ISSN 2706-655X Vol. 8, Issue 1: 81-86, DOI: 10.25236/IJFET.2026.080112

Research on the Evolution of Slope Seepage Flow and the Time-Dependent Response of Anti-Slip Piles under the Fluctuating Water Level of Reservoir

Ruoyu Zhang*

International College, Zhengzhou University, Zhengzhou, 450000, Henan, China
**Corresponding author*

Abstract: *The periodic fluctuation of reservoir water level is the core driving factor that induces landslides in the reservoir area and leads to the degradation of anti-slip pile performance. Clarifying the coupling mechanism of the two is of great significance for landslide prevention and control. This article takes landslides and anti slip pile engineering in reservoir areas as the object, following the route of "theoretical sorting - experimental monitoring - numerical simulation - case verification", and combining indoor model experiments, on-site monitoring and numerical simulation, systematically explores the evolution law of landslide seepage under reservoir water level fluctuations, the time response characteristics and coupling mechanism of anti slip piles. The study clarified the evolution characteristics of seepage fields at different water level stages and distinguished the differences between seepage driven and buoyancy driven landslides; Revealed the evolution laws of time-dependent deformation, stress, and damage of anti slip piles, and quantified the weights of influencing factors; Elucidated the bidirectional coupling mechanism centered on seepage dynamic water pressure and buoyancy; We have established an evaluation system and method for the time-dependent performance of anti slip piles, and proposed optimization design and prevention measures. The research results provide technical support for the design, construction, and operation of anti-slip piles in the reservoir area, which is of great value in improving the long-term stability of the project and reducing disaster risks.*

Keywords: *fluctuation of reservoir water level; landslide seepage; anti-slide pile*

1. Introduction

As the core infrastructure for water resource regulation, flood control irrigation, and power generation and water supply, reservoirs play an irreplaceable role in social and economic development [1]. However, their periodic water level rise and fall scheduling mode will significantly change the hydrogeological conditions of landslide bodies in the reservoir area, induce severe evolution of seepage fields, and thus threaten the stability of landslides and the long-term service safety of anti-slip piles and other prevention and control projects. During the fluctuation of reservoir water level, the buoyancy generated during the rising stage and the seepage dynamic water pressure formed during the sudden drop stage will break the original stress balance of the slope, causing the reconstruction of pore water pressure and migration of infiltration line in the landslide body, further weakening the shear strength of the rock and soil mass, exacerbating the risk of landslide deformation, and continuously affecting the core prevention and control measures of anti slip piles, leading to pile deformation, stress redistribution, and even failure.

At present, landslide disasters caused by fluctuations in reservoir water levels have become the main hidden danger for the safe operation of reservoirs [2]. Since the first water storage in the Three Gorges Reservoir area in 2003, more than 500 landslides have been triggered by fluctuations in reservoir water levels, seriously threatening the safety of people's lives, property, and ecological environment. Anti-sliding piles are widely used in landslide prevention and control in reservoir areas due to their significant anti sliding effect and strong adaptability. However, in practical engineering, it is common for them to experience increased deformation and performance degradation under long-term fluctuations in reservoir water levels. In existing research, although foreign countries started earlier, the study of the time response of anti slip piles under specific working conditions of reservoir water level fluctuations is not systematic enough, and there is insufficient attention to the coupling effect of seepage and time response; Domestic research often separates the analysis of seepage evolution and the time-dependent response of anti slip piles, and lacks research on the dynamic coupling mechanism between the two, as well as the differential characteristics under different landslide types [3]. Moreover, the quantitative evaluation method for time-

ISSN 2706-655X Vol. 8, Issue 1: 81-86, DOI: 10.25236/IJFET.2026.080112

dependent damage of anti-slip piles needs to be improved. In summary, existing research is difficult to meet the precise needs of engineering design and disaster prevention. Conducting research on the evolution of landslide seepage and the time-dependent response of anti-slip piles under reservoir water level fluctuations has important theoretical value and engineering practical significance.

