DOI: 10.23968/2500-0055-2025-10-4-56-64

EFFECTS OF RAINFALL AND WATER LEVEL ON THE STABILITY OF THE BAU TRANG LAKE BANK, BAC BINH DISTRICT, BINH THUAN PROVINCE, VIETNAM

Ngoc Thinh Pham, Thi Mai Suong Nguyen*, Van Phu Dang

Thuyloi University, Hanoi, Vietnam

*Corresponding author's email: suongntm@tlu.edu.vn

Abstract

Introduction. This study evaluates the impact of lake water levels, rainfall, and the presence of small pits on the stability of the banks of Bau Trang Lake, a national scenic site in Binh Thuan Province, Vietnam. **Methods.** To assess the slope stability safety factor, several scenarios were simulated using GeoStudio 2024 software with the SEEP/W and SLOPE/W modules. **Results.** With a safety factor reduction of less than 1%, the results show that the small pit has a minimal effect on lake bank stability. The lake water level plays a critical role: low water levels increase the likelihood of instability, whereas high water levels enhance stability and lower pore water pressure. Particularly when combined with low water levels, intense or prolonged rainfall significantly decreases the safety factor by increasing soil saturation and reducing shear strength. The study recommends maintaining stable water levels, reinforcing high-risk areas, and implementing effective drainage systems to mitigate the effects of rainfall. These findings provide a scientific basis for sustainable management strategies to preserve the environment and landscape of Bau Trang Lake, and guide future research on shoreline stability under geological and climatic influences.

Keywords: Bau Trang Lake; slope stability; lake level; rainfall; GeoStudio.

Introduction

One significant issue that requires careful attention on lake and river banks is slope erosion. According to previous research, the erosion process is influenced by both natural and human-induced factors, including geography, geology, water levels, wind-blown sand, and human activities. Slope stability is strongly affected by rainfall characteristics such as intensity, duration, and patterns (Na et al., 2023; Qian et al., 2021; Wang et al., 2022; Zhang and Lu, 2021). Prolonged and intense rainfall can increase pore water pressure and soil moisture, thereby reducing the soil's shear strength and undermining slope stability (He et al., 2023; Huang et al., 2023; Liu, 2023; Na et al., 2023). This can raise the likelihood of landslides, particularly during long periods of heavy rainfall. Additionally, the initial moisture content and groundwater level of the slope are important factors determining slope stability under rainy conditions (He et al., 2021; Huang et al., 2023; Liu, 2023; Zhang and Lu, 2021). Slopes are more prone to sliding during intense rainfall when humidity and groundwater levels are high. Studies have shown that slopes with high moisture content and elevated groundwater levels are more susceptible to instability during rainfall (Morya et al., 2019; Wang et al., 2021). The distribution of soil layers and soil structure also affects slope stability. Cracks, fissures, and transitions between soil layers can increase permeability, enhancing the infiltration of rainfall into the soil (Dou et al., 2021; Li et al., 2023; Zeng et al., 2018). Uneven water distribution within soil layers can alter pore water pressure and reduce the soil's shear strength, thereby increasing the likelihood of slope failure.

The shape and height of a slope also influence its stability under rainfall. Slopes that are steep and high are more susceptible to rainfall-induced instability (Qian et al., 2021; Zhang et al., 2023). Studies have shown that the steeper and higher the slope, the more likely it is to experience failure during heavy rainfall. Therefore, assessing slope geometry is important for predicting the likelihood of slope failure. Slope reinforcement measures, such as the use of anti-sliding piles, bioreinforcement, and tree planting, have been shown to be effective in mitigating the impact of rainfall on slope stability (Huang et al., 2023; Sun et al., 2020; Wang et al., 2021). These measures help improve soil strength and reduce the likelihood of slope failure during heavy rainfall events. The use of numerical models and physical simulation experiments has contributed to understanding the complex interactions between rainfall, water levels, and slope stability, providing important insights into sliding mechanisms and the effects of different factors on slope behavior (Lv, 2023; Tang et al., 2020; Wang et al., 2022; Zhang et al., 2023). Numerical models also help predict scenarios that may occur in practice, thereby supporting more effective slope design and management.

