Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 7, No. 07, July, 2021

Stability and Deformation Analysis of Landslide under Coupling Effect of Rainfall and Reservoir Drawdown

Muhammad Shoaib [1], Wang Yang [1*], Yang Liang [1], Gohar Rehman [2]

[1] *Faculty of Engineering, China University of Geosciences, 430074, Wuhan, Hubei, China.*

[2] *School of Geosciences, College of Construction Engineering, Jilin University, 130026, Changchun, Jilin, China.*

Received 10 April 2021; Revised 03 June 2021; Accepted 23 June 2021; Published 01 July 2021

Abstract

Landslides, a devastating hazard, continue to happen, affecting the lives of thousands of people each year. Fluctuation in the Reservoir Water Level (FRWL) is one of the leading features disturbing the slope stability in reservoir areas, drawdown is more crucial than the rise to the stability of landslide. Latest studies grounded on field investigation and monitoring data propose that landslides in reservoir areas are initiated not solely by one issue like precipitation or FRWL, however conjointly by their joint actions. Zhulinwan landslide in Chongqing, China, Three Gorges Reservoir (TGR) area was analyzed by field investigation and numerical modelling to evaluate the characteristics of the landslide. The changes in landslide stability and deformation under the effect of reservoir drawdown and rainfall is analyzed using GEOSLOPE Software. The seepage analysis is done using SEEP W Model, afterward deformation and stability analysis using SLOPE W and SIGMA W respectively. The analysis confirmed that the coupling effect of reservoir drawdown at 1.2 m/d and rainstorm of once in 50 years return period makes the landslide unstable. Moreover, deformation at the same condition is maximum 0.049 m. The findings may be used by local authorities to help make decisions about slope stabilization in the event of a confirmed significant rainfall event.

Keywords: Landslide; Geoslope; Stability; Deformation; Reservoir Drawdown; Rainstorm.

1. Introduction

The Three Gorges Dam Project is the world`s largest hydropower project. Many slopes became unstable and landslides happened in June 2003 when the reservoir level rose to 135 m [1]. After its completion in 2009, the reservoir water level fluctuates sporadically between 145 m and 175 m. In reservoir area more than 2000 landslides are reported that are strongly or partially affected by the water storage [2-6]. The survival of local residents and property is threatened by potential landslide instability. FRWL is one of the most significant extrinsic influences affecting landslide deformation and stabilization [7]. The two major factors FRWL and rainfall, which cause slope failures, have been reported well in earlier studies [8-13]. But still there is need to study the behavior of slope under heavy rainstorm coupled with reservoir drawdown. If the correlation among deformation behavior and precipitation or reservoir water level has been established, the landslide prediction model can be established [14].

More than 4000 research papers on the landslide threat in TGR have been reported to date [15]. The articles have focused on the followings (1) identifying and describing the cases of individual landslide; (2) Evaluation of the formation

* Corresponding author: wangyangcug@126.com

http://dx.doi.org/10.28991/cej-2021-03091713

and behavior of landslide cases; (3) Preventive stabilization steps are being developed, researched, and implemented; and (4) Geohazards are being tracked and protocols of early warning are being implemented. The reservoir impoundment and subsequent rise and fall of the water level are the key activating factors for reservoir-induced landslides [16-19]. The triggering mechanism as a result of the dry–wet circulation situation may be (1) a change in the slope's hydraulic boundary conditions or (2) deterioration of the mechanical properties [20-23].

Many studies have recently investigated landslide seepage and stabilization in relation to FRWL and heavy precipitation. Saturated coefficients of permeability [24] and the rates at which reservoir water levels fluctuates [25] effect the groundwater and pore water pressure. Therefore, the stability factor of landslide is affected by saturated coefficient of permeability and variations in reservoir water level. [26-30]. The reservoir landslide was analyzed in [31] on the basis of different coefficients of permeability, and the landslide stability factor under extreme climatic conditions were investigate by [32]. However, the behavior of the wading landslides with a different coefficient of permeability is not well studied under heavy precipitation conditions and rapid decline of reservoir water.

The study analyses Zhulinwan landslide1s stability and deformation under the action of rainfall and varying rates of reservoir drawdown. We hope that this study would contribute to a greater understanding of wading landslide issues as well as realistic expertise and knowledge of reservoir-induced landslide research.

The structure of the paper is as follows. The study's analysis methods are briefly summarized in Section 2. Section 3 goes into the data source, site morphology, hydrological patterns, lithology, physical, and mechanical properties of the landslide. Section 4 outlines the setting of numerical model and used parameters. The data is analyzed in Section 5 and 6, and the findings are discussed. Section 7 summarizes the analytical observations and completes the paper's claim.

2. Research Methodology

The study used combination of site investigation and numerical modeling. The landslide mapping was done in detail, to outline the altitude of the slope, its location and geomorphology. Material and structures of the landslide body was studied by geological survey, trenches and boreholes. Boreholes of substantial depth obtained the lithology, thickness and structural physiognomies of sliding body and bedrock. Surface displacement was monitored using GPS from 2006 to 20014, while inclinometer was placed to measure the deep displacement. Crack displacement was monitored from 2004 to 2014. Numerical simulation was done using GEOSLPE software [33]. Seepage, stability and deformation were analyzed by SEEP/W, SLOPE/W and SIGMA/W, respectively. The research flow chart is outlined in Figure 1.

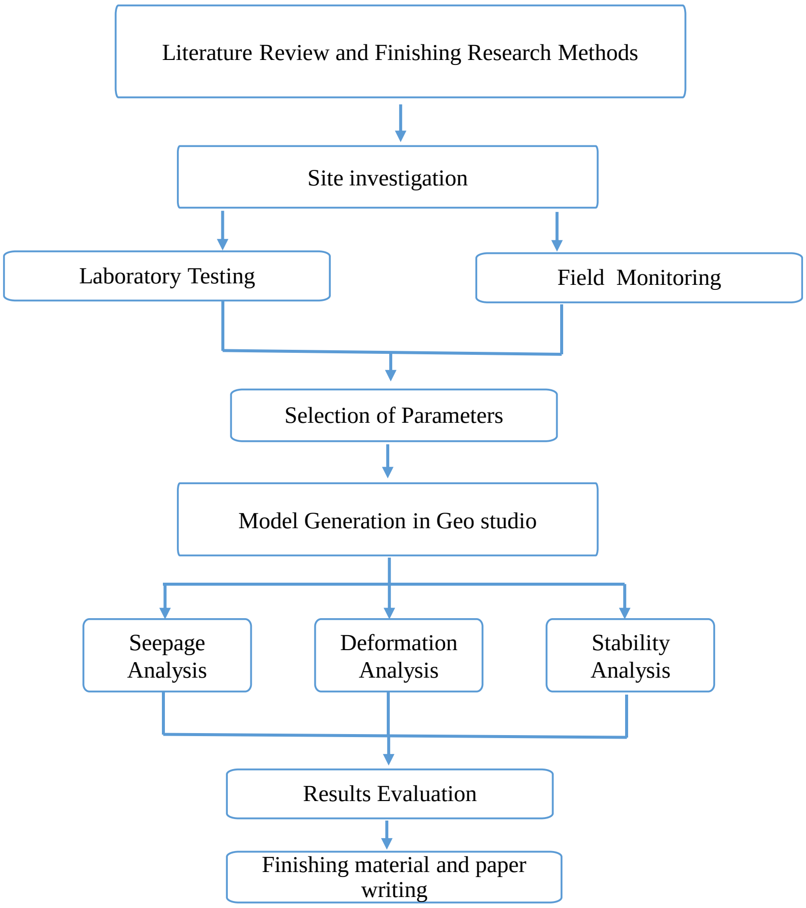


Figure 1. Research flowchart

3. Geological Setting

The study area situated on the eastern edge of the Sichuan Basin and the heart of the TGR area. The terrain extends diagonally from northwest to southwest. The landslide area is situated in Nanzhu Village, Longkong Town, Fengdu County, Chongqing City, with geographic coordinates of 107°51'52.96" longitude and 30°4'25.64" latitude Figure 2. The average annual rainfall in Fangdu County is 1207.8mm, while maximum daily rainfall can reach up to 184 mm Figure 3.

