cohesion C'/KPa	Poisson's ratio	Saturated permeability coefficient (m/h)
Plain fill	1810	10	7.28	10	0.36	5×10^{-5}
Gravel soil	2070	24	50	28	0.24	2.7×10^{-4}
sandstone	2520	33.4	3095	1830	0.18	5×10^{-6}

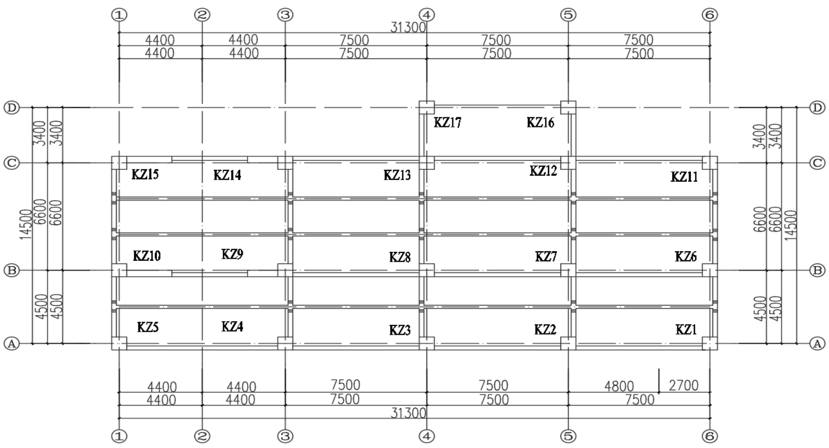


Fig. 2. ground floor plan

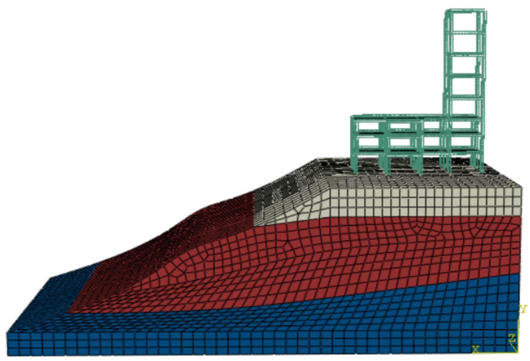


Fig. 3. overall model diagram

The finite element calculation mainly included the following steps: (1) The steady-state analysis of the bank slope–foundation–upper building overall model was conducted under the constant reservoir water level, its stress was extracted, and the stress file was established. (2) The stress file was inputted into the model as the initial condition to balance the initial stress and perform the transient analysis. The reservoir water-level fluctuation speed (slope bottom elevation of 165.5m) was used as a variable in this study (Table 2) given that influence laws of the reservoir water-level fluctuation speed on the reservoir bank building are mainly explored in this study.

Table 2. working conditions

Working conditions	Descriptions
1	Increase speed 4.2m/d Decrease speed 2.2m/d: The reservoir water rises from an elevation of 170.5m to 191.5m at a speed of 4.2m/d, runs stably for 5 days, and then drops to 182.5m at a speed of 2.2m/d.
2	sing speed 3.2m/d and falling speed 2.2m/d: The reservoir water rises from an elevation of 170.5m to 191.5m at a speed of 3.2m/d, runs stably for 5d, and then drops to 182.5m at a speed of 2.2m/d.
3	Increase rate of 2.2m/d and decrease the rate of 4.2m/d: The reservoir water rises from an elevation of 170.5m to 191.5m at a rate of 2.2m/d, runs stably for 5d, and then descends to 182.5m at a rate of 4.2m/d.
4	Increase speed 2.2m/d and decrease speed 3.2m/d: The reservoir water rises from an elevation of 170.5m to 191.5m at a speed of 2.2m/d, runs stably for 5 days, and then drops to 182.5m at a speed of 3.2m/d.
5	Increase speed 2.2m/d Decrease speed 2.2m/d: The reservoir water rises from an elevation of 170.5m to 191.5m at a speed of 2.2m/d, runs stably for 5 days, and then drops to 182.5m at a speed of 2.2m/d.

4 Experimental studies

4.1 Analysis of phreatic line

The reservoir water seeped inside the slope after the reservoir water level elevated, but the seepage resistance caused the hysteresis phenomenon of change in the groundwater level on the bank slope. Although the groundwater level was already elevated at the side close to the reservoir region, the groundwater level at the side far from the reservoir region was still low, as shown in Fig. 4. The groundwater level failed to respond to the change in the reservoir water level in a timely manner due to the seepage resistance in the descending phase of the reservoir water level. Although the groundwater level at the front edge of the slope had already descended, the groundwater level in the middle of the slope was still high, as shown in Fig. 5.

