

Stability of the Coastal Revetment Using 2D and 3D Simulations: A Case Study in Vinh Long, Vietnam

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Abstract. Coastal erosion in the Mekong Delta has intensified due to climate change and rising sea levels, necessitating robust protective structures. This study evaluates the stability of a coastal revetment in Duyen Hai, Vinh Long province, using both two-dimensional (2D) and three-dimensional (3D) numerical simulations. Vinh Long, following its 2025 administrative merger, faces significant pressure from the East Sea's irregular tidal regime and monsoon-driven wave energy. The stability analysis was conducted using the Simplified Bishop Method within the Limit Equilibrium Method (LEM) framework via the GeoStudio software suite (SLOPE/W and SLOPE3D). Results indicate that the safety factors (FS) for all considered load combinations, basic and extreme, comply with the Vietnamese national standard TCVN 9901:2023. Notably, the 3D simulations yielded FS values approximately 11.2% higher than the 2D counterparts, with the 3D model providing a more realistic representation of soil-structure interaction by accounting for lateral resistance and interaction forces between cross-sections. Furthermore, under an extreme loading combination representing the rainy season, where upstream discharge artificially elevates the landside water level by 1.5 m, the safety factors decrease due to increased pore water pressure within the embankment. This research demonstrates that while 2D analysis remains a conservative and safe approach for design, 3D modeling offers critical insights for cost-effective design refinement and a more accurate understanding of complex failure mechanisms in soft-soil coastal foundations.

Keywords: Protective structure stability, Limit Equilibrium Method, 2D simulation, 3D simulation, Bishop Simplified Method, Mekong Delta

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Устойчивость берегового укрепления с использованием 2D- и 3D-моделирования: исследование на примере Виньлонга, Вьетнам

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Аннотация. Эрозия побережья в дельте Меконга усилилась из-за изменения климата и повышения уровня моря, что требует внедрения надежных защитных сооружений. Авторами проведена оценка устойчивости берегового укрепления в районе Дуенхай, провинция Виньлонг, с использованием двухмерного (2D) и трехмерного (3D) численного моделирования. После административной реформы 2025 г. Виньлонг испытывает значительное давление со стороны нерегулярного приливного режима Восточного моря и энергии волн, вызванных муссонами. Расчет на устойчивость выполнен упрощенным методом Бишоп в рамках метода предельного равновесия (МПР) с помощью программного комплекса GeoStudio (SLOPE/W и SLOPE3D). Результаты показывают, что коэффициенты запаса (КЗ) для всех рассматриваемых сочетаний нагрузок — как основных, так и особых — соответствуют требованиям национального стандарта Вьетнама TCVN 9901:2023. Примечательно, что значения КЗ, полученные при расчете 3D-модели, оказались примерно на 11,2 % выше, чем у 2D-модели. Трехмерная модель дает более реалистичное представление о взаимодействии грунта и сооружения за счет учета бокового сопротивления и взаимодействия сил между сечениями. Кроме того, при сочетании нагрузок с особыми воздействиями, соответствующими сезону дождей (когда сброс воды искусственно повышает уровень воды с внутренней стороны укрепления на 1,5 м), коэффициенты запаса снижаются из-за увеличения порового давления воды в теле насыпи. Исследование демонстрирует, что 2D-расчет остается подходом для безопасного проектирования с избыточным запасом прочности, однако 3D-моделирование предоставляет критически важные сведения для экономической оптимизации конструкции и более точного понимания сложных механизмов разрушения фундаментов в мягких прибрежных грунтах.

Ключевые слова: устойчивость защитных сооружений, метод предельного равновесия, 2D-моделирование, 3D-моделирование, упрощенный метод Бишоп, дельта Меконга

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1. Introduction

Coastal erosion driven by climate change and sea-level rise represents a critical threat to low-lying deltaic regions globally. In Vietnam, particularly within the Mekong Delta, this dynamic is exceptionally severe. Currently, nearly 40% of the Vietnamese Mekong Delta's 744.0 km coastline experiences severe

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erosion, with hotspot retreat rates reaching alarming levels of up to 50 to 95 meters annually [1]. The underlying drivers of this catastrophic erosion are complex, involving climate-induced sea-level rise, localized subsidence, and a critical reduction in sediment supply; the sediment load of the Mekong River has plummeted from historical highs to an estimated 42 million tons per year due to extensive upstream damming and sand mining [1]. Vinh Long province is highly vulnerable to these compounding factors. Following the July 2025 national administrative reform, which consolidated Ben Tre, Tra Vinh, and Vinh Long into a single provincial unit under Resolution No. 60-NQ/TW, drastically expanding its coastal administrative boundary [2], the region faces unprecedented pressure from the East Sea's irregular semi-diurnal tidal regime (with amplitudes up to 3.5 to 4.0 meters) and monsoon-driven wave energy.