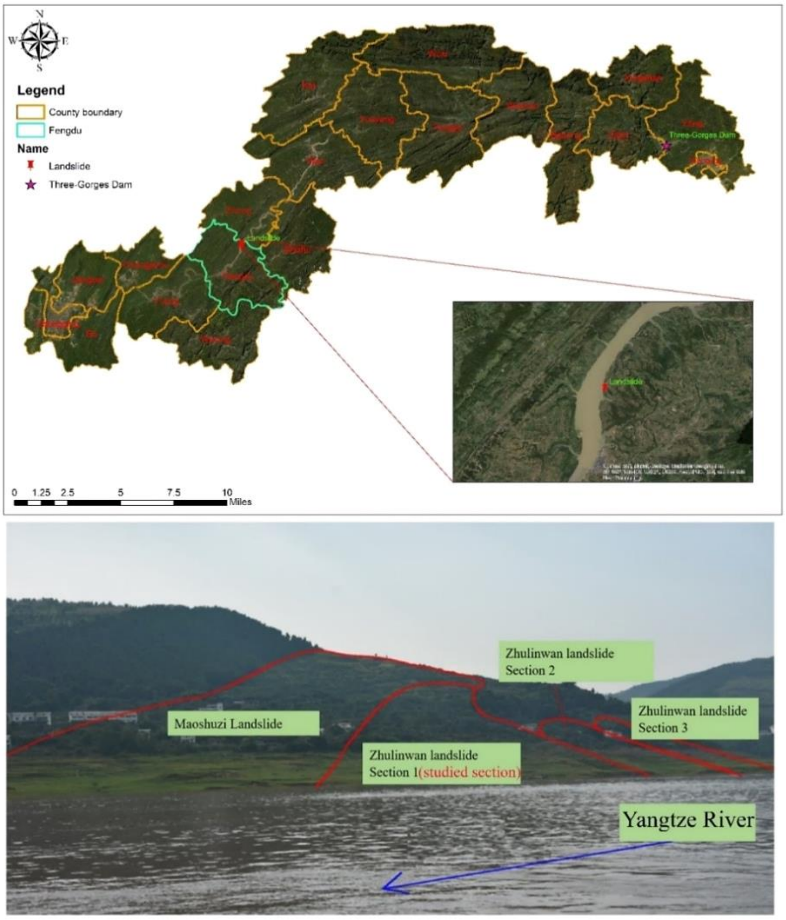


Figure 2. Location and Geomorphology of the Zhulinwan landslide

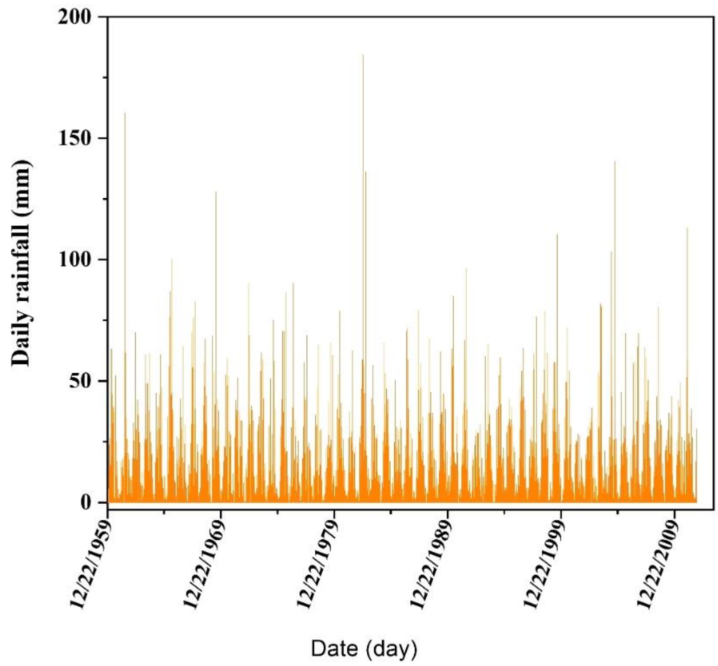


Figure 3. Daily rainfall in Fengdu County from 1959 to 2010

Zhulinwan landslide from Maoshuzi-Zhulinwan landslide group, is a forward slope with a slope direction of 305°, a slope length of 622 m, a slope height of 126 m and a slope angle about 10°. The topography of the landslide is shown in Figure 4.

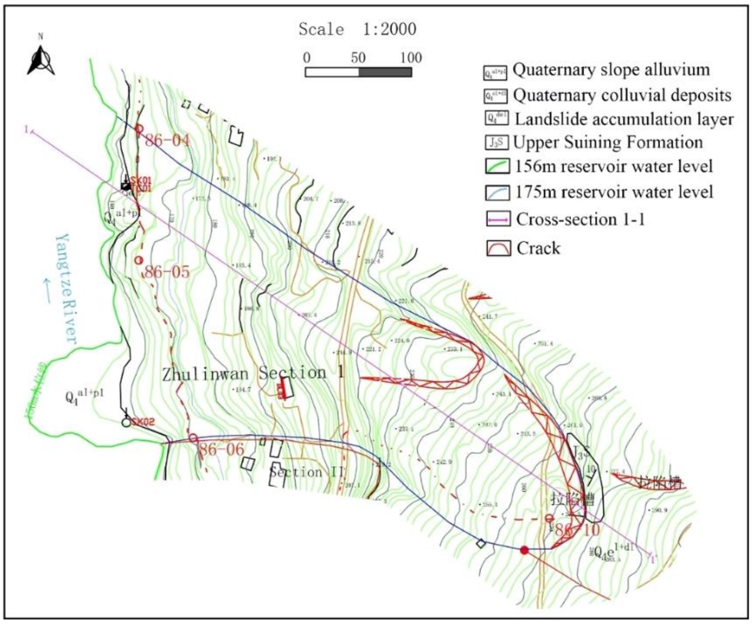


Figure 4. Topography of Zhulinwan Landslide

The Zhulinwan landslide is a rock landslide, having a long strip foot like shape and a stepped profile, with the volume of 137.46 million m^3 and an area of 10.57 million m^2. The Lithology of sliding body is purple-red silty clay mixed with brown-red sandstone and sandstone fragments. Sliding zone is not obvious only 2 ~ 3 mm mud film. The bedrock is the Jurassic upper Suining Formation (J_3S). The reservoir water in the area of study fluctuates between 175 to 145 m. The reservoir water level annual variations are shown in Figure 5. The drawdown from 159 to 145 m was selected for the analysis.

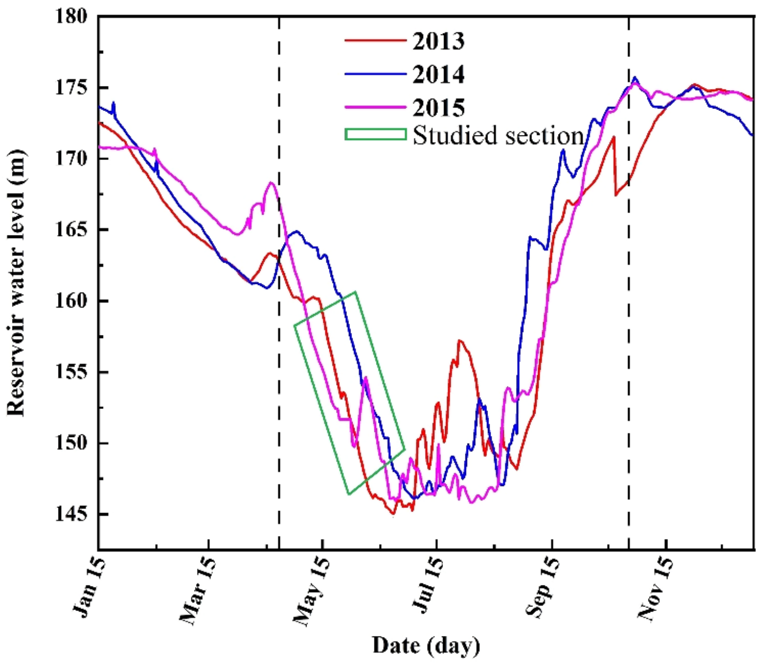


Figure 5. Annual fluctuation of water level at Three Gorge Reservoir 2013-2015

3.1. Landslide Materials and Structural Features

Material Composition

Figure 6 shows the geological Section 1-1 of the Zhulinwan landslide. Material of the landslide is predominantly silty clay intercalated gravel. Parent rock is purple-red mudstone and maroon siltstone, with a thickness of 4.6 to 7.1 m.

