Analysis of landslide stability under the impact of rainfall and reservoir water: a landslide in Southwestern China as an example

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Abstract

Reservoir landslides seriously affect the people's life and property safety. There is an important reality significance to carry out the work of reservoir landslide monitoring and early warning and stability analysis. In order to study the impact of rainfall and variation of reservoir water level on the landslide stability and provide the theoretical foundations of prevention and reduction of reservoir landslide, it takes a landslide of Southwestern China as an example. Based on the monitoring data of rainfall, reservoir water level, ground water level and surface displacement, the SEEP module and SLOPE analysis module of GeoStudio software are used to calculate the safety coefficient of landslide. The results show that the safety coefficient increases to the peak value gradually and then decreases to a certain value when the reservoir water level rises. The rise of reservoir water level has the larger rate and the peak value of safety coefficient is bigger, and vice versa. The safety coefficient decreases to the minimum and then increases gradually when the reservoir water level declines. The decline of reservoir water level has the larger rate and the minimum of safety coefficient is smaller, and vice versa. Fractures development of landslide surface providing channels for the rainfall infiltration is the main reason of landslide instability. The combination of heavy rainfall and water level declining is the most disadvantageous condition for landslide stability. Storage and drainage of reservoir should be arranged reasonably and the drainage of landslide surface should be strengthened at the same time.

Keywords: reservoir landslides, rainfall, reservoir water level fluctuation, safety coefficient

1. Introduction

Reservoir landslides happen occasionally with the constructions of large and medium sized reservoirs located in alpine and gorge regions of Southwestern China. Reservoir landslides have a serious impact on the people's life and property safety, such as Tangyanguang landslide in the Zhexi Reservoir of Hunan province in March 1961 and Qianjiangping landslide in the Three Gorges Reservoir in July 2003. (Jin and Wang, 1986; Yin and Peng, 2007) Hence, there is an important theoretical and practical significance to carry out the work of reservoir landslide monitoring and early warning and stability analysis. Based on the monitoring contents, the work of reservoir landslide monitoring concludes monitoring of absolute displacement and relative displacement, monitoring of deep displacement, monitoring of physical field, monitoring of ground water, monitoring of external trigger factors, and so on. (Zhou, 2004; Peng et al., 2012) Some new technologies such as three-dimensional laser scanner, GPS-RTK, remote sensing InSAR and BOTDR are applied into the landslide monitoring fields, which enrich the monitoring method and improve the monitoring accuracy. Chen et al. (2005) studied the relationship of landslides of Three Gorges Reservoir and the condition of rainfall, which shows that the landslides of Three Gorges Reservoir mainly occurred in the rainy season from April to October, especially in heavy rainy season from June to August. Wang et al. (2010) summarized the characteristics of the landslides of Three Gorges Reservoir after impounding, which shows that rainfall is the common factor to cause the reservoir landslides to happen. Forty-nine percents of landslides are induced by rainfall and thirty-nine percents of landslides are caused by storage and drainage of reservoir, while twelve percents of landslides induced by engineering activities. Liao et al. (2012) studied the application of data of SAR in the monitoring of landslides of Three Gorges Reservoir. The results show that there is not too large deformation of landslide whenever the reservoir has high water level or low water level. However, the deformation of landslide changes intensely with the reservoir water level rising or declining quickly.

In order to study the impact of rainfall and variation of reservoir water level on the landslide stability and provide the theoretical foundations of prevention and reduction of reservoir landslide, it takes a landslide of Southwestern China as an example. Based on the monitoring data of rainfall, reservoir water level, ground water level and surface displacement, the SEEP module and SLOPE analysis module of GeoStudio software are used to calculate the safety coefficient of landslide.

2. Engineering geology characteristics

The reservoir landslide of Southwestern China belongs to the landslide of bedding multi-level creep type, the length and width of which are both about eight hundred meters and the mean slope of which is fifteen degrees. In this paper, the study like a long tongue area is the east part of the landslide, which has the most intense activity. The length of study area is about four hundred and fifty meters. The width is about one hundred and thirty meters. The mean thickness of study area is about twenty five meters and the total volume is about one point five million cubic meters.

