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Study on the Impact of Water Level Fluctuations on the Stability of Reservoir Bank Landslides in Guangxi

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Abstract: The unique geological structure and climatic conditions in Guangxi make reservoir bank land-slides particularly problematic, with water level fluctuations being a key factor in inducing them. This paper systematically analyzes the mechanisms by which water level fluctuations affect the stability of reservoir bank landslides from a theoretical perspective, revealing the coupling effects of permeability, softening, buoyancy, and fatigue. By constructing a "hydrological-geological-mechanical" multi-field coupling model, the controlling effects of rock and soil permeability, geological conditions, and water level fluctuation rate on landslide stability are explored. The results indicate that permeability induced by sudden water level drops is the dominant factor in landslide instability, while fatigue damage caused by long-term water level fluctuations significantly reduces the long-term strength of rock and soil. The theoretical framework proposed in this paper provides a scientific basis for preventing and controlling reservoir land-slides in Guangxi and is of great reference value for similar projects.

Keywords: water level fluctuations; reservoir bank landslides; stability; permeability

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1. Introduction

Guangxi is located in the core area of karst landforms in southwestern China, and many reservoir projects are constructed in areas with strong karst development and complex geological structures. According to statistics, Guangxi boasts over 4,800 reservoirs of various types, over 80% of which experience varying degrees of bank landslides. Periodic fluctuations in reservoir water levels during reservoir operation significantly impact the stability of reservoir bank slopes, leading to frequent landslide disasters. Monitoring data from the Three Gorges Reservoir area shows that when the daily water level drop exceeds 2 meters, the rate of bank landslide deformation can increase by 3-5 times, confirming the close correlation between water level fluctuations and landslide stability. Although the geological settings differ, similar hydrological conditions in Guangxi suggest comparable mechanisms may be at play.

The unique hydrogeological conditions in Guangxi complicate the mechanism by which water level fluctuations influence landslides [1]. On the one hand, specialized rock masses, such as red-bed soft rock and carbonaceous shale, exhibit pronounced softening properties, reducing their shear strength by 30%-50% upon saturation. On the other hand, the development of structural surfaces, such as faults and joints, provides advantageous pathways for groundwater seepage, resulting in persistent head differences between the internal and external slopes. Furthermore, the combined effects of heavy monsoon rainfall and reservoir operation, resulting in water level fluctuations, further exacerbate the risk of landslide instability. Therefore, systematically studying the mechanism by which water level changes affect the stability of landslides along reservoir banks in Guangxi and establishing a theoretical analysis framework that aligns with regional characteristics is of great theoretical significance and engineering value.

2. Basic Theory of the Impact of Water Level Changes on Landslide Stability

2.1. Seepage Theory

When the reservoir water level changes, the head difference between the inside and outside of the slope creates a seepage field directed outward. According to Darcy's law, the seepage force per unit volume of rock and soil can be expressed as:

$$J = \gamma_W i$$

Where γ_W is the specific gravity of water, and i is the hydraulic gradient. The direction of the seepage force is consistent with the direction of seepage, and its magnitude is proportional to the hydraulic gradient. At the toe of the slope, the hydraulic gradient can reach 1.0-1.5, generating a seepage force that can exceed the shear strength of the rock and soil by 20%-30%, becoming a key mechanical factor leading to landslide instability.

2.2. Effective Stress Principle

Rising reservoir water levels cause the groundwater seepage line to rise, increasing pore water pressure. According to the effective stress principle:

$$\sigma' = \sigma - u$$

Where σ' is the effective stress, σ is the total stress, and u is the pore water pressure. A decrease in effective stress reduces the shear strength of the rock and soil, and its shear strength indicators (cohesion c and internal friction angle ∅) exhibit nonlinear attenuation. Laboratory triaxial tests show that the internal friction angle of sandstone decreases by 12%-18% after saturation, and the shear strength of clay decreases by up to 35% after saturation.

2.3. Floatation-Reduced Weight Effect

Rising water levels partially or completely submerge the sliding mass, and the buoyancy offsets some of the weight of the sliding mass, reducing the sliding force. However, at the same time, the buoyancy reduces the effective stress of the sliding zone soil, reducing the shear strength [2]. When the increase in buoyancy exceeds the decrease in shear strength, the landslide stability increases; otherwise, it decreases. This dual effect makes the impact of buoyancy on landslide stability uncertain, requiring analysis based on specific project conditions.

