

Stability Analysis of Riverbank Slopes Under Fluctuating Water Levels: A Case Study on Martapura River

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This study investigates the stability of natural slopes along the Martapura River, particularly in areas adjacent to roadways, with a focus on assessing the impact of river water level fluctuations on slope safety factors. The analysis was performed using SLOPE/W, a GeoStudio module, based on the widely adopted limit equilibrium method. Several hydrological scenarios, including dry, normal, rapid rise, and rapid drawdown conditions, were simulated to evaluate their influence on slope behavior. The results demonstrate that both river and groundwater level variations significantly affect slope stability. Rising groundwater levels increase pore water pressure, reduce effective stress, and lower the factor of safety (FS) from 1.118 under dry conditions to 1.102 in the normal-water scenario (−1.4%). In contrast, a sudden increase in river level induces a temporary stabilizing effect, elevating the FS to 1.473 (+33.7% relative to normal), before stabilizing at 1.323. The most critical condition arises during rapid drawdown, where a sudden drop in river level while groundwater remains high leads to elevated pore pressure, loss of hydrostatic support, and a significant FS reduction to 0.929 (−30%), posing a risk of slope failure. Moreover, the hydrologic hysteresis between river and groundwater responses, mainly governed by soil permeability, emerges as a key factor influencing slope stability dynamics. These findings highlight the importance of integrating hydrological variability into slope monitoring and risk mitigation strategies.

Kata kunci: slope stability, water level, hydrologic hysteresis, safety factor.

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Introduction

Indonesia is a tropical country endowed with thousands of rivers, both large and small, distributed across its vast territory. Rivers play a vital role in supporting the livelihoods of communities, serving as sources of water, means of transportation, and zones that sustain economic activities. However, the geographical conditions, high rainfall intensity, and infrastructure development along river basins have led to various challenges, such as slope instability on riverbanks (Aisah & Gofar, 2022; Anggraini et al., 2022; Aslam & Gofar, 2022; Miao et al., 2022; Riskyanto et al., 2023; Semmad et al., 2022). Natural slopes along riverbanks, particularly in urban areas, frequently experience equilibrium disturbances due to erosion, and changes in river flow patterns, as well as the construction of roads and residential areas (Amir et al., 2024; Ardiansyah, 2023).

One of the areas facing such challenges is the riverbank of the Martapura River in Banjar Regency,

South Kalimantan. This river flows through the city and plays a significant role in supporting local transportation, trade, and the social life of the community (Juliana et al., 2022). At several points along the riverbank, slope instability has been observed in the form of landslides, which pose risks to public safety and disrupt access to roads located above these slopes. Therefore, a slope stability analysis in this area is of critical importance.

Slope instability along riverbanks not only disrupts road infrastructure but also has the potential to impede economic activities and endanger the safety of surrounding communities. The stability of a slope is influenced by various factors, including the mechanical properties of the soil, slope geometry, hydrological conditions, and fluctuations in river water levels, which can increase pore water pressure (Chang et al., 2023; Chowdhury et al., 2023; Murgia et al., 2022). Significant variations in river water levels, particularly during the rainy season or flooding events, may reduce soil-bearing capacity and accelerate slope failure. Research conducted at the Three Gorges Reservoir in China

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demonstrated that the combination of water level fluctuations and rainfall can result in complex slope failure patterns, leading to large-scale landslides along riverbanks (Miao et al., 2022). Additionally, studies in river basin areas of Southern Thailand revealed that prolonged rainfall and rising river levels can induce repeated shear-type and cantilever-type slope failures, with riverbank retreat exceeding five meters during a single flood period (Semmad et al., 2022). These findings highlight the importance of incorporating hydrological influences, such as river water level, in riverbank slope stability analyses.