For citations: Pham, N. T., Nguyen, T. M. S., Dang, V. P. (2025). Effects of rainfall and water level on the stability of The Bau Trang Lake Bank, Bac Binh District, Binh Thuan Province, Vietnam. Architecture and Engineering, No 4 (10), pp. 56–64. DOI: 10.23968/2500-0055-2025-10-4-56-64.

Bau Trang Lake, a national scenic site located in Hoa Thang Commune, Bac Binh District, Binh Thuan Province, Vietnam, is a unique natural freshwater ecosystem featuring striking landscapes, including white sand dunes interlaced with clear blue waters. In addition to its ecological and economic functions, Bau Trang is also a tourist destination with great potential due to its pristine natural scenery and favorable environmental conditions. The conservation and sustainable use of Bau Trang Lake are therefore of practical importance in the context of developing tourism linked to the protection of local natural resources. However, lake shore erosion has become an increasing concern, particularly after the severe erosion event at Bau Ba, a part of Bau Trang Lake, on May 3, 2023, which caused significant damage to the ecosystem and terrain and may have endangered tourist safety. This incident underscores the urgent need to assess the causes of landslides in the area. This study examines the effects of rainfall and water levels on the stability of Bau Trang Lake's banks using numerical modeling techniques (GeoSlope software).

Research Data and Methodology

Research Area

Bau Trang Lake is a freshwater lake surrounded by a system of coastal sand dunes. It is located in Hoa Thang Commune, Bac Binh District, Binh Thuan Province (10°00'50" – 11°09'30" N; 108°16'55" – 108°31'12" E) (Fig. 1). Two primary types of terrain occur in the study area: (1) sand dunes, mainly distributed in the northern and northeastern parts of the lake and formed on Pleistocene and Holocene deposits; and (2) flat surfaces, found in the western and southwestern parts of the lake and developed on Pleistocene marine deposits.

Data Collection

a) *Topographic data*

Topographic data were collected from two main sources: 1:10,000 topographic maps issued by the Vietnam Department of Surveying and Mapping, and 5 m resolution Digital Elevation Model (DEM) data from the ASTER GDEM dataset. For spatial analysis, the research team used ArcGIS software to process and integrate the data, thereby generating detailed slope and slope direction maps to assess the current terrain conditions of the area (Fig. 2).

Based on these maps, topographic analysis was performed to identify areas at high risk of landslides through a comprehensive assessment of factors such as slope, slope direction, and the geological characteristics of the ground. In particular, the main research cross-section was selected at the site of the serious landslide incident on May 3, 2023, in order to focus on analyzing the specific causes of instability at that location.

A specific factor considered in the study was the presence of a small waterhole located approximately 135 meters from the landslide site. This waterhole was hypothesized to have influenced groundwater infiltration and movement in the area. Therefore, a detailed analysis of the relationship between this waterhole and the existing geotechnical conditions was conducted to clarify the role of groundwater in destabilizing the slope and triggering the landslide.

b) *Geological data*

The study area is mainly composed of Cenozoic sediments, including two major formations — Pleistocene and Holocene — each with distinct origins, material compositions, and geotechnical properties. Pleistocene sediments include two main groups: marine sediments of the Phan Thiet

