Centrifugal model test of deformation law under different reservoir water fluctuation rates: Muyubao landslide case study

Xiaoyu Yi¹, Wenkai Feng¹,²*, Rui Meng³, Ruihua Xiao⁴, Yongchao Su⁴

1. State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu 610059, China
2. Key Laboratory of Geohazard Prevention of Hilly Mountains, Ministry of Natural Resources, Fuzhou 350002, China
3. Sichuan Academy of Territorial Space Eco-restoration and Geohazard Prevention, Chengdu, 610081, China
4. China Institute of Geo-Environment Monitoring, China Geological Survey, Beijing, 100081, China

*Corresponding author: fengwenkai@cdut.cn, https://orcid.org/0000-0001-7747-8836

Abstract. Many ancient landslides have become active due to the impoundment of the Three Gorges Reservoir. Considering the Muyubao landslide in the Three Gorges Reservoir area as the research object, we analyzed the long-term deformation law since the impoundment of the reservoir and conducted centrifugal model tests of the landslide deformation process under different reservoir water fluctuation rates. The monitoring data analysis reveals that the deformation of the Muyubao landslide is mainly affected by the elevation of the reservoir water level and its rising and falling rate. A deformation greater than 30 mm mainly occurs at the water level of 165–175 m. A higher reservoir water rising rate promotes landslide deformation, with a monthly cumulative displacement of above 30 mm in the reservoir water rising stage. Further, a lower reservoir water decline rate can promote several landslide deformation events with monthly cumulative displacement greater than 30 mm. A Centrifugal model test demonstrates the Muyubao landslide deformation to the hydrodynamic buoyancy pressure of reservoir water. The head difference inside and outside the slope is minimal when the reservoir water rising and the falling rate is small, and the reservoir water buoyancy controls the deformation of landslides. However, the head difference inside and outside the slope increases with the reservoir water rise and fall rate, leading to increased hydrodynamic pressure, which weakens the landslide deformation in the reservoir water rising stage, and strengthens the deformation in the reservoir water-falling stage. The results provide a significant reference for landslide control and reservoir operation optimization in the Three Gorges Reservoir area.

1. Introduction
The Three Gorges Project is the largest hydropower station globally, covering 21 counties and cities in Hubei Province and Chongqing City, and plays a significant role in flood control, power generation,
and shipping. When the Three Gorges Reservoir water level is 175 m, the average daily power generation is $2.32 \times 10^8$ kW·h; when the water level is 156 m, the average daily power generation is $1.91 \times 10^8$ kW·h, accounting for only 80% of normal power generation. Thus, reducing the water level drop time by increasing the rate of water level change can indirectly extend the 175 m water level operation time of the Three Gorges Reservoir and better use the reservoir’s overall advantage. However, it must be proven if increasing the rate of water level fluctuation in the reservoir area would impact the stability of water-related landslides [1].

The reservoir bank landslide deformation mechanism under reservoir water fluctuation and the deformation response law of different fluctuation rates have become crucial research content to investigate balancing geological disaster prevention, flood control, drought relief, and economic benefits. The centrifugal model test has irreplaceable advantages compared with deformation monitoring and numerical simulation [2–3] because it can intuitively reproduce the landslide stress field and truly reveal the deformation and failure processes [4–6]. In contrast, the relevant research mostly considered the limitations of test conditions using the numerical simulation method to study wading landslide deformation response law under the different reservoir water rising and falling rates [7].

This study considers the Muyubao landslide in the Three Gorges Reservoir area as the research object. Because of the long-term deformation law of the Muyubao landslide, a centrifugal model test was used to conduct a series model test. Monitoring equipment, such as pore water pressure sensors and earth pressure sensors, can obtain real-time data of several physical quantities during the test. Thus, we analyzed the deformation mechanism and response law of the Muyubao landslide based on the surface displacement time-series monitoring data and centrifugal model test under different reservoir water fluctuation rates. The research results provide a significant reference for landslide control and reservoir operation optimization in the Three Gorges Reservoir area.