This study adopts a numerical approach using the limit equilibrium-based software GeoStudio (SLOPE/W) to conduct slope stability analysis. The software allows for the simulation of various slope conditions and water level scenarios, and it calculates the factor of safety (Semmad et al., 2022; Tan et al., 2023; Th Al-Hadidi & Hashim, 2021). A study by Sun et al., (2023) demonstrated that SLOPE/W can effectively analyze slope stability and water level fluctuations, showing that rapid drawdown in front of a slope can generate

significant downward flow forces, reduce the factor of

safety, and increase the likelihood of failure. The data used in this analysis include slope geometry, soil parameters obtained from field and laboratory investigations, and river water level data.

The objective of this research is to analyze the stability of natural slopes along the Martapura River, particularly at locations adjacent to roadways, and to examine the influence of river water level fluctuations on changes in slope safety factors. The findings are expected to contribute to landslide risk mitigation efforts and support more informed slope protection planning in the area.

Methods

This research involves a numerical simulation aimed at evaluating slope stability along the Martapura Riverbanks. The primary objective is to investigate how fluctuations in river water levels affect the factor of safety of slopes within the study area. The analysis is conducted using SLOPE/W, a module within the GeoStudio software suite, which is widely used in previous studies for slope assessment based on the limit equilibrium method (Sudani et al., 2023; Wubalem, 2022).

Study Area

This study was conducted at a selected point along the Martapura Riverbank in South Kalimantan. The location was chosen due to indications of slope instability in the area. It is situated above a roadway that is frequently used by commuters. The site was selected based on historical data indicating signs of slope instability in the region. Specifically, the study area is located on Jl. Martapura Lama, Sungai Batang, Martapura Barat Subdistrict, Banjar Regency, Kalimantan Selatan Province. presents the location of the study area.



Figure 1 Study area on the Martapura River, South Kalimantan.

Site Characterization

The soil characteristic used in this study is obtained through direct geotechnical investigation in the field. This includes the results of the Standard Penetration Test (SPT) as well as laboratory testing of soil samples, such as moisture content, specific gravity, and shear strength parameters (cohesion and internal friction angle). The soil stratigraphy can be interpreted based on the SPT results, borehole log data obtained during drilling and laboratory tests (Dewi et al., 2024). The interpreted soil profile of the slope in this study is illustrated in Figure 2.

A total of four distinct soil layers were identified at the study site. The uppermost layer is composed of fill material with Standard Penetration Test (SPT) values ranging from 2 to 3 and an average thickness of approximately 4 meters. Beneath it lies a sandy silt layer with an SPT value of around 4 and a thickness of about 2 meters. The third layer consists of silty clay, exhibiting SPT values between 5 and 7 and extending up to 6 meters in thickness. The deepest layer is denser clay, characterized by SPT values ranging from 10 to 13. The geotechnical parameters derived from these layers were used as input for slope stability modeling using the SLOPE/W module. A summary of the soil parameters is presented in Table 1.

Table 1 Soil physical properties

Physical Properties	Soil Layer			
	1	2	3	4
Unit Weight, γ (kN/m ³)	16.3	16.0	14.0	18.5
Specific Gravity, G_s	2.60	2.67	2.64	2.68
Cohesion, c (kPa)	10	12	32	50
Internal friction angles, ϕ' (°)	23	19	17	10

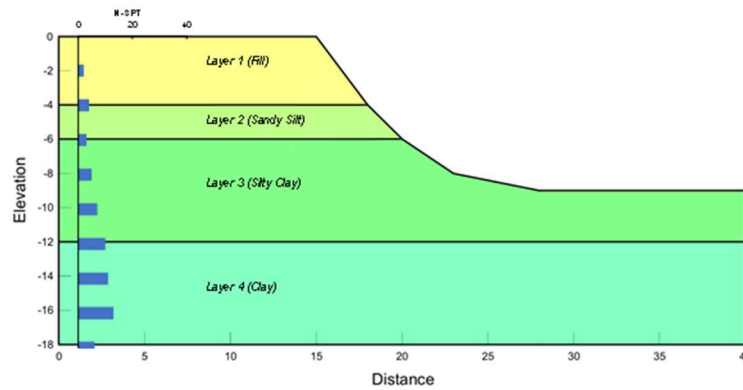


Figure 2 Soil Profile Interpretation Derived from Field and Laboratory Investigations