Based on the investigation of adjacent stratum lithology and the analysis of drilling data, the landslide dipping South East is monoclinic, including loose weak sandstone, siltstone, shale, mudstone and coal seam of Triassic System and overlying residual deposits and slope deposits material of about two to ten meters. There are slope deposits of gravel soil in the front of landslide, the gravel compositions are made up of rock debris of Xujiahe Formation. The sliding bed is composed of feldspar, lithic sandstone and siltstone mingled with shale and coal seam. There are two-stage sliding faces. (Fig. 1)

Due to the long-term creep of landslide, the main generated engineering geology problems include surface tension fracture, surface collapse, threshing ground sedimentation, house cracking and so on, as are seen in Fig. 2.

3. Hydrogeololgy characteristics

The study area of landslide is located in the transitional zones of basin marginal climate zone and Western Sichuan province plateau and mountain climate zone. The general meteorological

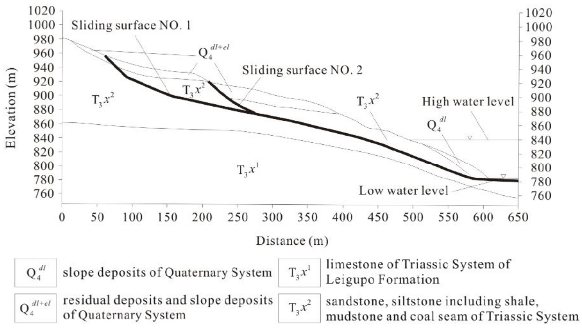


Fig. 1 Profile of engineering geology of reservoir landslide (study area)

(a) Surface tension fracture

(b) Surface collapse

(c) Threshing ground sedimentation

(d) House cracking

Fig. 2 Engineering geology problems

characteristics show that the rainfall is abundant. The annual precipitation is ranged from 1001.9 millimeter to 1264.7 millimeter. The rainfall of June to August accounts for sixty-six percent to seventy-six percent of annual precipitation. The annual evaporation is ranged from 733.1 millimeter to 920.8 millimeter. The climate of study area is warm and wet. The annual average temperature is ranged from 15.2 ℃ to 15.9 ℃. The annual average relative humidity is ranged from eighty-one percent to eighty-four percent. The annual average sunshine rate is ranged from twenty-four percent to thirty percent (Wang, 2001). The abundant surface runoff provides beneficial conditions for the formation of ground water. The exposure of landslide stratum is relatively good. The geological structure, weathering and corrosion have effects on the fissures development of landslide. The loose deposits of landslide surface transformed into terraced fields are widely distributed, which provides beneficial conditions for the rainfall collection and seepage. The ground water of landslide is divided into three categories, which are fracture pore water of clastic rocks, karstic water of carbonatite and pore water of loose accumulation. The supplies of ground water include lateral supply and vertical supply. The lateral supplies of ground water are mainly from karstic water and fissure water of overlying klippe. The vertical supply is mainly from rainfall, which is the important supply source. The discharge way of ground water is relatively complicated, which includes evaporation, subsurface runoff and so on. The supply and discharge of ground water of landslide is affected by the seasons.

4. Monitoring results analysis

The monitoring results of rainfall, reservoir water level, ground water level and surface displacement show that the variations of ground water level data from three water holes were similar from July 2012 to March 2014. The impact of rainfall on the variation of ground water level was obvious. The ground water level fluctuated in the rainy seasons and declined in the dry seasons. Short-term heavy rainfall resulted in the rapidly rise of ground water level, which declined rapidly after rainfall. Due to the rainstorm on July 10, 2013, the landslide formed large deformations, which was related to the influences of the erosion, full water load and water pressure from heavy rainfall on the landslide. As a result, rainfall is one of major factors of deformation of landslide. There were twice storages and drainages from July 2012 to March 2014, the highest water level and lowest water level were 841 meters and 785 meters respectively. When the reservoir water level declined rapidly from middle of July to middle of August 2013, the deformation of landslide increased. The reason is that there was a water head difference between ground water and reservoir water due to the hysteresis effect of decline of ground water when the reservoir water level declined rapidly, which generated the seepage force pointing to the outside of landslide. There were few deformations when the reservoir water level remained unchanged. As is mentioned above, the variation of reservoir water level especially the rapid decline of reservoir water level is another major factor of landslide deformation.

