Hindawi
Geofluids
Volume 2023, Article ID 2476246, 14 pages
https://doi.org/10.1155/2023/2476246

Research Article

Study on the Hysteresis Effect of the Stability of Longyangxia Dam Bank Slope with the Fluctuation of Water Level

Guangxiang Yuan,[1] Hu Wang,[1] Zhiquan Huang ,[1,2] and Luqing Zhang[3]

[1]*North China University of Water Resources and Electric Power, Zhengzhou 450046, China*
[2]*Luoyang Institute of Science and Technology, Luoyang 571023, China*
[3]*Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China*

Correspondence should be addressed to Zhiquan Huang; huangzhiquan@ncwu.edu.cn

Received 4 September 2022; Revised 22 October 2022; Accepted 24 November 2022; Published 20 January 2023

Academic Editor: Dongjiang Pan

Reservoir landslide is a common geological disaster during the operation of hydropower projects. The fluctuation of reservoir water level is an important factor that induces slope instability. The natural slope will gradually lose stability under the rapid rise and fall of reservoir water level. A variety of landslide examples show that, on the premise of not suffering from extreme environmental conditions, the reservoir landslide often occurs after the rapid fluctuation of the reservoir water level for a period of time, and there is a certain time difference between its instability failure and the rapid rise and fall of the reservoir water level. In order to study the hysteresis effect between the stability change of the reservoir slope and the fluctuation of the reservoir water level, taking the Chana landslide in the reservoir area of Longyangxia Hydropower Station as an example, combining the field survey, geological survey data, and the actual change of the reservoir water level, the finite element simulation software is used to restore the actual working condition, and the research is carried out from three aspects of slope seepage field, displacement field, and stability. The results show the following: (1) The hysteresis of slope seepage change during the rising period of reservoir water level is more obvious than that during the falling period of reservoir water level. The deformation potential of Chana landslide is greater during the falling period of reservoir water level, while the deformation is restrained during the rising period of reservoir water level. (2) The incremental displacement simulation results of Chana landslide show that there are deformation incubation period and deformation release period of Chana landslide. The deformation incubation period occurs during the rapid rise and fall of reservoir water level, and the deformation release period occurs during the stable change of reservoir water level. (3) The incremental displacement produced during the deformation release period of the slope is large, but the slope remains stable, which reflects the existence of the internal antisliding mechanism of the landslide from the side. (4) The stability coefficient of Chana landslide changes greatly during the drawdown period. When the drawdown rate of water level is kept at 0.03~0.07 m/d, the stability coefficient of Chana landslide changes slightly and the slope is relatively stable.

1. Introduction

The rise and fall of the reservoir water level will change the hydrogeological conditions of the reservoir bank slope, affect the mechanical properties of the rock and soil mass, and cause stress concentration in some local areas of the slope or reduce the safety reliability and ultimately may lead to slope instability and failure [1]. For example, Qianjiangping landslide occurred in the Three Gorges reservoir area on July 13, 2003 [2]; Outang Landslide in the Three Gorges Reservoir Area in June 2003 [3]; from July to October 1963, the landslide of Vajont Reservoir in Italy [4]; in December 1959, the landslide of the Calpase Reservoir in France [5]; nad the Canelles reservoir landslide in Spain in 2006 [6]. Jones et al. [7] found that 30% of the landslides occurred during 1941-1953 around Roosevelt Lake were caused by the sudden drop of reservoir water level. Nakamura [8] also found in the statistical process that 60% of the reservoir landslide disasters occurred during the sudden drawdown of the reservoir water level. In view of the time correlation between the fluctuation of the reservoir water level and the stability change of the reservoir bank slope, scholars at home and abroad have carried out a lot of research, such as Zhang et al. [9] taking Xiaping landslide in Wanzhou, Chongqing, as an example, studied the stability change and failure probability of the landslide during the rapid decline of the Three Gorges reservoir water level. Manzoo and Timothy [10] inverted the reactivation mechanism of the landslide by analyzing the change of strength parameters of sliding slope rock and soil mass under the effect of water storage. Guo et al. [11] found that the annual displacement variation under the action of high-speed and low-speed rise and fall of reservoir water level reached 30 times through monitoring the Longmen Mountain landslide. Through field monitoring, Marko et al. [12] and Benoit et al. [13] studied the change of hydraulic mechanism of reservoir bank slope under the condition of reservoir level rise and fall.

Since the Longyangxia Hydropower Station was built and put into operation in 1986, the long-term fluctuation of the reservoir water level has had a significant impact on the stability of the reservoir bank slope, and the geological disasters in the reservoir area have gradually emerged. Wangshike landslide occurred in June 2002 [14]. In November 2005, high-speed landslide occurred on the west bank of the south side of Wenchang Temple during the high water level operation of the reservoir [15]. The Chana landslide, which had slipped in 1943, also found cracks at the back edge in April 2009, showing signs of secondary sliding. By analyzing the occurrence time of landslides in the reservoir area of Longyangxia Hydropower Station and the reservoir water level regulation, it can be seen that these landslides often occur after the rapid fluctuation of water level, and there is a certain time hysteresis, which indicates that it is important to study the hysteresis effect of reservoir bank slope stability affected by the change of reservoir water level. Based on these, taking the Chana landslide in Longyangxia reservoir area as an example, with the help of finite element simulation software, through analyzing the change process of slope seepage field, displacement field, and stability coefficient, the corresponding hysteresis calculation formula is established to study the hysteresis effect of slope with water level fluctuation.

2. Engineering Geology of Longyangxia Hydropower Station Bank Slope

2.1. Regional Geological Setting. The Longyangxia Hydropower Station is located in Hainan prefecture, Qinghai Province, the mainstream of the upper reaches of the Yellow River. Regionally, the reservoir area belongs to the rhombic depression block in the eastern Gonghe basin of the South Qilian West Qinling Hercynian fold belt in the Qinghai Tibet Plateau, and seismic zones formed by deep and large faults are distributed around the block [15]. The structural signs in the region mainly include SN trending structure, NE trending structure, Qilu system NWW trending structure, and Hexi NNW trending structure. These structural belts extend and cross in different directions and jointly control the structural framework of the region. In addition, the Gonghe basin where the Longyangxia hydropower station is located has deposited a large number of semi diagenetic soils, which are the products of inland lacustrine deposits in the early and Middle Pliocene and Pleistocene. Controlled by the large-scale uplift and differential uplift movement of the Qinghai Tibet Plateau since the late Tertiary, after the Yellow River pierced the Longyangxia estuary, a series of high and steep slopes in a wide range were formed on the South Bank of the reservoir area near the dam due to the strong regional uplift movement and the deep action of the Yellow River.

2.2. Formation Lithology. The exposed strata in the reservoir area are mainly quaternary fluvial and lacustrine loose deposits. At the end of the reservoir, there are sporadic Permian lower and middle carbonate rocks, Triassic middle and lower clastic rocks, and Indosinian intrusive rocks. The Quaternary strata are widely distributed in the reservoir area, with complex genetic types and diverse lithology. There are mainly two types: ① lower pleistocene alluvial lacustrine deposit ($Q^1_{al\text{-}l}$): concentrated on the South Bank of the Yellow River and the South Bank of Laganxia Yangqu in the lower reaches of the reservoir area. It is a set of coarse and fine stratum, and the lithology is sand gravel, silty sand, fine sand, medium sand, sandy soil, clayey soil, muddy sandy soil and muddy clayey soil, and some parts contain spiral shell fossils. ② Upper pleistocene alluvium and diluvium ($Q^3_{al\text{-}pl}$): distributed in Taratai mountain and piedmont inclined plain, with binary structure. The upper part is sub sandy soil, loose slightly dense, with vertical joints, with uneven thickness ranging from 1 m to 30 m. The lower part is gravel layer, 4~8 m thick. The gravel is subangular, and the parent rock is composed of sandstone, limestone, and granite [15]. The properties of the semidiagenetic soil in the high and steep slopes of the reservoir area are closely related to the inland lacustrine deposits and the local arid and rainless climate. Some scholars have shown through soil chemistry tests that the content of soluble calcium salt and sodium salt in the semi diagenetic soil is high, generally higher than 20%, in which the proportion of insoluble calcium salt is very large. The microdebris and viscose particles in the rock and soil are bound by microcrystalline calcium carbonate. The material composition is quite the same as that of the old loess [16].