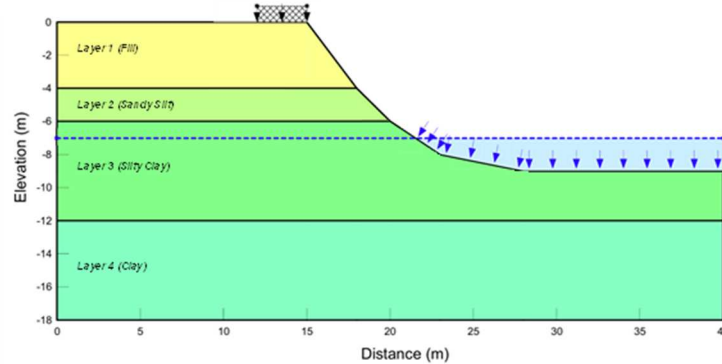


Figure 3 SLOPE/W simulation model showing soil layers, slope geometry, surcharge load, and groundwater conditions

Modeling of Slope Stability

Both natural and engineered slopes are prone to instability when the terrain is inclined, due to the gravitational force acting downslope on the soil mass. This force can initiate movement if it surpasses the soil's shear resistance along a potential slip plane. Slope stability assessments aim to evaluate this risk by analyzing the balance between the mobilized shear stress along a presumed failure surface and the soil's available shear strength. (Braja, 1995).

In general, slope stability can be assessed by calculating the factor of safety, which can be determined using Equation 1 (Braja, 1995).

$$FS = \frac{\tau_f}{\tau_d} \quad (1)$$

In this context, FS refers to the factor of safety, τ_f indicates the shear strength of the soil, and τ_d signifies the mobilized shear stress along the potential failure plane. The mobilized shear strength is influenced by two primary parameters: cohesion and the angle of internal friction. This relationship can be represented by Equation 2, in which c denotes soil cohesion, ϕ is the internal friction angle, and σ represents the normal stress acting on the anticipated slip surface.

$$\tau_f = c + \sigma \tan \phi \quad (2)$$

In riverbank regions, fluctuations in groundwater and river water levels are among the most critical and variable factors impacting slope stability. These changes can significantly influence the pore water pressure within the soil mass, which in turn affects the slope's factor of safety. The resulting variation in shear strength due to changes in pore pressure is described by Equations 3 and 4, where c' denotes effective cohesion, ϕ' is the effective internal friction angle, σ' represents the total normal stress, and u is the pore water pressure.

$$\tau = c' + \sigma' \tan \phi' \quad (3)$$

$$\tau = c' + (\sigma - u) \tan \phi' \quad (4)$$

SLOPE/W, part of the GeoStudio software package, is extensively applied in conducting slope stability analyses. It utilizes the general limit equilibrium method originally proposed by Fredlund & Krahn (1977) and later refined by Fredlund (1981). This method incorporates two distinct factor of safety calculations, allowing for a range of assumptions regarding interslice shear and normal forces. One equation evaluates safety based on moment equilibrium (F_m), while the other assesses it through horizontal force equilibrium (F_f). These can be determined using Equations 5 and 6 (Seequent, 2022).

$$F_m = \frac{\sum (c' \beta R + (N - u \beta) R \tan \phi')}{\sum W_x - \sum N f \pm \sum D d} \quad (5)$$

Table 2 Water level conditions of groundwater and river water across different simulation scenarios.

