

GEOTECHNICAL ASSESSMENT AND SUSTAINABLE ENGINEERING SOLUTIONS FOR LANDSLIDE MITIGATION AT BAU TRANG LAKE, LAM DONG, VIETNAM

Nguyen Thi Mai Suong¹, Pham Ngoc Thinh^{2*}, Dang Van Phu², Le Xuan Bao², Truong Van Doan², Le Ngoc Thanh³

¹ Vietnam Aviation Academy, Ho Chi Minh City, Vietnam

² Thuyloi University, Hanoi, Vietnam

³ Nguyen Tat Thanh University, Ho Chi Minh City, Vietnam

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

Abstract

Introduction. This study assesses the landslide and proposes appropriate measures to safeguard the lake system along the Bau Trang shoreline, a well-known ecotourism destination in Binh Thuan province (now part of Lam Dong province), Vietnam. The area is threatened by shoreline landslips caused by both natural hazards and human activity. **Methods.** The methodology employed topographic and geomorphological geotechnical techniques, remote sensing, and Geographic Information Systems (GIS), using Geo-studio models. **Results.** The findings indicate that sections of the lakeshore with low safety factors are particularly vulnerable due to the reservoir's fluctuating water level, vibrations, and the movement of cruise ships. To improve lakeshore stability, various technical solutions were proposed, including live load reduction plates, geotechnical textiles, reinforced concrete (RC) sheet piles, Melaleuca (Cajuput) timber piles, and sandbag revetments. These measures are expected to not only ensure the safety of the lakeshore but also protect the ecosystem and environment, supporting the need to preserve this outstanding natural and scenic location.

Keywords: lakeshore erosion; landslide mitigation; geotechnical stability; Geo-studio; Bau Trang lake; sustainable engineering; eco-tourism.

Introduction

Lakeshore environments, particularly those of significant ecological and socio-economic value, are increasingly recognised as fragile ecosystems vulnerable to geomorphological instability (Medeu et al., 2023; Yang et al., 2019). Bau Trang Lake, situated in Hoa Thang Commune, Bac Binh District, Binh Thuan Province (now part of Lam Dong Province), Vietnam, is a prime example of such a vulnerable system. Renowned for its unique landscape featuring striking white sand dunes juxtaposed with diverse aquatic habitats, Bau Trang has been officially designated a National Scenic Landscape by the Vietnamese Ministry of Culture, Sports, and Tourism (Binh Thuan Portal, 2021). This status underscores its immense natural and cultural importance, contributing significantly to regional tourism and local livelihoods, especially following the post-COVID-19 resurgence in visitor numbers.

However, the integrity of Bau Trang Lake is under considerable threat from lakeshore erosion. A particularly severe event occurred on May 3, 2023, along the northeastern shore of Bau Ba, a constituent

part of the Bau Trang lake system. This event resulted in an approximately 80-metre-diameter semi-circular scarp, triggering substantial public and governmental concern regarding the site's stability and long-term preservation (Phap Luat, 2023). Such instabilities not only jeopardise the delicate aquatic ecosystem and the aesthetic appeal crucial for tourism but also pose direct risks to public safety and local infrastructure, potentially undermining the regional economy. The Binh Thuan (now Lam Dong) Provincial People's Committee subsequently initiated urgent investigations to determine the causative factors and formulate remedial strategies (Phap Luat, 2023).

The instability of lakeshores is a complex phenomenon driven by a confluence of natural and anthropogenic factors. Natural drivers prominently include wave action and fluctuations in water levels, which can significantly alter sediment dynamics and induce erosion, as documented in studies of various lake systems globally (Medeu et al., 2023; Davidson-Arnott and Ollerhead, 1995). For instance, rapid reservoir drawdown rates have been shown

to decrease bank stability by increasing pore water pressures and reducing effective stress (Yang et al., 2019). Soil properties and groundwater seepage also play a critical role in determining susceptibility to erosion and mass movement (Hansom and McGlashan, 2000). Furthermore, the escalating impacts of climate change, manifesting as altered hydrological regimes and an increased frequency of extreme weather events, are expected to exacerbate these erosional processes in lacustrine environments (Sun, 2014; Arnaud, 2016). Anthropogenic activities often compound these natural vulnerabilities. Even though protection structures are meant to be remedial, their construction may unintentionally exacerbate erosion nearby (Abrahams, 2008). Increased vehicle traffic along lakeshores can put additional strain on slopes in areas with high tourism intensity, such as Bau Trang, which could lead to collapses. While extensive research has elucidated many of these individual factors, and various modelling approaches, including machine learning techniques, have been developed to predict landslide susceptibility in reservoir environments (Holanda et al., 2021), a holistic understanding of the synergistic interplay between natural processes and intense, localised tourism-related pressures in a designated national heritage site remains a critical area for investigation.

This study aims to address this gap by undertaking a comprehensive assessment of the shoreline transformations and geotechnical stability of Bau Trang Lake. The specific objectives are: (1)

to evaluate the historical and recent evolution of landslides and shoreline changes using integrated field surveys and multi-temporal remote sensing data; (2) to analyse the geotechnical stability of the lakeshore under various natural and anthropogenic loading scenarios using advanced numerical modelling with Geo-studio; and (3) to propose and evaluate environmentally considerate engineering solutions designed to enhance shoreline stability and ensure the long-term protection of this valuable landscape. The findings are anticipated to provide a robust scientific basis for sustainable management strategies at Bau Trang and offer transferable insights for other ecologically sensitive and economically vital lakeshore systems facing similar challenges worldwide.