The slip zone soil on the top surface of the bedrock is not obvious, mainly mudstone gravel soil, only 2～3 mm mud film is seen on the slip surface. Only scratches are seen on the top surface of the bedrock, and the direction of the scratches is about 310°, which represents the sliding direction.

The sliding surface is straight, high on the left, low on the right side and generally stepped with an inclination angle of about 10°. The sliding bed rock mass is the top stratum of the Suining Formation of the Upper Jurassic System. The lithology is interbedded with purple-red, red mudstone and siltstone of varying thickness, with a single layer of gray feldspar quartz sandstone with a thickness of 1 to 3 m.

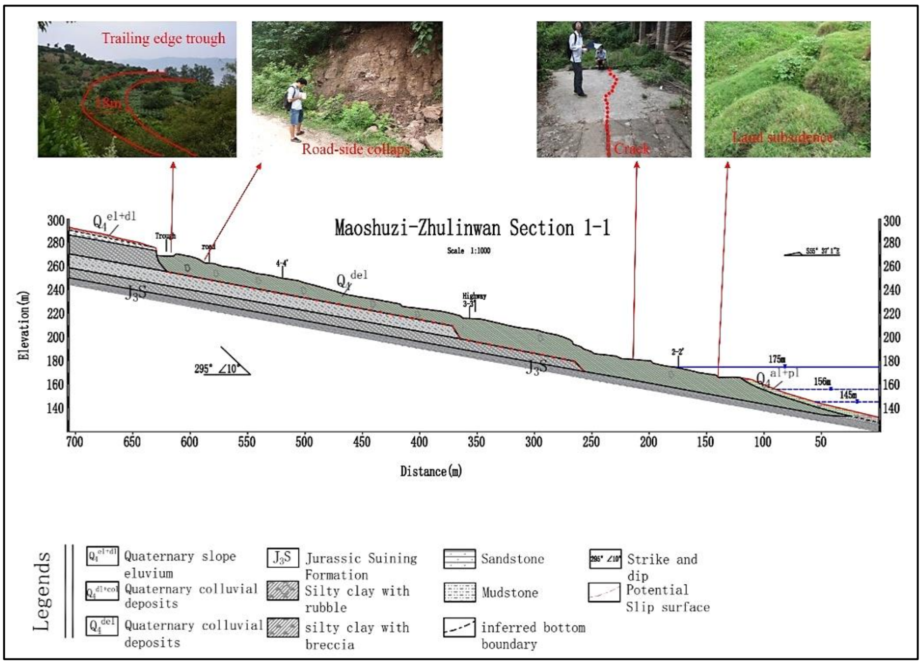


Figure 6. **Geological Profile section and the signs of landslide activity**

Mechanical and Physical Properties of Soil

The natural water content of the landslide soil of Maoshuzi-Zhulinwan Landslide Group is 15.8-17.0%, natural unit weight is 21.4. ～21.6 kN/m^3, void ratio 0.485～0.502, and liquidity index is -0.11～0.04. The natural water content of slip zone soil is 19.4-25.9%, natural unit weight 19.6-20.6 kN/m^3, void ratio 0.59-0.71, and liquidity index is generally between 0.21 and 0.38.

The compressibility of the Maoshuzi-Zhulinwan landslide soil is 0.14～0.16 MPa^{-1}, and the compression modulus is 9.52～10.31 MPa. Natural shear strength: cohesion 53.0～59.0 kPa, internal friction angle 16.1～17.4°. Saturated consolidation rapid shear peak strength: cohesion 52.0～61.0 kPa, internal friction angle 15.3～16.4°. Residual strength: Cohesion 40～47.5 kPa, internal friction angle 12.0～13.2°. The natural shear strength of Maoshuzi-Zhulinwan landslide slip zone soil: cohesion is 26.5～50.0 kPa, internal friction angle is 12.7～17.2°. Saturated consolidation rapid shear peak strength: cohesion is 30.0～45.0 kPa, internal friction angle is 10.8～15.2°. Residual strength: Cohesion is 18.5～35.0 kPa, internal friction angle is 8.2～13.1°

3.2. Deformation Characteristics

Surface Deformation

The soil body has sunk several cracks ranging from 0.1 to 0.3m, with crack lengths ranging from 5 to 10 m, and a crack width of 3 to 5 cm, the citrus tree is skewed. The trailing edge trough is 18m wide and 3 to 6 m deep with a strike of 323°, as can be seen in Figure 4 and Figure 6. The middle draw groove is 5 ~ 8 m, with a visible length of 70 m, the left side is 273 °, and the right side is 292°. At present, there are no obvious deformations in the two troughs.

Deformation Monitoring

The landslide was monitored for couple of years. The GPS started displacement monitoring in 2006, with no obvious displacement in first two years. The plane cumulative displacement peaked to 51 mm in 2012, while the maximum value of vertical displacement 31 mm was recorded in 2013. The monitoring was abandoned in 2014. The borehole inclinometer got blocked in the start of the monitoring process and no deep displacement data was retrieved. The surface crack displacement was monitored from 2004 to 2014, the curves shown in the graph below Figure 7.

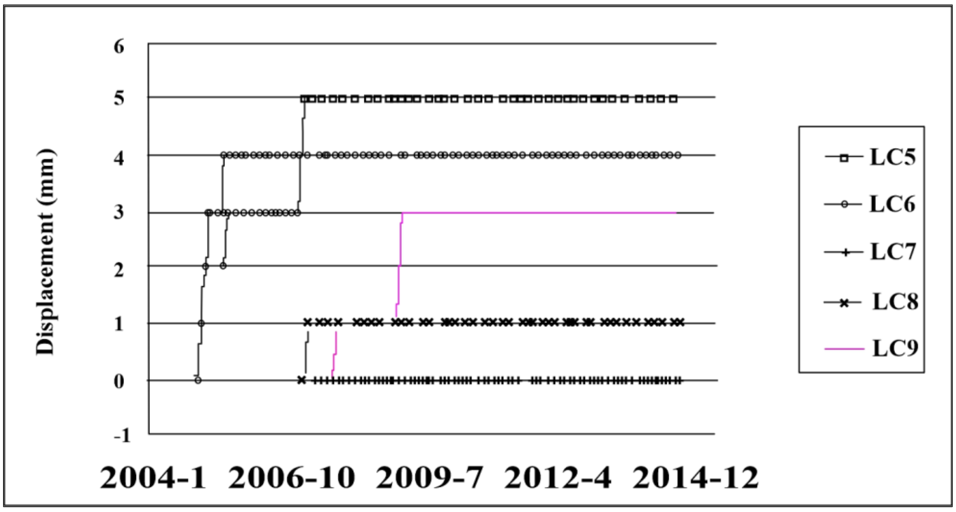


Figure 7. Maoshuzi -Zhulinwan Landslide Group Crack Displacement-Time Curve (LC5-LC9)

4. Numerical Simulation of Stability and Deformation

4.1. Numerical Model Execution

GEO-Studio Software was used to simulate seepage, stability and deformation of the landslide. Figure 7 depicts the geological model meshes from a longitudinal perspective (cross-section in Figure 6). The elevation of landslide model at the front edge of the shear outlet is 138m, and the elevation of the trailing edge is about 269m. According to the established finite element model of the Zhulinwan landslide, the finite element grid form is an unstructured grid of quadrilateral and triangular elements. This simulation uses a 3m grid to divide the sliding body, and a total of 7,354 elements are obtained. After establishing in AUTOCAD software the model was imported into GEO-STUDIO. Afterward, two hydrological boundary conditions given in Table 1 were used to quantify it. The materials applied were Silty clay with gravel and impermeable bedrock (Figure 8). For all of the material, the Mohr–Coulomb model was used. The mechanical and physical parameters used in analysis are given in section 3.1.2.