Scenario	Grounwater Level (m)	River Water Level (m)	Description
1	-7.00	-7.00	Dry condition
2	-5.00	-5.00	Normal condition
3	-5.00	-1.50	Initial flood condition
4	-1.50	-1.50	Flood condition
5	-1.50	-5.00	Post-flood river water drawdown

$$F_f = \frac{\sum (c' \beta \cos \alpha + (N - u \beta) \tan \phi' \cos \alpha')}{\sum N \sin \alpha - \sum D \cos \omega} \quad (6)$$

In this study, the slope model in SLOPE/W was constructed based on the initial field conditions. The slope geometry, including height, length, and inclination, is illustrated in Figure 3. The soil parameters used in the model were derived from the laboratory test results presented in Table 1 and were assumed to be uniform within each soil layer. A uniform load of 20 kN/m³ was applied at the top of the slope to simulate the effect of roadway and vehicular loads. In this study, the modelling focuses solely on the influence of river water level fluctuations.

Scenarios and Analytical Method

The simulation was conducted for five different groundwater and river water level scenarios: dry condition, normal condition, flood onset, peak flood condition, and post-flood water recession. These five scenarios represent the water level conditions observed along the Martapura River. Slope stability analysis was carried out using the Morgenstern-Price method in SLOPE/W software. Table 2 presents the groundwater and river water elevations for each modelled scenario.

The first scenario represents dry season conditions, where both the groundwater and river water levels are at an elevation of -7 m relative to the slope surface. In the second scenario, water levels rise to -5 m, reflecting normal conditions following the rainy season. The third scenario corresponds to the initial stage of flooding, during which the river water level rapidly increases to -1.5 m, while the groundwater level remains at -5 m due to delayed response. The fourth scenario depicts the peak of the flood event, where both the groundwater and river water levels are at -1.5 m. Finally, the fifth scenario represents the recession phase after the flood, where the river water level has dropped back to -5 m, but the groundwater level remains elevated at -1.5 m.

Results and Discussion

Simulation Results

In this study, a numerical analysis of slope stability along the Martapura Riverbank by considering five scenarios of groundwater and river water level fluctuations. The analysis was performed with SLOPE/W, utilizing the Morgenstern-Price method within the limit equilibrium framework to determine the slope's factor of safety (FS) under different water

level scenarios. The modelling results focus on changes in FS values due to the interaction between groundwater and river water levels as they vary incrementally. Table 3 presents a summary of the modelling results in this study for all scenarios.

The first and second scenario simulations indicated that an increase in groundwater level from -7 m to -5 m, without any change in the river water level, resulted in elevated pore water pressure and a reduction in effective stress within the slope mass. Consequently, the factor of safety (FS) decreased from 1.118 to 1.102

Table 3 Factor of Safety (FS) results for slope stability analysis under various groundwater and river water level conditions.

Scenario	Description	SF
1	Dry condition	1.118
2	Normal condition	1.102
3	Initial flood condition	1.473
4	Flood condition	1.323
5	Post-flood river water drawdown	0.929

(1.4%), reflecting a decline in slope stability. This is attributed to the increased pore water pressure, which reduces the soil shear strength and subsequently lowers the slope's stability.

The third condition shows a significant increase in the factor of safety (FS) from 1.102 to 1.473 (increase 0.371 or 33.7%) when the river water level rises to an elevation of -1.5 m, while the groundwater level remains at -5 m. Although this appears to indicate stability, it reflects a temporary stabilization due to the delayed infiltration of floodwater into the slope, influenced by the hydraulic conductivity of the slope soil in response to the rising river water level (Xia et al., 2014). When the river water level rises rapidly (during a flood), water does not immediately infiltrate the slope, creating an inward seepage force that temporarily increases the slope's safety factor (Zhao et al., 2024). This occurs when the rate of river water rise exceeds the infiltration rate into the soil mass, meaning the system has not yet reached hydraulic equilibrium. This condition is only temporary, as the situation changes when the groundwater level rises and leads to increased pore water pressure.