Fig. 1. Location of Bau Trang Lake on Google

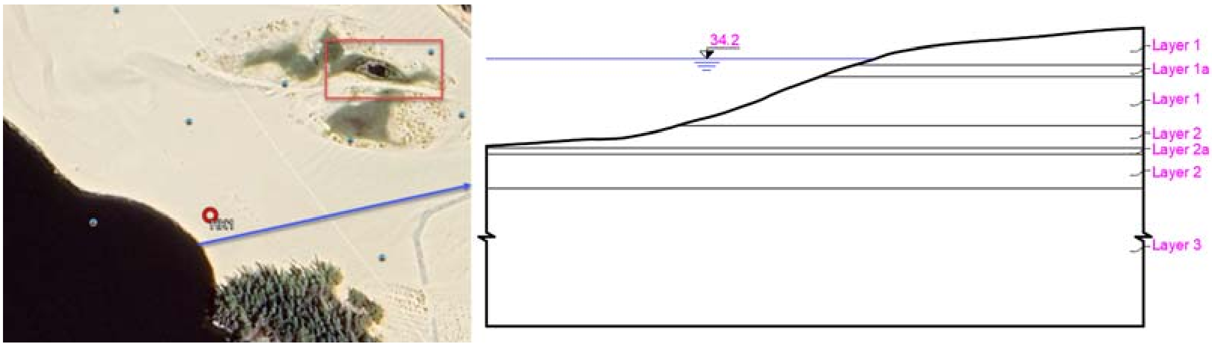

Fig. 2. Geological cross-section of the study area

Formation ($mQ_{12}pt$) and wind-drift sediments (vQ_{12}). The marine sediments consist primarily of fine- to medium-grained sand, sometimes mixed with silty sand, with colors ranging from white and yellow to red, reflecting different stages of deposition in the Pleistocene marine environment. In contrast, the wind-drift sediments are characterized by fine-grained quartz sand with a yellow-brown color, indicating the influence of arid climatic conditions and high wind speeds in the past. Holocene sediments include both wind-borne and fluvial deposits. The wind-borne sediments (vQ21−2, vQ22−3) are mainly medium-grained quartz sand with pearly particles, and their colors range from yellow-brown to light yellow. The fluvial sediments (aQ22−3) consist primarily of silty sand and sand, reflecting transport and deposition under fluvial or nearshore conditions.

The analysis showed that the soils are mainly sandy soils and sandy loams, classified according to the mechanical composition of the sediments. For sandy soils of the Holocene sediments, the physical and mechanical properties — natural moisture content (W), porosity (n), saturation (Sr), compaction coefficient (a), cohesion (c), and internal friction angle (ϕ) — were 18.2 %, 36.2 %, 84.3 %, 0.013 cm²/kg, 0.014 kg/cm², and 24.56°, respectively. These values reflect the typical properties of sandy soils formed in Holocene environments, characterized by moderate compaction and low shear strength. For sandy soils of the Pleistocene sediments, the corresponding physical properties were 18.3 %, 35.2 %, 89.1 %, 0.010 cm²/kg, 0.011 kg/cm², and 26.46°, indicating slight differences in saturation and cohesion compared to the Holocene sandy soils. For sandy loam soils of the Pleistocene sediments, the values were 17.5 %, 34.6 %, 88.1 %, 0.009 cm²/kg, 0.012 kg/cm², and 28.56°, showing improved shear resistance and higher overall stability.

Geological data were collected from a 30 m deep borehole (code: HK1) located at the landslide site. A standard penetration test (SPT) was performed throughout the borehole at 2 m intervals. Soil samples were analyzed in the laboratory to determine the physical and mechanical properties of the soil, including grain size distribution, natural moisture content, porosity, saturation, compaction coefficient, cohesion, and internal friction angle.

Parameters of soil layers are shown in Table 1.

Table 1. **Parameters of soil layers**

Soil layer	γ [kN/m³]	φ [°]	c [kPa]
1	19.9	24˚56′	1.4
1a	20.1	25˚14′	1.9
2	20.3	26˚46′	1.1
2a	19.9	26˚45′	1.8
3	20.5	28˚56′	1.2

c) *Hydrological data*

Rainfall: Rainfall data were collected from the Bau Trang meteorological station. Observations from 1978 to 2020 show a decrease in annual rainfall from 1,325.7 mm in 2016 to 436.3 mm in 2020. The rainfall regime in the area is divided into two distinct seasons: the rainy season, from June to November, with an average rainfall of 724 mm, and the dry season, from December to May of the following year, with an average rainfall of 48 mm. In this study, rainfall of 9 mm over a 2-hour period was used to simulate the influence of rain on the stability of the Bau Trang Lake slope (Fig. 3).

Lake water level: Lake water level data (Fig. 4) were continuously recorded by a TF-Luna LIDAR sensor at hourly intervals. This sensor uses laser distance measurement technology to determine the lake's water level with high precision relative to a fixed reference point. Using these data, changes in water level over time were examined and their effects on slope stability were assessed. The lake water level varied consistently during the first five months of 2024 (January 1 – May 31, 2024) compared with 2023. The water level remained at 2.5 m throughout January and for nearly half of February, but by May it decreased by 0.1 m. Specifically, the water level was stable at 2.3 m in May, both before and after the Bau Ba lake bank landslide (which occurred at approximately 10:30 a.m. on May 3, 2023).