To counteract these existential threats, provincial governments have implemented structural protective measures covering approximately 68% of the affected shorelines in the Mekong Delta [3]. Structural engineering interventions, including traditional sea dikes, Busadco breakwaters, semi-circular breakwaters, and centrifugal pile-rock systems, have been widely deployed [3–11]. Empirical monitoring demonstrates the physical efficacy of these structures; for instance, breakwaters in the region achieve a 62% reduction in wave transmission heights, facilitating rapid sediment storage and creating alluvial offsets at rates up to 3.1 cm per month. However, while these structures effectively mitigate hydrodynamic forces, their placement on the highly cohesive, low-bearing-capacity soft clays characteristic of the Mekong Delta may cause significant potential slip failures.

Despite extensive documentation regarding the hydrodynamic performance and wave-reduction efficiency of these physical coastal defenses, a critical analytical gap persists regarding the computational modeling of their geotechnical stability. In engineering practice, stability analyses of protective structures and coastal embankments are overwhelmingly performed using two-dimensional (2D) Limit Equilibrium Methods (LEM) [12–15], treating the slope as an infinite plane-strain condition. While computationally efficient, contemporary geotechnical advances demonstrate that 2D plane-strain assumptions systematically yield a highly conservative factor of safety by artificially assuming the shear resistance along the lateral boundaries (end effects) of the finite sliding mass is exactly zero [16]. Modern variational limit equilibrium frameworks prove that for slopes comprised of highly cohesive soils, the magnitude of this 3D spatial effect increases approximately linearly with soil cohesion [16]. Therefore, relying exclusively on 2D methodologies systematically underestimates safety margins and can lead to the specification of over-engineered, excessive physical reinforcements, necessitating the adoption of advanced 3D spatial modeling to accurately capture realistic failure mechanisms.

Therefore, the specific object of this research is the 900-meter-long Long Huu — Hiep Thanh coastal revetment system, constructed on highly cohesive soft-soil foundations in Duyen Hai, Vinh Long province. The primary aim of this study is to evaluate the structural stability and identify the complex spatial failure mechanisms of the revetment under dynamic, monsoon-driven hydrological loading conditions. To fulfill this aim, the specific objectives of the study are: (1) to execute comparative steady-state seepage and limit equilibrium stability analyses using Bishop's Simplified Method in both 2D (SLOPE/W) and 3D (SLOPE3D) computational environments; (2) to quantitatively assess the safety factor variance generated by the inclusion of lateral shear resistance inherent to 3D space in cohesive clays; and (3) to rigorously validate the structural integrity of the revetment against the threshold criteria mandated by the TCVN 9901:2023 national standard under both basic and extreme loading combinations.

2. Research Methods

Slope stability is one of the most important and challenging problems in geotechnical engineering, directly related to the safety of infrastructure projects such as dams, roads, and mining areas [12; 13]. Mechanically, a slope is considered stable when the anti-slip forces of the soil mass are large enough to resist the sliding forces caused by gravity or external influences. In the history of soil mechanics, the Limit Equilibrium Method (LEM) has become a dominant tool due to its high practicality. Among the LEM methods, the Bishop method, specifically the simplified Bishop method, plays an important bridging role

between less accurate classical methods and complex modern methods. Bishop's simplified method is based on key mechanical assumptions to address the static indeterminacy of the problem [12]. First, this method applies only to slip surfaces in the shape of a circular arc. Second, Bishop assumes that the shear forces between blocks (X) are zero, meaning that the interaction forces between the soil blocks consist only of horizontal normal forces (E). Third, the safety factor is calculated based on the overall moment equilibrium condition with respect to the center of the circular slip surface and the vertical force equilibrium for each individual block. Although this method does not satisfy the horizontal force balance condition for the entire mass, experimental and verification studies have shown that Bishop's safety factor results are often very close to those of more accurate methods, such as the Spencer or Morgenstern-Price methods. This makes Bishop the commonly adopted method in engineering practice for analyzing circular slip surfaces.