2. Muyubao landslide
Muyubao landslide is located in Zigui County, Hubei Province, Three Gorges Reservoir area, on the right bank of the Yangtze River, 57 km away from the Three Gorges Dam (Figure 1). The front shear outlet elevation is about 100 m, the crown elevation is 520 m, and valleys bound the two sides. A flat and smooth sliding wall exists at the back edge of the landslide, with a primary main sliding direction of 20°. The landslide plane shape is similar to a horseshoe shape; the landslide is 1500 m long, 1200 m wide, with a total area of 1.80 km², a landslide toe thickness of approximately 50–70 m, a crown thickness of about 20–40 m, and a volume of about 9000×10⁴ m³ (Figure 2).

Figure 2 shows that the upper sliding body of the landslide is a quaternary accumulation composed of gravel soil, and the lower sliding body is a disturbed and destroyed layered quartz sandstone. The middle and rear parts of the rock mass are relatively complete, with a broken front edge. The middle and rear part of the sliding body is a bedding slide, the front sliding body slides in the cutting layer, and the rock layer progressively changes from inclined to bending and reverse warping. The sliding zone is a weak coal measure strata and is composed of black, gray silty clay, and gravel breccia soil, with a thickness of 0.1–0.3 m. The sliding bed is thick quartz sandstone of the Xiangxi formation of the Jurassic system, with $25° \lesssim 27°$.

The Three Gorges University set up 12 monitoring stations for surface displacement in the Muyubao landslide to understand its deformation characteristics. The monitoring work started in October 2006, and the data were collected once a month. The rainfall comes from the rainfall station near the landslide, and the water-level data are obtained from the Three Gorges Group website.

Based on the monitoring data from April 2008–2018, the monthly cumulative displacement scatter diagram of each Muyubao landslide-monitoring station under different reservoir water-level elevations and monthly water level fluctuations are constructed (Figure 3). The reservoir water level rises from 145 to 172 m, with a monthly reservoir water rise height of 3–9 m, and a monthly cumulative monitoring station displacement of less than 30 mm. When the reservoir water level rises from 172 to 175 m, the reservoir water monthly rise height reaches 15–18 m, with a monthly
cumulative landslide displacement of more than 50 mm. Further, when the reservoir water level is lowered from 175 to 172 m, the monthly reservoir water drop height is 0–3 m, and many monthly cumulative displacements of more than 30 mm (part of which reaches more than 50 mm) are generated by the landslide. When the water level of the reservoir decreases from 172 to 165 m, the rate of water drop increases, and the monthly cumulative displacement will also be greater than 30 mm. However, the monthly cumulative displacement will not exceed 50 mm. When the reservoir water level drops from 165 to 145 m, the rate of water drop can be further increased, but the monthly cumulative displacement remains below 30 mm.

Figure 1. Location of the Muyubao landslide

Figure 2. Geological cross-section of the Muyubao landslide

The above analysis reveals that the Muyubao landslide deformation response is related to the rise and fall rate of reservoir water and water-level elevation. When the water level is increased from 165 to 175 m, landslide deformation events can occur due to a higher reservoir water rising rate, with monthly cumulative displacement greater than 30 mm. However, a lower reservoir water-falling rate can cause many landslide deformation events with monthly cumulative displacements greater than 30 mm. When the water level is 145–165 m, the landslide deformation response to the reservoir water rise and fall rate decreases, and the monthly cumulative landslide displacement is below 30 mm.
Figure 3. Monthly cumulative variation in water level of different reservoirs and monthly deformation under reservoir water-level conditions of the Muyubao landslide