Materials and Methods

Study Area

This research concentrated on the northeastern shoreline of Bau Ba Lake, a constituent of the larger Bau Trang Lake system in Binh Thuan Province (now part of Lam Dong Province), Vietnam (Fig. 1). This specific area, encompassing the Trinh Nu dune, has been subject to significant recent landslide activity and is characterised by extensive aeolian sand dunes, a diverse but fragile ecosystem, and high sensitivity to both natural geomorphological processes and anthropogenic pressures, particularly from tourism-related activities.

Data Collection

A multi-faceted data collection strategy was employed, integrating field surveys with remote

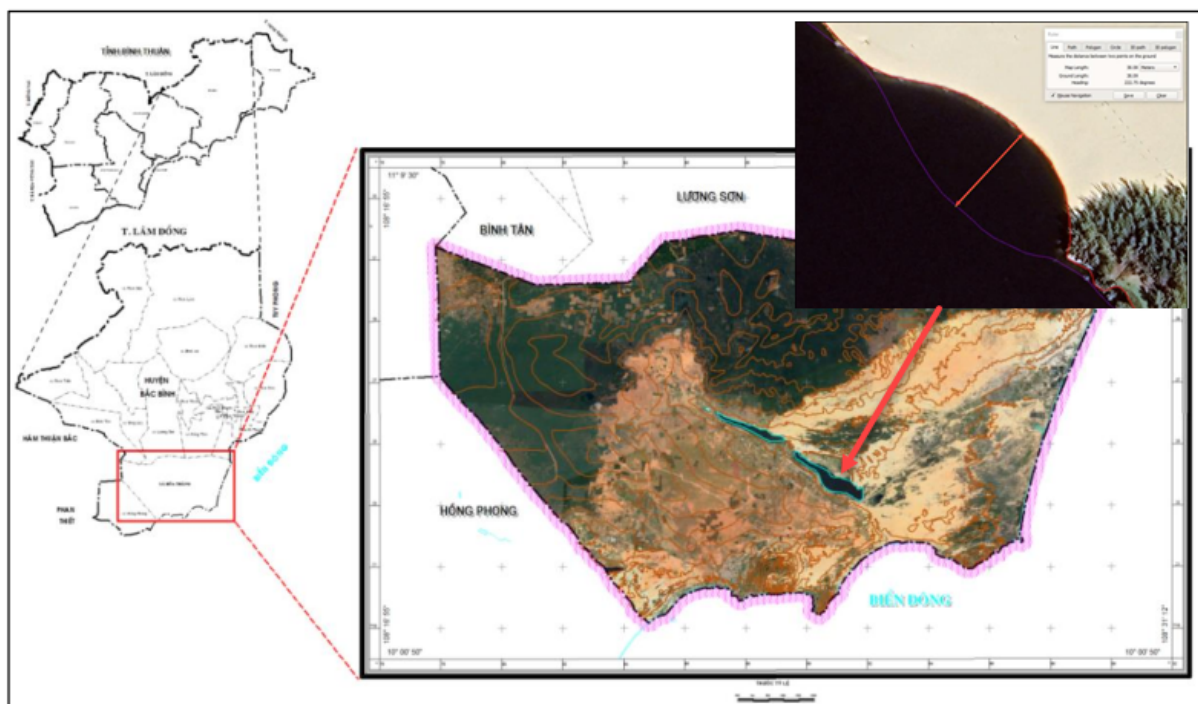


Fig.1. The study area

sensing techniques to provide a comprehensive understanding of the site's conditions and dynamic processes.

a) Field surveys

Direct field investigations were conducted to gather high-resolution data on current landslide geometry, sediment characteristics, and shoreline morphology. These surveys involved:

- detailed measurement of landslide depths and dimensions;
- collection of soil samples for the determination of geotechnical parameters, including sediment composition and physical properties;
- topographic profiling and slope angle measurements along critical sections.

A total of 53 survey points were established along key shoreline segments, selected based on pre-assessment of erosion hotspots and historical data. Repeat surveys of the Trinh Nu dune area were conducted on January 25, 2024; February 25, 2024 and March 25, 2024, to monitor short-term transformations of the dune.

b) Remote sensing and Geographic Information System (GIS) methods

Multi-temporal remote sensing data were utilised to assess long-term topographic changes, shoreline evolution, and sand dune migration patterns. The datasets included:

- Satellite Imagery: A chronological series of satellite images spanning from 1984 to 2022 was acquired. This included moderate-resolution imagery

for historical trend analysis and high-resolution imagery (0.5 m spatial resolution) available from 2006 onwards for more detailed recent assessments (Fig. 2).

- Historical Maps: Cartographic records, including maps from the early 19th century, the French colonial era, the 1950s-1960s (US era), and current VN2000 standard topographic maps, were consulted for historical shoreline positions.

- UAV-derived Digital Elevation Models (DEMs): High-precision DEMs were generated from Unmanned Aerial Vehicle (UAV) surveys to accurately map recent changes in slope, elevation, and landform features.