2.3. Hydrogeological Condition. Since the completion of Longyangxia Reservoir in 1986, the water level of the reservoir began to rise in July, reached the peak in November, and then began to decline gradually until it reached the lowest point in the next spring. The groundwater in the reservoir area is deeply buried with small flow and is mainly buried in the sand layer and sandy loam at the lower part of layer I and layer III of lacustrine strata. The underground water level elevation at 300 m in the bank is mostly below 2510 m, 400~500 m lower than the slope top. The groundwater belongs to pore fissure water

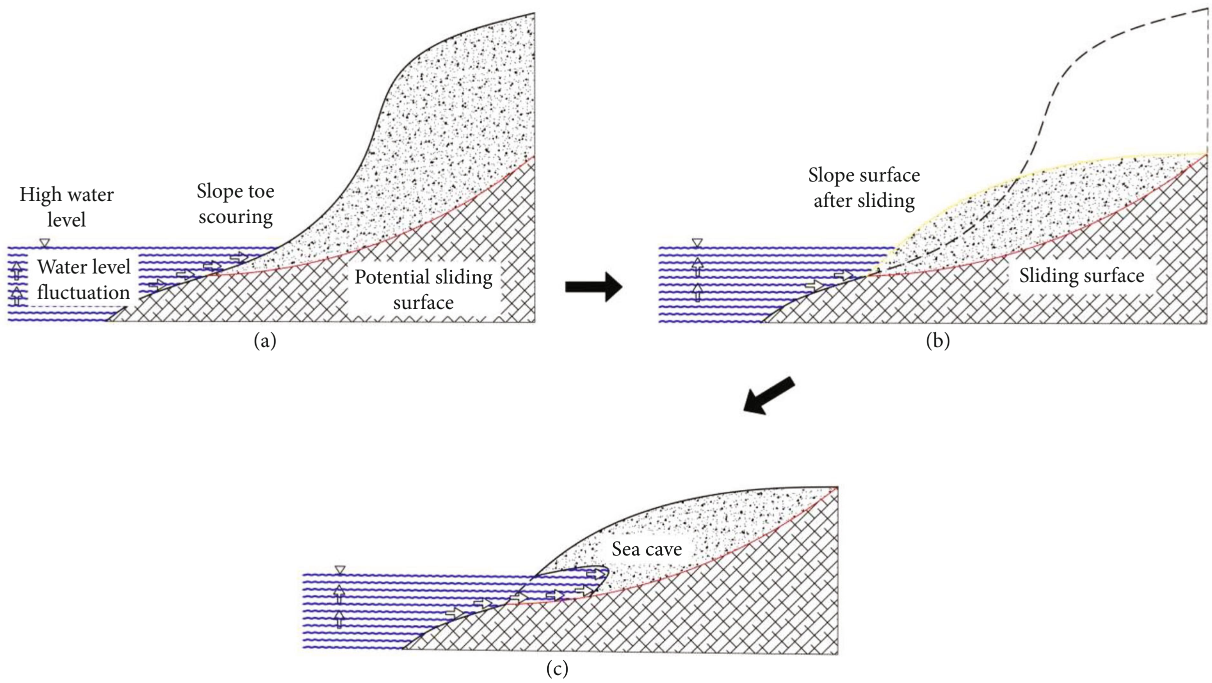

Figure 1: Slope change process.

and discharges to the Yellow River with a hydraulic gradient of 3%~8%. Due to the arid climate environment in this area, the dynamic change of groundwater is little affected by atmospheric precipitation, and it mainly receives the stable recharge of distant groundwater [17]. The monitoring and investigation results of scholars over the years show that the actual rise of the groundwater level in the same period is 7%~36% of the rise of the reservoir water level, and the annual change of the water level is generally less than 5 m. The rise of the groundwater level is also affected by the reservoir/groundwater level difference. When the reservoir water level continues to rise and the reservoir/groundwater level difference is greater than 30~40 m, the groundwater level rises significantly; on the contrary, there is no significant change in the groundwater level [18].

2.4. Slope Sliding History. The main hidden danger of landslide since the operation of the reservoir comes from the ancient landslide and old landslide in the reservoir area. Under the influence of nearly 40 years' immersion and reservoir water level fluctuation, the reservoir bank slope has undergone three processes (Figure 1).

(A) At the initial stage of dam construction, the water storage of the reservoir results in the infiltration of the slope toe of the reservoir bank, while the upper overburden of the high and steep slope near the dam bank is semidiagenetic soil that is easy to soften when encountering water. Under the action of water, the slope toe will undergo long scouring, unloading, and stress concentration until the potential sliding surface is connected, resulting in landslide, and the upper overburden will slip

(B) After the upper covering layer slides, the lower hard rock layer is exposed, but it is soon covered by the falling gravel soil, and the slope is in a temporary stable stage. Subsequently, affected by the rise and fall of the reservoir water level, the slope toe continued to be washed away, resulting in the washing away of the covered gravel and the continuous softening of the rock stratum by immersion [19]

(C) Erosion cavities are formed at the rock mass at the toe of the slope due to the scouring of reservoir water, which increases the free face of the rock mass and leads to bank collapse under the influence of water softening of the rock mass, which is the breeding condition for subsequent slope failure or secondary failure [16]

3. Establishment of Finite Element Model

3.1. Computational Model and Boundary Conditions. In this paper, the Chana landslide 6.5 km away from the dam is selected as a typical case analysis (Figure 2). The Chana landslide (Figure 3) experienced a large-scale sliding in 1943, with a sliding volume of 160 million m^3. The front edge of the sliding body advanced about 3 km, burying the forest belt and Chana Village on the Bank of the Yellow River. The groundwater is located below the origin coordinate of the model, and the initial stress is related to the slope self-weight and groundwater.

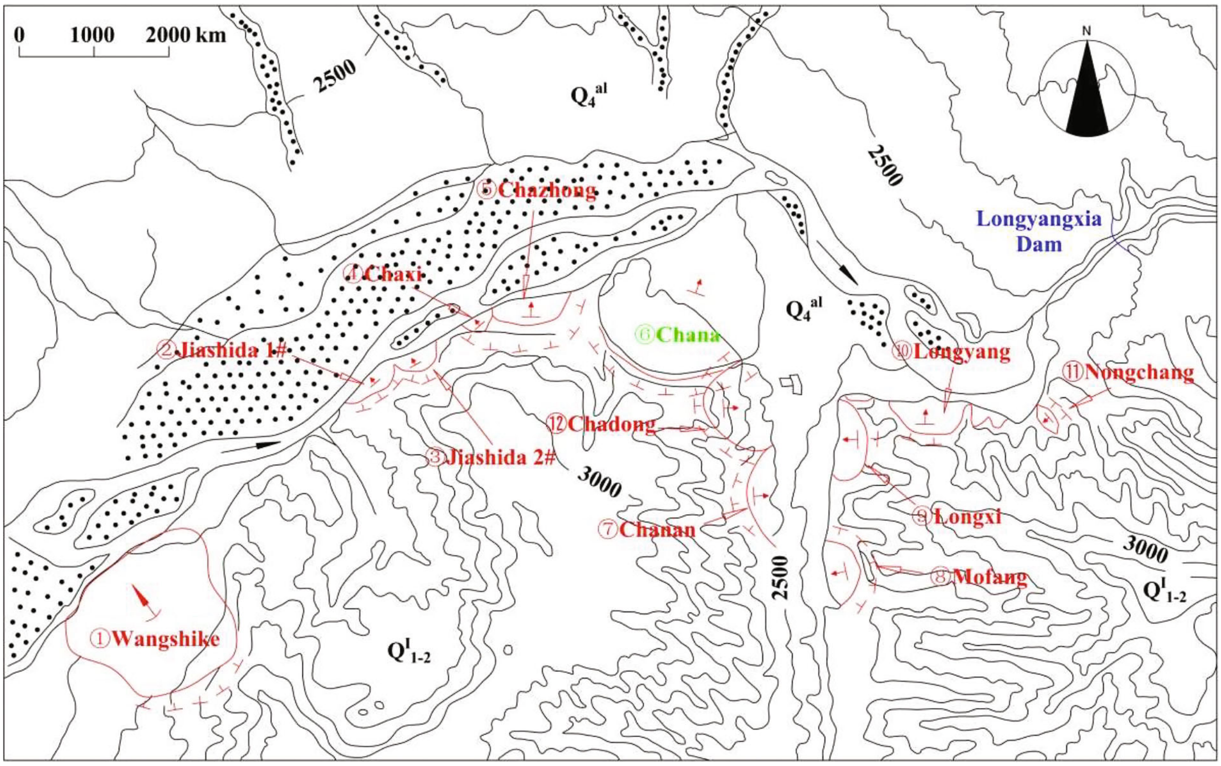

Figure 2: Study slope location [20].

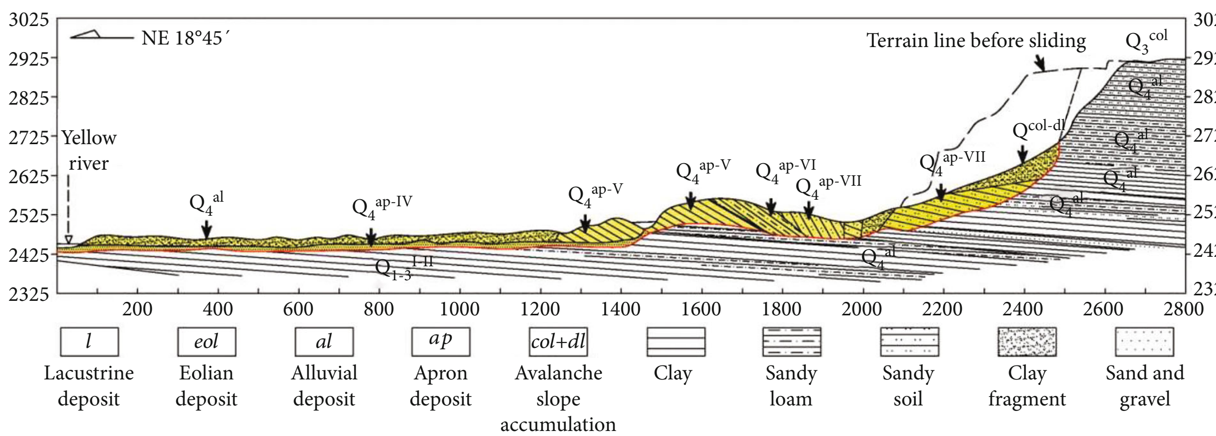

Figure 3: Geological profile of Chana landslide [20].