In slope stability analysis, the two-dimensional (2D) simulation method is the most popular in engineering practice due to its convenience and long history of development. 2D simulations are based on the assumption of plane deformation, in which the sliding mass is divided into vertical slices [12; 13]. 2D analysis has a distinct advantage in terms of computational efficiency. Solving a 2D problem typically takes only a few seconds to a few minutes, allowing engineers to perform a series of sensitivity analyses of geological and hydrological variables. Furthermore, 2D methods (such as simplified Bishop or Morgenstern-Price) often yield lower (conservative) safety factors than observed in reality, due to the omission of resistance at the edges of the sliding mass [16]. This inadvertently creates a safety margin for the structure design. The primary technical constraint of 2D analysis is its inability to describe complex geometric conditions. For embankment sections with horizontal curvature, abrupt changes in embankment crest elevation, or heterogeneous geology along the alignment, the plane deformation assumption becomes unsuitable. In addition, 2D analysis does not account for lateral resisting forces, which are crucial for stabilizing finite-sized sliding masses.

To address the limitations mentioned above, three-dimensional simulation has become increasingly attractive. In which the Slope3D module extends the capabilities of GEOSTUDIO by applying a method of columns instead of slices, allowing for the simulation of sliding masses in real three-dimensional space [16–19]. This provides a highly suitable analytical framework for complex geotechnical systems that cannot be fully covered by 2D models. The advantages of 3D modeling lie in its ability to fully consider boundary effects and slope curvature. Studies have shown that for highly cohesive soils and large depth-to-surface landslides. Slope3 allows direct integration of 3D geological models from software such as Leapfrog, enabling accurate depiction of weak points, faults, and changes in subsurface layers. The ability to search for landslide surfaces using the Cuckoo algorithm or automatic optimization helps to determine a more representative failure mechanism in complex space. 3D analysis requires a much larger amount of geological and topographic survey data than 2D analysis [20]. The modeling process and problem-solving time are also more expensive, sometimes requiring powerful computing systems and a significant investment in software and personnel training. The introduction of Slope3D into the GeoStudio ecosystem represents a leap forward in the ability to capture realistic three-dimensional failure mechanisms. Instead of considering only a single cross-section, Slope3D allows for the simulation of the entire potential slip mass, thereby accounting for side resistance, a factor that often increases the safety factor compared to 2D analyses. Comparative studies show that 3D safety factors are typically 15 to 30% higher than 2D under symmetrical conditions. Still, they may be lower if the geology has localized weak areas that a 2D cross-section cannot fully cover.

Slope3D extends Bishop's theory by replacing 2D slices with vertical 3D columns, as shown in Figure 1. The potential sliding mass in 3D space is discretized into a network of columns with cross-sections ($dx \times dy$) [21]. Each of these columns becomes a basic computational unit, subject to a more complex system of forces in three-dimensional (x, y, z) space. For any given column in Slope3D, the forces involved include its own weight (W), the pore water pressure at the base of the column (U), the normal force at the base (N), and the mobilized shear force at the base (S) [19; 22]. Similar to 2D, the lateral interaction forces between columns play a crucial role in establishing equilibrium.