- Google Earth Timelapse: Imagery from Google Earth Timelapse (1984-2022) was used for a qualitative visual assessment of broad-scale land cover and environmental changes in the Bau Trang area over several decades.

c) Geotechnical modelling

The stability of the lakeshore slopes was analysed using Geo-studio 2021 software (Geo-Slope International Ltd.), a widely recognised suite for geotechnical modelling. The SLOPE/W module, which employs limit equilibrium methods, was specifically used for slope stability analysis.

- Cross-sections: Nine critical cross-sections were selected for detailed analysis (Fig. 7): four within the Bau Ong area (MC5, MC6, MC7, MC9) and five within the Bau Ba area (L1, L4, L8, MC2, MC4), with L1, L4, and L8 directly traversing the recent landslide zone.

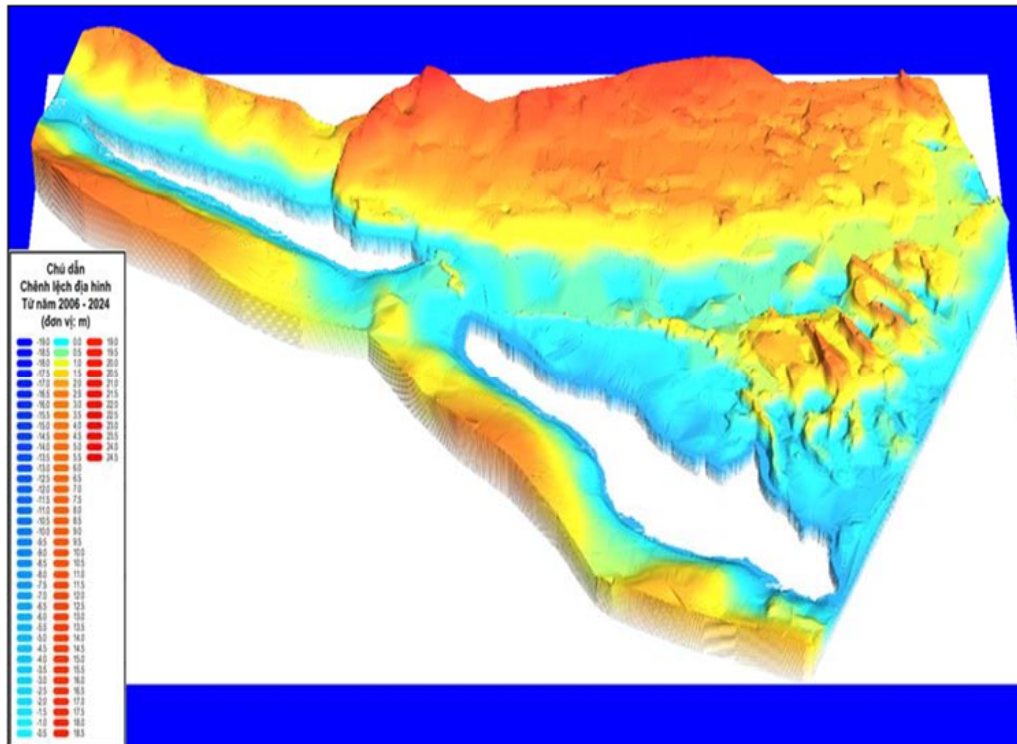


Fig. 2. Three-dimensional model of terrain difference in the Bau Trang lake area (2006–2024)

- **Soil Parameters:** The Mohr-Coulomb failure criterion was adopted for the soil model. Geotechnical parameters, including unit weight (γ), cohesion (c), and angle of internal friction (ϕ) for different soil layers (Table 1), were derived from the field investigations and laboratory testing of collected samples.

- **Analysis Scenarios:** The stability analyses were conducted under various scenarios to evaluate the influence of:

- **Water Level Fluctuations:** different lake water levels were considered for Bau Ba (+32 m, +33 m, +34.2 m mean, +36 m) and Bau Ong (+36 m, +38.6 m, +40 m).

- **Live Loads:** static surcharge from tourist vehicles (2.0 - 2.5 ton pickup trucks and smaller ATVs), applied approximately 3 m from the lake shore, was modelled according to TCVN 2737–2023.

- **Seismic Loads:** dynamic loading due to vibrations from tourist vehicles was incorporated, using a maximum ground acceleration of 14.4 m/s² (equivalent to 0.00147 g), as recorded on February 25, 2024.

- Associated seepage and stress analyses were also performed where relevant.

d) Data analysis and stability assessment criteria

Geographic Information System (GIS) software was employed for processing satellite imagery, analysing DEMs, quantifying spatial changes in shoreline position and topography, and generating cartographic outputs. The stability of the slopes was assessed based on the calculated Factor of Safety (FoS). According to Vietnamese standard TCVN 8216:2018 for hydraulic structures, a minimum FoS of 1.25 is generally required for Class IV earth fill dams under normal operating conditions, a threshold adopted for assessing the stability of the lakeshore slopes in this study.