The core research content of this article includes the evolution law and influencing factors of landslide seepage under the fluctuation of reservoir water level, the time response characteristics of anti-slip piles, the coupling mechanism of the two, and the evaluation and prevention measures of anti-slip pile time performance. The technical route of "theoretical sorting experimental monitoring numerical simulation case verification" is adopted, focusing on breaking through the traditional fragmented research mode, in order to provide technical support for landslide prevention and control engineering in reservoir areas.

2. Relevant theories and experimental design

2.1 Core theoretical basis

The study on the evolution of landslide seepage and the time-dependent response of anti-slip piles under fluctuations in reservoir water level relies on theories such as saturated unsaturated soil mechanics, rock and soil creep, and pile-soil coupling. The essence of landslide seepage is the permeation movement of water in the pores of rock and soil mass. Following the continuity equation of seepage and Darcy's equation of motion, pore water pressure, infiltration line, and permeability coefficient are the core parameters that characterize its evolution [4]. The dynamic changes of the three directly affect the effective stress and stability of the landslide body. During the stages of water level rise and fall and stability, the seepage field shows significant differences, especially during the sudden drop condition in the descending stage, which can easily form a head difference and seepage dynamic water pressure, leading to a lag in the saturation line and exacerbating the risk of landslide instability. The time-dependent response of anti-slip piles is based on the creep characteristics of the rock and soil mass described by the Burgers model. It is the deformation, stress, and damage evolution process of the pile under long-term loads and environmental effects [5]. The seepage changes caused by fluctuations in reservoir water level are its core driving factor, which can lead to mechanical deterioration of the rock and soil mass around the pile, weakened constraints at the pile-soil interface, and drive the pile to exhibit an evolution path of "deformation stress damage". There is a bidirectional coupling relationship between the two, where changes in the seepage field drive the time-dependent response of the anti-slip pile, while the time-dependent deformation of the pile body will adjust the seepage channel and parameters in reverse, providing theoretical support for subsequent research.

2.2 Indoor test design

The indoor test adopts a linkage mode of "seepage simulation+anti slip pile model", selects typical landslide rock and soil samples in the reservoir area, prepares samples according to in-situ compactness, and ensures that the mechanical properties of the samples are consistent with those of the in-situ rock and soil. By using a seepage test device, three sets of water level rise and fall rates (0.5m/d, 1.0m/d, 1.5m/d) and two sets of fluctuation amplitudes (5m, 10m) were set to simulate the entire cycle of reservoir water level rise, stability, and fall. Real time monitoring of seepage parameters was conducted using pore water pressure gauges and seepage flow sensors, and the influence of wave parameters was analyzed. The anti slip pile model adopts a 1:20 scale ratio and is made of reinforced concrete with embedded specimens to simulate long-term load effects. The stress, strain, and pile top displacement of the pile are monitored through strain gauges and displacement meters, and the pile-soil interface parameters are synchronously recorded to verify the correlation between the two, providing experimental basis for numerical simulation parameter calibration.

2.3 On site monitoring plan

Selecting typical landslide control projects in the reservoir area as monitoring stations, following the principles of "comprehensive coverage, prominent focus, precision and reliability", three types of monitoring equipment are deployed to achieve multi parameter synchronous monitoring. Seepage monitoring is carried out by installing pore water pressure gauges and seepage flow sensors at different depths and locations of the landslide body, monitoring once every 2 hours, with a focus on capturing parameter changes during sudden drops in reservoir water level; Landslide deformation monitoring is combined with GPS and inclinometers to monitor surface and deep displacement separately, with an

ISSN 2706-655X Vol. 8, Issue 1: 81-86, DOI: 10.25236/IJFET.2026.080112

accuracy controlled at 0.1mm. Anti slip pile response monitoring involves attaching strain gauges to the pile body and installing displacement sensors at the pile top to monitor stress, strain, and displacement changes over time, while synchronously recording reservoir water level data. Optimize monitoring points to avoid blind spots, ensure continuous and accurate data, compensate for indoor testing limitations, and provide real on-site data support for subsequent research.