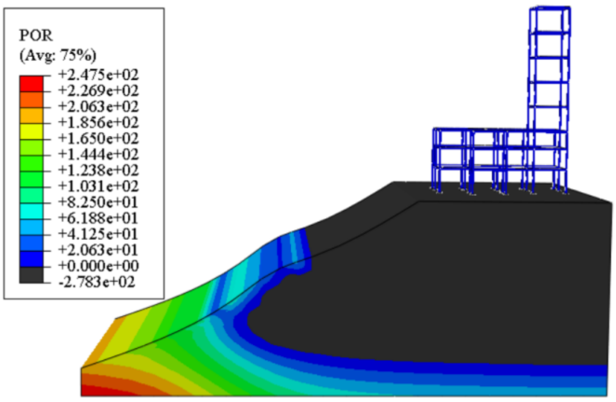


Fig. 4. phreatic line of reservoir water rising stage

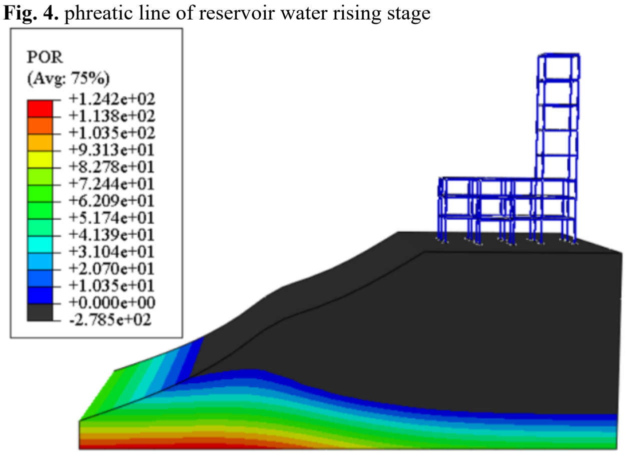


Fig. 5. phreatic line of reservoir water falling stage

Change laws of the phreatic line (groundwater level) of the bank slope under different work conditions were shown in Fig. 6 and Fig. 7. The phreatic line inside the bank slope presented different heights under different reservoir water-level fluctuation speeds. When there was a difference in the height of the saturation line, the seepage force was generated, and the seepage force formula is shown in equation (9).

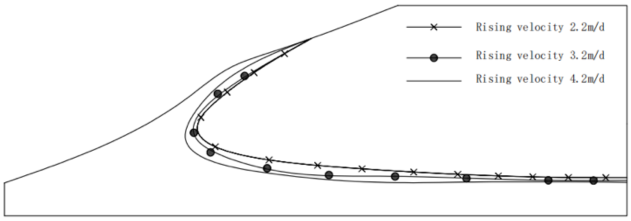


Fig. 6. phreatic line when reservoir water rises

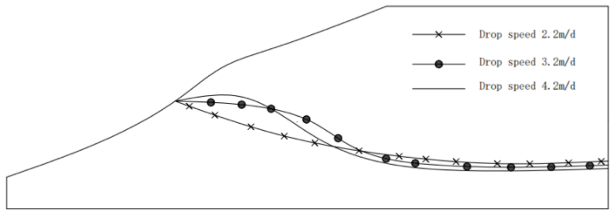


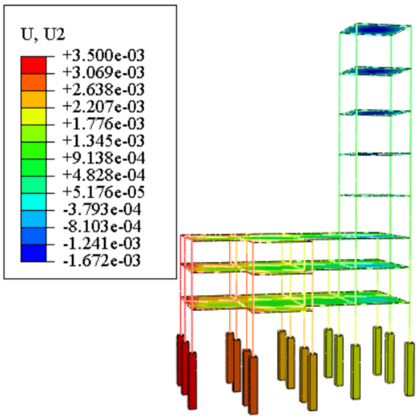
Fig. 7. phreatic line when reservoir water falls

$$G_d = \gamma_w I \tag{9}$$

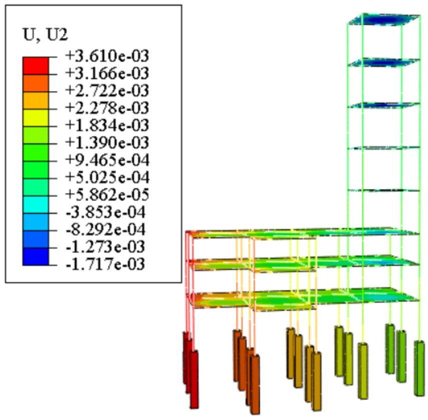
where G_d is the seepage force, γ_w is the unit weight of water, and I is the water head gradient (water level difference). The unit weight of water was fixed; hence, a large groundwater level difference indicated a large seepage force. The vertical seepage of groundwater in the bank slope moves upward and generates the upward seepage force in the ascending phase of reservoir water level. Thus, the bulging phenomenon of the building foundation intensified when the reservoir water level ascended at high speed. The seepage of groundwater and the seepage force moved toward the rear edge of the slope in the horizontal direction. Hence, the sidesway generated to the building foundation toward the rear edge of the slope increases with the fast elevation of the reservoir water level. A low descending speed of reservoir water level indicated the low position of the phreatic line at the front edge of the slope. Small seepage force suggestd a reduced amplitude of the foundation deformation in the descending phase of the reservoir water level.

4.2 Vertical displacement analysis of building

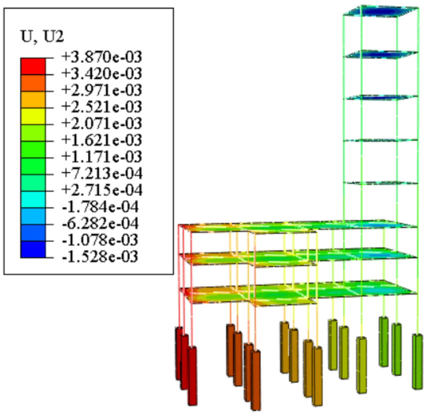
The vertical displacement of the building foundation exerted a strong influence on the structural safety of the building, especially when the vertical displacement varies in each foundation. Horizontal members of the building undertake the vertical shear action, generated the deformation, and may even result in failure. Vertical displacements of the bank slope building under different working conditions were extracted to analyze the deformation of the bank slope building under different reservoir water-level fluctuation speeds and illustrate the cloud picture, as shown in Fig. 8.