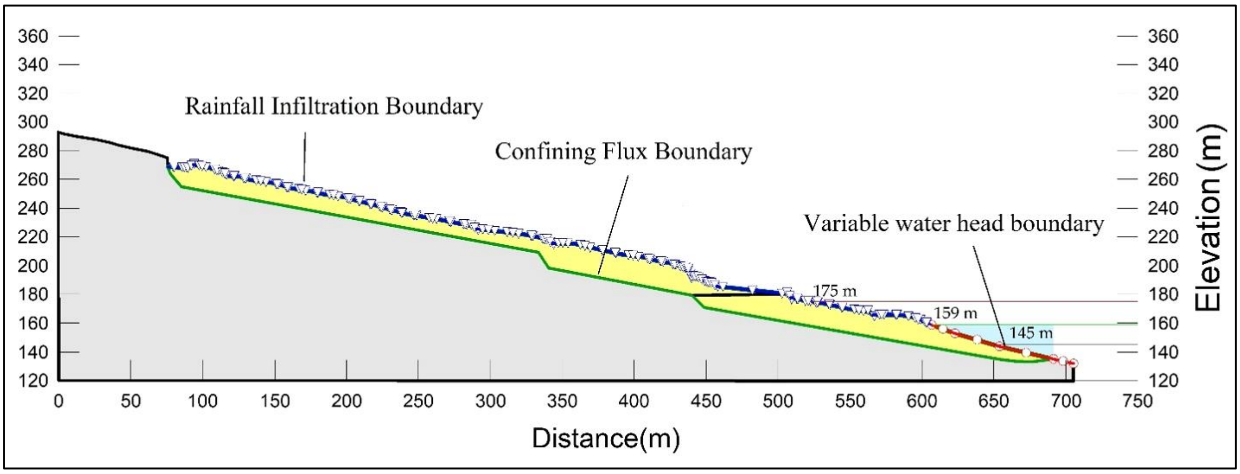


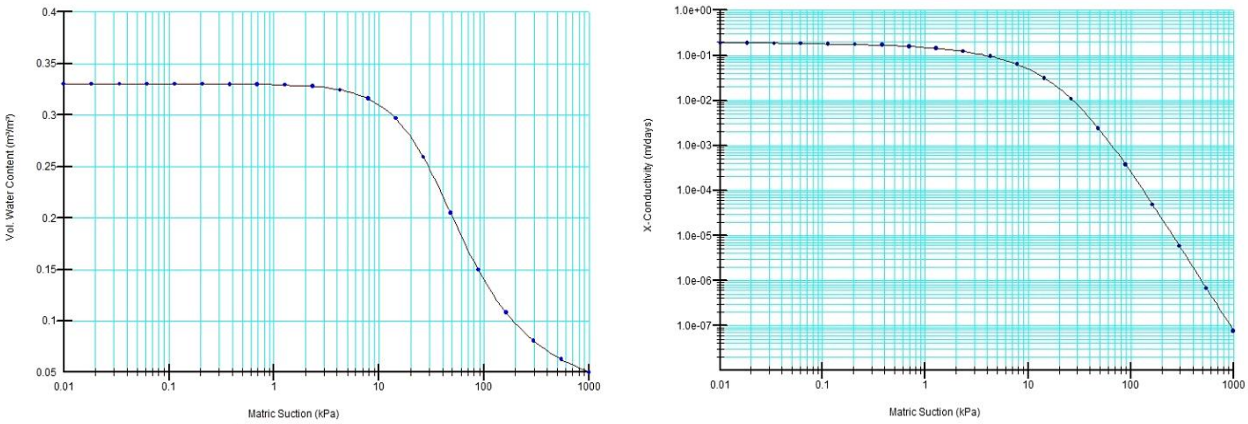
Figure 8. Model for Zhulinwan Landslide built by Geo-Studio

4.2. Seepage Calculation Parameters

When the SEEP module for seepage field simulation in the software, the permeability coefficient and volumetric water content of landslide rock and soil materials should be regarded as pore water pressure function of slope [34]. When the rock and soil body is in a saturated state, the permeability coefficient and volumetric water content are fixed values; while when the rock and soil body is in an unsaturated state, its permeability coefficient and volumetric water content should be determined through experiments [35]. According to predecessor survey data, the permeability coefficient of the Zhulinwan landslide borehole water injection test is 1.5×10^{-4} cm/s. The coefficient of permeability and volumetric water content of the soil can also be calculated using an analytical model [36], especially the model of Van-Genuchten [37]. The Van-Genuchten model has a strong alignment with experimental findings, and it can be used to calculate the soil water characteristics curve of Silty clay. To simulate Zhulinwan landslide seepage field, parameters in saturated state and Van-Genuchten empirical curve in the SEEP/W module are used for the calculation of soil water characteristic curve of sliding body (Figure 9).

Table 1. Zhulinwan Landslide calculation parameters

Component		Unit Weight(KN/m^3)	Cohesion (kPa)	Internal Friction Angle (°)
Sliding body	Natural	22.5	11	11.5
	Saturated	23.3	7	10.3
Slide bed		Impermeable		



permeability function curve Soil-water characteristic curve

Figure 9. SWCC and permeability function of sliding body

4.3. Working and Boundary Conditions

The reservoir water from 175 to 159 m usually drops at the rate of 0.13m/d, but from 159 to 145 the rate gets faster. The faster rate of drawdown is crucial for the stability of river banks slope [38]. The drawdown from 159 to 145 m was analyzed with coupling effect of rainfall. Table 2 shows the applied working conditions.

1. The surface above 175 m is designated as the rainfall infiltration boundary, 175 m to 145m is variable water head boundary and confining flux boundary is assigned for the bedrock floor.
2. From 1960 to 2013, daily rainfall data in Fengdu County was analyzed statistically to get the results of three days heavy rainfall of 78 mm for once in 20 years returns period and 93.3mm for once in fifty years return.

Table 2. Combination of operating conditions for stability of the landslide

Conditions	Rainstorm (mm/d)	Continuous combined load	Rate of drawdown (m/d)
1.1 1.2	78 for 3 days (once in 20 years) 93 for 3 days (once in 50 years)	Deadweight + surface load + drawdown from 159m to 145m	(0.6)
2.1 2.2	78 for 3 days (once in 20 years) 93 for 3 days (once in 50 years)	Deadweight + surface load + drawdown from 159m to 145m	(1.2)

5. Model Results and Interpretation

5.1. Seepage Analysis of Zhulinwan Landslide

The Zhulinwan landslide seepage fields are measured under various operational conditions. The saturation lines and velocity vectors are shown in Figure 10 for each measurement state. The analysis results show that the seepage field of this landslide conforms to the general seepage law and has the following characteristics:

(1) As the water level of the TGR drops, the free surface of the infiltration line in the slope also declines with time. There is a lag in the decline of the infiltration line [7]. The depth of the groundwater surface at the slope's junction with the field is often greater than the reservoir water level. Water in the pores is drained too late because the river water level drops faster than the water level within the body, resulting in a distinct groundwater level hysteresis within the slope.

(2) Rainfall has a certain impact on the groundwater level of the landslide body, but its impact is not very large, it only has a certain impact on the surface of the landslide, and has a small impact on the interior of the landslide body. Under the conditions of the reservoir water level falling in the flood season + rainfall conditions, rainfall increased the groundwater level at the rear of the landslide body, which increased the hydraulic gradient and seepage force.

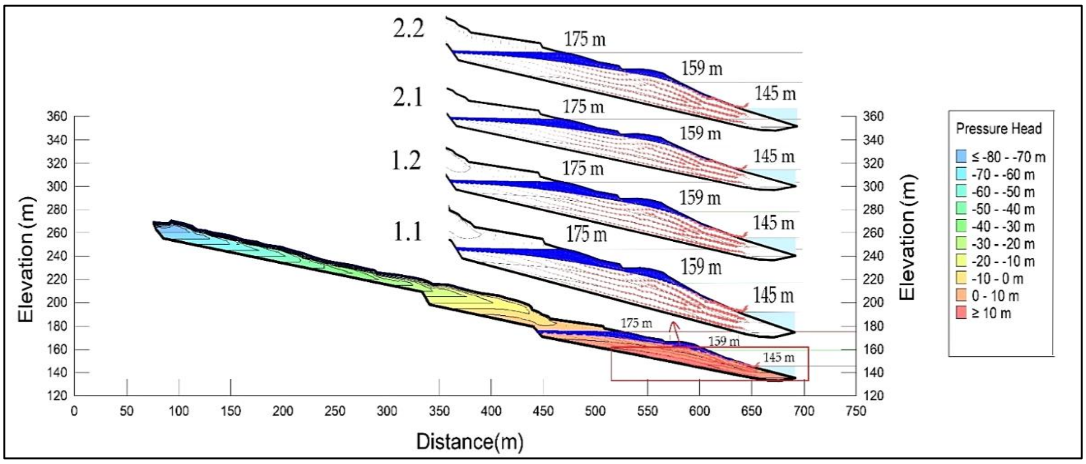


Figure 10. Transient changes under different conditions

5.2. Deformation Analysis of Zhulinwan Landslide

The Figure 11 shows the deformation at different calculation conditions. The deformation trend gradually develops from surface to the position of sliding zone. Main deformation area is concentrated on the front edge of the landslide. The impact of the deformation on the back end and on the surface is relatively small about 25 to 30 mm of displacement on some points. While on the front edge the deformation reached to more than 49 mm. The condition 1 is the 0.6 m/day drawdown of the reservoir from 159 to 145 meters. The landslide's displacement is centered on its front edge and back section, with peak displacements of 47.3 and 47.8 mm at conditions 1.1 and 1.2, respectively. The condition 2 is the 0.6 m/day abrupt drawdown of the reservoir from 159 m to 145 m meters. The landslide's displacement is centered on its front edge and back section, with peak displacements of 47.3mm and 47.8mm at conditions 2.1 and 2.2, respectively.