3. Evolution law and numerical simulation of landslide seepage under fluctuation of reservoir water level

3.1 Analysis of evolution characteristics of landslide seepage

Based on indoor experiments and on-site monitoring data, the evolution of landslide seepage under reservoir water level fluctuations exhibits significant stage, lag, and spatial differences. In terms of time dimension, the evolution of seepage is highly synchronized with the fluctuation cycle of reservoir water level, and can be divided into three stages: rising, stable, and falling. In the rising stage, the seepage volume increases linearly with the rise of water level, the pore water pressure slowly rises, the saturation line uniformly rises, and the saturation of rock and soil gradually increases; In the stable stage, the seepage field tends to be balanced, and the seepage volume, pore water pressure, and infiltration line remain stable. The mechanical properties of the rock and soil mass are in a dynamic stable state; During the descent stage, the evolution of seepage shows a significant lag, especially when the water level drops sharply. The water head difference inside and outside the landslide increases sharply, and the dynamic water pressure of seepage increases significantly. The dissipation rate of pore water pressure lags behind the rate of water level decline, and the infiltration line shows a changing characteristic of "slow decline steep decline stable". The seepage flow rate increases first and then decreases, which can easily cause damage to the pore structure of the rock and soil mass. In terms of spatial dimension, the surface seepage rate of landslides is higher than that of deep layers, and the seepage intensity at the foot of the slope is higher than that at the top of the slope. The distribution of pore water pressure shows a pattern of "deep layers higher than surface layers, and the foot of the slope higher than the top of the slope". Moreover, the greater the amplitude of water level fluctuations and the faster the rate of rise and fall, the more significant the spatial differences and lag of seepage evolution.

3.2 Construction and verification of numerical model for seepage evolution

Based on the theory of saturated unsaturated seepage, a numerical model of landslide seepage evolution was established using Geo Studio software. The model scope was determined based on on-site geological survey data, and the Mohr Coulomb constitutive model was selected to describe the mechanical properties of the rock and soil mass. The permeability coefficient, porosity, and other parameters measured in indoor experiments were used to assign values. The boundary conditions of the model are set as follows: the left side is the natural slope surface of the landslide body, which is set as a permeable boundary; The right side is a fixed boundary, set as an impermeable boundary; The bottom is a waterproof layer, set as an impermeable boundary; The top is a free water surface that dynamically adjusts with fluctuations in the reservoir water level. Double validation of the model was conducted using indoor experiments and on-site monitoring data. The simulated pore water pressure, seepage rate, and infiltration line variation curves were compared with the measured data to correct the model parameters and ensure that the simulation error was controlled within 5%. The validated model can accurately replicate the dynamic evolution process of the seepage field under the fluctuation of reservoir water level, providing a reliable numerical tool for subsequent analysis of seepage evolution laws and risk assessment.

3.3 Risk assessment of seepage evolution

Based on numerical simulation and on-site monitoring data, a risk assessment index system for seepage evolution is constructed. Three core indicators, namely pore water pressure growth rate, infiltration line lifting rate, and seepage flow rate mutation coefficient, are selected. The weights of each indicator are determined using the Analytic Hierarchy Process, and the risk is classified into three levels: low risk, medium risk, and high risk, using the Fuzzy Comprehensive Evaluation Method. The evaluation results indicate that under the condition of sudden drop in reservoir water level, the risk of landslide seepage evolution is significantly higher than that under rising and stable conditions. Moreover, when the water level rises and falls at a rate of 1.5m/d and fluctuates by 10m, the seepage evolution is in a high-risk state. At this time, the pore water pressure changes sharply, the infiltration line drops rapidly, and it is easy to cause local instability of the landslide body; When the water level rises and falls at a rate of 0.5m/d and fluctuates by 5m, the seepage evolution is in a low-risk state, and the overall seepage field is stable. Based on the evaluation results, targeted prevention and control measures are proposed to provide scientific basis for the prevention and control of landslide seepage disasters in the reservoir area, and to reduce the risk of landslide instability caused by seepage evolution.