Fig. 3. Movement of the sand dunes during three surveys of the Trinh Nu hill

Results

a) Topographic and geomorphological changes in the Trinh Nu dune area

Repeated topographic surveys of the Trinh Nu dune area between January and March 2024 revealed significant short-term dynamics. The crest of the Trinh Nu dune exhibited a discernible westward migration towards Bau Ba Lake. Over the three survey periods, the northern part of the dune crest shifted by approximately 5 m, while the southern part moved by approximately 10 m (Fig. 3). Despite this lateral movement, no significant changes in the overall crest elevation range (30–83 m) were observed.

Analysis of DEM difference maps (Fig. 4a and 4b, scale 1:1,000) illustrated these changes more clearly. For the period from January 25 to February 25, 2024, localised areas experienced elevation decreases of up to 2 m, predominantly in the central part of the surveyed dune, interspersed with elongated sand deposits along the dune toe. Concurrently, areas of accretion, with elevation gains of 1 to 4 m, were noted around the periphery of the Trinh Nu dune.

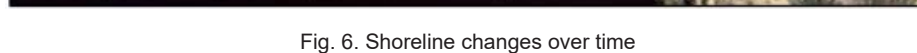
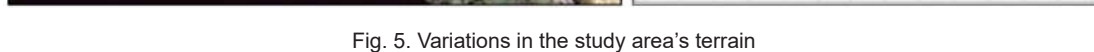
During the subsequent period (from January 25 to March 25, 2024), more pronounced changes occurred, with some areas showing elevation decreases of up to 6 m and more widespread accretion of up to 4 m. A consistent observation was the formation of new, elongated lakeside dunes oriented northwest-southeast along the margin of Bau Ba Lake, characterised by steep slopes ranging from 20° to 55°, which later steepened to 30°–55°. Within a specific 0.48-hectare area identified as highly prone to landslides (Fig. 5), the average ground elevation decreased by 0.52 m over the two-month observation period (from January 25 to March 25, 2024), from an initial average of 37.88 m to 37.36 m.

b) Shoreline transformations of Bau Ba lake (Trinh Nu area)

Analysis of satellite imagery spanning eight distinct time periods between 2006 and 2023 indicated a predominant trend of southwestward migration of the Bau Ba Lake shoreline in the vicinity of the Trinh Nu dune. This migration is attributed to the progressive deposition of aeolian sand transported by the prevailing northeast monsoon winds (Fig. 6). The rate of shoreline change was not uniform; the northern section of the shoreline experienced more

Table 1. Parameters of soil layers

Soil layer	Gama [kN/m ³]	Phi [o]	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



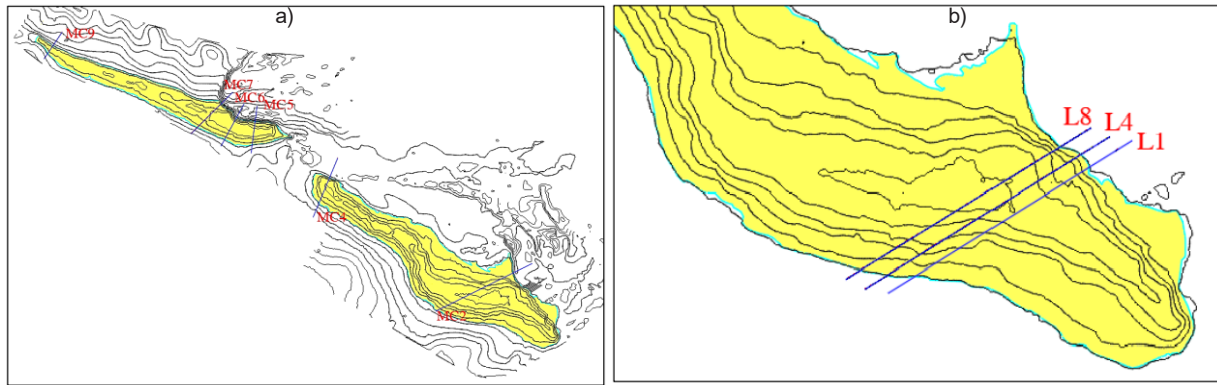


Fig. 7. Shoreline cross-sections: (a) cross-section along the Bau Ong shoreline; (b) cross-section along the Bau Ba shoreline

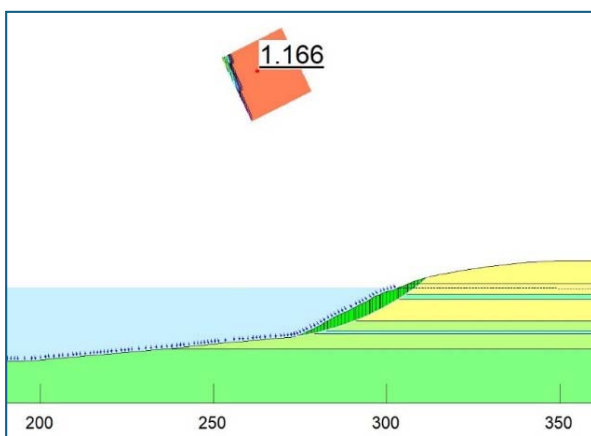


Fig. 8. Results of the calculation model for cross-section L8 at water level +34.2 m

rapid accretion, advancing approximately 50 m (an average of 3 m per year), which is five times greater than the southern section, where accretion was approximately 10 m (an average of 0.6 m per year), excluding the area directly affected by the recent major landslide.

c) Geotechnical stability analysis of the existing shoreline (pre-mitigation)

The geotechnical stability of nine selected cross-sections (Fig. 7) along the Bau Ong and Bau Ba

shorelines was evaluated using Geo-studio SLOPE/W, incorporating the soil parameters detailed in Table 1.