In the fourth condition, the groundwater level rises to align with the river water level at an elevation of -1.5

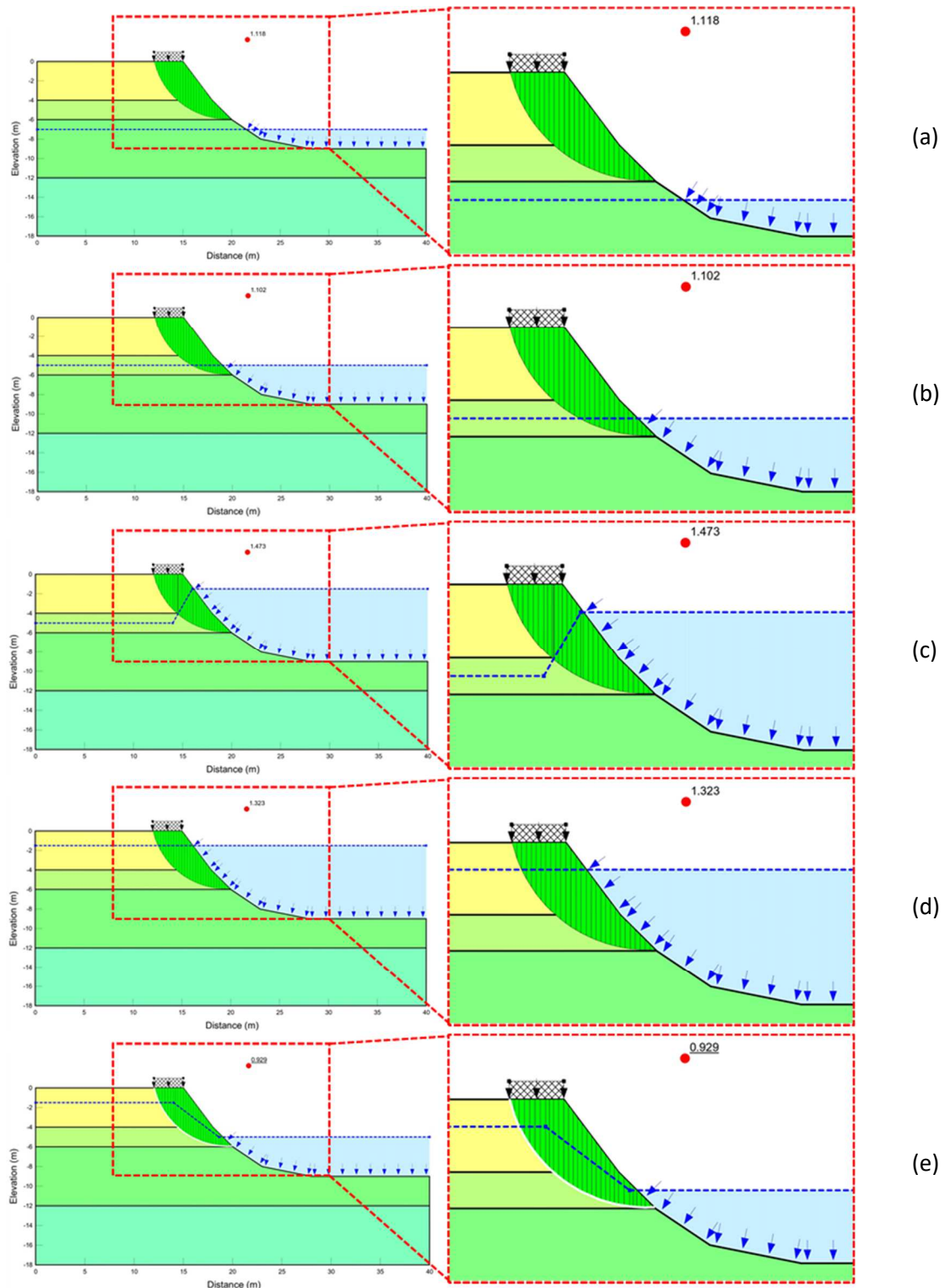


Figure 4 Slope stability modeling results under different water level scenarios: (a) Scenario 1 – Dry conditions, (b) Scenario 2 – Normal conditions, (c) Scenario 3 – Initial flood stage, (d) Scenario 4 – Flood conditions, (e) Scenario 5 – Post-flood river water drawdown

m. This change results in the loss of the negative hydraulic gradient and the elimination of capillary pressure that previously contributed to stabilization. Consequently, pore water pressure increases significantly while effective stress decreases, causing the factor of safety to drop from 1.473 to 1.323 (-10.2 % from Scenario 3). This phenomenon confirms that the

high stability observed in the previous condition was temporary.