5. Seepage and stability analysis method

5.1 Unsaturated - saturated seepage theory

The Richards Equation (Richards, 1931) is used to solve the seepage problem in the unsaturated soil, as can be seen in formula (1).

$$\partial[k_x\cdot(\partial H / \partial x)] / \partial x + \partial[k_y\cdot(\partial H / \partial y)] / \partial y + Q = m_w\cdot\gamma_m\cdot(\partial H / \partial t) \quad (1)$$

Where H is the absolute height of water head, k_x is the permeability coefficient in the direction of x, k_y is the permeability coefficient in the direction of y, Q is the item of boundary source, m_w is density than water, γ_m is water unit weight, t is time.

Richards Equation is nonlinear partial differential equation. To solve this equation, it's necessary to confirm the initial condition and boundary condition. The initial condition is initial ground water level, which is determined by measured data.

The boundary condition of water head is

$$H \mid \Gamma_1 = f_1 (x, y, t) \quad (2)$$

The boundary condition of flow is

$$\partial H / \partial n \mid \Gamma_1 = - f_2 (x, y, t) / k \quad (3)$$

5.2 Unsaturated soil strength theory

Vanapalli et al. (1996) put forward unsaturated soil strength criterion formula:

$$\tau = c' + (\sigma - u_a) \tan\Phi' + (u_a - u_w)\cdot[(\theta_w - \theta_r) / (\theta_s - \theta_r)\cdot\tan\Phi'] \quad (4)$$

Where c' is effective cohesion, σ is total stress, u_a is barometric pressure on the sliding surface, Φ' is effective internal friction angle, u_w is hydrostatic pressure on the sliding surface, θ_w is volumetric water content, θ_r is residual volumetric water content.

5.3 Stability analysis theory

The angle variation of trailing edge of landslide sliding surface trailing edge is more than 10 degrees. In addition, the landslide sliding surface is mansard sliding surface. So authors adopt Morgenstern – Price method to solve the security coefficient.

The normal force E_n and moment M_n between soil stripes integrated by equilibrium differential equations need satisfy the condition:

$$E_n (F_s, \lambda) = 0 \quad (5)$$

$$M_n = \int (X - E\cdot dy / dx)\, dx = 0 \quad (6)$$

Where $y=Ax+B$, λ、A and B are constants, X is tangential force between soil stripes, E is normal force between soil stripes.

Suppose a λ and F_s, the E_n and M_n are integrated by stripes. If the values of E_n and M_n are not zero, λ and F_s are corrected by iteration. When the iterative values of E_n and M_n reach zero simultaneously, the safety coefficient can be obtained.

6. Numerical simulation of stability under rainfall and reservoir water level variation conditions

6.1 Reservoir landslide simplified model

Based on the engineering geological and hydrogeological data and monitoring data, the landslide simplified model containing main geological and hydrological characteristics is established. To satisfy the requirements of numerical simulation, boundary conditions are set reasonably, as can be seen in Fig. 3 and Tab. 1.

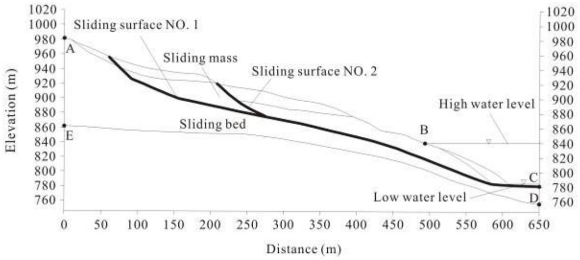


Fig. 3 Reservoir landslide simplified model

The rainfall of a hydrologic year from January 1, 2013 to December 31, 2013 was set as the boundary condition. The calculations show that the influence depth of rainfall infiltration was limited, the influence depth of which was ranged from 2 to 4 meters. The influence depth of rainfall infiltration is different with the increase of rainfall time and difference of rainfall distribution. When the rainfall time was longer, the influence depth was deeper. The long-term rainfall could form continuous ground water in a certain depth. As a result, the steady-state of initial ground water level was analyzed by the annual average rainfall infiltration.

6.2 Numerical calculation parameters

There are not obvious sliding zones, the physical and mechanical properties of which are similar to those of sliding mass. Therefore the test parameters of weak layers of sliding mass are regarded as the parameters of sliding zones. The sliding mass parameters of physical and mechanical parameters are obtained from large-scale direct shear test. The calculation parameters of trailing edge residual deposits and leading edge slope deposits are acquired by engineering analogy method, as can be seen in Tab. 2. The impact of initial position of ground water level on the seepage computation is maximal. Suppose reservoir water level accepts the infiltration of rainfall after it reaches a lowest point. When the ground water level reaches a steady state, it will be set as the initial ground water level of landslide. The steady state of initial ground water level was analyzed by annual average rainfall infiltration capacity. Considering the plant intercept and infiltration rate, the value of daily average rainfall infiltration is 8.0×10^{-4} m/day.