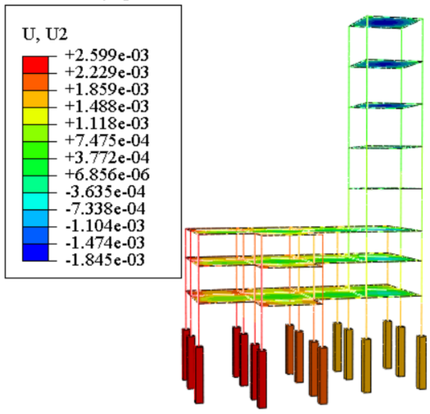
(a) The rising speed of reservoir water level 4.2m/d



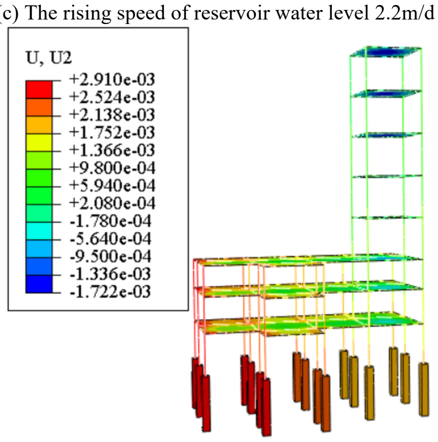
(b) The rising speed of reservoir water level 3.2m/d



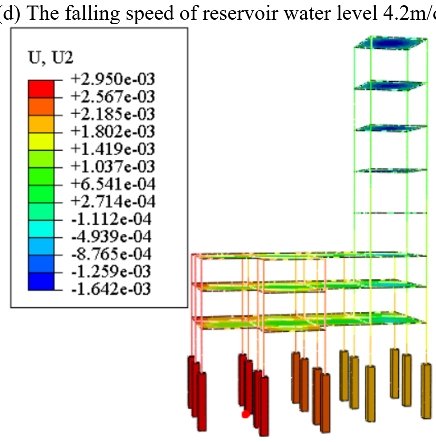
(c) The rising speed of reservoir water level 2.2m/d



(d) The falling speed of reservoir water level 4.2m/d



(e) The falling speed of reservoir water level 3.2m/d



(f) The falling speed of reservoir water level 2.2m/d

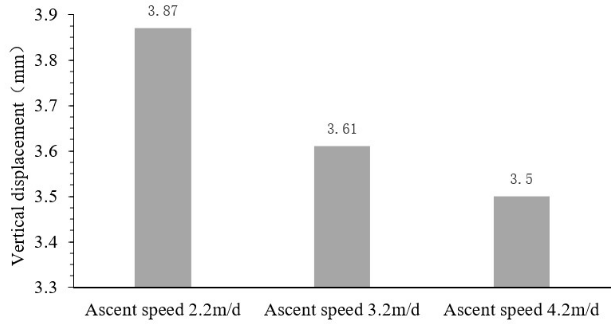
Fig. 8. comparison of different lifting speeds (Same range)

Fig. 8 shows that the vertical displacement distribution of the building is consistent and presents an overall gradual reduction trend from left to right (from the front edge to the rear edge of the slope) during the rise and fall of reservoir water. This finding is caused by the significant influence of the reservoir water-level fluctuation on the foundation close to the reservoir region and the greater left vertical displacement of the building than that of the right one. The vertical displacement of the building varied under different reservoir water-level fluctuation speeds. Maximum vertical displacement values of the building under different working conditions were extracted to analyze change laws of vertical displacement of the building comparatively under different reservoir water-level fluctuation speeds. The histogram is shown in Fig. 9.

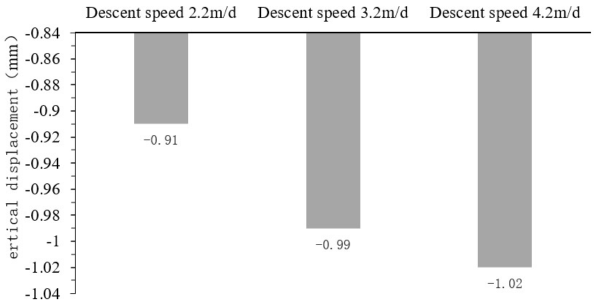
Vertical displacements of the building are all positive under different working conditions when the reservoir water level elevated. Notably, the building experienced bulging in the ascending phase of the reservoir water level. Vertical displacements under different working conditions are all negative given that the reservoir water level descended; the building went through settlement in the descending phase of the reservoir water level.