The analysis is carried out with the help of Plaxis2D finite element software, and the establishment of the model is shown in Figure 4. The Chana landslide model is 525 m high and 1400 m long. The stratum is divided into seven layers. See Table 1 below for basic parameters of different strata. The mesh element type of the model is triangle mesh, which is divided into 1682 element meshes and 13845 nodes. The boundary condition of the model is that the left and right boundaries constrain the horizontal displacement, and the bottom boundary is all fixed constraints. In addition, the seepage surface is set on the slope surface, so that the external water level can only penetrate into the slope from the slope surface, and cannot cross the boundary. The failure basis of Plaxis2D calculation is the strength reduction method. Its core is to reduce the strength parameters of the soil mass in an equal proportion until the reduced strength parameters make the soil force reach a critical state. Then, it is considered that this reduction parameter is a safety factor that can reflect the stability of the slope. The reduction formula is as follows:

$$C_r{}' = \frac{C'}{F}, \qquad \phi_r{}' = \arctan\left(\frac{\tan\phi'}{F}\right), \tag{1}$$

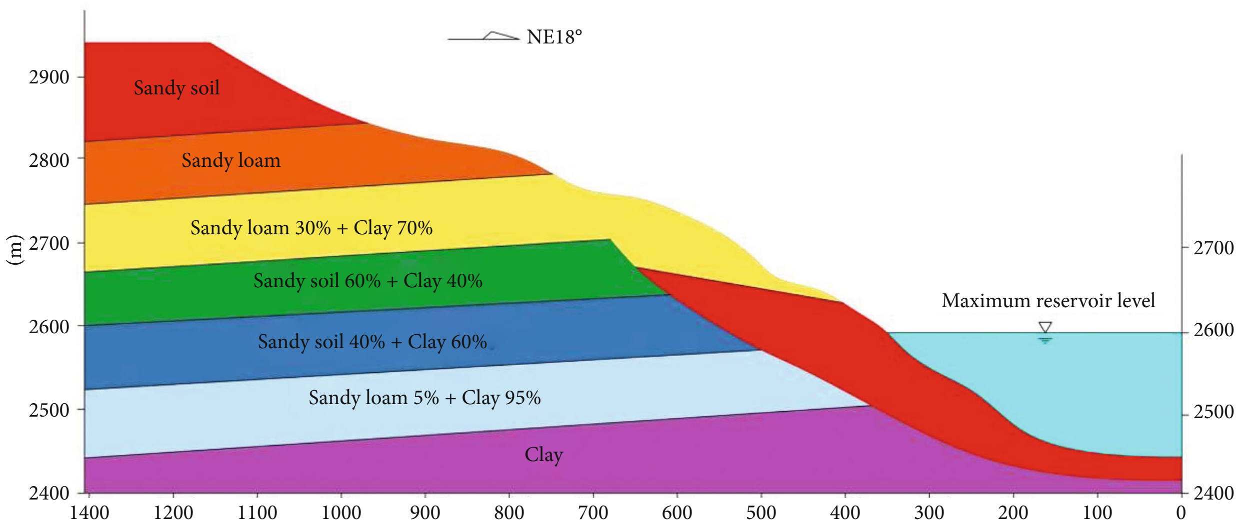

Figure 4: Two-dimensional finite element model of Chana landslide.

Table 1: Strength parameters of rock and soil mass.

Stratum	Natural-unit-weight (kN/m^3)	Stratum-unit-weight (kN/m^3)	E (MPa)	e	ϕ (°)	ϕ' (°)	C' (kPa)	K (m/d)
I	21.1	20.9	479	0.452	35	33	323	8.64×10^{-5}
II	18.7	20.6	468	0.554	37	35	317	8.58×10^{-5}
III	21.1	21.8	347	0.459	35	33	88	8.36×10^{-2}
IV	18.7	20.59	325	0.554	37	35	245	6.96×10^{-5}
V	22.0	22.8	339	0.355	32	30	79	6.73×10^{-5}
VI	17.3	20.3	222	0.573	38	—	39	0.865
VII	17.5	20.5	243	0.594	38	—	36	4.6

where $C_r{}'$ and $\phi_r{}'$ are the strength parameters after reduction, C' and ϕ' are the actual strength parameter, and F is the reduction factor.

3.2. Variation Characteristics of Reservoir Water Level. Longyangxia Hydropower Station has the regulation performance for many years. In the early years, the reservoir operated under the low water level of 2575 m for a long time. After the reservoir water level reached the historical maximum of 2597.62 m on November 19, 2005, the reservoir entered the high water level operation stage. Figure 5 shows the water level elevation change curve in recent five years drawn by using the water level data of Longyangxia Hydropower Station published by the Yellow River Water Conservancy Commission of the Ministry of water resources [21]. It can be seen from Figure 5 that the reservoir water level shows a downward trend from January to June in a hydrological cycle year, of which the downward trend is faster in April, May, and June and reaches the lowest value of the reservoir water level in the whole year in June and then starts to show an upward trend. The upward trend is faster in July and August, and the water level rises to the peak in October and November and remains stable until the next water level year.

3.3. Selection of Strength Parameters of Rock and Soil Mass. The formation lithology in the study area is mostly quaternary middle and early Pleistocene lacustrine strata, which can be divided into seven layers (Figure 4). The upper part of the slope is mainly sandy soil; the middle and lower parts are mainly composed of highly dense, overconsolidated semidiagenetic clayey soil mixed with thin sandy soil stratum, and the lower part of the bank slope is mainly clayey soil with a thickness of about 250 m. There are many changes in sedimentary rhythm inside, and there are multiple layers of 0.30 m~3.0 m thin sand layer, which is the main stratum soaked by reservoir water. The upper part is mainly sandy soil, with a total thickness of 150 m~300 m [18]. According to the previous data [17], the values of rock and soil mass strength parameters of each layer are shown in Table 1.

3.4. Calculate the Choice of Working Conditions. It can be seen from Figure 5 that the variation range of water level of Longyangxia Hydropower Station in 2021 is the most uniform. According to the water level change trend of the whole year in 2021 (Figure 6), it can be divided into the stable operation period (0 m/d), slow water level rise period (rise rate +0.03~+0.04 m/d), medium water level rise period (rise rate+0.05 ~ +0.08 m/d), fast water level rise period (rise rate

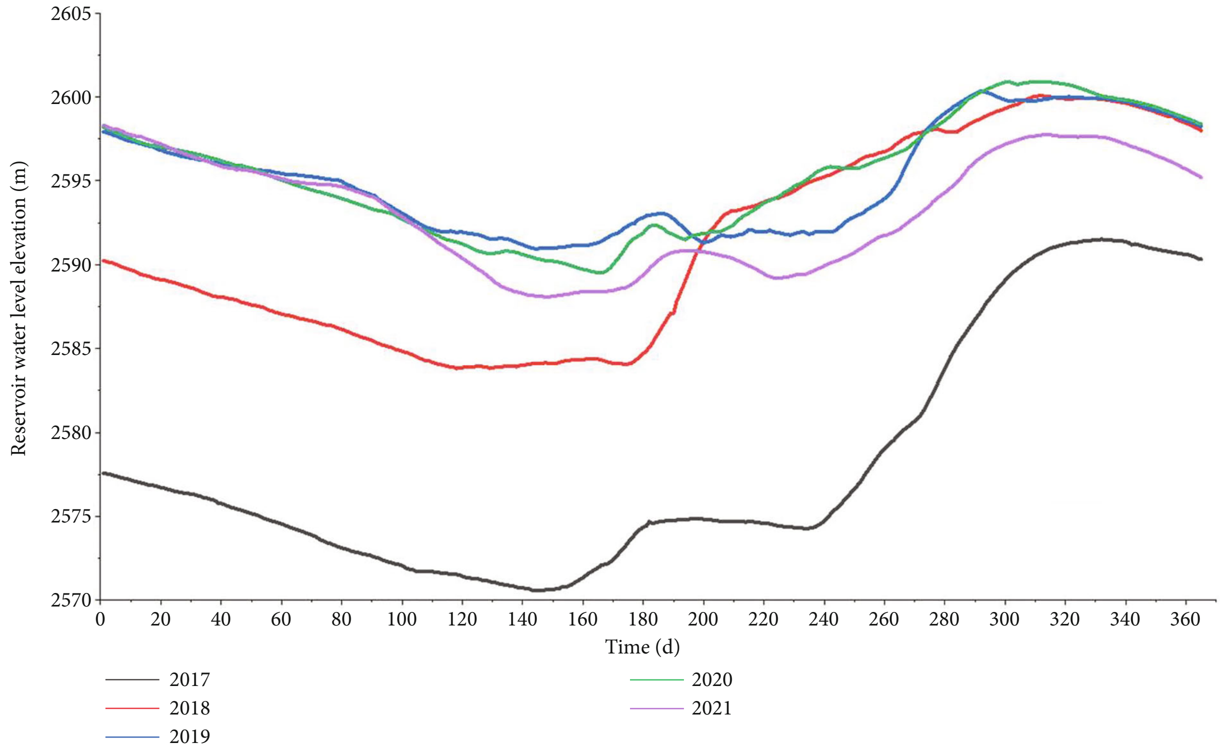

Figure 5: Changes of reservoir water level and elevation of Longyangxia Hydropower Station in recent five years.