3. Centrifuge model test scheme

Centrifugal model tests were conducted using the TLJ-500 geotechnical centrifugal testing machine of the Chengdu University of Technology. The section displayed in Fig. 2 is simplified to obtain the centrifuge test model (Figure 4) based on the centrifugal tandem model principle [8]. In the two conversions, \( m \) is 10.7, and \( n \) (centrifugal acceleration) is 130. The test model slip bed was filled with masonry and concrete. The slip zone was prepared with an 8:2 ratio of clay to quartz sand, a moisture content of 7.5%, and a thickness ranging from 3 to 6 mm, depending on the prototype thickness. The rocky slide was prepared with similar materials using barite powder, fine quartz sand, gypsum, cement, and water in the ratio of 36:108:5:45:30 and cut according to the development of landslide prototypical nodal fissures, and the gaps were bonded using similar materials (Table 1). The cover layer was made of clay and quartz sand in the ratio of 5:5 and applied to the model surface in equal proportions based on the thickness of the prototype landslide cover layer. The test model was fabricated and left to solidify in preparation for the test. In addition, during the fabrication of the model, earth pressure sensors, pore water pressure sensors, and displacement sensors were buried simultaneously, and a high-speed camera was used to record the test process.

![Figure 4](image)

**Figure 4** (a) Centrifugal test model and sensor location; (b) Side view of centrifugal test model; (c) enlarged view of the front of the centrifuge test model

**Table 1.** Physical and mechanical parameters of landslide and its similar materials

| Material type | Parameter | Muyubao landslide | Similar materials |
|---------------|-----------|--------------------|-------------------|
The dynamic response characteristics of landslides in the reservoir water fluctuation are investigated by setting up several different water fluctuation rates. Table 2 shows the test-loading scheme, and the test process can be divided into three stages. The first stage is the centrifugal force loading stage (0–2600 s). The centrifugal acceleration gradually rises to 130 g, and the reservoir water level progressively rises to 20.7 cm (145 m). The second stage is the reservoir water rising and falling test (2600–6000 s). The centrifugal acceleration is maintained at 130 g in this stage, and the reservoir water level is between 20.7–23.0 cm (145–175 m). The model tests of different reservoir water rising and falling rates are divided into Test 1, Test 2, and Test 3. The third stage is the centrifugal force unloading stage (6000–6900s); the centrifugal acceleration and water level gradually decreased, and the test ended.

**Table 2 Process of reservoir water-level fluctuation rates with times**

| Test stage | Water level fluctuation(cm) | Time(s) | Cumulative time(s) | Fluctuation rate of reservoir water(mm/s) |
|------------|-----------------------------|---------|-------------------|----------------------------------------|
| Stage I    |                             |         |                   |                                        |
| Test 1     | 0→20.7                      | 2600    | 2600              | —                                      |
|            | 20.7→22.7                   | 800     | 3400              | 0.025                                  |
|            | 22.7                        | 300     | 3700              | —                                      |
|            | 22.7→20.7                   | 500     | 4200              | 0.040                                  |
|            | 20.7                        | 200     | 4400              | —                                      |
| Stage II   |                             |         |                   |                                        |
| Test 2     | 20.7→23.0                   | 300     | 4700              | 0.077                                  |
|            | 23.0                        | 300     | 5000              | —                                      |
|            | 23.0→20.7                   | 300     | 5300              | 0.077                                  |
|            | 20.7                        | 200     | 5500              | —                                      |
| Test 3     | 20.7→23.0                   | 150     | 5650              | 0.153                                  |
|            | 23.0→20.7                   | 400     | 6050              | 0.058                                  |
| Stage III  |                             |         |                   |                                        |
|            | 20.7→0                      | 950     | 7000              | —                                      |