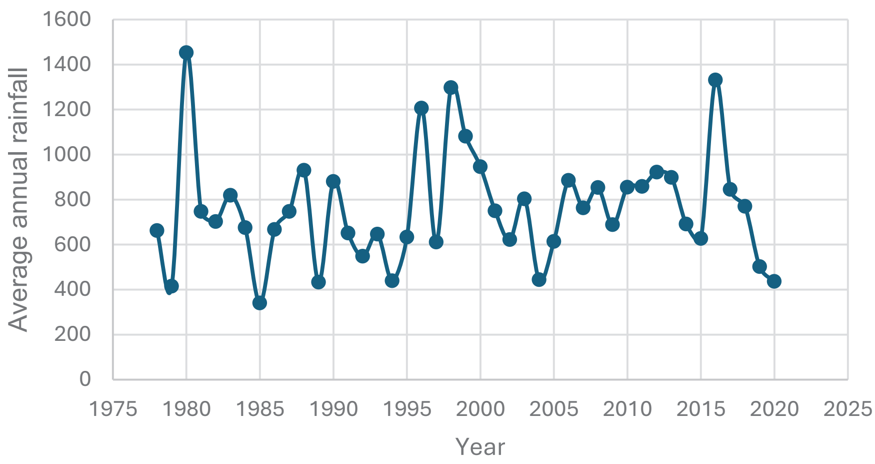

Fig. 3. Average annual rainfall at the Bau Trang station

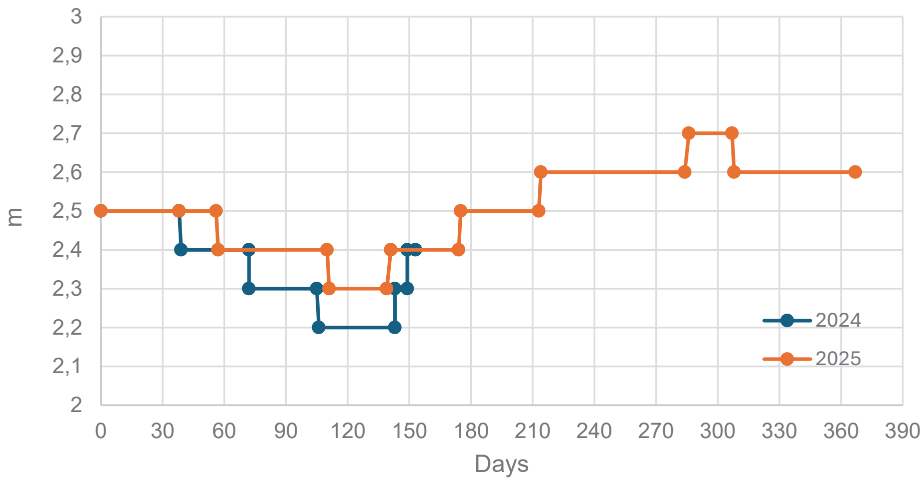

Fig. 4. Water level fluctuations of Bau Trang Lake

Stability Analysis Model

This study uses GeoStudio 2024 software developed by GEO-SLOPE, focusing on two main modules: SEEP/W and SLOPE/W. SEEP/W is a powerful tool for analyzing seepage flow and calculating permeability coefficients and pore water pressures under different soil conditions. Meanwhile, SLOPE/W plays a key role in slope stability analysis by identifying potential sliding surfaces and calculating safety factors.

It is important to note that SLOPE/W is closely integrated with SEEP/W, allowing the calculation of safety factors based on effective stress and pore water pressure. This integration not only improves the accuracy of the analysis but also supports engineers in predicting and mitigating slope failure risks, especially in environments with complex hydraulic conditions.

SEEP/W, a specialized module of the GeoStudio software suite, is widely used to analyze seepage flow in soils under various hydraulic conditions. The tool is based on the fundamental principles of seepage mechanics — Darcy's law. Darcy's law (q = –ki) states that the seepage flow rate (q) is directly proportional to the hydraulic gradient (i) and the permeability coefficient (k). The negative sign indicates that water always flows from a region of high potential to a region of low potential. A thorough understanding of this law forms the basis for developing more complex governing equations describing seepage flow.