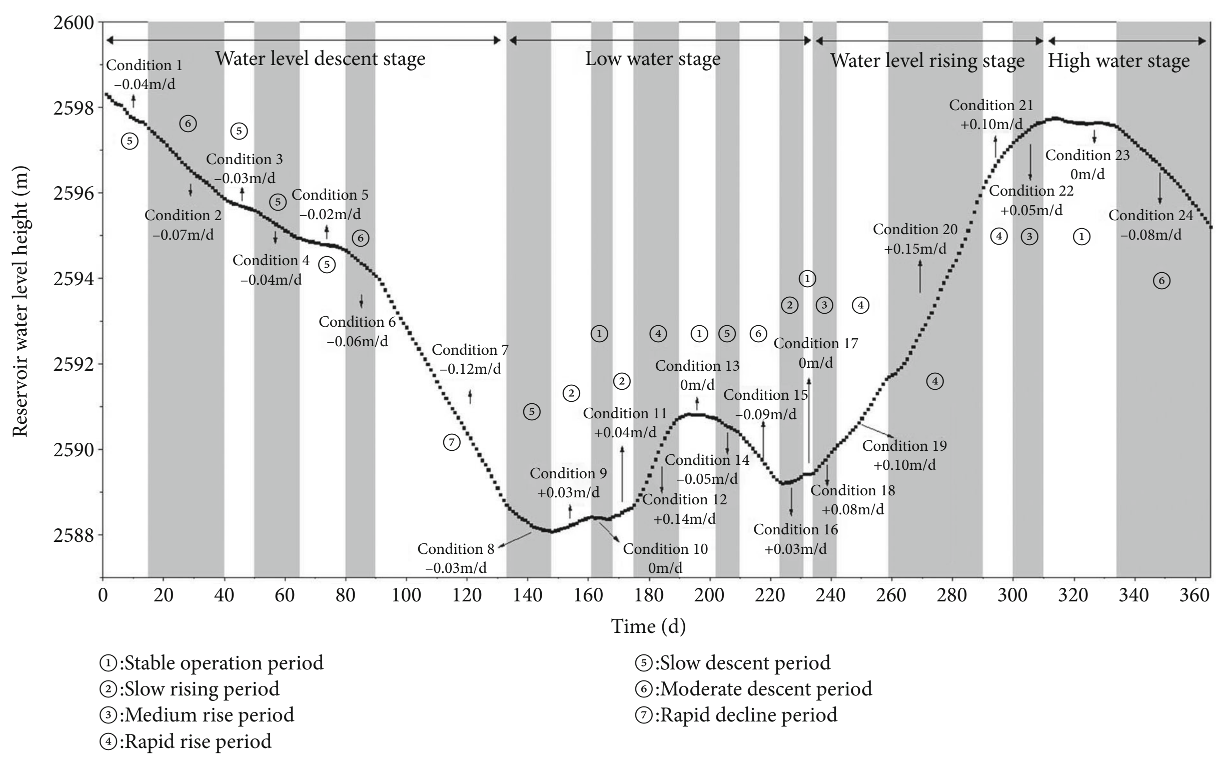

Figure 6: Water level fluctuation of Longyangxia Hydropower Station and selection of working conditions in 2021.

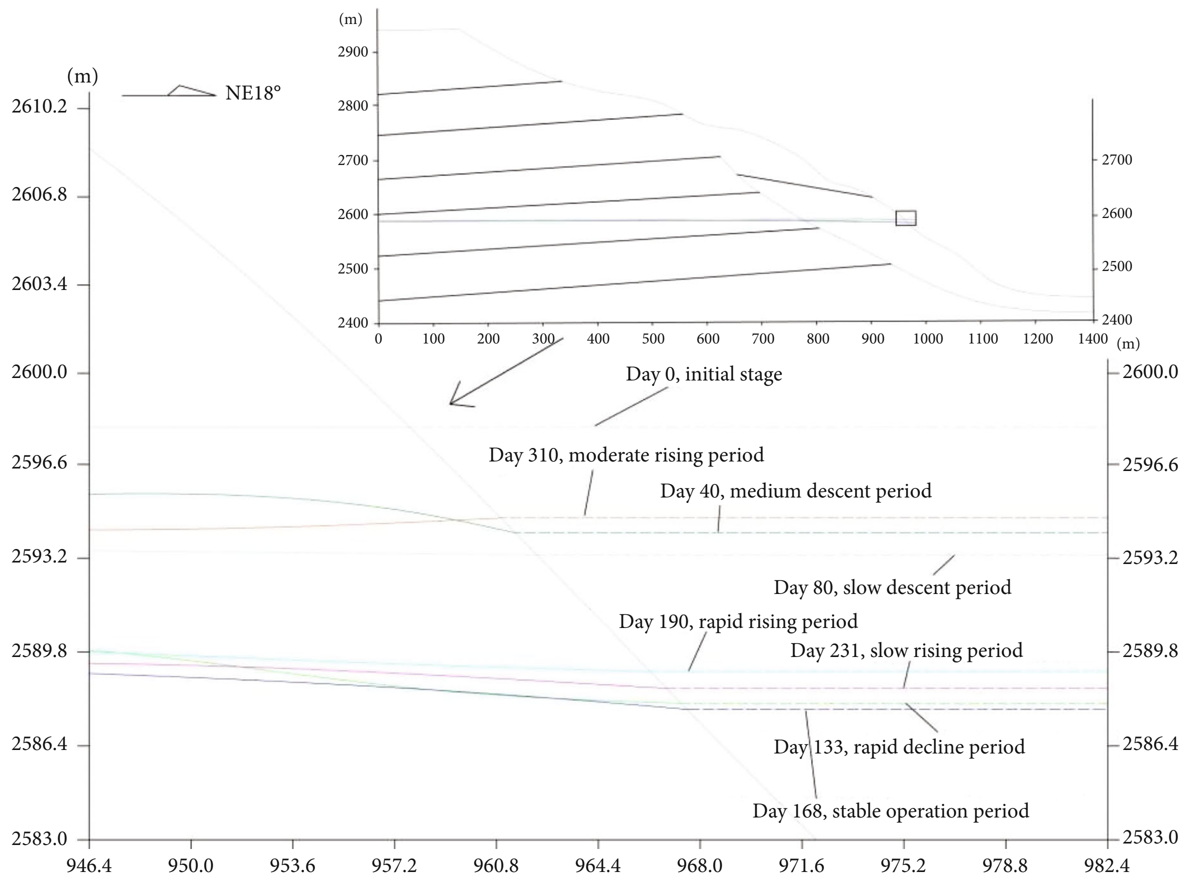

Figure 7: Phreatic line of Chana landslide at different times.

+0.10 ~ +0.15 m/d), slow water level decline period (decline rate -0.02~ -0.05 m/d), medium water level decline period (decline rate -0.06~ -0.09 m/d), and 7 types of rapid drawdown period (drawdown rate -0.12 m/d). Because the reservoir water level is in dynamic change, the initial water level and the rise and fall rate in each period are different. In order to fully restore the hysteresis effect of the slope under the actual reservoir operation, the calculation is carried out under 24 working conditions according to the initial water level and rise and fall rate of each period (Figure 6).

4. Analysis of Numerical Simulation Results

4.1. Analysis of Seepage Field Calculation Results. The change of reservoir water level will cause the change of seepage field in the slope, that is, it will affect the change of saturation line and the distribution of pore water pressure in the slope. According to the phreatic line (Figure 7) calculated under some working conditions, due to the influence of the permeability coefficient of rock and soil mass, the change rate of water level in the slope hysteresis behind the change rate of reservoir water level, and the hysteresis effect gradually increases from the slope to the inside of the slope. The unequal water level on both sides of the slope will directly lead to the change of the groundwater dynamic field of the slope. From the mechanical effect, ① in the rising stage of the reservoir water level, the pore water pressure effect (suspension load shedding effect) plays a major role in the stability of the bank slope and ② in the drawdown stage of reservoir water level, the seepage pressure effect of groundwater and the saturated loading effect of groundwater play a major role in the stability of bank slope [22].

With the change of reservoir water level, the hysteresis effect of water level on slope is the most obvious. The water level hysteresis coefficient W_s represents the hysteresis effect of the internal water level of the slope under the fluctuation of the reservoir water level, that is, the ratio of the internal and external water level difference at the slope to the change time, which determines the lower limit of the internal and external water pressure difference of the slope and can reflect the change of the groundwater dynamic field of the slope. See formula (2) for the calculation formula of water level hysteresis coefficient W_s:

$$W_s = \frac{\Delta H_1 - \Delta H_2}{T}, \tag{2}$$

where ΔH_1 is the change value of water level height outside the slope, ΔH_2 is the height change value of water level measured on the slope, and T is the time of water level change. The results of water level hysteresis coefficient W_s calculated under different working conditions are shown in Figure 8.