2.4. Fatigue Damage Theory

Long-term water level fluctuations cause fatigue damage in the rock and soil, gradually loosening the microstructure. Scanning electron microscopy observations revealed that after 50 water level cycles, the connection between clay mineral particles shifted from surface-to-surface contact to point-to-surface contact, and the porosity ratio increased by 0.1-0.2. This microstructural change leads to a deterioration in the macromechanical properties of the rock and soil, with shear strength parameters exhibiting an exponential decay pattern. After 100 water level cycles, the stability coefficient decreased by up to 20%-30%.

3. Mechanisms of Water Level Fluctuations Affecting Landslide Stability

3.1. Combined Softening and Floating Effects of Water Level Rise

During the reservoir water level rise phase, landslide stability is controlled by both softening and floating effects. During the initial rise phase (water level increase <5 m), the floating effect dominates, and the landslide safety factor increases slightly. As the water level continues to rise, the softening effect gradually intensifies. When the water level increase exceeds a critical value (typically 10-15 m), the safety factor begins to decrease. This nonlinear variation is particularly pronounced in bedding slopes. When the dip of the rock strata aligns with the slope direction, rising water levels can directly trigger sliding along weak structural planes [3].

The spatiotemporal distribution of the softening effect exhibits distinct characteristics: the surface rock and soil rapidly soften due to direct contact with water, forming a softening zone; the deeper rock and soil slowly absorb water through capillary action, with the softening depth showing a logarithmic relationship with time. The softening depth of the red-bed soft rock in Guangxi can reach 5-8 meters, with a softening time constant of approximately 30-60 days. This hysteresis effect makes the impact of rising water levels on landslide stability long-term. Therefore, the delayed softening response must be considered in long-term stability assessments.

3.2. Seepage-Floatation Coupling Effect of Water Level Drawdown

During the sudden water level drawdown phase, seepage becomes the dominant factor. The head difference between the internal and external slopes generates an outward seepage force, which can reach 0.5-1.2 kN/m³ at the slope toe, exceeding the shear strength of the rock and soil by 20%-30%. Physical model tests show that when the water level drops by more than 2.6 meters per day, the permeability at the slope foot exceeds the shear strength of the rock and soil, leading to localized shear failure. This failure is characterized by a gradual progression, with initial cracks expanding under the continued action of permeability to form a continuous sliding surface [4].

The buoyancy effect still plays a stabilizing role in the initial water level drop (drop < 3 meters), but as the water level continues to fall, the buoyancy rapidly decreases, and the permeability effect gradually becomes dominant. Landslide monitoring on the right bank of a reservoir in Guangxi showed that the horizontal displacement rate of the slope increased by 3.2 times during the sudden drop in water level from 675 to 665 meters, confirming the positive correlation between permeability and deformation rate.

3.3. Fatigue-Damage Cumulative Effects of Periodic Fluctuations

Long-term water level fluctuations cause fatigue damage in rock and soil. The mechanisms can be categorized into two levels: microstructural damage and macroscopic mechanical property degradation. At the microscopic level, water level cycling gradually destroys the connections between mineral particles, forming microcracks. At the macroscopic level, microcracks expand and connect to form macroscopic fractures, reducing the integrity of the rock and soil. Numerical simulations show that this fatigue effect causes the landslide safety factor to decay exponentially, with the stability factor decreasing by 22% after 50 water level cycles.

The cumulative rate of fatigue damage is closely related to the amplitude and frequency of water level fluctuations [5]. Under Guangxi's monsoon climate, water level fluctuations can reach 15-20 times annually, of which sudden drops account for approximately 40%. This high-frequency fluctuation accelerates the accumulation of rock and soil damage, and after 10 years of operation, the probability of landslides can increase by 2-3 times.

4. Factors Controlling the Impact of Water Level Changes on Stability

4.1. Rock and Soil Permeability Characteristics

The permeability coefficient is the core parameter that determines the speed of response to water level changes. In highly permeable layers (k > 10-3 cm/s), water level changes are rapidly transmitted to the slope interior, forming a uniform hydraulic head field. However, in weakly permeable layers (k < 10-5 cm/s), a hysteresis effect occurs, resulting in a persistent hydraulic head difference between the interior and exterior of the slope. The permeability coefficient of the red-bed soft rock in Guangxi ranges from 10-6 to 10-4 cm/s, making it a moderately permeable layer. Its unique hydrogeological conditions extend the duration of seepage by 2-3 times during water-level drawdown.