In two-dimensional seepage analysis, a 2D governing equation is used to model the movement of seepage through soil. This partial differential equation, derived from the law of conservation of mass and Darcy's law, provides a mathematical foundation for predicting pore water pressure distribution and modeling seepage flow within the soil

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial H}{\partial y}\right) + Q = \frac{\partial \theta}{\partial t}, \tag{1}$$

where:

- H is the hydraulic head;
- k_x and k_y are the permeability coefficients in the x and y directions, respectively;

- Q is the source term, representing the amount of water added to or removed from the system per unit volume;
- θ is the volumetric water content;
- t is time.

Another important factor in soil mechanics is the soil's water retention capacity, measured through the volumetric water content (VWC) index. This capacity is influenced by soil type, porosity, and soil structure. VWC plays an essential role in analyzing and evaluating the characteristics of unsaturated soils.

SLOPE/W analyzes slope stability using the limit equilibrium approach. The method is based on dividing the slope into slices and evaluating the force equilibrium of each slice. A body remains in a static state when all acting forces are in balance (Fig. 5). This means that the total force and total moment acting on the body must be zero.

∑M0 = 0 (the sum of moments about point O is zero).

∑FH = 0 (the sum of horizontal forces is zero).

∑FV = 0 (the sum of vertical forces is zero).

The general formula of the limit equilibrium method is expressed through two safety factor (FoS) equations:

$$F_m = \frac{\sum (c'\beta R + (N - u\beta) R \tan\phi')}{\sum W_x - \sum Nf \pm \sum Dd}, \quad (2)$$

$$F_f = \frac{\sum (c'\beta \cos\alpha + (N - u\beta) \tan\phi' \cos\alpha)}{\sum N \sin\alpha - \sum D \cos\alpha}, \quad (3)$$

where:

- F_m and F_f are the safety factors calculated from moment equilibrium and force equilibrium, respectively;
- c' is the effective cohesion;
- β is the width of the slice;
- R is the radius of the slip arc;
- N is the normal force;

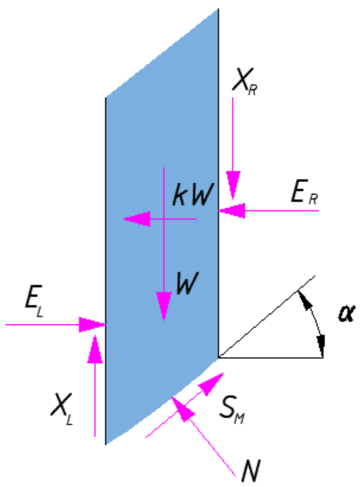

Fig. 5. Diagram of forces acting on a soil slice

- u is the pore water pressure;
- ϕ' is the effective internal friction angle;
- W_x is the horizontal component of the slice weight;
- N_f is the normal force due to external loading;
- Dd is the pull or thrust force;
- α is the inclination angle of the slice.

Results

To assess slope stability under various rainfall and water level conditions, four representative simulation scenarios were analyzed using the SEEP/W and SLOPE/W modules of GeoStudio.

Case 1. Lake water levels at elevations 34.2 m and 32.0 m, without water in the small hole.

Case 2. Lake water levels at elevations 34.2 m and 32.0 m, with water in the small hole.

Case 3. Lake water levels at elevations 34.2 m and 32.0 m, without water in the small hole, with rainfall.

Case 4. Lake water levels at elevations 34.2 m and 32.0 m, with water in the small hole, with rainfall.

The calculated stability safety factors for all four scenarios are presented in Figs. 6–9 and summarized in Table 2.

The results in Table 2 show that at a water level of 34.2 m, the safety factor decreased slightly from 1.414 to 1.399 when the small hole contained water, with a slight difference of about 1 %. Similarly, at a water level of 32.0 m, the safety factor decreased from 1.296 to 1.263 under the same conditions. However, this reduction remains within acceptable safety limits. Therefore, the small hole plays only a secondary role and is not a major factor influencing the stability of the lake bank. The findings indicate that the presence of the small hole near Bau Trang Lake had only a minor effect on overall slope stability.

The variation in water levels (34.2 m and 32.0 m) clearly influences the safety factor. When the water level is at 34.2 m, the average safety factor is approximately 1.4, significantly higher than the average value of 1.27 corresponding to a water level of 32.0 m. This demonstrates that higher water levels help reduce pore water pressure, thereby enhancing slope stability. Conversely, lower water levels increase pore water pressure and soil saturation, which substantially reduces stability. Maintaining the lake water level within a stable range is therefore an important measure to ensure the safety of the shoreline.