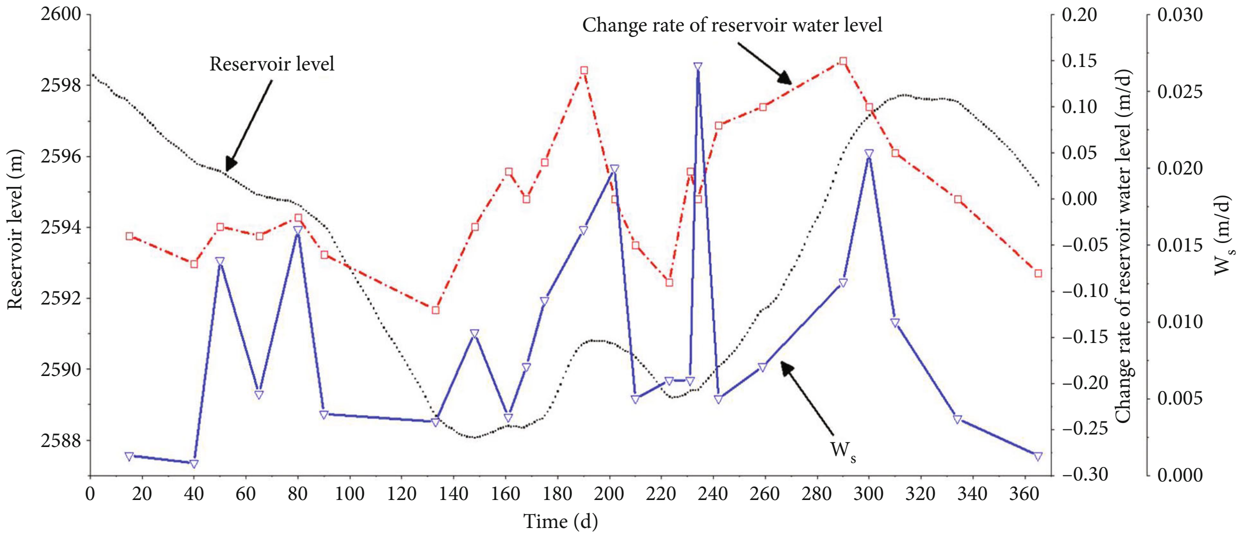

Figure 8: Calculation results of water level hysteresis coefficient.

Chana landslide is affected by the sliding history, and the change of reservoir water level mainly affects the sandy soil layer. The actual working conditions include the stable stage of the reservoir water level. The duration of this stage is short, and the change of the external water level of the slope is almost 0, which leads to very large calculation results, which is illogical. Therefore, it is necessary to eliminate the calculated outliers of the water level lag coefficient (conditions 13 and 17). The average value of the water level hysteresis coefficient in the slow decline period of the landslide is 0.0085 m/d, the average value of the water level hysteresis coefficient in the medium decline period is 0.0031 m/d, the average value of the water level hysteresis coefficient in the fast decline period is 0.0035 m/d, and the average value of the water level hysteresis coefficient in the slow rise period is 0.0071 m/d. The average value of the water level hysteresis coefficient in the medium rise period is 0.0075 m/d, and the water level hysteresis coefficient in the fast rise period is 0.0142 m/d. It can be seen that the hysteresis coefficient of water level in the rising period of reservoir water level is 1.7~2.2 times that in the falling period, that is, the hysteresis effect of water level change in the slope is more obvious when the water level rises. The water level sensitivity coefficient is also affected by the change rate of the reservoir water level. During the decline of the reservoir water level, the hysteresis of the water level change in the slope first decreases and then increases with the increase of the decline rate. When the reservoir water level drops at a medium rate, the hysteresis of the water level in the slope is small and reaches the lowest value at 0.07 m/d. In contrast, in the rising period of water level, the hysteresis becomes more and more obvious with the rising rate of water level. When the rising rate of reservoir water level is 0.15 m/d, the hysteresis effect reaches the peak. The influence of dynamic change of water level on slope stability is mainly in two aspects: ① groundwater will reduce the physical and mechanical properties of slope rock and soil mass and weaken the shear strength of slope and ② the rise and fall of reservoir water will change the pore water pressure in the slope; at the same time, it will also cause scouring and softening argillization on the slope [23].

4.2. Analysis of Incremental Displacement Calculation Results. The incremental displacement nephogram is the increment of the last calculation step relative to the previous calculation step. Its distribution can reveal the mechanism of slope destruction and the location of the slip arc (potential slip surface) [24]. In this paper, the slip arc under the limit state is revealed by analyzing the displacement nephogram under the condition that the landslide produces the maximum incremental displacement (Figure 9).

Incremental displacement of slope decreases gradually from sliding surface to slope surface. In order to study the variation characteristics of slope incremental displacement with the fluctuation of reservoir water level, the incremental displacement data under 24 working conditions are calculated and plotted (Figure 10).

The incremental displacement of the slope has a similar change pattern in the drawdown stage (0-133 days) and the rising stage (231-310 days), both of which increase first and then decrease, and the incremental displacement range is 6.4~33.5 mm. However, during the stable operation period of the two water levels, it showed abnormal. Although the water level is relatively stable, the change of incremental displacement is abnormal. On the contrary, it reached a peak of 52.88 mm at 168 days of low water level operation period after the end of the period of significant water level decline and then increased to 20.41 mm at 310 days of high water level operation period after the end of the period of water level rise. The slope shows the hysteresis accumulation of deformation, that is, the deformation accumulates continuously in the stage of water level change, and the deformation scale is small. It will be released when the reservoir water level is stable. In view of the hysteresis of slope deformation with reservoir water level, two models should be studied. The first is the sensitivity study of slope deformation with reservoir water level. The deformation sensitivity coefficient

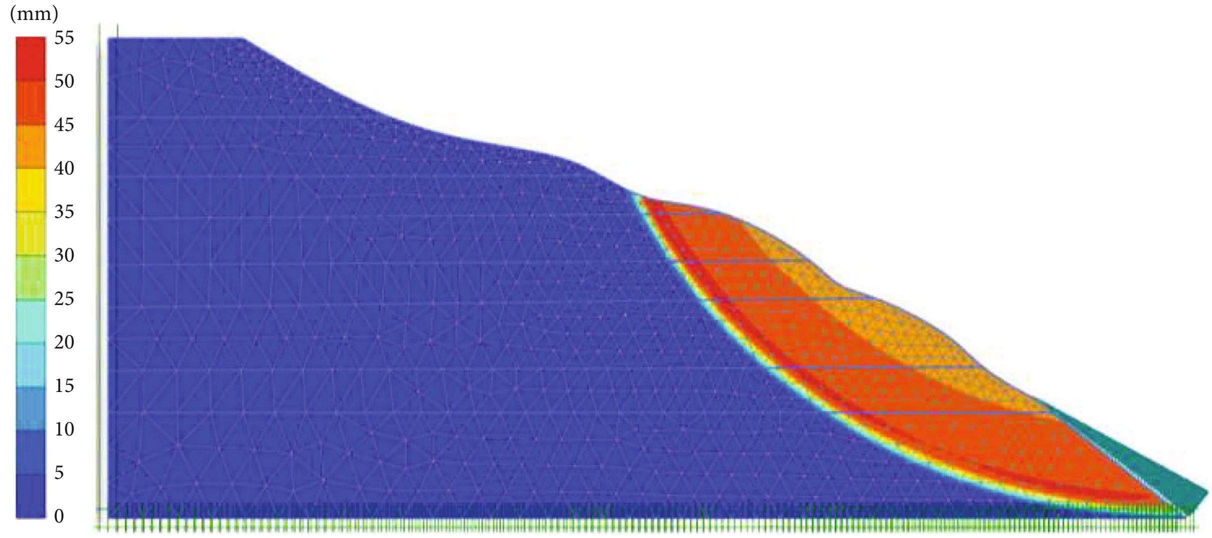

Figure 9: Incremental displacement nephogram of landslide (condition 10).

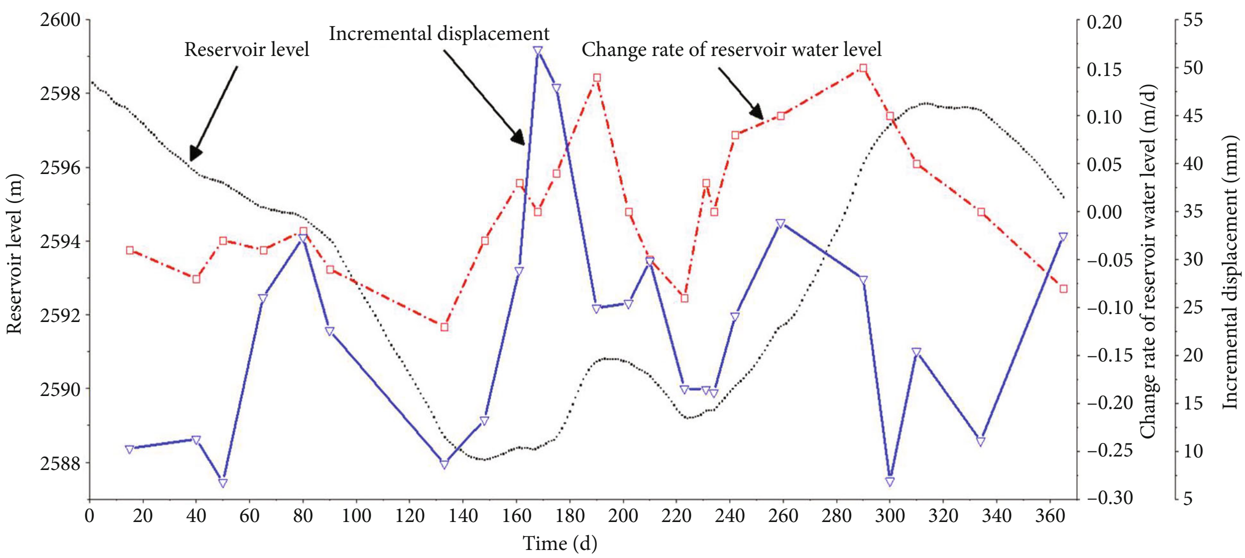

Figure 10: Incremental displacement calculation results.