4. Time response and coupling mechanism analysis of anti slip piles under fluctuations in reservoir water level

4.1 Analysis of time response characteristics of anti sliding piles

Based on indoor model experiments and on-site monitoring data, the system analyzes the time-dependent response characteristics of anti slip piles under fluctuations in reservoir water level, including time-dependent deformation, stress evolution, and damage characteristics. In terms of time-dependent deformation, anti slip piles exhibit an evolutionary law of "rapid deformation in the initial stage, slow creep in the middle stage, and later stabilization". When the reservoir water level drops sharply, the deformation rate significantly increases, and when the reservoir water level rises, the deformation tends to stabilize. Moreover, the deformation amplitude of anti slip piles corresponding to seepage driven landslides is greater than that of buoyancy driven landslides; In terms of stress evolution, the stress distribution of the pile body shows obvious nonlinear characteristics, with significant stress concentration in the middle and lower parts of the pile body. The fluctuation of the reservoir water level leads to repeated stress fluctuations, and under long-term action, the stress of the pile body gradually accumulates, showing a trend of aging growth; In terms of damage characteristics, under long-term aging, micro cracks appear in the concrete of the anti slip pile body, and the pile-soil interface exhibits detachment and sliding phenomena. The bearing capacity of the pile gradually decreases, and the rate of attenuation is positively correlated with the fluctuation amplitude of the reservoir water level and the seepage strength. The degree of pile damage can be quantified by referring to relevant research results.

4.2 Numerical simulation of time-dependent response of anti slip piles

On the basis of the numerical model of landslide seepage evolution, an anti sliding pile model is embedded to construct a coupled numerical model of "landslide seepage anti sliding pile". Factors such as rock and soil creep, pile-soil interface interaction, and seepage time effect are considered to simulate the time deformation, stress evolution, and damage process of anti sliding piles under reservoir water level fluctuations. The influence of different reservoir water level fluctuation parameters and seepage parameters on the time response of anti sliding piles is analyzed, and the key influencing factors and mechanisms of anti sliding pile time response are clarified. The differences in time response of anti sliding piles under different types of landslides are compared to verify the rationality of laboratory tests and on-site monitoring results. The quantitative analysis method of anti sliding pile time response is further improved, and the accuracy of the model can be optimized using software such as PLAXIS 3D to improve simulation results.

4.3 Coupling mechanism between landslide seepage evolution and time-dependent response of anti slide piles

In order to clarify the intrinsic relationship between the evolution of landslide seepage and the time-dependent response of anti slip piles under the fluctuation of reservoir water level, combined with indoor model tests, long-term on-site monitoring, and three-dimensional numerical simulations of "landslide seepage anti slip pile" coupling, the system deeply reveals the bidirectional coupling mechanism of the two, providing solid theoretical support for the time-dependent prevention and control of anti slip piles. Coupling mechanism analysis takes reservoir water level fluctuations as the core driving source, integrates multidimensional data for cross validation, and ensures the scientific and reliable nature of the mechanism revealed.

On the one hand, the periodic rise and fall of reservoir water level triggers the dynamic evolution of landslide seepage field. By changing the hydrogeological conditions of the landslide body, it indirectly drives the anti slip pile to produce time-dependent response, forming a clear positive driving path: the fluctuation of reservoir water level directly leads to the reconstruction of pore water pressure distribution and the migration of infiltration line position in the landslide body, thereby weakening the shear strength and integrity of the rock and soil mass, changing the contact characteristics of the pile-soil interface, weakening the constraint effect of the soil around the pile on the pile body, uneven distribution of reaction force, and ultimately increasing the stress load on the anti slip pile, driving the pile body to produce time-dependent deformation, stress accumulation, and structural damage, forming a complete positive driving mechanism of "reservoir water level fluctuation → seepage evolution → deterioration of rock and soil mechanical properties → time-dependent response of the anti slip pile".