The analyses considered various scenarios of lake water levels and applied loads. Particular attention was given to cross-sections L1, L4, and L8 within the Bau Ba landslide zone. For instance, under a lake water level of +34.2 m and subjected to dynamic loads from tourist vehicles, cross-section L8 exhibited a Factor of Safety (FoS) of 1.166 (Fig. 8). The critical slip surface for this scenario was characterised by a depth of approximately 4 m and a width of about 35 m, extending from an elevation of +36.5 m down to +20.5 m.

The relationship between FoS and lake water level for the Bau Ba sections is presented in Fig. 9, and for the Bau Ong sections in Fig. 10. These results indicated that several cross-sections, notably L8, MC2, and MC4 in Bau Ba, and MC5, MC6, and MC7 in Bau Ong, possessed FoS values below the recommended minimum of 1.25 (TCVN 8216:2018, 2018), signifying a high risk of instability. Cross-sections L4 and L8 were identified as particularly vulnerable, with stability further deteriorating under conditions of reduced lake water levels.

d) Proposed engineering solution for landslide mitigation

Based on the stability analyses and site conditions, an integrated engineering solution was

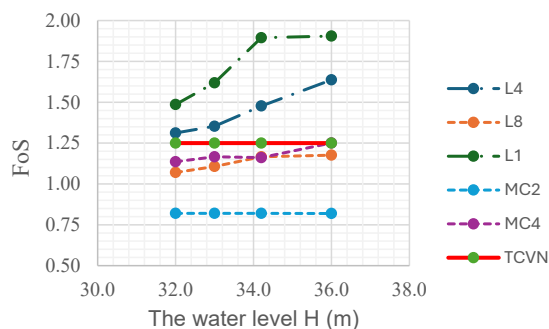


Fig. 9. Stability calculation results for Bau Ba Lake

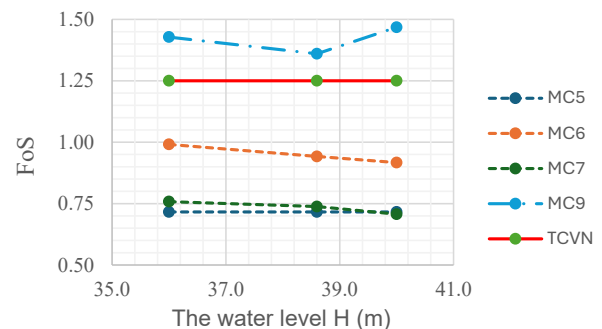


Fig. 10. Stability calculation results for Bau Ong Lake

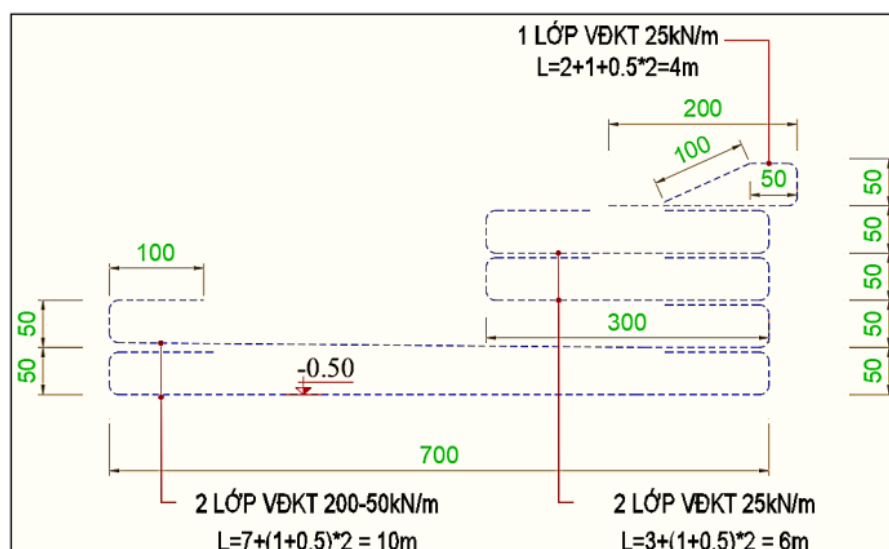


Fig. 11. Geotextile layout details

developed to mitigate landslide risk, particularly for the unstable sections of Bau Ba Lake. The design adhered to principles of heritage conservation, environmental compatibility, and technical efficacy. The proposed solution (detailed for the representative cross-section L8 in Fig. 12) comprises a combination of:

- Reinforced concrete (RC) sheet piles: To be installed from approximately +34.7 m down to +14.7 m elevation to provide deep-seated stabilisation at the interface between the slumped material and the intact ground.
- Melaleuca (Cajuput) timber piles: Driven into the ground for soil reinforcement and support. These piles are specified with an 8–10 cm butt diameter and lengths of 5.5 m and 4.5 m, installed at a density of approximately 8 piles per meter.
- Geotextile layers: Multiple layers of geotextiles with specified tensile strengths (ranging from 25–50 kN/m to 200 kN/m) are incorporated for soil reinforcement, separation, filtration, and load distribution (Fig. 11).
- Sandbag revetment: To provide immediate, temporary protection for the slope toe against wave action during the implementation of more permanent measures.