D_c represents the sensitive effect of slope deformation with the change of reservoir water level during the period of large change of water level, that is, the extent to which the incremental displacement is affected by the change of reservoir water level. See formula (3) for calculation of deformation sensitivity coefficient D_c:

$$D_c = \frac{D}{\Delta H_1}, \tag{3}$$

where D is the incremental displacement obtained under each calculation condition and ΔH_1 is the change value of water level height outside the slope. The second is the hysteresis cumulative effect of the two water level stable operation stages.

Here, the cumulative hysteresis coefficient C_t is used to represent the magnification of the displacement during slope deformation release relative to the displacement during deformation incubation. The cumulative hysteresis coefficient C_t is calculated as shown in

$$C_t = \frac{\Delta D_2}{\Delta D_1}, \tag{4}$$

where ΔD_1 is the average incremental displacement during deformation incubation period and ΔD_2 is the average incremental displacement during deformation release period. The results of deformation sensitivity coefficient D_c and cumulative hysteresis coefficient C_t calculated under different working conditions are shown in Figure 11.

According to the calculation results of deformation sensitivity coefficient, the water level decline stage and the water level rise stage show the opposite change trend. With the continuous decline of the water level, the deformation sensitivity

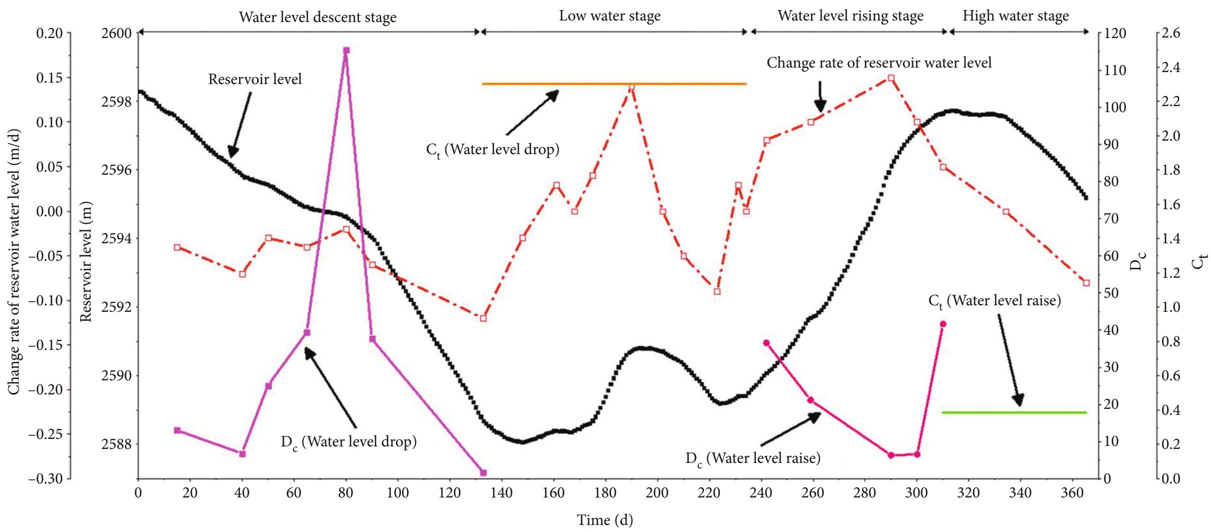

Figure 11: Deformation sensitivity calculation results.

of the slope first increases and then decreases. The mean values of the deformation sensitivity coefficients obtained under the three types of decline rates are as follows: rapid decline $D_c = 1.62$, medium decline $D_c = 22.2$, and slow decline $D_c = 48.2$. When the decline rate reaches 0.02 m/d, the slope deformation is most affected by the reservoir water level, and the deformation sensitivity coefficient reaches 115.3. When the water level rises continuously, the sensitivity of slope deformation decreases first and then increases. When the rising rate is 0.15 m/d, the slope deformation is least affected by the reservoir water level, and the deformation sensitivity coefficient is 6.31. The calculation results of deformation sensitivity coefficient show that when the reservoir water level drops slowly, the groundwater in the slope is fully infiltrated, resulting in hydrodynamic pressure pointing out of the slope, and the slope deformation is released to a certain extent. When the reservoir water level rises, the dynamic water pressure points to the slope. The faster the rising rate is, the greater the difference between internal and external water pressure is, the greater the antisliding force of the slope is, and the deformation is restrained.

The calculation results of the cumulative hysteresis coefficient further confirm the above analysis. The cumulative hysteresis coefficient intuitively reflects the deformation difference between the release period and the incubation period of slope deformation. The larger the calculation results are, the greater the deformation potential of the slope in the incubation period of deformation is. It can be seen from the calculation results that the cumulative hysteresis coefficient in the water level falling period is 2.3, and the cumulative hysteresis coefficient in the water level rising period is 0.38; the former is about 6 times of the latter. This shows that the amount of deformation during the period of water level decline is much greater than that during the period of water level rise, which is consistent with the above conclusion that the deformation is restrained when the water level rises.

4.3. Stability Analysis Results. The stability calculation results of Chana landslide under different working conditions are shown in Figure 12. The stability coefficient change curve of Chana landslide is generally divided into five stages, corresponding to the four reservoir water level change stages. ① S stage (0 ~133 days): the slope stability decreases with the decrease of water level, and the faster the water level decreases, the faster the stability decreases. The stability coefficient reached the lowest value of 1.33 on the 133rd day, when the slope just experienced a significant decline in water level. ② Stage (133~173 days): the slope stability gradually recovers under low water level operation. At this stage, the reservoir water level was basically stable, and the bank slope was reduced by external influences. The stability coefficient increased from 1.33 to 1.67, an increase of 26%. ③ Stage (173~235 days): after 40 days of stability, the reservoir water level began to rise and fall slightly, and the slope stability coefficient decreased slightly, from 1.67 to 1.58, with a decrease of only 4.4%. ④ Stage (235~300 days): the slope stability increases again with the rise of reservoir water level. The stability coefficient increased from 1.58 to 1.82, with an increase of 15.1%, indicating that the rise of the reservoir water level improved the stability of the slope. ⑤ Stage (300~365 days): the slope stability has decreased under the high water level, but still remains at a high level. The stability coefficient gradually decreases from 1.82 to 1.76, a decrease of only 3%. The stability coefficient of Chana landslide in high water level period is higher than that in low water level period, which reflects that high reservoir water level is helpful to maintain slope stability. The subsequent downward trend also proved that the improvement of slope stability by high water level was only temporary.

The stability change of Chana landslide has a similar trend with the change of reservoir water level. Here, the stability hysteresis coefficient S_c is used to characterize the

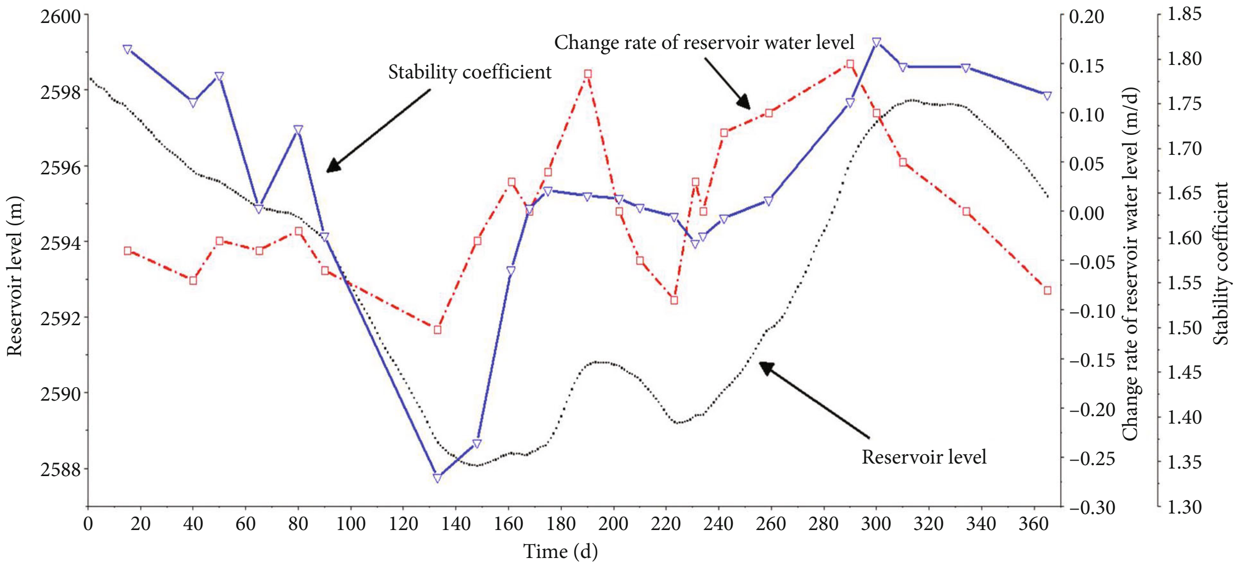

Figure 12: Variation curve of landslide stability coefficient.