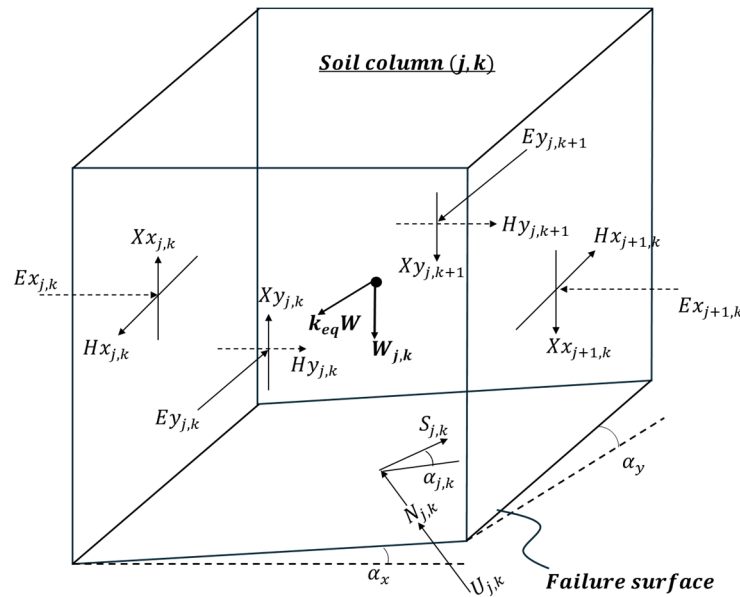


Figure 1. Forces acting on the soil column

Source: made by H.P. Tran.

In GeoStudio's Bishop 3D method, the following simplification assumptions are applied [17; 20]. First, side shear forces between columns in the vertical direction are ignored (total equal to zero). Second, it is assumed that normal interaction forces between columns are horizontal. Finally, the direction of slip of the entire mass is determined uniformly, usually the one with the greatest tendency toward instability.

The Bishop 3D safety factor equation, Eq. (1), can be expressed as an integral over the entire projected area of the sliding block [19]:

$$FS = \frac{\sum R_{j,k} \left(c_{j,k} A_{j,k} + W_{j,k} (1 - r_{u,j,k}) \tan \Phi_{j,k} \right) / m_{\alpha,j,k}}{\sum W_{j,k} \left[R_{j,k} m_z + k_{eq} e_{j,k} \right]} \quad (1)$$

The coefficient $m_{\alpha,j,k}$ for each column (j, k) now depends on the normal vector of the slip surface at the bottom of that column and the assumed slip direction. A subtle point in Slope3D is the handling of the normal force (N). Because N depends on FS, the problem in 3D becomes more sensitive to boundary conditions and slip surface shape, especially when the slip surface is not a perfect sphere.

3. Case Study

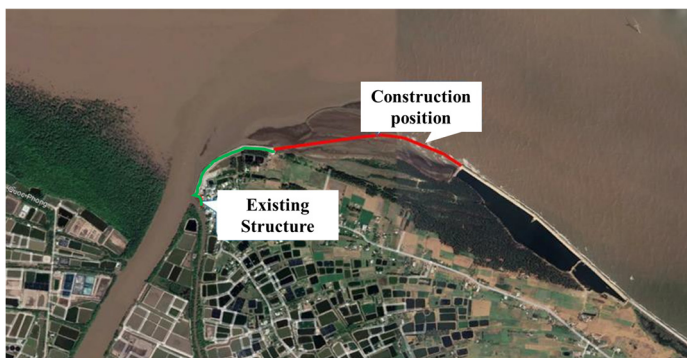


Figure 2. Location of the construction site

Source: made by H.P. Tran.

The construction site is located at Duyen Hai Town, Vinh Long Province, Vietnam, as illustrated in Figure 2. This is a 900 m long construction line that is going to be constructed to protect the shoreline in this area. The cross-section of the coastal revetment and the soil properties of the soil at this construction site are presented in Table 1 and Figure 3. Two distinct loading combinations were established for the numerical simulations, i.e., basic and extreme loading combinations. Basic loading combination represents the high-probability,

everyday operational conditions of the coastal defense system with the landside water level at +1.00 m and the seaside water level at –2.57 m. Extreme loading combination simulates a low-probability, critical stress event representative of the monsoon rainy season. Under this condition, heavy upstream discharge artificially elevates the landside water level by 1.5 meters relative to the normal level. Thus, the landside water level is at +2.50 m, and the seaside water level is at –2.57 m. This differential creates a severe hydraulic gradient, drastically increasing pore water pressures within the embankment body and foundation, thereby representing the most severe threat to slope stability in this area.

Table 1. Soil properties

Item	Symbol	Unit	Embankment	Layer 1	Layer 2	Concrete	Crushed stone
Unit weight	γ	kN/m ³	18.9	18.9	16.5	24.0	22.0
Saturated unit weight	γ_{sat}	kN/m ³	19.1	19.1	16.6	24.0	23.0
Friction angle	ϕ	Degree	22.03°	22.03°	4.10°	35°	40°
Cohesion	c	kPa	6.9	6.9	6.0	1000	5
Hydraulic conductivity	k_x, k_y	m/s	6.74e-06	6.74e-06	5.94e-08	–	–

Source: made by H.P. Tran.