4. Results of centrifugal model test

4.1. Surfer displacement

Figure 5 shows the vertical displacement monitoring curve during the test, and the sensor displacement sensor (DPS) 2 malfunctions due to fault. In the centrifugal acceleration-loading stage, the landslide soil is consolidated under self-weight action, and the sliding mass is compacted. The deformation rate of DPS1 is consistent with the change of reservoir water during the first test (Test 1). DPS3’s deformation rate first decreases then increases until it reaches the maximum water level. The deformation rates of DPS1 and DPS3 increased when the reservoir water increased to 23.0 cm (175 m) during the second reservoir water-lifting test (Test 2); subsequently, the deformation rates of DPS1 and DPS3 first increase then decrease during the process of water-level decline and lag in the overall water-level change. The deformation rates of DPS1 and DPS3 are almost negatively correlated with the reservoir water level during the third test (Test 3). The deformation rates of DPS1 and DPS3 increase significantly in the reservoir water decline stage. The test results show that the first impoundment significantly affected the landslide deformation. The overall landslide deformation rate in the later reservoir water rise and fall stages shows that the sensitivity to reservoir water-level change
gradually weakens. The deformation characteristics of landslides are affected by the rate of reservoir water level change. The lag in the response of landslide deformation to the changes in reservoir water level becomes increasingly obvious as the reservoir water level fluctuates. The landslide’s substantial deformation period is concentrated in the reservoir water-level decline stage.

Figure 5. Monitoring results of vertical deformation varying with time. (a) The whole test process. (b) DPS1 displacement and displacement rate of stage II. (c) DPS3 displacement and displacement rate of stage II.

4.2. Earth pressure

The earth pressure sensor (EPS) 2 did not measure useful data during the test, and the EPS3 sensor was damaged. Figure 6 shows the EPS1 and EPS4 earth pressure monitoring curves during the test. EPS4, located in the front area of the test model, is affected by the reservoir water-level fluctuation. The earth pressure curve changes substantially, indicating a significant correlation with the reservoir water evolution. Figure 6b shows that the landslide model is consolidated and compacted in the centrifugal acceleration-loading stage. The EPS1 earth pressure value gradually increases and becomes stable at 2.22 kPa when the centrifugal acceleration reaches 130 g. When the reservoir water level rises to 175 m for the first time under the centrifugal acceleration of 130 g, the buoyancy effect of reservoir water on the front sliding mass reduces sliding resistance, and the earth pressure value of EPS1 increases to 2.87 kPa due to the compression of traction sliding at the landslide’s rear edge. The landslide response to the reservoir water change was weakened in the two subsequent reservoir water upgrading processes, the overall landslide deformation rate slowed, and the EPS1 earth pressure remained stable.
Figure 6. Measured earth pressure varying with time. (a) The whole test process. (b) Earth pressure monitoring curve of EPS1

4.3. Pore pressure
Figure 7 shows the pore water pressure monitoring data during the test. The water-level fluctuation does not affect the pore water transducer sensor (PPT) since PPT1 is located at the back of the model, which is higher than the maximum water level. Thus, the measured pore water pressure is stable. In the initial centrifugal acceleration-loading stage, each sensor’s pore pressure exhibits no obvious change because the water level does not rise to the sensor height. However, when the water level rises to 175 m, the pore pressure of PPT2 and PPT3 suddenly changes and further decreases with the water level. In the reservoir water level rise and fall test, PPT3’s pore pressure maintains the synchronous change with the reservoir water level, indicating a rapid response of the front part of the landslide to the reservoir water level fluctuation, and the pore pressure is most affected by the reservoir water level. PPT2’s pore pressure in the middle of the landslide is lagged due to its location. The front water level drops rapidly in the drainage stage, the pore water pressure in the landslide dissipates gradually, and the values of pore pressure sensors decrease progressively.

Figure 7. Measured pore pressure varying with time. a The entire test process. b The test period with stage II.