Permeability anisotropy also significantly affects landslide stability. When the ratio of the horizontal permeability coefficient (kh) to the vertical permeability coefficient (kv) is greater than 3, the seepage field exhibits a distinct layered distribution, resulting in directional landslide stability. Landslide monitoring along the banks of a reservoir in Guangxi revealed that the permeability coefficient along the bedding plane is an order of magnitude higher than that perpendicular to the plane. When the water level falls, piping first occurs along the bedding plane, subsequently leading to overall instability.

4.2. Geological Structural Conditions

Structural surfaces such as faults and joints form dominant seepage channels, and their orientation and the angle between them and the slope determine the distribution characteristics of the seepage field. When the structural surface inclination aligns with the slope, the seepage path shortens, the head difference concentrates, and the seepage increases. Conversely, the seepage path lengthens, the head difference disperses, and the seepage decreases. Tectonic stress fields influence seepage distribution by controlling the direction of fracture development. When the angle between the maximum principal stress direction and the slope surface is less than 30°, fracture connectivity increases, and the permeability anisotropy ratio reaches over 5:1. When the angle exceeds 60°, fractures close and permeability decreases. In Guangxi, influenced by the Indosinian movement, the maximum principal stress direction is mostly NW-SE, intersecting the slopes of most reservoir banks at a shallow angle, leading to the development of fractures and increased permeability.

4.3. Water Level Change Rate

The critical drawdown rate is an important indicator for assessing landslide stability. Inverse analysis has determined that the critical daily drop rate for sandstone-mudstone interbedded slopes in Guangxi is 1.8-2.4 m. Exceeding this threshold causes the safety factor to drop by over 0.15. The impact of the water level rise rate is relatively weak, but rapid water accumulation (daily rise >3 m) can trigger excess pore water pressure, leading to temporary instability.

The frequency of water level changes also significantly affects landslide stability. High-frequency fluctuations (period < 30 days) prevent the rock and soil from fully responding, accelerating the rate of damage accumulation. Low-frequency fluctuations (period > 90 days) allow the rock and soil to partially recover, slowing the rate of damage accumulation. Under Guangxi's monsoon climate, water level fluctuations typically occur within a 45–60 day period, falling between high and low frequencies. Their cumulative effects warrant special attention.

5. Evolution of Landslide Stability

5.1. Short-Term Response Characteristics

During a sudden water level drop, landslide stability exhibits a three-stage evolutionary pattern: the initial stage (0-12 hours), during which permeability increases linearly and the safety factor decreases slowly; the acceleration stage (12-48 hours), during which permeability exceeds shear strength and the deformation rate increases exponentially; and the stabilization stage (after 48 hours), during which the sliding surface is broken through and deformation stabilizes. Measured data from a reservoir in Guangxi show that during a water level drop from 680 m to 670 m, the duration of each stage was 8 hours, 32 hours, and 60 hours, respectively, agreeing 89% with the theoretical model.

Short-term response characteristics are closely related to the permeability characteristics of the rock and soil. In highly permeable layers, seepage quickly reaches stability, shortening the duration of the three stages. In weakly permeable layers, seepage hysteresis is significant, extending the duration of the three stages. Guangxi's red-bed soft rock belongs to a moderately permeable layer, and its short-term response characteristics fall somewhere between these two stages. The stage classification criteria need to be modified based on the specific permeability coefficient.

5.2. Long-Term Evolution Trend

Long-term water level fluctuations cause landslide stability to exhibit cyclical decay. A 10-year analysis shows an annual decay rate of the safety factor of 0.8%-1.2%, with the first three years accounting for over 60% of the total decay. This nonlinear decay is closely related to the accumulation of rock and soil damage. When the damage variable D exceeds 0.3, the landslide enters the accelerated deformation stage. Numerical simulations predict that the probability of a reservoir bank landslide will increase by 2.7 times after 50 years of operation at a reservoir in Guangxi.

Long-term evolution trends are significantly controlled by geological and tectonic conditions. In fault-prone areas, the rate of damage accumulation accelerates, and the safety factor decreases by 30%-50% more than in intact rock areas. In the core of the fold, stress concentration leads to accelerated crack propagation, increasing the damage accumulation rate by 20%-40%. Therefore, long-term stability assessments must fully consider the impact of geological structures. Thus, the long-term evolution of slope stability is essentially a cumulative process of repeated short-term responses under geological and tectonic constraints.

6. Prevention and Control Strategies and Recommendations

6.1. Engineering Prevention Measures

Adopt a comprehensive "interception-drainage-protection" management system: A drainage ditch should be constructed at the top of the slope to intercept surface water, with a depth of at least 0.8m and a slope of at least 5%. Horizontal drainage holes should be arranged within the slope, spaced 3-5m apart, with a diameter of 110mm and an inclination of 5°-10°. Prestressed anchor cables should be used to reinforce unstable rock mass. The design anchoring force should be 1.2-1.5 times the rock mass's deadweight, and the anchor cable length should penetrate 3-5m into the potential sliding surface. A project in Guangxi has demonstrated that this system can increase the landslide safety factor by 0.25-0.32.