This combined system is designed for an expected service life of 15–20 years.

e) Stability analysis of the shoreline with proposed solution (post-mitigation)

The stability of the critical cross-section L8 was re-analysed using SLOPE/W after incorporating the proposed engineering solution. The results demonstrated a significant improvement in stability, with the Factor of Safety increasing from the pre-mitigation value of 1.166 to 1.568 (Fig. 13). This indicates that the proposed measures effectively

enhance the stability of the lakeshore to an acceptable level.

Discussion

a) Interpretation of key findings

The observed topographic changes within the Trinh Nu dune area, particularly the westward migration of the dune crest and the formation of new lakeside dunes, are consistent with active aeolian processes driven by the prevailing northeast monsoon. The quantified movement of the dune crest, up to 10 m in its southern part over a short three-month period, highlights the dynamic nature of this landscape and its direct influence on the Bau Ba Lake shoreline through sediment input. The concomitant decrease in average ground elevation within the landslide-prone zone suggests ongoing mass wasting, likely exacerbated by this continuous sediment loading and undercutting at the toe by lake processes.

The long-term shoreline dynamics of Bau Ba Lake confirm the dominant role of wind-driven sediment transport in shaping this environment. The differential accretion rates, with the northern shoreline advancing more rapidly, can be attributed to variations in sediment supply and local exposure to wind action. These geomorphological observations align with studies elsewhere that emphasise the role of aeolian transport in coastal and lacustrine environments (Kirk et al, 2000).

The geotechnical stability analyses revealed that several sections of the Bau Trang lakeshore, particularly L4 and L8 in the Bau Ba area, possess Factors of Safety below the nationally accepted threshold of 1.25 (TCVN 8216:2018, 2018), rendering them susceptible to failure. The low stability is attributed to a combination of factors: the inherent properties of the predominantly sandy soils (low