The soil-water characteristic curve and permeability function curve of landslide can be seen as Fig. 4 and Fig. 5.

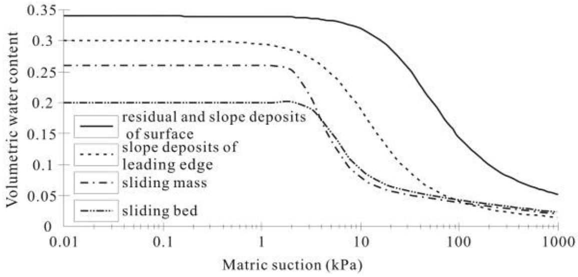


Fig. 4 Soil-water characteristic curve

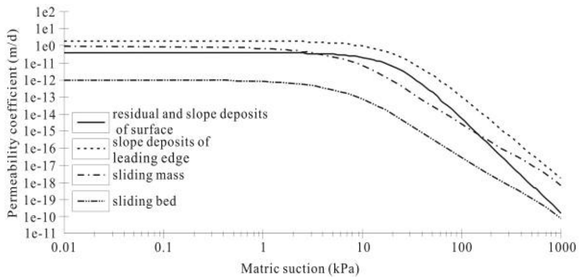


Fig. 5 Permeability function curve

6.3 Stability calculation under the condition of water level rising

To study the effect of different rising rate of reservoir water level on the landslide stability, the calculation situations can be seen in Tab. 3.

There are two sliding surface in the landslide (Fig. 3). The Fig. 6 shows that the safety coefficients of sliding surface NO.1 and NO.2 are 1.262 and 1.160 respectively at the beginning of reservoir water level rising, which become 1.264 and 1.182 when the reservoir water level reach the maximum water level and remain stable. The variation trends with time of safety coefficients of sliding surface NO.1 and NO.2 are similar. The safety coefficient increases to the peak value gradually and then decreases to a certain

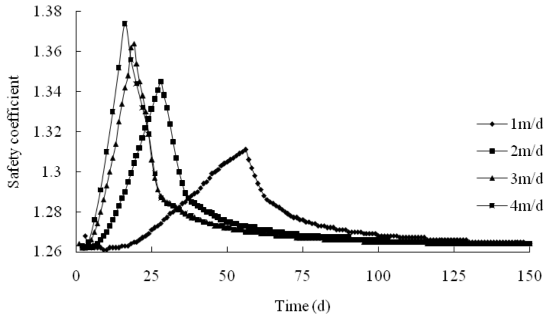
Tab. 1 Simplified model boundary condition

Boundary	Condition	Remark
AB	Rainfall flow boundary	—
BC	Water head boundary of reservoir water level variation	Reservoir water level rises
	Overflow boundary	Water level declines
CD、EA	Flow boundary	Constrain in the horizontal direction free in the vertical direction
DE	Flow boundary	Constrain in the vertical direction free in the horizontal direction

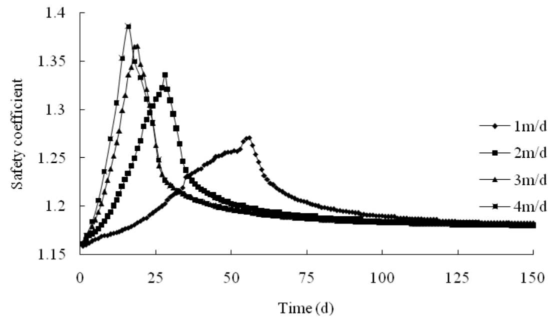
Tab. 2 Calculation parameters

Title	Density (g/cm^3)		Total stress parameters		Effective stress parameters	
	Natural	Saturate	c (kPa)	Φ (°)	c' (kPa)	Φ' (°)
Trailing edge residual deposits	2.20	2.24	20.0	31.0	—	—
Leading edge slope deposits	2.15	2.22	30.0	31.0	—	—
Sliding mass	2.21	2.23	35.0	33.0	20	35.2
Sliding zones	2.19	2.23	25.0	22.7	9.7	20.1
Sliding bed	2.30	2.32	45.5	35.5	—	—