5. Discussion
5.1. Deformation mechanism
Both EPS4 and PPT3 are arranged in front of the wading body. The relationship between displacement and stress is obtained based on the principle of effective stress (Figure 8). In the reservoir water rising stage, the earth pressure and pore water pressure increase when the reservoir water enters the slope. The sliding body’s effective stress decreases due to the reservoir water’s floating effect. The effective focus is at the lowest value when the reservoir water level is maintained at a high level. The pore water pressure at the measuring point decreases as reservoir water seeps out of the slope during the reservoir
water decline process, allowing the effective stress to gradually recover. The anti-sliding effect of a wading landslide is reduced by the reservoir water uplift, which is beneficial to landslide deformation; the anti-sliding force of the wading landslide is restored after the reservoir water drops, and landslide deformation is slowed. The change in pore water pressure slightly lags behind the reservoir water level when its rise and fall rate increase, resulting in the effective stress at a lower level in the high water-level operation and the early stage of the decline of the high reservoir water-level, and the maximum landslide deformation rate changes from the high reservoir water level to its early stage of the decline. A certain water head difference inside and outside the slope exists at the initial reservoir water level decline stage after its rise and fall rate. The buoyancy effect of reservoir water level on the landslide remains obvious. The superimposed hydrodynamic pressure outside the slope simultaneously promotes the deformation rate of the landslide during this period.

![Graph](image.png)

**Figure 8.** The relationship between effective stress and deformation rate.

The rising and falling rate of reservoir water is slow during Test 1, and the earth and pore water pressures synchronously change when the reservoir water enters and leaves the slope. The floating effect of reservoir water at a high reservoir water level decreases the landslide soil’s effective stress, and the deformation rate reaches the maximum. The rapid rise and fall of reservoir water in Tests 2 and 3 causes pore water pressure change to lag behind the reservoir water level. Therefore, the effective stress is at a lower level in the initial high reservoir water-level decline stage and the maximum landslide deformation rate changes from the high reservoir water level to its initial decline stage.

Compared with the landslide-monitoring results (Figure 3), the buoyancy force affects the stability of landslides in the reservoir water fluctuation, and the hydrodynamic and hydrostatic pressures generated in the same period will either restrict or enhance landslide deformation in different periods.

5.2. Geomechanical model

The bedding sliding mass is compressed downward along the sliding zone under the action of gravity (Figure 9) because the dip angle of the rock stratum in the middle and rear parts of the Muyubao landslide is close to the slope angle, constituting the main sliding promoting section of the landslide. The rock layer in front of the landslide gradually becomes gentle from the middle dip and then transforms to bending and anti-warping. The relatively gentle slope of the sliding surface and the larger thickness of the sliding mass tend to be stable under the action of self-weight, which constitutes the main anti-sliding section of the landslide. Therefore, pushing creep deformation occurs from the sliding section to the free surface under the control of the shape of the chair-shaped bank slope and the driving force of gravity, reservoir water, and other factors.
The hydrodynamic force acting on the slope element can be expressed as seepage force \((F_S)\) and buoyancy force \((F_B)\). Seepage force \((F_S)\) represents the frictional resistance of water flowing through the gap, which is proportional to the hydraulic gradient and operates in the flow direction. The hydrodynamic pressure effect [9] describes the influence of seepage force \((F_S)\) on the slope stability; buoyancy force \((F_B)\) can modify the effective weight of the sliding mass, thus increasing or decreasing the sliding force of the landslide. The influence of this force on landslide stability is called the buoyancy weight reduction effect [10].

![Figure 9. Geomechanical model of the Muyubao landslide](image)

In the reservoir water level rising stage, the buoyancy increase in the reservoir water lags behind the hydrodynamic pressure, which promotes landslide stability and delays sliding deformation. Subsequently, reservoir water infiltration increases the groundwater level, decreasing the head difference between the inside and outside of the slope, and the dynamic water pressure and buoyancy force within the wading slide fluctuate. The front slide’s slip resistance decreases significantly with an increase in reservoir water level, and the slide’s deformation rate increases gradually, reaching its maximum deformation rate when it is located at the highest water level. The weight of the front part of the sliding body is reduced, the anti-sliding force is weakened, and the hydrodynamic pressure turns out of the slope concurrently when the reservoir water level drops slightly at a high water level. The middle and rear sliding mass forces the front landslide to accelerate deformation under this superimposed action, significantly increasing the landslide displacement. When the reservoir water level gradually drops to 145 m, the reservoir water buoyancy decreases, and the seepage force outside the slope also decreases with the water head difference inside and outside the landslide. During this period, the landslide gradually recovers its stability.