The fifth condition represents the most critical phase in the simulation, where the river water level drastically drops to an elevation of -5 m while the groundwater level remains high at -1.5 m. This rapid decline strips away the external hydrostatic support

that previously restrained the soil mass, causing the factor of safety (FS) to fall from 1.323 in the preceding flood condition to 0.929—a drop of 0.394, or roughly 30 %. Such a sharp reduction confirms the classic rapid-drawdown failure mechanism, long recognized as one of the most hazardous triggers of slope instability near water bodies (Ali et al., 2022; Kafle et al., 2022; Mase et al., 2022; Zhao et al., 2024). Consequently, this drawdown phase demands heightened attention in slope-management and monitoring programs, especially at sites where groundwater responds sluggishly to river-level fluctuations.

Temporary Stability Condition

The variation in the slope's factor of safety observed in Scenario 5 is largely governed by the time lag between fluctuations in river water levels and the corresponding groundwater response—a phenomenon known as hydrologic hysteresis. In natural riverbank environments, groundwater does not respond instantaneously to changes in surface water levels. Instead, its movement is delayed, particularly in low-permeability soils such as clays and silts. The duration of this delay is influenced by the soil's hydraulic conductivity, storage capacity, and stratification (Ali et al., 2022; Nasr & Ati, 2023). As a result, temporary but significant hydraulic gradients develop within the slope, especially during periods of rapid drawdown or rise, as clearly illustrated in Scenarios 3 and 5.

When the river water rises rapidly, the slope may temporarily become more stable due to the transient confining pressure exerted by the elevated water level. This external pressure counteracts internal pore pressures, increasing the net effective stress and momentarily improving slope stability, as seen in Scenario 3. However, during a rapid drop in river stage, as simulated in Scenario 5, the situation reverses. The hydrostatic pressure that previously supported the slope face dissipates quickly, while the pore water within the slope remains trapped due to slow drainage through finer soils. This mismatch in hydraulic response leads to the buildup of excess pore-water pressures, which reduce effective stress and weaken the soil's shear resistance, particularly near the slope face and potential failure surfaces.

Under these conditions, the soil mass remains saturated and heavy, contributing to downslope driving forces at the same time that its shear strength is significantly diminished. This combination makes the slope most vulnerable during or immediately after the drawdown phase, despite its apparent stability during the peak flood stage. The time-lagged nature of the groundwater response means that the most critical conditions do not always align with the highest external water level, but rather with the mismatch in pressure gradients between the inside and outside of the slope.

Moreover, the effects of hydrologic hysteresis are most pronounced during the falling limb of the

hydrograph. While groundwater may rise relatively quickly in response to flooding, the recession is delayed, especially in layered or heterogeneous soils with lower permeability. This lag causes prolonged high pore pressures and generates strong outward seepage forces acting perpendicular to the slope surface. These forces further reduce effective stress and can initiate or accelerate failure mechanisms, particularly in slopes with pre-existing weaknesses or minimal safety margins.

Therefore, the post-flood drawdown period represents the most critical window for riverbank stability assessment. Conventional steady-state models may significantly underestimate the risk during this phase. It is essential to adopt transient seepage analyses, incorporate soil-specific hydraulic parameters, and utilize real-time monitoring systems to capture the dynamic interactions between surface and subsurface water (Khatun et al., 2019). Ignoring this time-dependent behavior and the effects of hydrologic hysteresis may lead to misleading conclusions regarding slope stability, potentially resulting in inadequate mitigation strategies or unsafe design decisions.