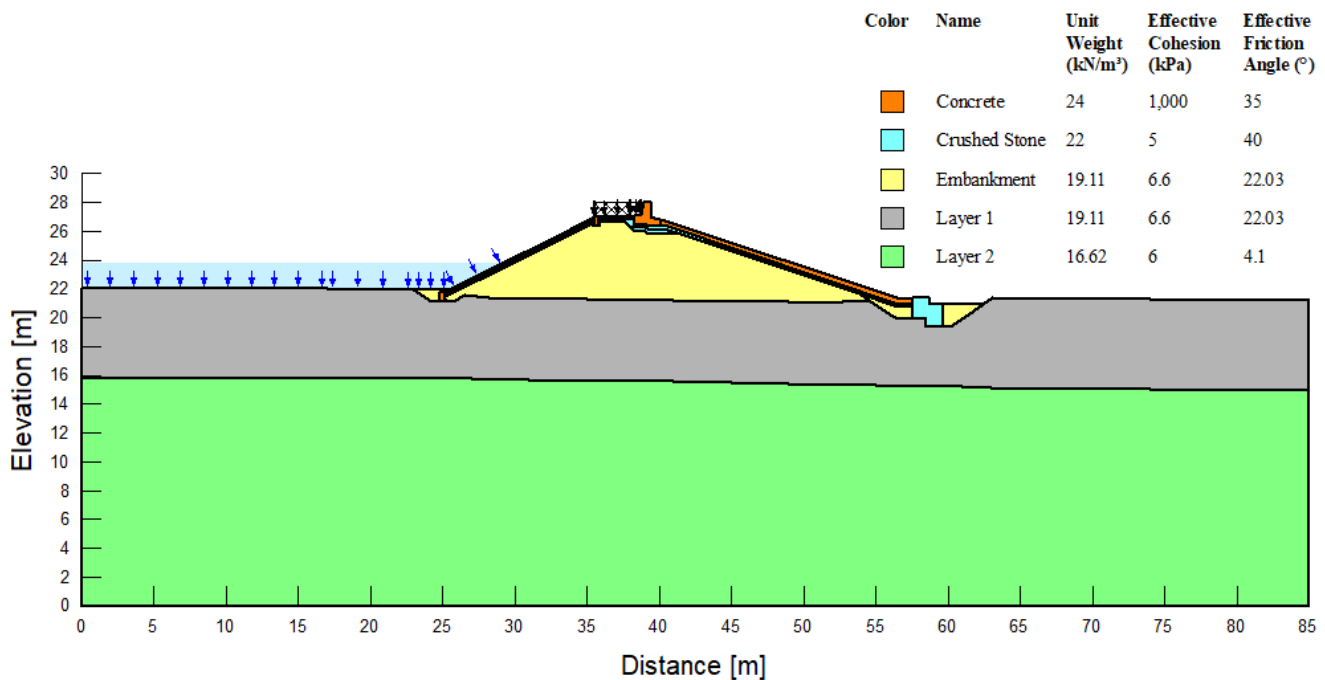


Figure 3. Cross-section of the coastal revetment and soil materials

Source: made by H.P. Tran.

4. Results and Discussion

4.1. Seepage and Stability Results

The analysis results from SLOPE/W 2D and SLOPE3D are shown in the figures below for three load combinations: the basic load combination and the extreme loading combination. First, the seepage analyses were carried out for these two load combinations as presented in Figure 4 to Figure 7. It is obvious that both the 2D and 3D simulations provide the same results of the piezometric line from the landside to the seaside and also the same of the pore-water pressure contour. The seepage flow mostly occurs at the embankment

and soil layer 1 to the toe of the embankment. It can be observed through Figure 8, which is a plot of the water rate at the toe on the right side of the embankment, the water rate at Point 2 is higher than that of the others. Additionally, the water rate at Point 2 obtained from the 3D simulation is higher than that of the 2D simulation by around 40%. Thus, there is a structure placed at the embankment toe to collect the water and to prevent the erosion caused by this flow.