hysteresis effect of slope stability with the change of reservoir water level, that is, the degree to which the slope stability is affected by the change of reservoir water level. See formula (5) for the calculation of stability hysteresis coefficient S_c:

$$S_c = \frac{\Delta M_{\mathrm{sf}}}{\Delta H_1}, \tag{5}$$

where ΔM_{sf} is the change value of stability coefficient and ΔH_1 is the change value of water level height outside the slope. According to the stability coefficient change curve (Figure 12), the stability coefficients of the four water level stable conditions are not different from those of the preceding conditions. Therefore, when the reservoir water level is unchanged, the slope stability will remain relatively stable. When calculating the stability hysteresis coefficient of the slope, if you participate in the calculation, the calculation result is infinitesimal (the change of reservoir water level is 0 m). The stability hysteresis coefficient S_c calculated after excluding abnormal points is shown in (Figure 13).

The mean value of the stability hysteresis coefficient in the slow decline period of the water level of the Chana landslide reservoir is 0.127, the mean value of the stability hysteresis coefficient in the medium decline period is 0.064, the mean value of the stability hysteresis coefficient in the fast decline period is 0.048, the mean value of the stability hysteresis coefficient in the slow rise period is 0.23, the mean value of the stability hysteresis coefficient in the medium rise period is 0.043, and the mean value of the stability hysteresis coefficient in the fast rise period is 0.027. It can be seen from the change results of the stability coefficient that the rapid drop of water level (85~133 days) will lead to a sudden drop in stability, and the corresponding water level will also drop sharply, which leads to a small stability hysteresis coefficient at this stage and a more synchronous change; in the rising stage of the reservoir water level (235~300 days), the slope stability increases steadily with the rising of the reservoir water level. The change trend of the two is the same. There is no repeated change of the stability in the falling stage of the reservoir water level, so the calculated stability hysteresis coefficient is small as a whole; However, in the low water level operation stage (133~235 days), the water level of the reservoir in this stage does not change much in the first 40 days, so the calculation results of the stability hysteresis coefficient vary greatly. The water level starts to rise and fall slightly in the last 50 days, the slope stability coefficient remains stable, and the hysteresis effect of the slope stability should not be obvious. During the operation of the reservoir, it is necessary to pay attention to the sharp change of slope stability, which is often a sign of slope instability. The above stability calculation results also show that the rapid decline of water level will lead to a sudden drop in stability. If you want to maintain a relatively small change in slope stability, you need to reasonably adjust the decline rate during the period of water level decline. The significance of the stability hysteresis coefficient is to determine the change rate of the reservoir water level and keep the slope relatively stable. According to the calculation results of the stability hysteresis coefficient, the lower the water level decline rate is, the better. There is a threshold value between them. When the decline rate is 0.02 m/d, the stability hysteresis coefficient is 0.29, which indicates that the slope stability change at this time is quite large. To sum up, the stability coefficient of the slope will drop sharply during the drawdown period of the reservoir water level. The stability coefficient will gradually recover during the low water level operation stage and continue to increase during the rising water level stage. Finally, it will remain relatively stable during the high water level operation stage. If the stability coefficient of the slope changes

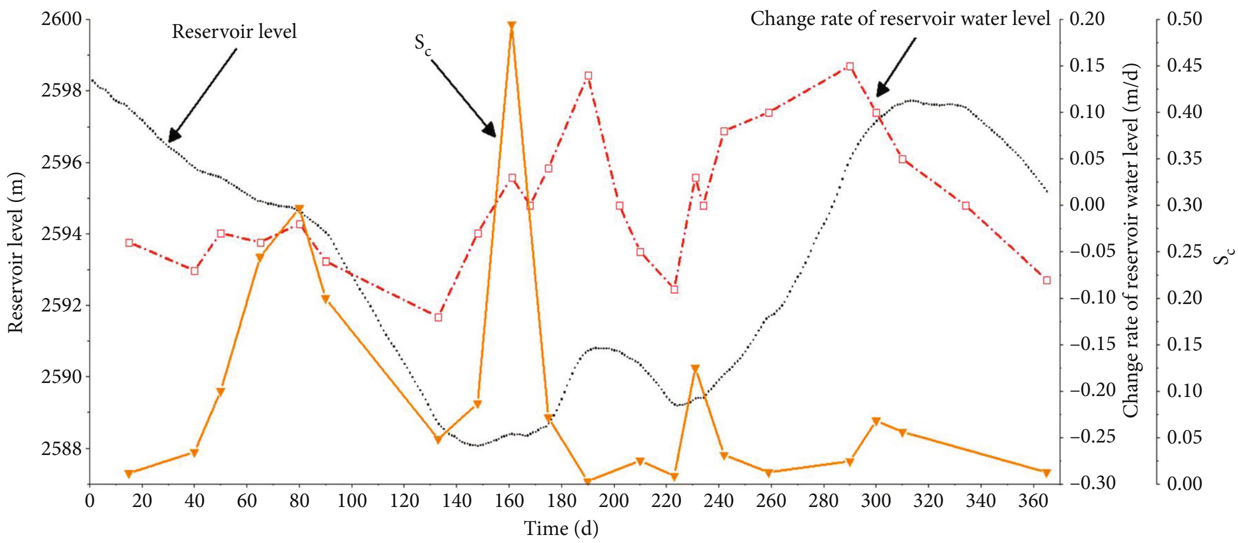

Figure 13: Calculation results of stability hysteresis coefficient.

relatively stably during the drawdown period, the drawdown rate should be kept at 0.03~0.07 m/d.

5. Discuss

The slope stability coefficient is an intuitive expression of whether the slope is stable or not. With the change of reservoir water level, the seepage field and deformation field of the slope are changing, which jointly controls the stability of the slope. In order to analyze the interaction of the three hysteresis effects and the lack of research, the discussion is carried out here.

In the hysteresis analysis of water level, the greater the hysteresis coefficient of water level is, the greater the hysteresis effect of water level in the slope is, and the slow change of water level in the slope has two effects on the slope: ① the greater the hysteresis effect of water level in the slope is, the greater the water pressure difference between inside and outside the slope is. ② The longer the immersion time, the more obvious the softening and argillization of rock and soil mass. These two kinds of effects exist globally with the change of water level. By analyzing the calculation results of the stability coefficient of the slope, it is found that the stability coefficient of the slope body increases during the rising period of water level. At this time, the water pressure difference inside and outside the slope body points to the slope, resulting in the antisliding effect. However, the degree of water's argillization and softening effect on the rock and soil mass is small, so the antisliding effect is dominant. In the stage of water level decline, the pressure difference between internal and external water points out of the slope, resulting in sliding increasing effect. The argillization and softening of rock and soil mass also degrade the slope stability. Therefore, the slope stability drops sharply under the superposition of the two. In the low water level operation stage, the water level rises and falls slightly at the same time, which involves the dry wet cycle of rock and soil mass. The "water saturation air drying" alternating action is a fatigue effect on rock and soil mass, which will cause the deterioration of rock and soil mass properties. Each time the effect may not be significant, but after repeated times, the loss will produce cumulative development [25]. From the results, the slope stability does decrease in the low water level operation stage, and there is no clear standard for the degree of water softening the rock. Therefore, it is very necessary to carry out relevant research on the influence of water on the properties of rock and soil mass of Chana landslide in the next step.

In the deformation hysteresis analysis, the deformation of the slope is divided into deformation incubation period and deformation release period by analyzing the deformation sensitivity coefficient. The deformation release period is mainly concentrated between 133 and 234 days. During this period, the internal deformation of the slope will increase significantly. The lowest point of slope stability occurs at the end of deformation incubation period and the beginning of release period, that is, the 133rd day, rather than the maximum point of incremental displacement. Many scholars [26–28] pointed out that the stability of many large slopes is controlled by the locked and fixed sections of the potential sliding surface, such as rock bridges and supporting arches. It should be emphasized that the locked section has an energy accumulation effect, which will store a large amount of elastic strain energy before it is penetrated, and will be converted into slope kinetic energy when the locked section breaks suddenly, resulting in the high-speed start-up of the landslide [29]. Chana landslide once experienced high-speed sliding in 1943, which is highly destructive. Based on the deformation sensitivity coefficient and stability calculation results, combined with the facts, it is inferred that Chana landslide is a locked landslide, and there is a locked section on its potential sliding surface, thus controlling the stability of the slope. In the final analysis, the stability analysis of landslide is for disaster prevention and mitigation. However, even for the slope with monitoring and early warning, there are few successful cases, which largely lies in the lack of clear physical and mechanical basis of the prediction model based on experience or statistics, and the lack of universality of the critical sliding threshold. In view of the difficulty in monitoring and early warning of landslide occurrence, we can combine the theory of hysteresis effect to calculate the hysteresis effect of landslide, analyze whether the landslide has anti sliding mechanism, and then determine the stress release period of landslide in the process of reservoir water level change, focus on monitoring the displacement of landslide in the stress release period, and grasp the time of large-scale displacement activities of landslide, so as to improve the accuracy of landslide early warning. In addition, by analyzing the hysteresis effect of landslide, the optimal speed of reservoir level rise and fall can also be calculated to provide a reference scheme for reservoir operation and increase the slope stability by artificial control.