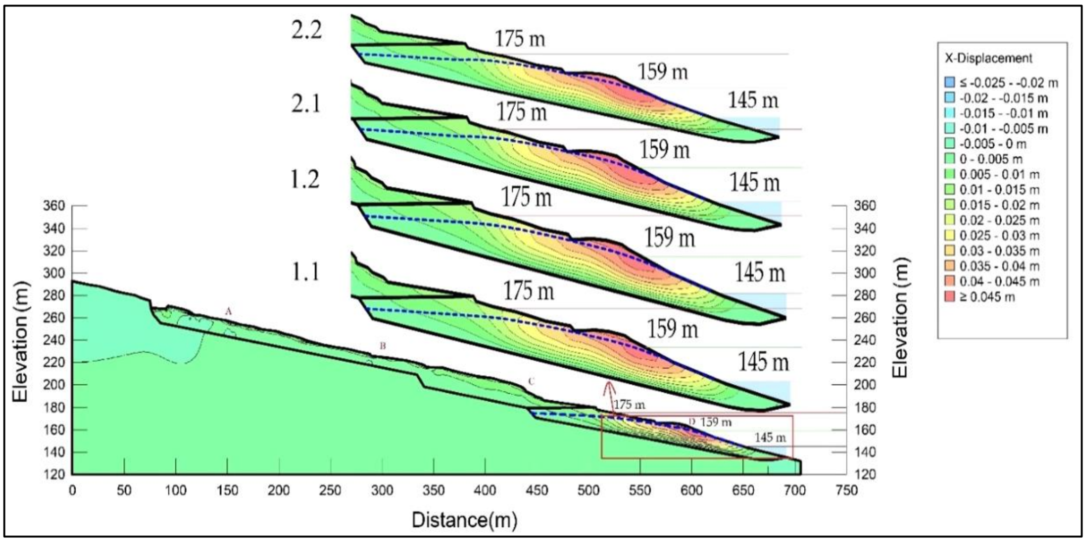


Figure 11. X Displacement of Zhulinwan landslide under different operating conditions

Moreover, as the position approaches the sliding zone, the horizontal displacement shows a gradual decreasing trend. It can be seen that the displacement value is positive, and the X-displacement direction of the landslide points out of the slope. Therefore, drop in reservoir water level coupled with heavy rainfall will promote greater deformation at landslide`s front edge [39]. Concluded that under the conditions of drawdown and plentiful rainfall, the Woshaxi landslide experienced significant deformation.

Four points A, B, C and D, along landslide surface were established at the distance of 150 m from each other, to check the deformation at each point. Where point D being near the front edge, C and B in the middle, and A at the rear end. The Figure 12 (a, b, c and d) shows the displacement at these points under different operating conditions. Where the displacement at point D is the highest. The Figure 11(e), shows the maximum displacement at point D, at all four conditions. The deformation is increasing with the increase in reservoir drawdown speed and heavy rainfall.

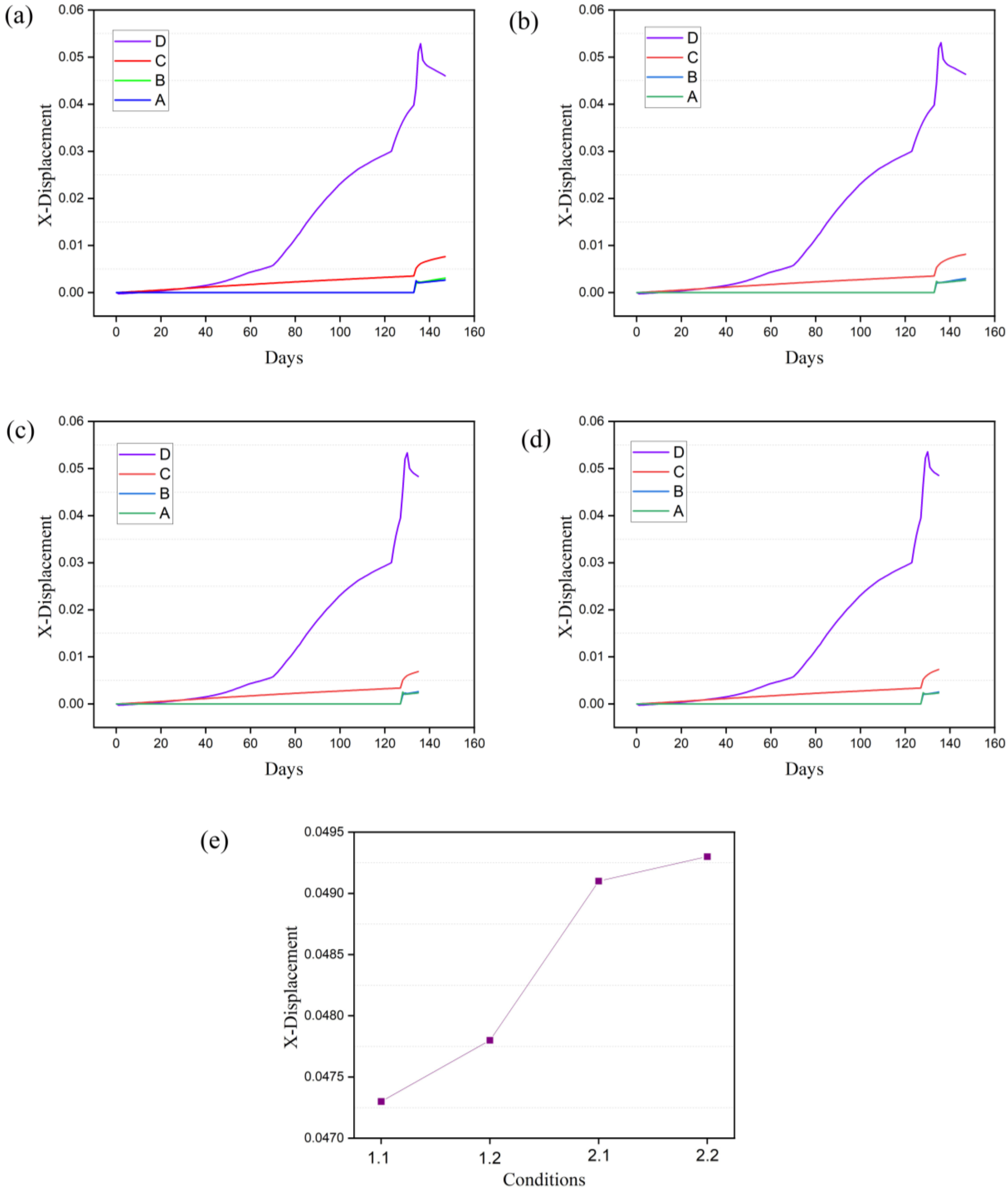


Figure 12. X Displacement (m) at four points under each operating condition. (e) Displacement (m) at point D under different operating conditions

In the deformation simulation of Zhulinwan landslide, as the level of reservoir water gradually declines, the hydrostatic pressure on the landslide gradually decreases, which is not conducive to the slope stability. The rainfall impact on landslide stability is mainly manifested in the large amount of rainwater infiltration, which leads to saturation of the soil and rock layer on the slope, and even water accumulation on the aquifer at the lower part of the slope, thus increasing sliding force and landslide weight, reducing soil and rock shear strength and contributing to overall landslide instability. The deformation of the rear edge of the landslide is mainly affected by rainfall. The occurrence of rainfall causes the deformation of the landslide along the direction of the landslide. Therefore, rainfall is detrimental to the stability of the landslide.