6. Conclusion
The deformation law of the Muyubao landslide under reservoir water fluctuation is investigated and centrifugal model tests under different reservoir water fluctuation rates are conducted based on displacement monitoring data of the Muyubao landslide collected over 12 years in the Three Gorges Reservoir area. The deformation of the Muyubao landslide is mainly affected by the elevation of reservoir water level and the rate of rising and falling based on monitoring data analysis, and the deformation greater than 30 mm occurs predominantly at the water level of 165–175 m. In the reservoir water rising stage, a landslide deformation event with a monthly cumulative displacement of above 30 mm can occur if the reservoir water increases rapidly. However, a lower reservoir water
The rate can cause many landslide deformation events with monthly cumulative displacement greater than 30 mm. Further, the deformation of the Muyubao landslide is related to the reservoir water hydrodynamic buoyancy, according to the centrifugal model test. The head difference inside and outside the slope is minimal when the reservoir water rising and falling rate is small, and the reservoir water buoyancy controls landslide deformation. When the reservoir water rising and falling rate increases, the head difference inside and outside the slope increases, leading to increased hydrodynamic pressure, which weakens landslide deformation in the reservoir water rising stage, but strengthens landslide deformation in the reservoir water-falling stage.

References
[1] Tang H, Wasowski J and Juang C H 2019 Geohazards in the Three Gorges Reservoir Area, China – Lessons learned from decades of research Engineering Geology 261 105267.
[2] Mao J, Guo J, Fu Y, Zhang W and Ding Y 2020 Effects of rapid water-level fluctuations on the stability of an unsaturated reservoir bank slope Advances in Civil Engineering 2360947.
[3] Du Y, Xie M, Jia J 2020 Stepped settlement: A possible mechanism for translational landslides Catena 187 104365.
[4] Miao F, Wu Y, Li L 2018 Centrifuge model test on the retrogressive landslide subjected to reservoir water level fluctuation Engineering Geology 245 169-179.
[5] Fan L, Zhang G, Li B 2017 Deformation and failure of the Xiaochatou Landslide under rapid drawdown of the reservoir water level based on centrifuge tests Bulletin of Engineering Geology & the Environment 76 891-900.
[6] Kaczmarek H, Mazaeva O A, Kozyreva E A 2016 Impact of large water level fluctuations on geomorphological processes and their interactions in the shore zone of a dam reservoir Journal of Great Lakes Research 42 926-941.
[7] Zhang Z, Huang X, Liu W 2020 Study on the Hydraulic Parameters of Woshaxi Landslide Soils during Water Level Drawdown of Three Gorges Reservoir Geofluids 1-14.
[8] Li L, Li C, He C 2019 Study on method of a new centrifugal tandem model test and its preliminary application Water conservancy and hydropower technology 50 200-204
[9] Wang S, Chen Y, Tian D 2017 Reactivation mechanism and stability evaluation method of landslide in Three Gorges Reservoir Area Beijing: Science Press
[10] Li S, Xu Q, Tang M 2017 Response law of old landslides with different sliding surface shapes under reservoir water level fluctuation Acta geologica Sinica 25 841-852

Acknowledgments
This study was supported by the National Natural Science Foundation of China (Grant Nos: 41977252, U2005205); the State Key Laboratory of Geohazard Prevention and Geoenvironment Protection Independent Research Project (Grant No. SKLGP2020Z001); the State Key Laboratory of Geohazard Prevention and Geoenvironment Protection Open Fund (Grant Nos. SKLGP2019K010, SKLGP2020K015).