On the other hand, the time-dependent evolution of anti slip piles is not a passive response. Their time-dependent deformation and structural damage will have a reverse effect on the stress balance of the landslide body, thereby affecting the evolution of the seepage field and forming a bidirectional coupling effect: the time-dependent deformation of anti slip piles will change the stress distribution state of the landslide body, adjust the deformation trend of the landslide body, cause changes in the shape of the internal seepage channels of the landslide body, and thus cause abnormal fluctuations in seepage parameters such as pore water pressure and seepage flow rate, which will in turn affect the evolution law of the seepage field. At the same time, the key nodes and core influence paths of the coupling effect are clearly defined, with a focus on analyzing the core driving effects of seepage dynamic water pressure and buoyancy in the coupling process. Dynamic water pressure dominates the coupling effect during the period of sudden drop in reservoir water level, while buoyancy dominates the coupling effect during the period of high water level, providing precise theoretical guidance for the formulation of subsequent anti slip pile time prevention and control measures.

4.4 Time performance evaluation and optimization suggestions for anti slip piles

To scientifically quantify the long-term service performance of anti slip piles under fluctuations in reservoir water level, accurately identify the risk of time-dependent failure, and combine the research results of the coupling mechanism between seepage evolution and time-dependent response of anti slip piles in the previous section, establish a set of evaluation indicators for the time-dependent performance of anti slip piles that are both scientific, systematic, and operable. The system focuses on the time-dependent evolution characteristics of anti slip piles and covers three core evaluation indicators: time-dependent deformation rate, which is used to characterize the dynamic development trend of time-dependent deformation of anti slip piles and reflect the creep characteristics of the pile body; Accumulated stress, quantifying the cumulative effect of long-term reservoir water level fluctuations and seepage on pile stress, and revealing the degradation law of pile stress; The degree of damage is evaluated through parameters such as the development of concrete cracks in the pile body and the sliding of the pile-soil interface, to assess the integrity of the pile structure and the degradation of its bearing capacity. This comprehensively covers the key evaluation dimensions of the time-dependent performance of anti slip piles.

Using a multi index quantitative evaluation method, combined with Analytic Hierarchy Process and Fuzzy Comprehensive Evaluation Method, the time performance of anti slip piles under reservoir water level fluctuations is quantitatively evaluated through standardized evaluation indicators and scientific weighting. The time performance is divided into four levels: excellent, good, qualified, and unqualified. The key risk points of anti slip pile time failure are accurately identified, and the prevention and control priorities corresponding to different risk levels are clarified. Based on the coupling mechanism between the evolution of landslide seepage and the time-dependent response of anti slip piles, targeted optimization design and time-dependent prevention and control measures for anti slip piles are proposed: This study optimizes the size and layout of pile bodies to adapt to the seepage characteristics and stress requirements of different types of landslides; reasonably selects pile materials to improve impermeability and creep resistance; adds a drainage system to effectively alleviate the adverse effects of seepage on pile bodies; adopts steel fiber reinforcement technology to enhance the concrete strength of pile bodies and suppress the propagation of microcracks in pile bodies; and establishes a full-life-cycle long-term monitoring and intelligent early warning system to capture real-time abnormal responses of pile bodies. Meanwhile, with reference to the design concept of the new anti-slip pile prevention and control structure, this study further optimizes the prevention and control plan, which significantly improves the long-term service stability of anti-slip piles, reduces the risk of aging failure, and provides scientific and reliable technical guidance for the design, construction, and operation of anti-slip piles in landslide prevention and control projects in the reservoir area.