4.3 Horizontal displacement analysis of building

The reservoir water-level fluctuation generated both vertical and horizontal displacements of the building, and the displacement value of the pile foundation close to the reservoir region was high. Varied horizontal displacements at different building parts resulted in the horizontal shear effect on vertical members. Hence, analyzing the horizontal displacement laws of the building is necessary. Horizontal displacements of the building under different working conditions to



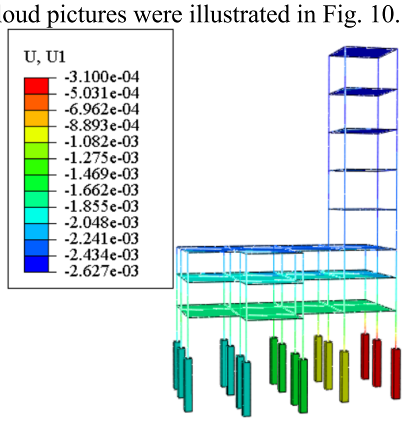
(a) Reservoir rising stage



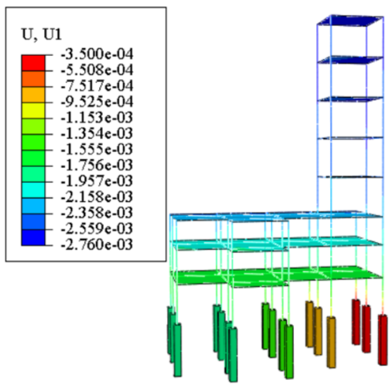
(b) Reservoir descent stage

Fig. 9. comparison of vertical displacement of buildings

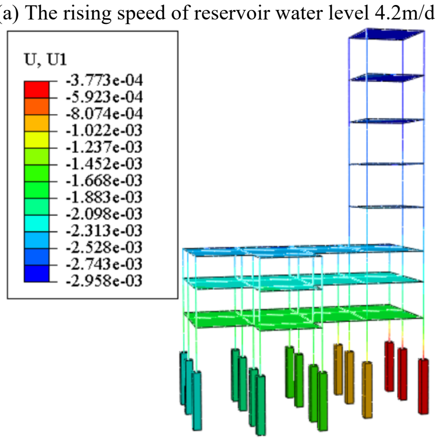
draw the cloud pictures were illustrated in Fig. 10.



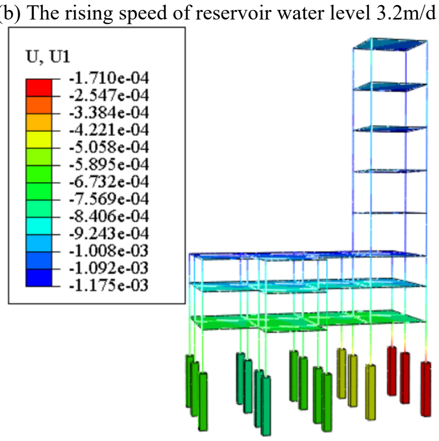
(a) The rising speed of reservoir water level 4.2m/d



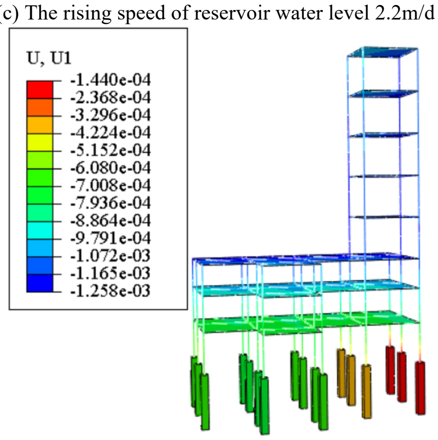
(b) The rising speed of reservoir water level 3.2m/d



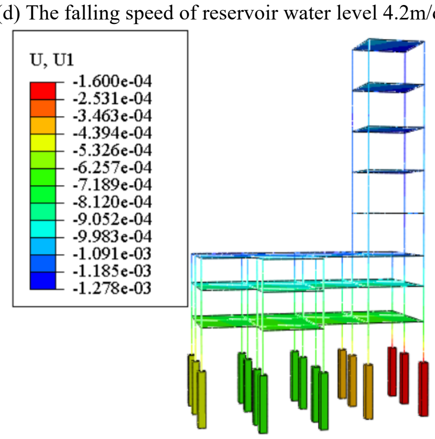
(c) The rising speed of reservoir water level 2.2m/d



(d) The falling speed of reservoir water level 4.2m/d



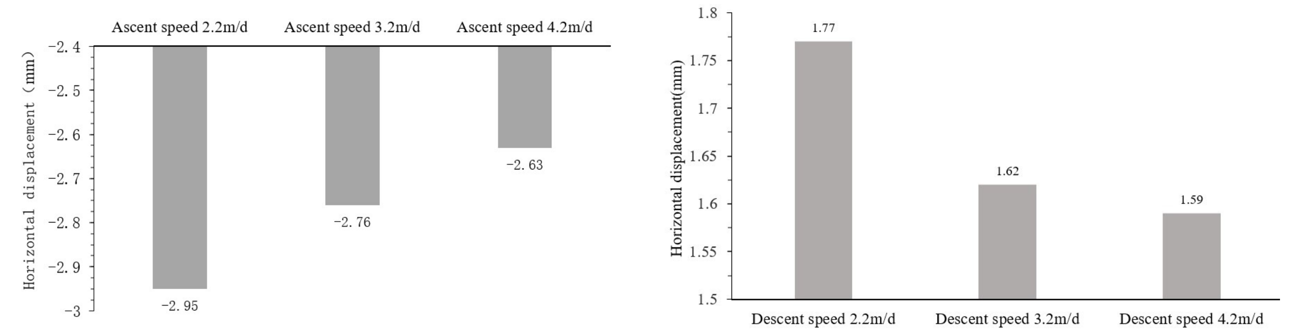
(e) The falling speed of reservoir water level 3.2m/d