6. Conclusion

Taking Chana landslide in Longyangxia Hydropower Station area as the research object, this paper studies the hysteresis effect of slope stability in the process of reservoir water level fluctuation, and draws the following conclusions:

(1) The calculation results of seepage field show that the water level hysteresis coefficient in the rising period of reservoir water level is 1.7~2.2 times that in the falling period, and the hysteresis effect of water level change in the slope is more obvious. When the reservoir water level drops, the hysteresis of the water level change in the slope first decreases and then increases with the increase of the decline rate, and the decline rate when the hysteresis is the lowest is 0.07 m/d. When the reservoir water level rises, the hysteresis of the water level change in the slope increases with the increase of the rising rate

(2) The results of incremental displacement calculation show that there are deformation incubation period and deformation release period of Chana landslide with the fluctuation of reservoir water level. The deformation potential in the period of water level falling is greater than that in the period of water level rising, and the deformation of the slope is restrained when the water level rises

(3) The stability calculation results show that the stability coefficient of Chana landslide will drop sharply during the water level decline period, and the stability coefficient will gradually recover when the water level remains stable or rises. In order to reduce the variation amplitude of the stability coefficient of the slope during the drawdown period, the drawdown rate of the reservoir water level should be maintained at 0.03~0.07 m/d

(4) Combined with the sliding history and research results of Chana landslide, it is speculated that Chana landslide is a locked landslide, and there is a locked section at the sliding surface. The energy accumulation effect of the locking section controls the relative stability of the slope

Data Availability

The (reservoir water level and mechanical parameters of rock and soil mass) data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This study was supported by the Second Tibetan Plateau Scientific Expedition and Research Program (STEP), Grant No. 2019QZKK0904; the Central Plains Science and Technology Innovation Leader Project (No. 214200510030), and the Key Research and Development Project of Henan Province (No. 221111321500).

References

[1] T. Junfeng, T. Xuemei, X. Peng, W. Hang, and L. Jiawu, “Under the action of water level fluctuation and rainfall large seepage stability analysis,” *Journal of Geological Science and Technology*, vol. 40, no. 4, pp. 153–161, 2021.

[2] W. Fawu and S. Kun, “Analysis on deformation and failure mechanism of slopes with different structures under fluctuation of reservoir water level – taking Qianjiangping landslide and Shuping landslide as examples,” *Journal of Engineering Geology*, vol. 29, no. 3, pp. 575–582, 2021.

[3] X. Jiefu, L. Yun'an, and C. Junming, “Model test study on response characteristics of Outang landslide under water level fluctuation,” *Journal of Engineering Geology*, vol. 28, no. 5, pp. 1049–1056, 2020.

[4] E. Semenza and M. Ghirotti, “History of the 1963 vaiont slide: the importance of geological factors,” *Bulletin of Engineering Geology and the Environment*, vol. 59, no. 2, pp. 87–97, 2000.

[5] Y. Y. Bai, C. L. Cui, and Y. Z. Yu, “Discussion on reservoir slope stability,” *Geology and Resources*, vol. 2005, no. 3, pp. 213–215, 2005.

[6] N. M. Pinyol, E. E. Alonso, J. Corominas, and J. Moya, “Canelles landslide: modelling rapid drawdown and fast potential sliding,” *Landslides*, vol. 9, no. 1, pp. 33–51, 2012.

[7] F. O. Jones, D. R. Embody, and W. L. Peterson, “Landslides along the Columbia river valley, Northeastern Washington,” *US Government Printing Office*, vol. 367, 1961.

[8] K. Nakamura, “On reservior landslide,” *Bulletin of Soil and Water Conservation*, vol. 10, no. 1, pp. 53–64, 1990.

[9] X. R. Zhang, K. L. Yin, Y. Li, H. Xia, and X. Fu, “Effect of reservoir water level decline and rainfall on Xiaping landslide stability in Wanzhou, Chongqing,” *Chinese Journal of Geo-Hazard and Prevent-Ion*, vol. 28, no. 2, pp. 22–29, 2017.

[10] H. Manzoor and D. Timothy, “Back-analysis of preexisting landslides,” *Geo-Frontiers*, vol. 32, no. 10, pp. 3659–3668, 2011.

[11] D. Guo, M. Hamada, and H. Jia, "Influential factors on slope stability and landslide mobility," *American Society of Civil Engineers*, vol. 32, no. 8, pp. 247–254, 2013.

[12] K. Marko, R. Holley, P. Mahapatra, H. van der Marel, and M. Bavec, "Coupling of GPS/GNSS and radar interferometric data for a 3D surface displacement monitoring of landslides," *Landslides*, vol. 12, no. 2, pp. 241–257, 2015.

[13] L. Benoit, P. Briole, O. Martin, C. Thom, J. P. Malet, and P. Ulrich, "Monitoring landslide displacements with the Geocube wireless network of low- cost GPS," *Engineering Geology*, vol. 195, pp. 111–121, 2015.

[14] P. J. Wang, "GPS landslide monitoring at the bank of Longyangxia Hydropower Station," *Qinghai Electric Power*, vol. 2003, no. 2, pp. 46–48+58, 2003.

[15] Y. F. Luo, W. L. Xu, H. Tian et al., "Geological environment conditions and development characteristics of landslide disaster in Longyangxia reservoir area of Yellow River," in *Annual Conference of National Engineering Geology, Science Press*, pp. 84–88, Xining, Qinghai, China, 2011.

[16] Q. W. Wu and C. H. Wang, "Chana giant semi-diagenetic landslide//typical landslide in China," in *Surface Rock Engineering Committee of Chinese Society of Rock Mechanics and Engineering, Engineering Geology Committee of Chinese Geological Society*, Science Press, 1986.

[17] Z. Y. Qing, "Study on surge wave of landslide near reservoir bank of Longyangxia Hydropower Station," *Hydraulic Power*, vol. 1985, no. 7, pp. 17–23+55, 1985.

[18] X. Wang, J. Li, Y. Zhang, and H. Zhao, "Deformation characteristics of Longxi landslide near the Bank of Longyangxia Hydropower Station in the Yellow River during high water level operation," *Dam and Safety*, vol. 2017, no. 6, pp. 35–39, 2017.

[19] W. Ma, S. B. Ma, L. J. Hu, F. Chen, and H. Li, "Quickbird-based investigation of Baicittan landslide in Longyang Gorge," *Qinghai Land & Land Review*, vol. 2010, no. 2, pp. 53-54, 2010.

[20] R. Q. Huang and Q. Xu, *Catastrophic Landslides in China*, Science Press, Beijing, 2008.

[21] H. H. Wang, "Water regime information of reservoirs in the upper reaches of the Yellow Rivera," 2022, http://61.163.88.227:8006/hwsq.aspx?sr=0nkRxv6s9CTRMlwRgmfFF6jTpJPtAv87.

[22] R. Q. Huang, Q. Xu, and G. G. Qi, *Evaluation and Prediction of Rainfalls and Reservoir-Induced Landslidesa*, Science Press, Beijing, 2007.

[23] K. J. Dai, *Study on factors influencing stability of complex soil slope under water level decline*, Chengdu university of technology, 2019.

[24] X. G. lv, K. R. Cui, D. Li, and Y. Zhou, "Analysis of influencing factors of soil slope stability based on Plaxis," *Journal of Anhui institute of Architecture & Industry (natural science edition)*, vol. 18, no. 3, pp. 67–71, 2010.

[25] J. Y. Zhang, L. P. Wan, H. Y. Pan, J. Li, Z. Luo, and H. Deng, "Long-term stability analysis of typical bank slope considering water-rock interaction," *Chinese Journal of Geotechnical Engineering*, vol. 39, no. 10, pp. 1851–1858, 2017.

[26] Z. Y. Zhang, S. T. Wang, and L. S. Wang, *Principle of Engineering Geology Analysis*, Geological Publishing House, Beijing, 1981.

[27] Q. Xu, X. J. Pei, and R. Q. Huang, *Large-Scale Landslides 7Induced by the Wenchuan Earthquake*, Science Press, Beijing, 2009.

[28] S. Q. Qin, Y. Y. Wang, and P. Ma, "Exponential laws of critical displacement evolution for landslides and avalanches," *Chinese Journal of Rock Mechanics and Engineering*, vol. 29, no. 5, pp. 873–880, 2010.

[29] L. Xue, S. Q. Qin, X. H. Pan, H. Chen, B. Yang, and K. Zhang, "Failure mechanism and physical prediction model of locked slope," *Journal of Engineering Geology*, vol. 26, no. 1, pp. 179–192, 2018.