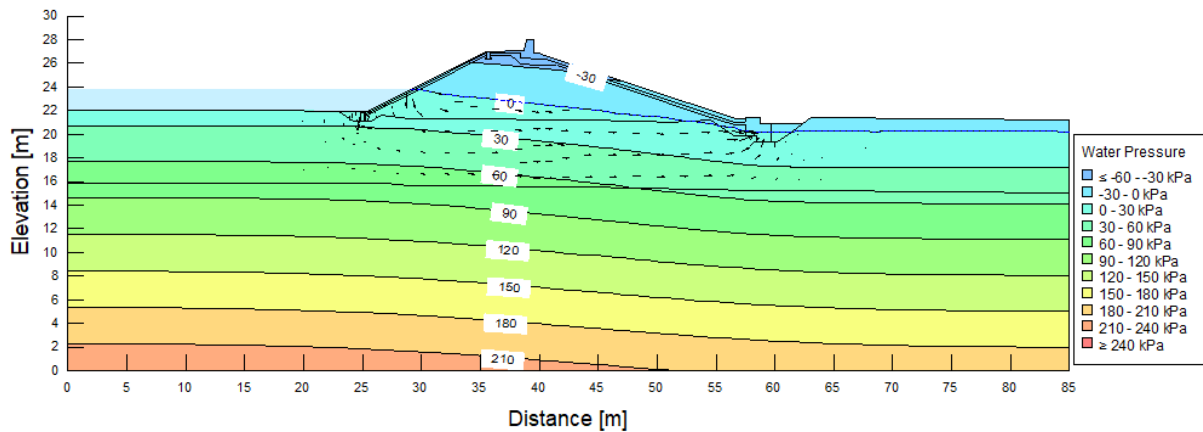


Figure 4. Seepage analysis using 2D simulation for basic loading combination

Source: made by H.P. Tran.

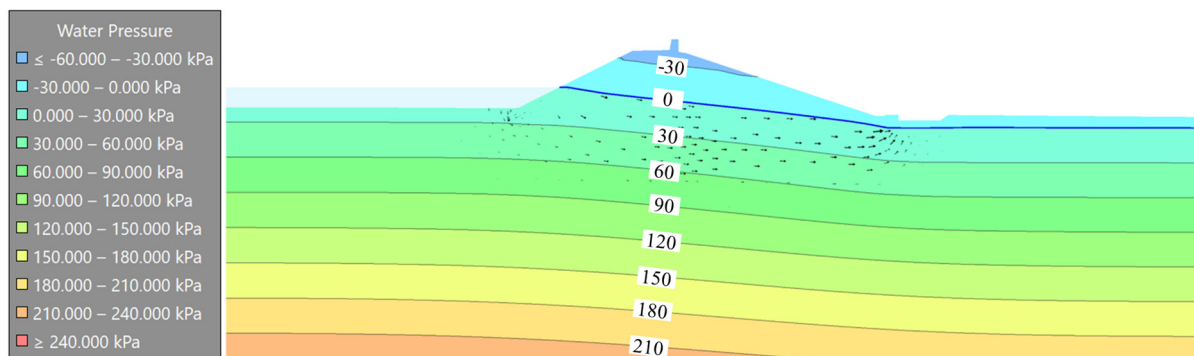


Figure 5. Seepage analysis using 3D simulation for basic loading combination

Source: made by H.P. Tran.