Rainfall also has a significant impact on the stability of the lake bank, especially when combined with water level fluctuations. During rainfall events, the safety factor at a water level of 34.2 m decreases slightly from 1.302 to 1.296. However, when the water level drops to 32.0 m, the safety factor decreases more sharply, from 1.074 to 1.066. This suggests that rainfall increases soil saturation, reduces shear strength, and weakens overall stability. Heavy or prolonged rainfall events heighten the risk of lake bank erosion, particularly when the water level is low.

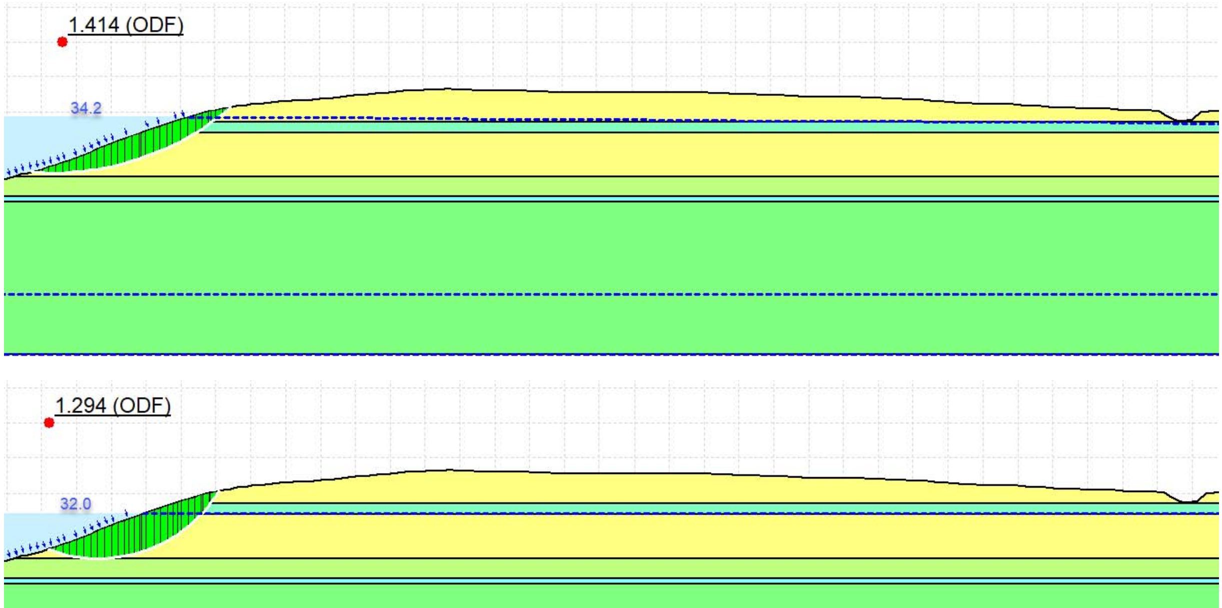

Fig. 6. Lake water levels at elevations 34.2 m and 32.0 m, without water in the small hole (Case 1)