value when the reservoir water level rises. The time to peak of safety coefficient is corresponds to that of reservoir water level rising to zenith. The rising slope of curve of safety coefficient varying with time is less than the declining slope, the tendency of which weakens gradually with the increase of rising rate of reservoir water level. The rise of reservoir water level has the larger rate and the peak value of safety coefficient is bigger, and vice versa. If the rising rate is larger, the curve of safety coefficient varying with time is steeper, and vice versa, which indicates that the rise of ground water level lags the rise of reservoir water level. The safety coefficient of reservoir water level rising to zenith is larger than the initial safety coefficient, which shows that the rise of reservoir water level is beneficial to the landslide stability.



(a) Safety coefficient of sliding surface NO.1 varying under different rising rate of reservoir water level



(b) Safety coefficient of sliding surface NO.2 varying under different rising rate of reservoir water level

Fig. 6 Safety coefficient varying under different rising rate of reservoir water level

6.4 Stability calculation under the condition of water level declining

The calculation situations can be seen in Tab. 4.

The Fig. 7 shows that the variation trends with time of safety coefficients of sliding surface NO.1 and NO.2 are similar. The safety coefficient decreases to the minimum and then increases gradually when the reservoir water level declines. If the declining rate is larger, the curve of safety coefficient varying with time is steeper and the occurrence time of minimum of safety coefficient is sooner, and vice versa. The decline of reservoir water level has the larger rate and the minimum of safety coefficient is smaller, and vice versa. The safety coefficient of reservoir water level declining to nadir is smaller than the initial safety coefficient, which shows that the decline of reservoir water level is adverse to the landslide stability. The conclusion is consistent with previous researches (Liu et al., 2005; Luo et al., 2008; Lu et al., 2014; Xiang et al., 2014).

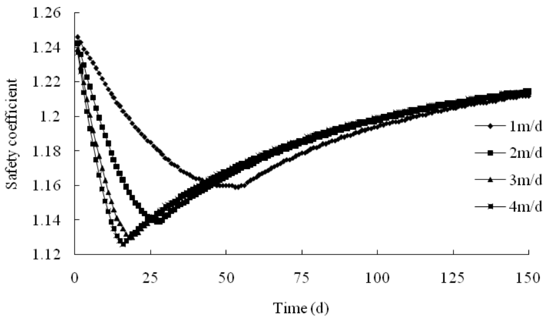
The Tab. 5 shows that if the declining rate is larger, the maximum seepage rate of ground water and the seepage force are larger. Comparing sliding surface NO.1 with NO.2, the safety coefficient of sliding surface NO.2 is smaller than that of sliding surface NO.1, which indicates that the impact of sliding surface NO.2 on the landslide stability is greater than that of sliding surface NO.1.

Tab. 3 Stability calculation situations of reservoir water level rising

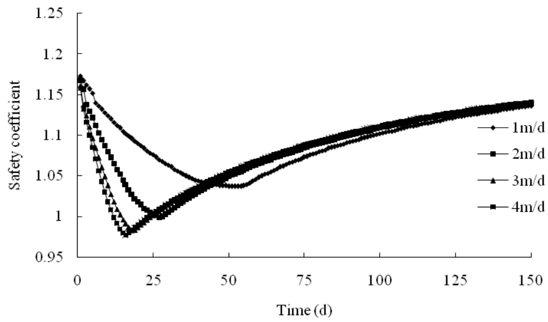
Reservoir water level (m)		Calculation situations	Water rising rate (m/d)	Completing days (d)	Operating days (d)
Initial water level	Final water level				
785	841	Ⅰ	1	56	94
		Ⅱ	2	28	122
		Ⅲ	3	18.7	131.3
		Ⅳ	4	14	136

Tab. 4 Stability calculation situations of reservoir water level declining

Reservoir water level (m)		Calculation situations	Water declining rate (m/d)	Completing days (d)	Operating days (d)
Initial water level	Final water level				
841	785	Ⅰ	1	56	94
		Ⅱ	2	28	122
		Ⅲ	3	18.7	131.3
		Ⅳ	4	14	136



(a) Safety coefficient of sliding surface NO.1 varying under different declining rate of reservoir water level



(b) Safety coefficient of sliding surface NO.2 varying under different declining rate of reservoir water level

Fig. 7 Safety coefficient varying under different declining rate of reservoir water level

The ground water level of landslide leading edge changes with reservoir water level varying. Under the action of ground water and alternation of wetting and drying, the physical and mechanical properties of landslide lower. When the reservoir water level declines, the direction of seepage rate of landslide leading edge is pointing to the outside of landslide, which is unfavourable to the stability of landslide leading edge, as is can be seen in Fig. 8.