Deformation Mechanism of Zhulinwan Landslide

The main factors that induce the resurrection of reservoir bank landslides generally include rainfall and periodic changes in the level of reservoir water. The characteristics of Zhulinwan landslide is large ground height difference, along the slope, and the slide bed is straight. The slope has basic conditions for landslide development. The main components of sliding bodies is loose soil layer with silty clay and crushed stones. Outside the underlying bedrock slope, under continuous rainfall or heavy rain conditions, the precipitation seeps into the slope and move along the slip zone, resulting in soil being in a saturated state causes the physical and mechanical indexes of the soil to decrease.

(1) The accumulation layer at the front edge of the landslide is thin, and the material in this part is relatively loose due to the soaking of the reservoir water and lateral erosion. When the reservoir water level drops, the hydrostatic pressure on the slope decreases, and the anti-sliding force at this time decreases. Because the rate of groundwater level decline lags behind the level of reservoir water, a hydraulic gradient is generated. When the local water overflows from the slope, the hydrodynamic pressure is generated on the landslide, and the direction of the force points to the outside of the slope, resulting in landslide deformation.

(2) The middle and rear part of the landslide body has loose structure and large pores. The rainfall washes the surface of the slope body. On the other hand, the infiltration of rainfall increases the seepage pressure and soften its rock and soil, and the instability of the slope becomes natural.

5.3. Slope Stability Analysis of Zhulinwan Landslide

The impact of reservoir water drawdown and rainfall on the stability of landslide was analyzed according to the "Code for Investigation of Landslide Prevention Engineering" (DZ/T0218—2006), the factor of safety (FOS) of the landslide < 1.00 , it is unstable; $1.00 \leq F < 1.05$, it is under latent instability state; $1.05 \leq F < 1.15$. It is basically stable; $F \geq 1.15$, for stable state. The factor of safety of the landslide is 1.013 at the reservoir drawdown rate of 0.6 m/d, and is 1.009 when the rate of 1.2 m/d. The landslide stability reduces as the water level decreases from 159 to 145 m. The faster the drawdown rate lower the factor of safety. At the rate of 0.6 and 1.2 m/d drawdown without rainfall the landslide status changes from basically stable to under stable state as shown in Figure 13.

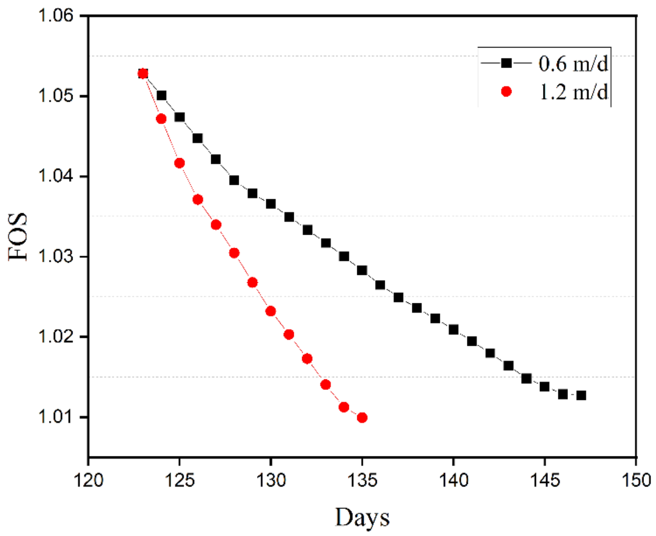
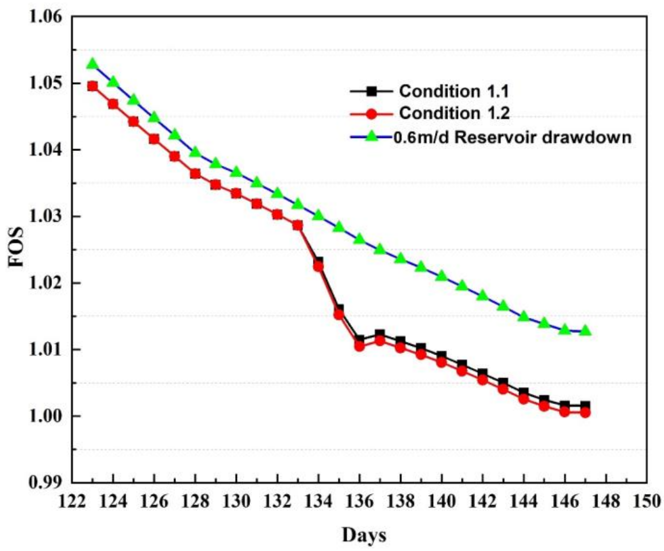


Figure 13. FOS at 0.6m/d and 1.2m/d without rainfall

(a)



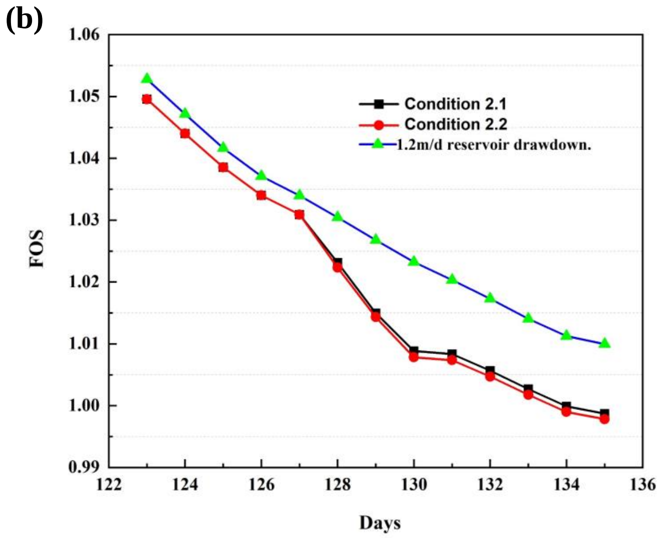


Figure 14. FOS at condition 1 and 2

At the condition 1 as shown in Figure 14(a), FOS is 1.001 and 1.00, at the drawdown from 159 to 145 m at a rate of 0.6 m/d, coupled with once in 20 and once in 50 years return period of rainfall and the landslide is in under latent instability state. While at Condition 2 as shown in Figure 14(b), FOS is 0.999 and 0.998 when reservoir level suddenly drops at the rate of 1.2 m/d, coupled with once in 20 and once in 50 years return period of rainfall, and the landslide becomes unstable. It can be seen that the value of stability coefficient suddenly drops with addition of rainstorm, which shows that the rainfall will have direct impact on landslide`s stability.

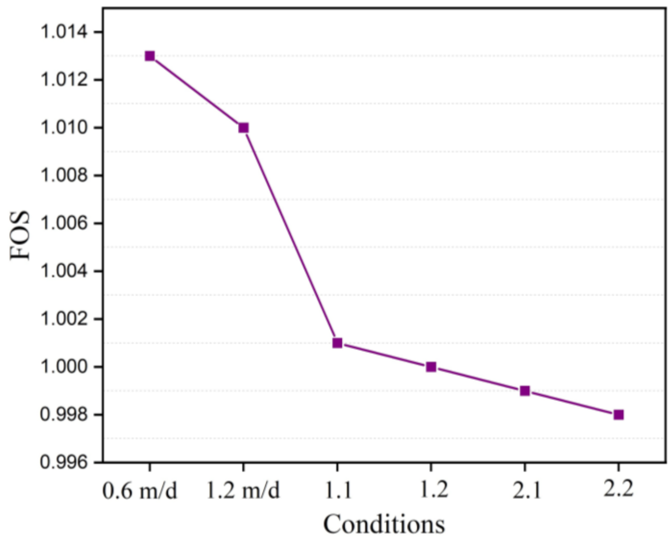


Figure 15. Minimum FOS at different conditions

Figure 15 shows the minimum FOS at different conditions. The analysis show that the rainstorm has negative effect on landslide stability, but the reservoir drawdown remains the main factor effecting the overall stability of Zhulinwan Landslide. Faster rate of drawdown is more crucial then then the slower rate. The influence of rain on FOS during high rate of drawdown is more significant than that during low rate of water level dropping, but the final effect is to reduce the stability of the landslide.