(f) The falling speed of reservoir water level 2.2m/d

Fig. 10. comparison of horizontal displacement of buildings at different descent speeds

The horizontal displacement of the building was constantly negative. The displacement direction pointed to the rear edge of the slope because the slope surface was under the reservoir water pressure toward the rear edge of the slope due to the ascending reservoir water level. Meanwhile, the seepage effect was generated inside the slope and the horizontal component of the seepage force also pointed to the rear edge of the slope. Thus, the displacement toward the rear edge of the slope occurred at the slope top in the horizontal direction and the building also experienced backward displacement in the ascending process of the reservoir water. The slope surface was under the unloading effect of the reservoir water pressure when the reservoir water level descended. Meanwhile, the seepage force pointed to the reservoir region although the horizontal displacement of the building gradually reduced. Horizontal displacement values of ground-floor columns of the building under different working conditions were extracted to analyze the influence laws of the reservoir water-level fluctuation speed on the horizontal displacement of the bank slope building accurately. The histogram was presented in Fig. 11.



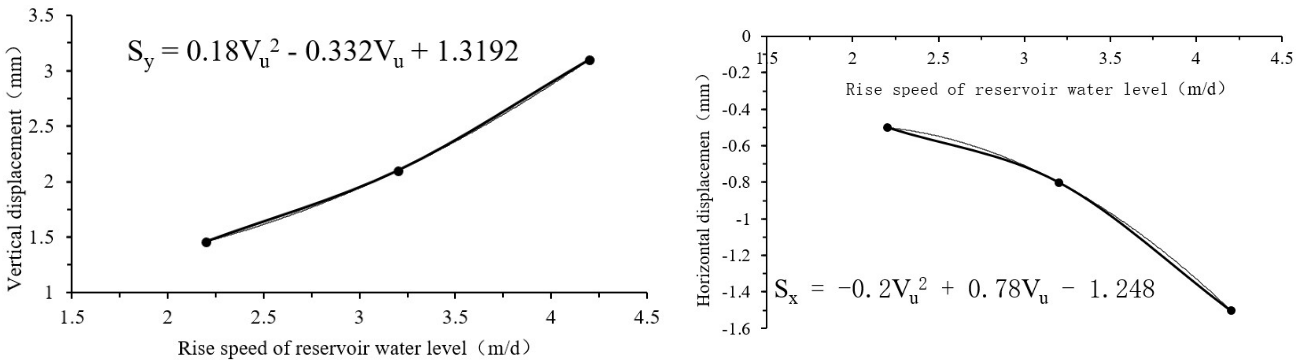
(a) Different reservoir water rising speed (b) Different reservoir water falling speed

Fig. 11. the maximum displacement of buildings under different reservoir water fluctuation

As shown in Fig. 11(a), the horizontal displacement value of the building was -2.63mm and -2.95mm under the reservoir water level ascending speed of 4.2m/d and 2.2m/d. Thus, the reservoir water-level ascending speed was negatively correlated with the horizontal displacement of the building. Fig. 11(b) shows that horizontal displacements under the reservoir water-level descending speed of 4.2m/d and 2.2m/d were 1.59mm and 1.77mm, respectively. Therefore, the reservoir water-level descending speed was also negatively correlated with the horizontal displacement of the building. A slow reservoir water-level ascending speed indicated a long duration of the fluctuation process. The long action time of the reservoir water pressure and seepage force demonstrated that the generated displacement is large.

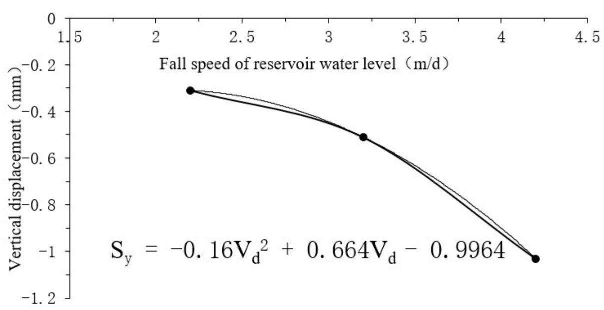
4.4. Relation between reservoir water-level fluctuation speed and displacement of the reservoir bank building

The previous analysis showed that the reservoir water-level ascending speed was negatively correlated with the final displacement value of the reservoir bank building. However, fast reservoir water-level ascending speed indicates a large seepage force in the slope, strong loading effect of the reservoir water pressure borne by the slope surface, large expansion degree generated by the reduction of the matric suction due to the water absorption of soil mass, and large displacement of the upper building within the same time period. This finding was inconsistent with the conclusion of the previous analysis because the displacement value of the reservoir bank building was influenced not only by the reservoir water-level fluctuation speed but also the duration of reservoir water-level change. Therefore, eliminating the disturbance of the reservoir water-level fluctuation time is necessary. Horizontal and vertical displacement values generated in the same time period under different working conditions are illustrated in Fig. 12 and Fig. 13 and relations are fitted using Equations 10 to 13.