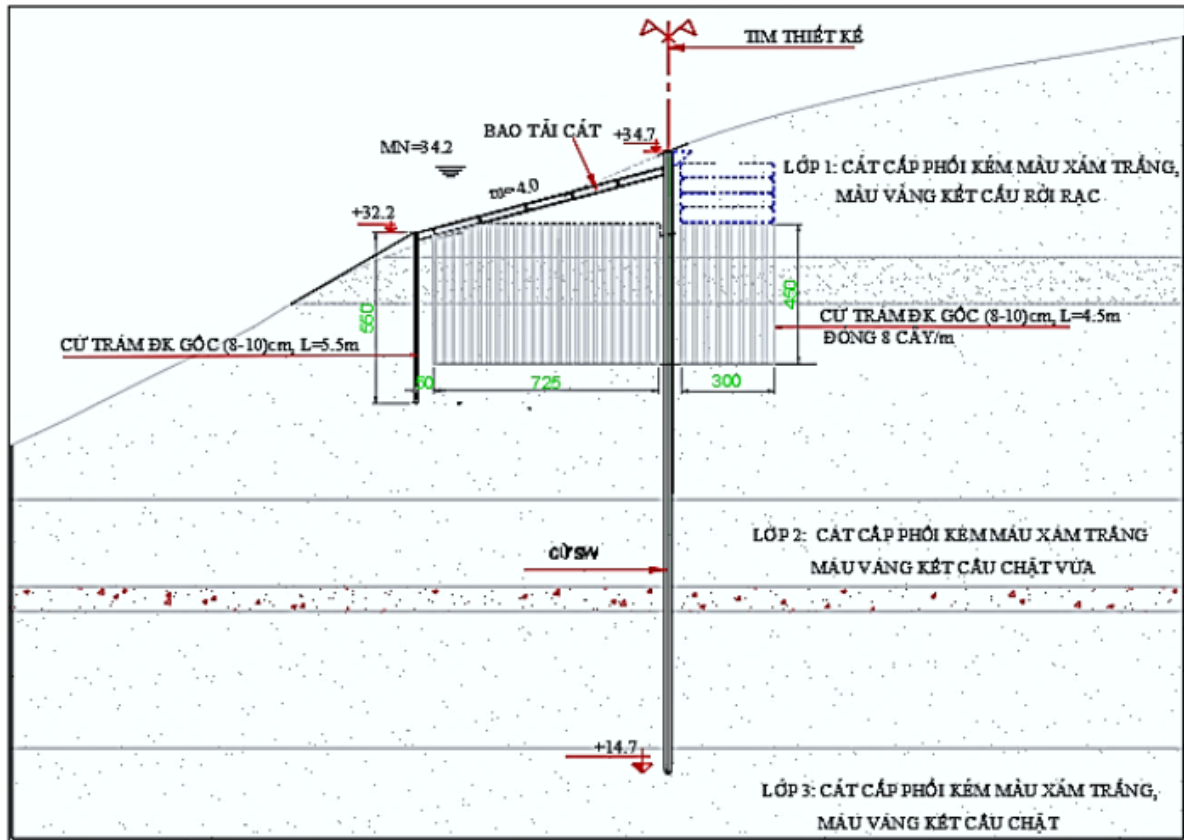


Fig. 12. Landslide prevention design for cross-section L8

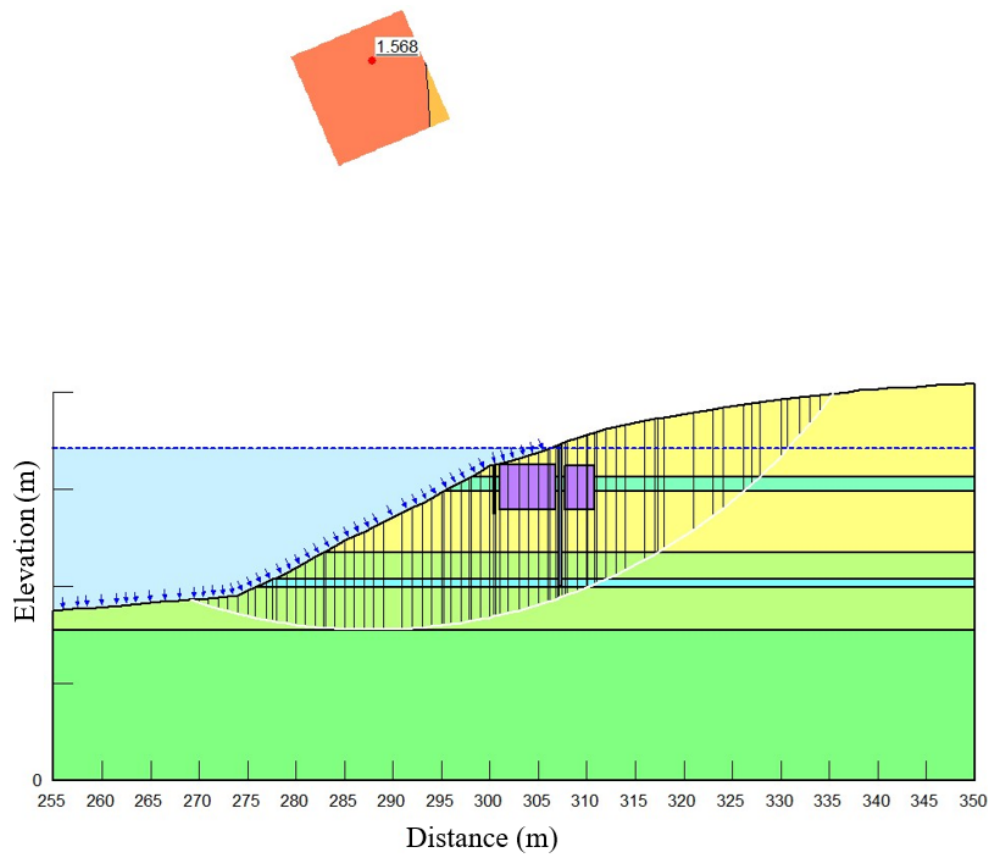


Fig. 13. SLOPE/W analysis results for cross-section L8

cohesion), the destabilising effect of reduced lake water levels which decrease buttressing support at the toe, and the superimposed dynamic loads from tourist vehicles. The identified critical FoS of 1.166 for section L8 under specific loading and water level conditions underscores the precarious state of these slopes and corroborates the observed landslide events. This sensitivity to water level fluctuations and surcharge loading is a well-documented phenomenon in slope stability assessments (Yang et al., 2019).

b) Effectiveness and rationale of proposed engineering solution

The proposed integrated engineering solution, combining RC sheet piles, Melaleuca timber piles, geotextile reinforcement, and sandbag revetment, was designed to address the complex failure mechanisms identified. RC sheet piles offer deep-seated stabilisation by creating a shear-resistant barrier and retaining the potentially unstable soil mass. The use of locally sourced, environmentally compatible Melaleuca piles contributes to internal soil reinforcement and improves drainage, enhancing the overall soil mass properties. Geotextiles play a crucial role in reinforcing the soil, distributing loads, preventing the migration of fine particles (filtration), and separating different soil layers. The sandbag revetment provides immediate, cost-effective toe protection against wave erosion during the construction phase and for short-term defence.

The significant improvement in the Factor of Safety for the critical L8 section, from 1.166 to 1.568 post-mitigation, demonstrates the technical efficacy of this composite solution in enhancing shoreline stability to well above acceptable engineering standards. This approach contrasts with some traditional hard engineering solutions, such as extensive rock revetments, which can be visually intrusive and may negatively impact local sediment dynamics and ecological habitats (Abrahams, 2008; Nakagawa et al., 2013). The chosen solution prioritises environmental sensitivity and aesthetic integration, which are paramount for a national scenic heritage site like Bau Trang.

c) Implications of the study

This research provides a critical scientific basis for immediate intervention and the development of long-term, sustainable shoreline management plans for Bau Trang Lake. The detailed assessment of instability mechanisms and the validated effectiveness of the proposed solution offer actionable insights for local authorities and site managers. Furthermore, the methodological framework, integrating field investigations, remote sensing, and geotechnical modelling, can be adapted for assessing and managing similar ecologically sensitive and economically important tourism destinations facing comparable erosion and landslide risks globally. The emphasis on environmentally considerate

engineering solutions is particularly relevant for protected areas where conservation objectives must be balanced with development needs.