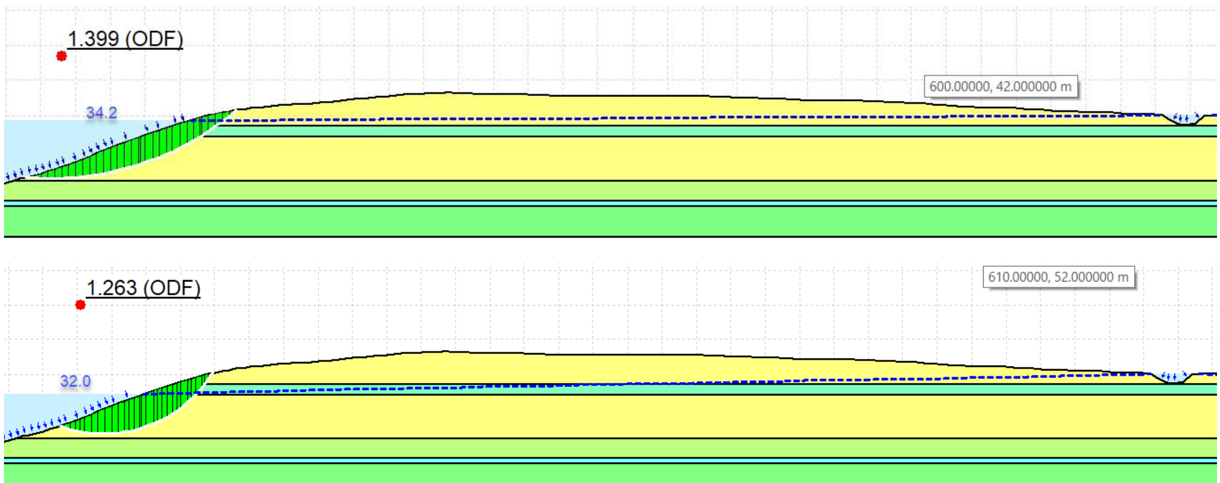

Fig. 7. Lake water levels at elevations 34.2 m and 32.0 m, with water in the small hole (Case 2)

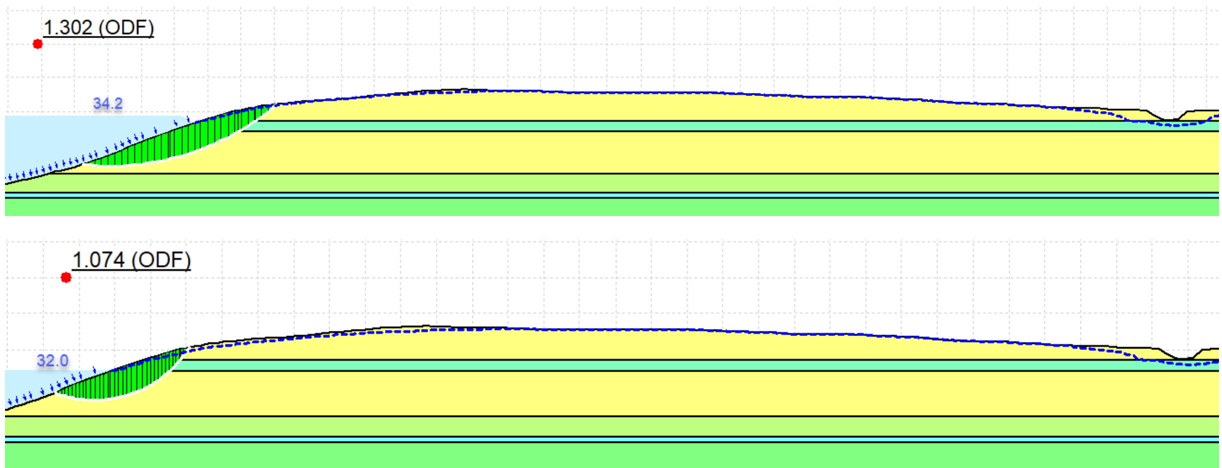

Fig. 8. Lake water levels at elevations 34.2 m and 32.0 m, without water in the small hole, with rainfall (Case 3)