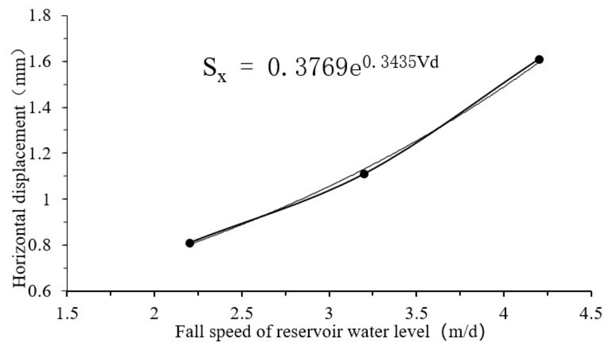


(a) Relation between reservoir water rising speed and vertical displacement (b) Relation between reservoir water rising speed and horizontal displacement

Fig. 12. relation curve between rising velocity and displacement of reservoir water



(c) Reservoir descent speed and vertical displacement



(d) Reservoir descent speed and horizontal displacement

Fig. 13. Relation curve of reservoir water descent speed and displacement

Fitted formulas of the above curves were extracted, and the respective relations between water-level ascending and descending speeds and displacement of the reservoir bank building in the ascending and descending phases of the reservoir water level are expressed as follows:

$$S_y = 0.18V_u^2 - 0.332V_u + 1.3192 \tag{10}$$

$$S_x = -0.2V_u^2 + 0.78V^u - 1.248 \tag{11}$$

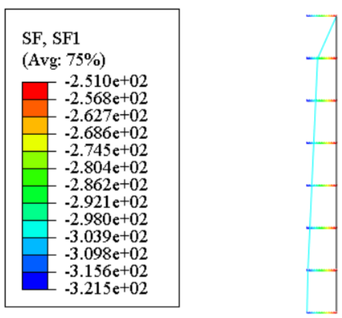
$$S_y = -0.16V_d^2 + 0.664V_d - 0.9964 \tag{12}$$

$$S_x = 0.3769e^{0.3435V_d} \tag{13}$$

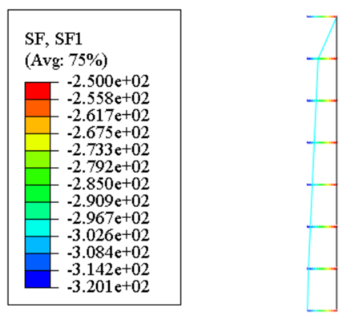
Where S_y and S_x are vertical and horizontal displacements of the reservoir bank building, respectively; V_u is the reservoir water-level ascending speed; and V_d is the reservoir water-level descending speed. Notably, this equation was only applicable to the displacement calculation of the slope with material parameters similar to those listed in Table. 1.

4.5. Structural internal force analysis of building

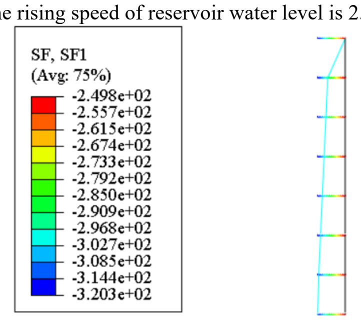
The displacement of the building that varies with rising and falling speeds of the reservoir water leads to a difference in the internal force of the structure. The above analysis demonstrated that the displacement value of KZ6 and the variation amplitude of its additional internal force are large. Hence, axial forces of KZ6 under different working conditions were extracted, as shown in Fig. 14. The maximum axial force of KZ6 was -324.5KN when the reservoir water-level ascending speed was equal to 2.2m/d. The maximum axial force gradually reduced to -320.1kn with the reduction of the reservoir water-level ascending speed. The axial force in the reservoir water-level descending phase was -320.3KN and -317.9KN when the reservoir water-level descending speed was 2.2m/d and 4.2m/d, respectively. Therefore, a low reservoir water-level ascending speed indicated a large additional axial force in the structural column and a high reservoir water-level descending speed presents a small additional axial force in the structural column.



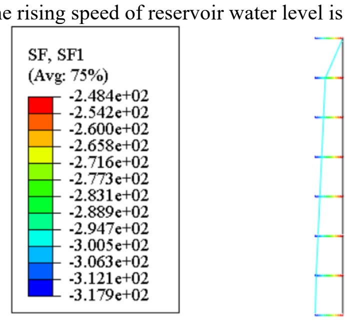
(a) The rising speed of reservoir water level is 2.2m/d



(b) The rising speed of reservoir water level is 4.2m/d



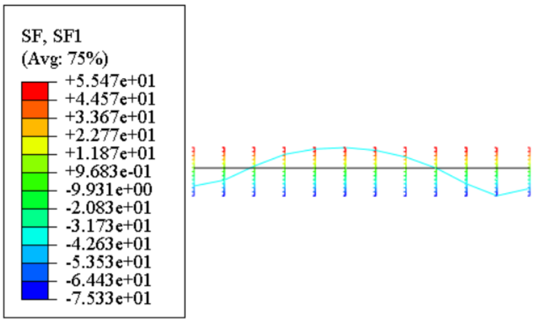
(c) The falling speed of reservoir water level is2.2m/d