6.5 Stability calculation based on the monitoring data of rainfall and reservoir water level

The calculations (Fig. 9) show that the safety coefficient of sliding surface NO.2 changes with the rainfall and reservoir water level varying, the value of which is ranged from 1.038 to 1.25. Because of reservoir water level declining in the beginning of

Fig. 8 Local collapse of landslide leading edge

March and the end of August, landslide is in the limit equilibrium state. The variation trend of safety coefficient is consistent with reservoir water level variation. The influence of rainfall on the safety is less than that of reservoir water level variation. Due to the climatic variation and tectonic movement, the joints and fissures develop, which destroy the global stability of landslide and provide the advantages to the rainfall infiltration.

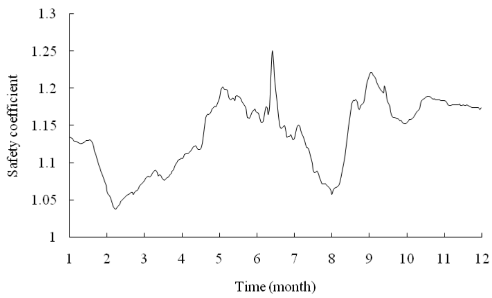


Fig. 9 Landslide safety coefficient variation under the combined effect of rainfall and reservoir water in a hydrologic year (sliding surface NO.2)

7. Conclusion

In order to study the impact law of rainfall and variation of reservoir water level on the landslide stability, it takes a landslide of Southwestern China as an example. Based on the monitoring data of rainfall, reservoir water level, ground water level and surface displacement, the SEEP module and SLOPE analysis module of GeoStudio software are used to calculate the safety coefficient of landslide.

Tab. 5 Safety coefficient and seepage rate under different declining rate of reservoir water level

Declining rate (m/d)	Occurrence time of minimum(d)		Minimum of safety coefficient		Maximum seepage rate (m/d)
	Surface NO.1	Surface NO.2	Surface NO.1	Surface NO.2	
1	53	50	1.159	1.037	1.171
2	27	27	1.139	0.999	1.229
3	18	18	1.130	0.983	1.236
4	16	16	1.126	0.977	1.245

The safety coefficient increases to the peak value gradually and then decreases to a certain value when the reservoir water level rises. The time to peak of safety coefficient is corresponds to that of reservoir water level rising to zenith. The rising slope of curve of safety coefficient varying with time is less than the declining slope, the tendency of which weakens gradually with the increase of rising rate of reservoir water level. The rise of reservoir water level has the larger rate and the peak value of safety coefficient is bigger, and vice versa. If the rising rate is larger, the curve of safety coefficient varying with time is steeper, and vice versa, which indicates that the rise of ground water level lags the rise of reservoir water level. The safety coefficient of reservoir water level rising to zenith is larger than the initial safety coefficient, which shows that the rise of reservoir water level is beneficial to the landslide stability.

The safety coefficient decreases to the minimum and then increases gradually when the reservoir water level declines. If the declining rate is larger, the curve of safety coefficient varying with time is steeper and the occurrence time of minimum of safety coefficient is sooner, and vice versa. The decline of reservoir water level has the larger rate and the minimum of safety coefficient is smaller, and vice versa. The safety coefficient of reservoir water level declining to nadir is smaller than the initial safety coefficient, which shows that the decline of reservoir water level is adverse to the landslide stability.

The developed joints and fissures provide the advantages to the rainfall infiltration, which has an adverse influence on the landslide stability. The combination of heavy rainfall and decline of reservoir water level is the most unfavourable condition for the instability of landslide.

Storage and drainage of reservoir should be arranged reasonably and too fast drainage should be avoided (especially in the rainy season). The drainage of landslide surface should be strengthened at the same time. To avoid the surface ponding infiltrating landslide from the fracture channel, escape canals are supposed to build. Surface fissures of landslide leading edge should be filled and tamped. Pay attention to landslide closely in the period of rapid variation of reservoir water level and rainy season.

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