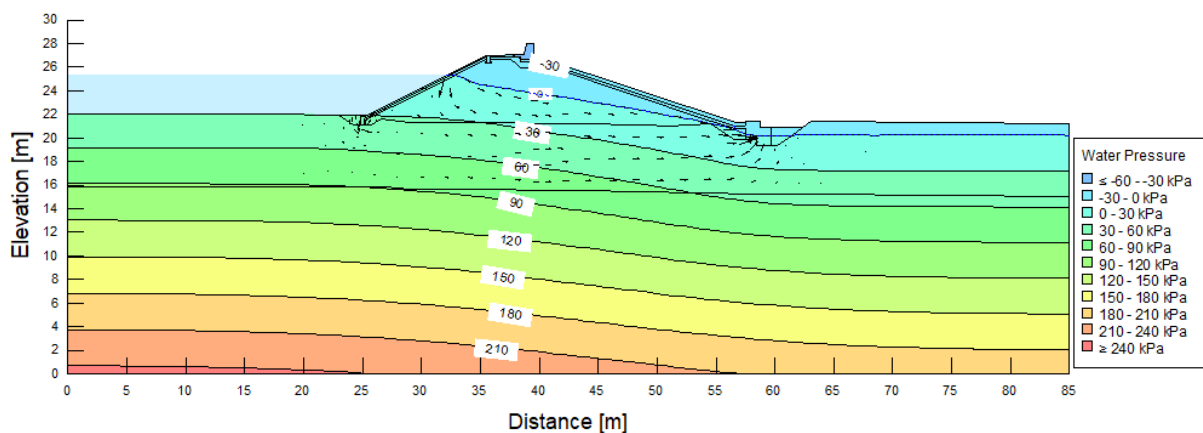


Figure 6. Seepage analysis using 2D simulation for extreme loading combination

Source: made by H.P. Tran.

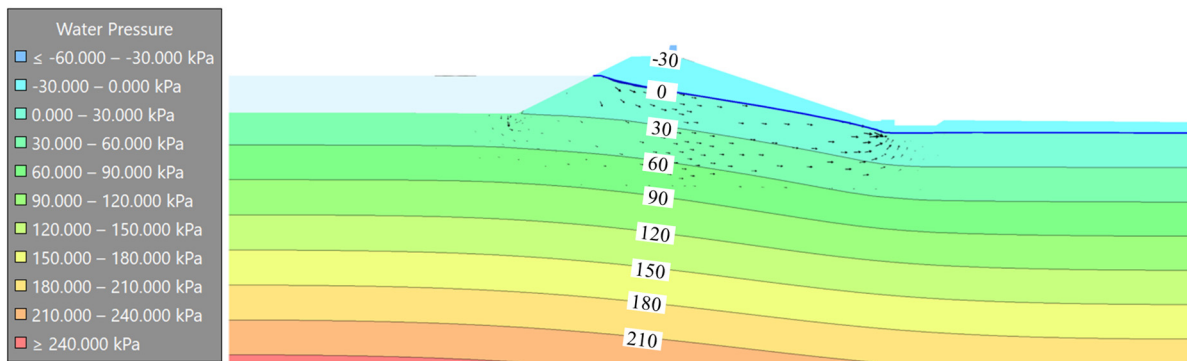


Figure 7. Seepage analysis using 3D simulation for extreme loading combination

Source: made by H.P. Tran.

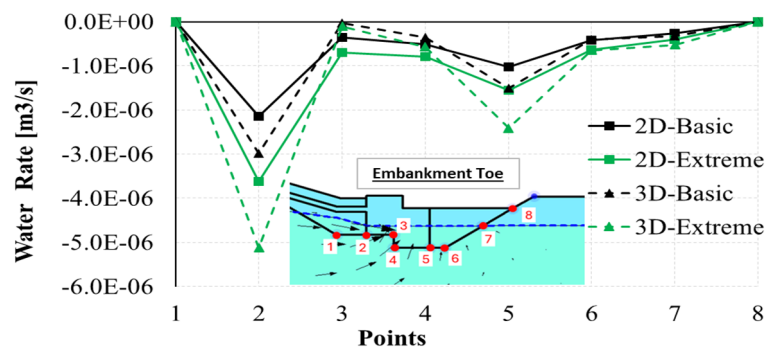


Figure 8. Seepage analysis using 3D simulation for extreme loading combination

Source: made by H.P. Tran.