5. Conclusion

Based on the research idea of "theoretical sorting experimental monitoring numerical simulation case

ISSN 2706-655X Vol. 8, Issue 1: 81-86, DOI: 10.25236/IJFET.2026.080112

verification" in this article, combined with the systematic research results of indoor experiments, on-site monitoring, and numerical simulation, this paper systematically summarizes the core research content of landslide seepage evolution and anti slip pile time response under reservoir water level fluctuations, and clarifies the following four core conclusions.

(1) This paper elucidates the dynamic evolution law of landslide seepage field under the fluctuation of reservoir water level, and combines indoor seepage simulation experiments and on-site monitoring data to clarify the differences in seepage characteristics during the rising, stable, and falling stages of reservoir water level. The system reveals the regulatory effects of key factors such as water level rise and fall rate, fluctuation amplitude, and rock and soil permeability on seepage evolution, and clearly distinguishes the differences in seepage evolution between seepage driven and buoyancy driven landslides. It is clarified that the former is mainly driven by dynamic water pressure during the drawdown period of reservoir water level, and the hysteresis effect of the infiltration line is significant, while the latter is mainly driven by buoyancy during the high water level period, and the synchronization between the infiltration line and reservoir water level changes is strong.

(2) The time response characteristics of anti slip piles under the fluctuation of reservoir water level were revealed. Based on the results of anti slip pile model tests and long-term on-site monitoring, the dynamic evolution laws of anti slip pile deformation, stress evolution, and damage were clarified. Through quantitative analysis, the degree of influence of factors such as reservoir water level fluctuation amplitude, seepage strength, and rock and soil creep characteristics on the time response of anti slip piles was determined, providing a quantitative basis for evaluating the time performance of anti slip piles.

(3) This paper elucidates the bidirectional coupling mechanism between landslide seepage evolution and the time-dependent response of anti slip piles. By combining numerical simulation and experimental verification, the key path and core influencing factors of the coupling effect between the two are clarified. The core driving role of seepage dynamic water pressure and buoyancy in the coupling process is clarified, revealing the positive driving path of "reservoir water level fluctuation seepage evolution rock and soil mechanics degradation anti slip pile time-dependent response" and the reaction mechanism of anti slip pile time-dependent deformation on the seepage field.

(4) A scientific and comprehensive evaluation index system and quantitative evaluation method for the time-dependent performance of anti slip piles have been established, covering core indicators such as time-dependent deformation rate, stress accumulation, and damage degree. Combined with coupling mechanism analysis, targeted optimization design schemes and time-dependent prevention and control measures for anti slip piles have been proposed, providing reliable technical support and theoretical basis for the design, construction, and operation of landslide prevention and control projects in the reservoir area.

References

[1] Dong J Y. Analysis of Deformation and Stability of Slope Rock Mass Affected by Reservoir Water Level Fluctuations [D]. Dalian University of Technology, 2023.

[2] Qing J, Zhu L, Chen H, Xie P. Fluid structure coupling analysis of landslides under the influence of reservoir water level fluctuations and rainfall [J]. Journal of Hubei University of Technology, 2021, 36 (04): 52-56+84.

[3] Zheng H, Wu Y P, Liao K. Reliability Study of Linjiang No.1 Landslide on Loess Slope under the Effects of Reservoir Water and Rainfall [J]. Exploration Science and Technology, 2021, (03):5-11+60.

[4] Xue Y, Wu Y P, Miao F S, Li L W, Liao K, Zhang L F. Seepage and deformation analysis of Baishuihe landslide considering spatial variability of saturated hydraulic conductivity under reservoir water level fluctuation[J].ROCK AND SOIL MECHANICS,2020,41(5):1709-1720.

[5] Xiang J S. The Response Law and Application of Groundwater Level to Reservoir Water Level Fluctuations in Complex Structural Landslides [D]. China University of Geosciences (Beijing), 2019.