6. Discussion

There is close relation between FRWL and stability of river bank slopes. Yang et al. (2017) [40] found out that the change in reservoir water level continues to correlate with the annual variation in landslide stability. The toughest condition for the Maliulin landslide's stability is when the water level is down and there is a significant rainfall. Our aim was to investigate the effect of faster drawdown rates (from 159 to 145m) coupled with heavy rainstorm on Zhulinwan Landslide. Based on our observation, the faster drawdown was more detrimental to the stability. Same was confirmed by Zhang et al. (2020) [41] during the seepage, stability and deformation analysis using FLAC3D software of the Xigouwan landslide. According to in situ monitoring and computational modeling, Shi et al. (2018) [42] discovered that both rainfall and FRWL had a substantial impact on the action of the Quchi reactivated landslide; FRWL destabilized rock masses at the landslide toe, while rainfall primarily mobilized materials in the rear part. According to our findings, the drawdown severely deforms the front portion of Zhulinwan landslide, while precipitation has some impact on the rear part.

Though the landslide is currently in a stable state, with minor deformations but the combined conditions (condition 2) investigated in our study confirms that the landslide will become unstable. Furthermore, it should be noticed that deformation from in situ monitoring (51 mm in 6 years) and simulated (49.3 mm at 2.1 m/d drawdown combined with strong rainstorm) seem to be of different magnitudes. This is due to the fact that the material parameters used in the modeling are homogeneous, and were evaluated on a small number of soil samples, which does not correspond to the real-world condition. Moreover, certain complex geographical conditions, as well as the natural environment and human behaviors, were neglected or simplified in simulation.

7. Conclusions

- Zhulinwan landslide is mostly localized, and the landslide is currently stable with no sliding trend. Rainfall and FRWL are the most important factors effecting landslide stability.
- The groundwater infiltration line appears "downstream" within a certain range of the slope during drawdown, based on the morphological characteristics of the groundwater infiltration line. The infiltration line has a "convex" shape, which is "hysteretic" when compared to the reservoir water level decline, and this phenomenon is primarily concentrated in the reservoir water level fluctuation zone at the front edge of the slope.
- Deformation is mainly concentrated at the landslide`s front edge. With the maximum deformation under condition 2.2 was noted 49.3 mm.
- When the reservoir water level is high, the landslide stability coefficient is higher than when the reservoir water level is low. The landslide stability coefficient decreases as the water level decreases. The analysis revealed that the rate of reservoir drawdown has a negative effect on landslide stability; the faster the drawdown rate, the lower the stability. The Zhulinwan Landslide will become unstable at the coupling effect of 1.2m/d drawdown and once in 50 years return period of rainfall.

8. Declarations

8.1. Author Contributions

M.S.: Conceptualization, Data curation, Methodology, Investigation, Software, Formal analysis, Roles/Writing - original draft. W.Y.: Funding acquisition; Project administration; Resources; Supervision; Writing - review & editing. Y.L.: Conceptualization; Investigation; Software; G.R.: Visualization; Validation. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

8.3. Funding

This research work was supported by the National Natural Science Funding of China (No. 42077277).

8.4. Conflicts of Interest

The authors declare no conflict of interest.

9. References

[1] Wang, Fawu, Yeming Zhang, Zhitao Huo, Xuanming Peng, Shimei Wang, and Shintaro Yamasaki. "Mechanism for the Rapid Motion of the Qianjiangping Landslide during Reactivation by the First Impoundment of the Three Gorges Dam Reservoir, China." Landslides 5, no. 4 (June 24, 2008): 379–386. doi:10.1007/s10346-008-0130-7.

[2] Wu, Na, Zhengzhao Liang, Jingren Zhou, and Lizhou Zhang. "Energy evolution characteristics of coal specimens with preformed holes under uniaxial compression." Geomechanics and Engineering 20, no. 1 (2020): 55-66. doi:10.12989/gae.2020.20.1.055

[3] YU, S. "Numerical Analysis Of The Seepage Characteristics Of Slopes With Weak Interlayers Under Different Rainfall Levels." Applied Ecology and Environmental Research 17, no. 5 5 (2019): 12465-12478. doi:10.15666/aeer/1705_1246512478.

[4] Zhou, Wei, Xuyang Shi, Xiang Lu, Chongchong Qi, Boyu Luan, and Fuming Liu. "The Mechanical and Microstructural Properties of Refuse Mudstone-GGBS-Red Mud Based Geopolymer Composites Made with Sand." Construction and Building Materials 253 (August 2020): 119193. doi:10.1016/j.conbuildmat.2020.119193.

[5] Liu, Jianhao, Shaoyun Pu, and Junying Rao. "Visco-Elastoplastic Constitutive Fatigue Model for Rocks." Advances in Civil Engineering 2020 (June 11, 2020): 1–11. doi:10.1155/2020/4292043.

[6] Zhang, Liguo, Xinquan Chen, Yonggang Zhang, Fuwei Wu, Fei Chen, Weiting Wang, and Fei Guo. "Application of GWO-ELM Model to Prediction of Caojiatuo Landslide Displacement in the Three Gorge Reservoir Area." Water 12, no. 7 (June 29, 2020): 1860. doi:10.3390/w12071860.

[7] Li, Chun, Huiming Tang, and Yankun Wang. "Study on the Deformation Mechanism of Reservoir Landslides Considering Rheological Properties of the Slip Zone Soil: A Case Study in the Three Gorges Reservoir Region." Sustainability 12, no. 16 (August 10, 2020): 6427. doi:10.3390/su12166427.

[8] Corominas, Jordi, and José Moya. "Reconstructing Recent Landslide Activity in Relation to Rainfall in the Llobregat River Basin, Eastern Pyrenees, Spain." Geomorphology 30, no. 1–2 (October 1999): 79–93. doi:10.1016/s0169-555x(99)00046-x.

[9] Baker, R. "Inter-Relations between Experimental and Computational Aspects of Slope Stability Analysis." International Journal for Numerical and Analytical Methods in Geomechanics 27, no. 5 (2003): 379–401. doi:10.1002/nag.277.

[10] Guzzetti, F., S. Peruccacci, M. Rossi, and C. P. Stark. "Rainfall Thresholds for the Initiation of Landslides in Central and Southern Europe." Meteorology and Atmospheric Physics 98, no. 3–4 (June 18, 2007): 239–267. doi:10.1007/s00703-007-0262-7.

[11] Keqiang, He, Wang Shangqing, Du Wen, and Wang Sijing. "Dynamic Features and Effects of Rainfall on Landslides in the Three Gorges Reservoir Region, China: Using the Xintan Landslide and the Large Huangya Landslide as the Examples." Environmental Earth Sciences 59, no. 6 (March 10, 2009): 1267–1274. doi:10.1007/s12665-009-0114-5.

[12] Yeh, Hsin-Fu, and Cheng-Haw Lee. "Soil Water Balance Model for Precipitation-Induced Shallow Landslides." Environmental Earth Sciences 70, no. 6 (February 21, 2013): 2691–2701. doi:10.1007/s12665-013-2326-y.

[13] Igwe, Ogbonnaya, Wilfred Mode, Okechukwu Nnebedum, Ikenna Okonkwo, and Ifeanyi Oha. "The Analysis of Rainfall-Induced Slope Failures at Iva Valley Area of Enugu State, Nigeria." Environmental Earth Sciences 71, no. 5 (July 9, 2013): 2465–2480. doi:10.1007/s12665-013-2647-x.

[14] Xu, Shiluo, and Ruiqing Niu. "Displacement Prediction of Baijiabao Landslide Based on Empirical Mode Decomposition and Long Short-Term Memory Neural Network in Three Gorges Area, China." Computers & Geosciences 111 (February 2018): 87–96. doi:10.1016/j.cageo.2017.10.013.

[15] Tang, Huiming, Janusz Wasowski, and C. Hsein Juang. "Geohazards in the Three Gorges Reservoir Area, China – Lessons Learned from Decades of Research." Engineering Geology 261 (November 2019): 105267. doi:10.1016/j.enggeo.2019.105267.