Hydraulic Conductivity and Soil Stratification Effects

One of the most influential factors in the slope's response to river water level fluctuations is the variation in hydraulic conductivity and the presence of stratified soil layers within the riverbank. In natural riverbanks such as those along the Martapura River, the subsurface is rarely homogeneous; instead, it often comprises alternating layers of silts, clays, and sandy materials, each with different permeability characteristics. This stratification plays a critical role in governing the rate at which pore water pressures dissipate during changes in river stage. Layers with low permeability, such as clay or silty clay, restrict vertical and horizontal drainage, slowing the adjustment of the groundwater table to external water level changes. As a result, pore pressures can remain elevated for extended periods within these finer layers, creating internal hydraulic gradients that reduce effective stress and promote instability, particularly during the drawdown phase.

In scenarios where more permeable materials such as sandy silt are sandwiched between or underlain by less permeable clays, water may become trapped in localized zones, leading to the formation of perched water tables or confined conditions that further exacerbate slope vulnerability (Gohardoust et al., 2017). These conditions not only delay the reduction in pore pressure but can also create differential seepage forces across soil interfaces, potentially initiating progressive failure or slippage along these boundaries. In this numerical model, the behavior is reflected in the persistence of high pore pressures in certain layers during drawdown, especially in Scenario 5, where slow-draining materials delayed the slope's hydraulic equilibrium. This response confirms that soil layering

and anisotropic permeability must be carefully considered when assessing riverbank stability, as simplifications assuming uniform soil behavior may underestimate the actual risk.

Moreover, stratification affects not only drainage patterns but also the location and shape of the potential failure surface, as water tends to accumulate above or within fine-grained horizons. These trapped pressures can induce softening of soil strength parameters, particularly cohesion and effective stress-dependent friction, resulting in shallow or compound failure surfaces. Therefore, a detailed understanding of the subsurface profile, gathered through field investigations such as borehole logging, permeability testing, or piezometer data, is essential to properly calibrate the model and to interpret slope behavior under fluctuating hydraulic conditions (Mantoglou & Gelhar, 1987). Failure to account for these stratified responses can lead to overly optimistic assessments of slope stability and ineffective mitigation strategies.

Conclusions

Based on the numerical analyses and simulations conducted in this study, several key conclusions can be drawn regarding the stability of the Martapura Riverbank slopes under varying water level conditions.

1. This analysis demonstrates that fluctuations in river water level and groundwater significantly influence slope stability along the Martapura Riverbank. Gradual rises in groundwater level (Scenario 2) led to increased pore water pressure and decreased effective stress, reduction the slope's factor of safety (FS) from 1.118 in Scenario 1 to 1.102 in Scenario 2 (-1.4%).
2. Conversely, a rapid increase in river water level can induce a temporary stability phenomenon (Scenario 3) where rising FS from 1.102 to 1.473 (increase 0.371 or 33.7%), which poses a risk of delaying early detection of potential slope failure.
3. The most critical slope failure occurs during the drawdown phase, where the river water level drops (Scenario 5) while groundwater remains elevated. The loss of hydrostatic support and the rise in pore-water pressure lower FS from 1.323 in Scenario 4 to 0.929 in Scenario 5 (-0.394 or -30 %), triggering slope failure.
4. The difference in response time between groundwater and river water levels (hydrologic hysteresis) is a key factor influencing slope stability fluctuations. This discrepancy is largely governed by soil permeability, underscoring the importance of considering hydrological dynamics in slope stability monitoring and analysis.
5. The findings of this study underscore the necessity for simultaneous monitoring of both river and groundwater levels to achieve more accurate predictions of slope stability. Furthermore,

mitigation strategies that incorporate hydrological characteristics and soil properties are essential to prevent slope failures that could threaten infrastructure and the surrounding environment.

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