For slopes with special rock and soil masses, targeted management measures are required. Red-bed soft rock slopes should be reinforced with cement grouting to a depth of 5-8m and intervals of 2-3m. Carbonaceous shale slopes should be reinforced with chemical grouting, using a low-viscosity, high-permeability grouting material. The shear strength of the rock mass after treatment should meet the following requirements: cohesion $c \geq 50$kPa, internal friction angle $\phi \geq 25°$. While engineering measures enhance the inherent resistance of slopes, optimization of reservoir operation reduces external driving forces.

6.2. Operational Scheduling Optimization

Establish a daily water level drawdown control standard: for normal water levels below 675m, the daily drawdown should not exceed 1.5m; for flood-limited water levels above 685m, the daily drawdown should be controlled to within 1.0m. A "stepped" drawdown scheme, with each step down by 0.5m and a rest interval of at least 6 hours, can reduce peak permeability by over 30%. For areas with complex geological conditions, the daily drawdown standard should be further reduced to 0.8-1.0m.

Optimize water storage scheduling to avoid excessive pore water pressure caused by rapid water storage. During the initial water storage phase (raising the water level from dead water level to normal storage level), a staged water storage method should be used, with each stage increasing by 1-2 meters and resting for 24-48 hours to allow pore water pressure to fully dissipate. For slopes with thick, highly permeable layers, the water storage rate should be controlled below 0.3 m/day. Even with engineering and scheduling interventions, continuous monitoring remains essential as a safeguard.

6.3. Monitoring and Early Warning System

Construct an integrated "air-space-ground" monitoring network: Utilize InSAR technology to monitor millimeter-level deformation, with a satellite revisit period of no more than 16 days; deploy GNSS monitoring points on the ground with a sampling frequency of once per hour; install deep-seated pore water pressure gauges with a range of 0-500 kPa and an accuracy of 0.1% FS; and deploy surface crack gauges with a range of 0-100 mm and a resolution of 0.01 mm. Monitoring data should be transmitted to the control center in real time, with processing delays of no more than 5 minutes. Set three levels of warning thresholds: when the deformation rate reaches 1mm/d, a yellow warning is activated, monitoring equipment is checked, and inspection frequency is increased; when it reaches 3mm/d, it is upgraded to an orange warning, and expert consultations are organized to prepare emergency measures; when it reaches 5mm/d, a red warning is issued, emergency evacuation is implemented, and engineering rescue is initiated. The warning system should be linked with the reservoir dispatching system to achieve coordinated control of water level adjustment and landslide prevention.

7. Conclusion

(1) Water level changes affect landslide stability through four mechanisms: permeability effect, softening effect, floating effect, and fatigue effect. Among them, the permeability effect of sudden water level drop is the dominant factor leading to instability, and the fatigue damage caused by long-term water level fluctuations significantly reduces the long-term strength of rock and soil, thus constituting a key mechanism of cumulative instability.

(2) The permeability characteristics of rock and soil, geological structural conditions, and water level change rate constitute a stability control factor system, and the coupling effect of the three determines the landslide response characteristics. The moderate permeability of Guangxi red-bed soft rock, the geological structure with developed faults, and the high-frequency water level fluctuations under the monsoon climate make the landslide problem in this area particularly prominent.

(3) The evolution of landslide stability exhibits a short-term "three-stage" response and a long-term exponential decay pattern. The safety factor can decrease by up to 40% during the 50-year operation period, with the first three years accounting for over 60% of the total. Therefore, special attention should be paid to the initial stability assessment.

(4) A three-in-one prevention and control system of "engineering prevention - scheduling optimization - monitoring and early warning" was proposed. This system has been verified by engineering projects and can reduce the probability of landslide occurrence by over 65%. It is recommended that subsequent research be conducted to study the criteria for landslide instability under multi-field coupling conditions and to improve the early warning model under extreme climatic conditions.

This paper systematically reveals the inherent correlation between water level fluctuations and landslide stability, constructs a theoretical analysis framework tailored to the characteristics of the Guangxi region, and provides scientific guidance for the safe operation of reservoirs. Further large-scale physical model experiments and in-situ field testing are needed to validate the theoretical model and improve the landslide prevention and control technology system.

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