[16] Zuo, Renguang, and Emmanuel John M. Carranza. "A Fractal Measure of Spatial Association between Landslides and Conditioning Factors." Journal of Earth Science 28, no. 4 (July 27, 2017): 588–594. doi:10.1007/s12583-017-0772-2..

[17] Pinyol, Núria M., Eduardo E. Alonso, and Sebastià Olivella. "Rapid Drawdown in Slopes and Embankments." Water Resources Research 44, no. 5 (May 2008). doi:10.1029/2007wr006525.

[18] Pinyol, Núria M., Eduardo E. Alonso, Jordi Corominas, and José Moya. "Canelles Landslide: Modelling Rapid Drawdown and Fast Potential Sliding." Landslides 9, no. 1 (May 17, 2011): 33–51. doi:10.1007/s10346-011-0264-x.

[19] Wang, Yankun, Jinsong Huang, and Huiming Tang. "Global Sensitivity Analysis of the Hydraulic Parameters of the Reservoir Colluvial Landslides in the Three Gorges Reservoir Area, China." Landslides 17, no. 2 (October 27, 2019): 483–494. doi:10.1007/s10346-019-01290-9.

[20] Cao, Chen, Qing Wang, Jianping Chen, Yunkai Ruan, Lianjing Zheng, Shengyuan Song, and Cencen Niu. "Landslide Susceptibility Mapping in Vertical Distribution Law of Precipitation Area: Case of the Xulong Hydropower Station Reservoir, Southwestern China." Water 8, no. 7 (June 28, 2016): 270. doi:10.3390/w8070270.

[21] Deng, H., L. Z. Wu, R. Q. Huang, X. G. Guo, and Q. He. "Formation of the Siwanli Ancient Landslide in the Dadu River, China." Landslides 14, no. 1 (September 27, 2016): 385–394. doi:10.1007/s10346-016-0756-9.

[22] Jiang, Jiwei, Wei Xiang, Wei Zhang, and Jiajun Pan. "Deformation Forecasting of Huangtupo Riverside Landslide in the Case of Frequent Microseisms." Journal of Earth Science 27, no. 1 (February 2016): 160–166. doi:10.1007/s12583-016-0617-4.

[23] Wang, Min, and Wen Wan. "A New Empirical Formula for Evaluating Uniaxial Compressive Strength Using the Schmidt Hammer Test." International Journal of Rock Mechanics and Mining Sciences 123 (November 2019): 104094. doi:10.1016/j.ijrmms.2019.104094.

[24] Yan, Zong-Ling, Jun-Jie Wang, and He-Jun Chai. "Influence of Water Level Fluctuation on Phreatic Line in Silty Soil Model Slope." Engineering Geology 113, no. 1–4 (May 2010): 90–98. doi:10.1016/j.enggeo.2010.02.004.

[25] Keqiang, He, Li Xiangran, Yan Xueqing, and Guo Dong. "The Landslides in the Three Gorges Reservoir Region, China and the Effects of Water Storage and Rain on Their Stability." Environmental Geology 55, no. 1 (August 8, 2007): 55–63. doi:10.1007/s00254-007-0964-7.

[26] Deng, Jianhui, Jinbing Wei, Hong Min, L. G. Tham, and C. F. Lee. "Response of an old landslide to reservoir filling: A case history." Science in China Series E Engineering & Materials Science 48, no. 1 (2005): 27-32. doi:10.1360/04zze3.

[27] Berilgen, Mehmet M. "Investigation of Stability of Slopes under Drawdown Conditions." Computers and Geotechnics 34, no. 2 (March 2007): 81–91. doi:10.1016/j.compgeo.2006.10.004.

[28] Luo, X.Q., H. Sun, L.G. Tham, and S.M. Junaideen. "Landslide Model Test System and Its Application on the Study of Shiliushubao Landslide in Three Gorges Reservoir Area." Soils and Foundations 50, no. 2 (April 2010): 309–317. doi:10.3208/sandf.50.309.

[29] Cojean, R., and Y. J. Caï. "Analysis and Modeling of Slope Stability in the Three-Gorges Dam Reservoir (China) — The Case of Huangtupo Landslide." Journal of Mountain Science 8, no. 2 (March 31, 2011): 166–175. doi:10.1007/s11629-011-2100-0.

[30] Paronuzzi, Paolo, Elia Rigo, and Alberto Bolla. "Influence of Filling–drawdown Cycles of the Vajont Reservoir on Mt. Toc Slope Stability." Geomorphology 191 (June 2013): 75–93. doi:10.1016/j.geomorph.2013.03.004.

[31] Mirzaie Aminian, Farzad, Ehsan Khojastehfar, and Hamid Ghanbari. "Effects of Near-Fault Strong Ground Motions on Probabilistic Structural Seismic-Induced Damages." Civil Engineering Journal 5, no. 4 (April 27, 2019): 796–809. doi:10.28991/cej-2019-03091289.

[32] Hsu, Chia-Feng, and Lien-Kwei Chien. "Slope stability analysis of transient seepage under extreme climates: case study of typhoon nari in 2001." Journal of Marine Science and Technology 24, no. 3 (2016): 399-412. doi: 10.6119/JMST-015-0813-1.

[33] Manual, GEOSTUDIO User'S. "Geo-slope international Ltd." Calgary, Alberta, Canada T2P 2Y5 (2012).

[34] Yeh, Hsin-Fu, Jinge Wang, Kang-Ling Shen, and Cheng-Haw Lee. "Rainfall Characteristics for Anisotropic Conductivity of Unsaturated Soil Slopes." Environmental Earth Sciences 73, no. 12 (January 22, 2015): 8669–8681. doi:10.1007/s12665-015-4032-4.

[35] Elkady, Tamer Y., Ahmed Al-Mahbashi, Muawia Dafalla, and Mosleh Al-Shamrani. "Effect of Compaction State on the Soil Water Characteristic Curves of Sand–natural Expansive Clay Mixtures." European Journal of Environmental and Civil Engineering 21, no. 3 (November 18, 2015): 289–302. doi:10.1080/19648189.2015.1112844.

[36] Ganjian, Navid, Yadollah Pashang Pisheh, and Seyed Majdeddin Mir Mohammad Hosseini. "Prediction of Soil–Water Characteristic Curve Based on Soil Index Properties." Experimental Unsaturated Soil Mechanics (n.d.): 355–367. doi:10.1007/3-540-69873-6_36.

[37] Van Genuchten, M. Th. "A Closed-Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils." Soil Science Society of America Journal 44, no. 5 (September 1980): 892–898. doi:10.2136/sssaj1980.0361599500440005 0002x.

[38] Sun, Guanhua, Yongtao Yang, Wei Jiang, and Hong Zheng. "Effects of an Increase in Reservoir Drawdown Rate on Bank Slope Stability: A Case Study at the Three Gorges Reservoir, China." Engineering Geology 221 (April 2017): 61–69. doi:10.1016/j.enggeo.2017.02.018.

[39] Wang, Haibin, Yinghao Sun, Yunzhi Tan, Tan Sui, and Guanhua Sun. "Deformation Characteristics and Stability Evolution Behavior of Woshaxi Landslide during the Initial Impoundment Period of the Three Gorges Reservoir." Environmental Earth Sciences 78, no. 20 (October 2019). doi:10.1007/s12665-019-8592-6.

[40] Yang, Beibei, Kunlong Yin, Ting Xiao, Lixia Chen, and Juan Du. "Annual Variation of Landslide Stability Under the Effect of Water Level Fluctuation and Rainfall in the Three Gorges Reservoir, China." Environmental Earth Sciences 76, no. 16 (August 2017). doi:10.1007/s12665-017-6898-9.

[41] Zhang, Yonggang, Shuyun Zhu, Junkun Tan, Lindan Li, and Xiangjie Yin. "The Influence of Water Level Fluctuation on the Stability of Landslide in the Three Gorges Reservoir." Arabian Journal of Geosciences 13, no. 17 (August 24, 2020). doi:10.1007/s12517-020-05828-3.

[42] Shi, Lei, Bin Zhang, Lei Wang, Han-xun Wang, and Hui-jie Zhang. "Functional Efficiency Assessment of the Water Curtain System in an Underground Water-Sealed Oil Storage Cavern Based on Time-Series Monitoring Data." Engineering Geology 239 (May 2018): 79–95. doi:10.1016/j.enggeo.2018.03.015.