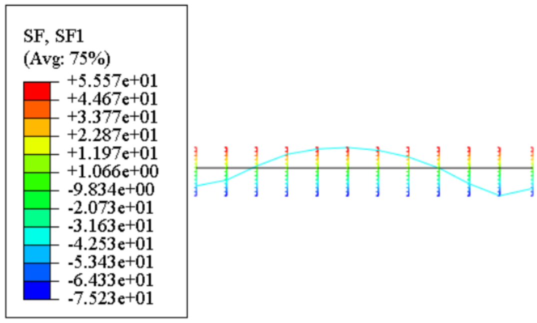
(d) The falling speed of reservoir water level 4.2m/d

Fig. 14. column axial force nephogram

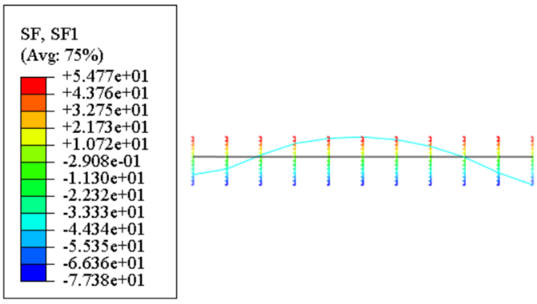
Fig. 15 shown the cloud picture of the axial force of the structural beam in the bank slope building under different reservoir water-level fluctuation speeds. The axial force of the beam varied with the reservoir water-level fluctuation speed. The maximum axial force of the beam was 55.47KN under the ascending speed of 2.2m/d and 55.57KN as the ascending speed elevated to 4.2m/d. The axial force in the descending phase was 54.77KN and 56.7KN under the descending speed of 2.2m/d and 4.2m/d, respectively. Therefore, the axial force of the beam was directly proportional to the reservoir water-level ascending speed in the ascending phase and negatively correlated with the descending speed in the descending phase.



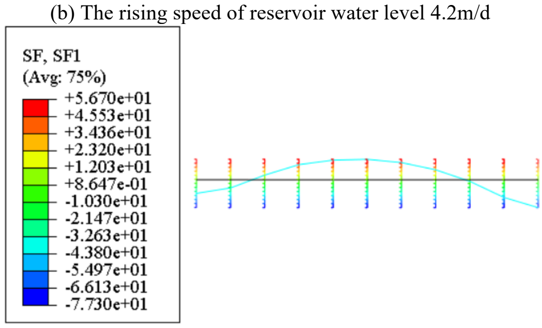
(a) The rising speed of reservoir water level 2.2m/d



(b) The rising speed of reservoir water level 4.2m/d



(c) The falling speed of reservoir water level 2.2m/d



(d) The falling speed of reservoir water level 4.2m/d

Fig. 15. cloud diagram of beam axial force

5. Conclusions

The typical bank slope and upper building in the Chongqing section of the Three Gorges Reservoir Region in China was taken as a study object to explore influence laws and the action mechanism of the reservoir water-level fluctuation speed on the displacement of the reservoir bank building and provide a reference for the structural design of reservoir bank building. The finite element software ABAQUS was used to construct the 3D overall model. Change laws of the seepage field of the bank slope as well as the displacement and structural internal force of the upper building foundation under the effect of reservoir water-level fluctuation were simulated and calculated on the basis of basic seepage–stress coupling theory. The following conclusions can be drawn from this study:

(1) A high reservoir water-level ascending speed indicates a large water head difference inside the sloping bank and large seepage force generated in the soil mass.

(2) The slope surface bears the loading action of the reservoir water pressure in the reservoir water-level ascending phase with the increase of the submerged depth of the reservoir water. The vertical upward seepage force is generated inside the bank slope due to the ascending groundwater level. Meanwhile, the soil expanded due to the decrease of matrix suction, which led to the uplift of the reservoir bank buildings and the lateral displacement to the back edge of the slope.

(3) The submerged depth of the reservoir water gradually reduced and the slope surface bears the unloading action of the reservoir water pressure in the reservoir water-level descending phase. The downward seepage force was generated on the slope due to the descending groundwater level. Meanwhile, the soil shrank due to the increase of matrix suction, which led to the settlement of the reservoir bank buildings and the lateral displacement to the front edge of the slope.

(4) The ascending speed presented a positive correlation with the building displacement when the reservoir water level changes within the same time period. The reservoir water fluctuation speed was negatively correlated with the building displacement under the same fluctuation amplitude. The significant difference in the vertical displacement between different pile foundations can easily cause the shear failure of horizontal members, such as beams and plates. The horizontal displacement between different pile foundations is slightly different; hence, the reservoir water fluctuation exerted a minor influence on vertical members, such as walls and columns.

(5) The ascending speed was negatively correlated with the axial force of the structural column and positively correlated with the axial force of the structural beam under the same reservoir water-level fluctuation amplitude. The descending speed was negatively correlated with the axial force of both the structural column and beam.

The finite element simulation method based on foundation–base–upper building combination and seepage–stress coupling theories can be used to analyze the relationship between the reservoir water-level fluctuation speed and the displacement of the reservoir bank building accurately and provided a reference for the structural design and safety evaluation of the reservoir bank building. However, certain errors unavoidably existed because changes in soil parameters were ignored in the numerical simulation due to the difficulty in finite element development. Synchronous changes of soil parameters should be considered in future investigations by the second development of finite element software to ensure consistency between the seepage simulation and the actual situation.