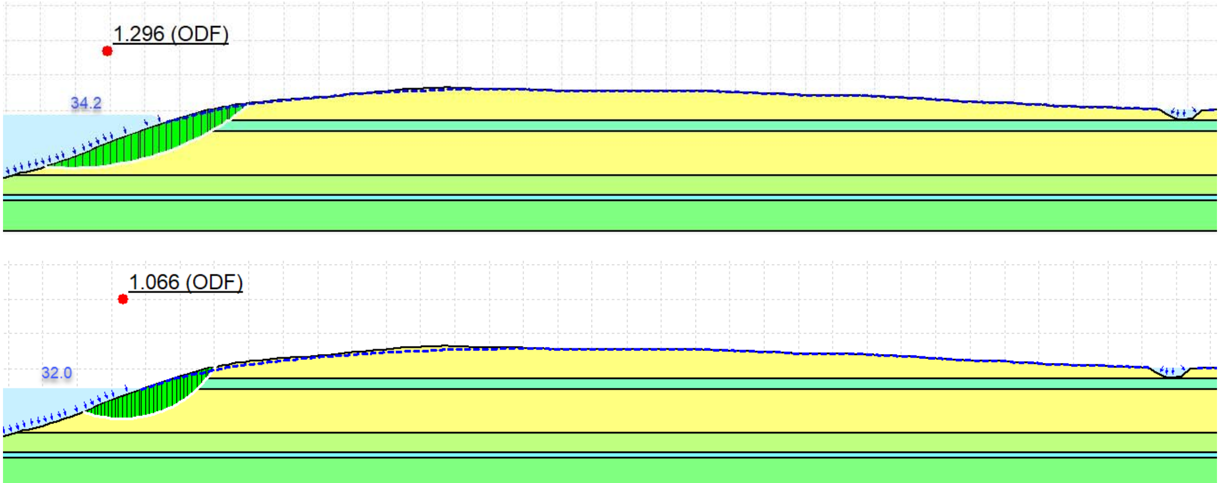

Fig. 9. Lake water levels at elevations 34.2 m and 32.0 m, with water in the small hole, with rainfall (Case 4)

Table 2. **Summary of calculated stability safety factors**

No.	Water level	Small hole without water		Small hole with water	
		Without rain	With rain	Without rain	With rain
1	34.2	1.414	1.302	1.399	1.296
2	32.0	1.294	1.074	1.263	1.066

Conclusion

This study evaluated in detail the effects of lake water level, rainfall, and the presence of small holes on the stability of the Bau Trang Lake bank. Based on the results of numerical simulations and analyses of experimental data, the following main conclusions are drawn:

1. The overall stability of the lake bank is not significantly affected by the presence of small holes near Bau Trang Lake (a reduction of approximately 1–2.5 %). Although the safety factor decreases slightly, the reduction remains within acceptable safety limits.

2. The stability of the lake bank depends largely on the lake's water level. The results show that higher water levels reduce pore water pressure and increase the safety factor, while low water levels raise the risk of instability, especially when combined with other adverse factors such as heavy rainfall (with reductions exceeding 21 %). Recommended measures include maintaining stable lake water levels and reinforcing high-risk areas to reduce erosion hazards and ensure bank safety.

3. Rainfall — particularly heavy or prolonged — leads to increased soil saturation and decreased shear strength. This significantly reduces the safety factor and heightens the likelihood of bank erosion, especially when water levels are low.

4. The study highlights the need for future research on lake shore stability under harsh and complex geological and climatic conditions.

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ВЛИЯНИЕ ОСАДКОВ И УРОВНЯ ВОДЫ НА УСТОЙЧИВОСТЬ БЕРЕГА ОЗЕРА БАУ ЧАНГ, РАЙОН БАК БИНЬ, ПРОВИНЦИЯ БИНЬТХУАН, ВЬЕТНАМ

Нгок Тхинь Фам, Тхи Май Сыонг Нгуен*, Ван Фу Данг

Университет Тхюилой, Ханой, Вьетнам

*Email: suongntm@tlu.edu.vn

Аннотация
Введение. В настоящем исследовании оценивается влияние уровня воды в озере, атмосферных осадков и наличия малых впадин на устойчивость берегов озера Бау Чанг — национального природного объекта в провинции Биньтхуан, Вьетнам. **Методы.** Для оценки коэффициента запаса устойчивости откосов было выполнено моделирование нескольких сценариев с использованием модулей SEEP/W и SLOPE/W программного комплекса GeoStudio 2024. **Результаты** показывают, что небольшая впадина оказывает незначительное влияние на устойчивость береговой линии, поскольку снижение коэффициента запаса составляет менее 1 %. Уровень воды в озере является ключевым фактором: низкие уровни повышают вероятность потери устойчивости, тогда как высокие уровни способствуют ее увеличению и уменьшают поровое давление. Особенно заметное снижение коэффициента запаса наблюдается при интенсивных или продолжительных осадках в сочетании с низким уровнем воды, что приводит к увеличению насыщенности грунта и снижению его прочностных характеристик. В работе рекомендуется поддерживать стабильный уровень воды, укреплять участки повышенного риска и внедрять эффективные дренажные системы в целях уменьшения воздействия осадков. Полученные результаты служат основой для разработки устойчивых стратегий управления с целью сохранения природной среды и ландшафта озера Бау Чанг, а также обосновывают необходимость дальнейших исследований устойчивости береговой зоны под влиянием геологических и климатических факторов.

Ключевые слова: озеро Бау Чанг; устойчивость склонов; уровень воды; осадки; GeoStudio.