d) Limitations of the study

While this study provides a comprehensive assessment, certain limitations should be acknowledged. The geotechnical parameters used in the modelling, although based on site investigations, may exhibit local spatial variability not fully captured. The direct observations of dune movement, while indicative of active processes, were conducted over a relatively short period (three months) and may not represent longer-term annual or decadal trends. The modelling of dynamic loads from tourist vehicles, while incorporating recorded accelerations, is a simplification of complex vehicle-ground interactions. Furthermore, the long-term ecological response to the implemented engineering solutions will require ongoing monitoring.

e) Recommendations for future research

To build upon this work, several avenues for future research are recommended. Long-term monitoring of the implemented stabilisation measures and continued surveillance of shoreline changes are crucial to evaluate the sustained effectiveness of the solutions and adapt management strategies if necessary. More detailed hydrogeological investigations could elucidate the complex interactions between groundwater levels, lake water levels, and slope stability. Research into the specific ecological impacts of both the landslides and the mitigation measures on the aquatic and terrestrial habitats of Bau Trang would be beneficial. Finally, the development of a holistic, integrated risk management plan for the entire Bau Trang ecosystem, considering all interacting natural and anthropogenic factors, should be a priority.

Conclusion

This study has comprehensively assessed the critical issue of shoreline erosion and landslide susceptibility threatening the ecological integrity and tourism value of Bau Trang Lake, a national scenic heritage site in Vietnam. The investigation revealed that specific sections of the lakeshore, particularly within the Bau Ba area (notably cross-sections L4 and L8), exhibit low Factors of Safety (FoS < 1.25), rendering them unstable under prevailing natural conditions and exacerbated by anthropogenic pressures, including fluctuating lake water levels and dynamic loads from tourism activities. The observed dune migration and shoreline changes further underscore the dynamic and vulnerable nature of this unique lacustrine environment.

An integrated engineering solution, comprising reinforced concrete sheet piles, Melaleuca timber piles, geotextile reinforcement, and sandbag revetments, was proposed and evaluated. Geotechnical modelling demonstrated that this

solution significantly enhances shoreline stability, increasing the Factor of Safety for the critical L8 section from 1.166 to 1.568. This confirms the technical feasibility and effectiveness of the proposed measures in mitigating landslide risk while being designed to be environmentally considerate and to preserve the aesthetic qualities of the site.

The findings provide a robust scientific foundation for immediate and long-term management interventions at Bau Trang Lake.

More broadly, this research offers a valuable methodological framework and a practical example of sustainable engineering applicable to other ecologically sensitive lakeshore environments facing similar geomorphological challenges globally. The study underscores the necessity for prompt implementation of these protective measures by relevant authorities, in collaboration with scientific expertise, to ensure the enduring conservation and sustainable development of the Bau Trang landscape for future generations.

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ГЕОТЕХНИЧЕСКАЯ ОЦЕНКА И УСТОЙЧИВЫЕ ИНЖЕНЕРНЫЕ РЕШЕНИЯ ДЛЯ ПРЕДОТВРАЩЕНИЯ ОПОЛЗНЕЙ НА ОЗЕРЕ БАУ ТРАНГ, ЛАМДОНГ, ВЬЕТНАМ

Нгуен Тхи Май Суонг¹, Фам Нгок Тхинь^{2*}, Данг Ван Фу², Ле Суан Бао², Чыонг Ван Доан², Ле Нгок Тхань³

¹ Вьетнамская авиационная академия, Хошимин, Вьетнам

² Университет Тхуйлой, Ханой, Вьетнам

³ Университет Нгуен Тат Тхань, Хошимин, Вьетнам

*E-mail: thinhtls@tlu.edu.vn

Аннотация

Введение. В данном исследовании проводится оценка оползней и предлагаются соответствующие меры по защите озерной системы вдоль береговой линии Бау Транг, известного места экотуризма в провинции Биньтхуан (ныне часть провинции Ламдонг), Вьетнам. Территория находится под угрозой береговых оползней, вызванных как природными катаклизмами, так и деятельностью человека. **Методы.** В исследовании использовались топографические и геоморфологические геотехнические методы, дистанционное зондирование и географические информационные системы (ГИС) с применением моделей Geo-studio. **Результаты** показывают, что участки береговой линии с низким коэффициентом безопасности особенно уязвимы из-за колебаний уровня воды в водохранилище, вибраций и движения круизных судов. Для повышения устойчивости береговой линии были предложены различные технические решения, включая пластины для снижения эксплуатационных нагрузок, геотехнические текстильные материалы, железобетонные шпунтовые сваи, сваи из древесины мелалеуки (каяпута) и укрепления из мешков с песком. Ожидается, что эти меры не только обеспечат безопасность береговой линии, но и защитят экосистему и окружающую среду ради сохранения этого выдающегося природного и живописного места.

Ключевые слова: эрозия береговой линии; предотвращение оползней; геотехническая устойчивость; Geo-studio; озеро Бау Транг; устойчивое строительство; экотуризм.