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References

1. He, L, L., "Study on the influence of sudden drop of reservoir water level and pile foundation on the stability of high fill bank slope". *Journal of disaster prevention and mitigation engineering,* 40(06), 2020, pp.959-966.
2. Xiao, J, F., "Model test on deformation characteristics of ancient landslide under reservoir water fluctuation and rainfall". *Geotechnical mechanics*, 42(02), 2021, pp.471-480.
3. Feng, W, K., Shi, Y, C., "Theoretical system of highway bank slope disaster risk analysis under reservoir water effect". *Journal of natural disasters*, (04), 2007, pp.6-12.
4. Huang, L., "*Stability characteristics of reservoir bank slope and analysis of uneven settlement cracks of slope houses*". Master thesis of Central South University, China, 2012, pp.1-40.
5. Li, Z, C., "Experimental study on the bearing capacity of building pile foundations under the influence of reservoir water level fluctuations". *Journal of Railway Science and Engineering,* 6(02), 2009, pp.38-42.
6. Deng, H, F., "Research on the influence mechanism of reservoir water level change on the stability of reservoir bank slope deformation". *Journal of Hydraulic Engineering*, 45(S2), 2014, pp.45-51.
7. Zhou, Z., "Mechanism of colluvial landslide induction by rainfall and slope construction: A case study". *Journal of Mountain Science*, 18(04), 2021, pp.1013-1033.
8. Chou, M., "Effectiveness of filter gabions against slope failure due to heavy rainfall". *Soils and Foundations*, (1),2021, pp.480-495.
9. Choi, S, K., "Preliminary report of a catastrophic landslide that occurred in Gokseong County". *Landslides*, (1-2),2020, pp.1-5.
10. Man, cha., M, T., "Three decades of landslide activity in western Nepal: new insights into trends and climate drivers". *Landslides*, 2021, pp.1-15.
11. Ernesto, A, A., "Landslide characterization using a multidisciplinary approach". *Measurement,* 104,2017, pp.294-301.
12. Vladimir, G., "Monitoring of post-failure landslide deformation by the PS-InSAR technique at Lubietova in Central Slovakia". *Environmental Earth Sciences 1*, 66(6), 2012, pp.1585-1595.
13. Cojean, R., "Analysis and modeling of slope stability in the Three-Gorges Dam Reservoir (China)-the case study of Huangtupo landslide". *Journal of Mountain Science,* (2),2011, pp.166-175.
14. Sarada, P., "Assessment of landslide-prone road cut rock slopes in Himalayan terrain:A finite element method based approach". *Journal of Rock Mechanics and Geotechnical Engineering*, 12(01), 2020, pp.59-73.
15. Bayer, B., "Using advanced In SAR techniques to monitor landslide deformations induced by tunneling in the Northern Apennines, Italy". *Engineering Geology*, 226, 2017, pp.20-32.
16. Marot, D., "Reservoir bank deformation modeling: application to Grangent reservoir". *Journal of Hydraulic Engineering*, 131(7),2005, pp.586-595.
17. Gallage, C., "Instrumented model slopes to investigate the effects of slope inclination on rainfall-induced landslides". *Soils and Foundations*, 61(3), 2021, pp.160-174.
18. Phuong, T., "Evaluation of deep learning algorithms for national scale landslide susceptibility mapping of Iran". *Geoscience Frontiers,* 2021, pp.505-519.
19. Shoki, T., "Amplification of flood discharge caused by the cascading failure of landslide dams". *International Journal of Sediment Research*, 36(03), 2021, pp.430-438.
20. Jia, Q., "Experimental study on the influence of uneven foundation settlement on frame structure". *China Civil Engineering Journal*, 78 (4), 44(11), 2011, pp.79-86.
21. Abdallah, M., "Behavior of a masonry wall subjected to mining subsidence, as analyzed by experimental designs and response surfaces". *International Journal of Rock Mechanics & Mining Sciences*, 100, 2017, pp.199-206.
22. Korff, M., "Empirical fragility curves for settlement-affected buildings: Analysis of different intensity parameters for seven hundred masonry buildings in The Netherlands". *Soils and Foundations*, 59(2), 2019, pp.380-397.
23. Bray, J, D., "6th Ishihara lecture: Simplified procedure for estimating liquefaction-induced building settlement". *Soil Dynamics and Earthquake Engineering*, 102, 2017, pp.215-231.
24. Dalgic, H., "A two-stage numerical analysis approach for the assessment of the settlement response of the pre-damaged historic Hoca Pasha Mosque". *International Journal of Architectural Heritage*, 13(5), 2019, pp.704-724.
25. Saeidi, A., "Development of building vulnerability functions in subsidence regions from empirical methods". *Engineering Structures*, 31 (10), 2009, pp.2275-2286.
26. He, W., "*Research on the impact of water level changes on the slope and buildings of the reservoir*". Master thesis of Central South University, China, 2012, pp.1-40.
27. Cho, S, E., "Instability of unsaturated soil slopes due to infiltration". *Computers and Geotechnics*, 28(3), 2001, pp.185-208.