Next, the stability analyses were conducted for both loading combinations using both the 2D and 3D simulations. The results are presented in Table 2 and Figure 9 to Figure 12. In general, the structural stability was evaluated against the safety thresholds prescribed by the Vietnamese National Standard TCVN 9901:2023 (Sea dike structures — Requirements for design) [23]. This standard utilizes a limit state design approach, mandating minimum allowable factors of safety, $[K]$, that reflect the reliability index required for coastal infrastructure in soft-soil environments. For the basic load combination, the standard requires $[K] \geq 1.10$. For extreme combinations (incorporating a simulated 1.5 m storm surge), the threshold is adjusted to $[K] \geq 1.05$ to account for the low probability of such events. These values align with global risk-based engineering frameworks, such as Eurocode 7's partial factor logic, which balances economic material allocation with a low probability of structural failure. As presented in Table 2, the deterministic stability analysis reveals that the revetment is safe under the basic and extreme load combinations according to the Vietnamese National Standard TCVN 9901:2023. It can be seen that the basic load combination yields the higher safety factor, while the special load combination yields the lower safety factor. This can be explained by the fact that, for the extreme loading combination, the water level on the landside is 1.5 m higher than in the basic loading combination. This results in a higher piezometric line, increasing pore water pressure in the embankment body, thereby reducing the stability of the coastal revetment.

Table 2. Safety factor from stability analysis

Loading Combination	2D	3D	$[K]$	Check
Basic loading combination	1.311	1.459	1.10	OK
Extreme loading combination	1.252	1.389	1.05	OK

Source: made by H.P. Tran.

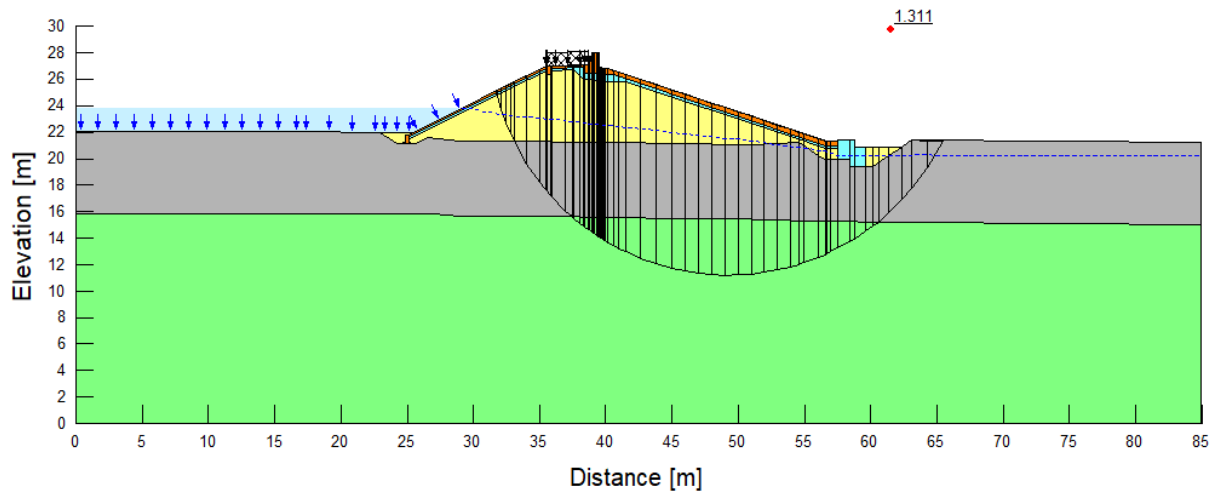
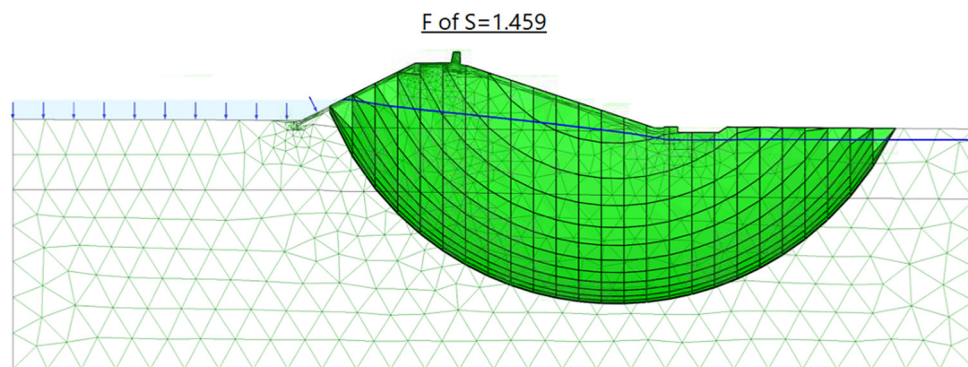
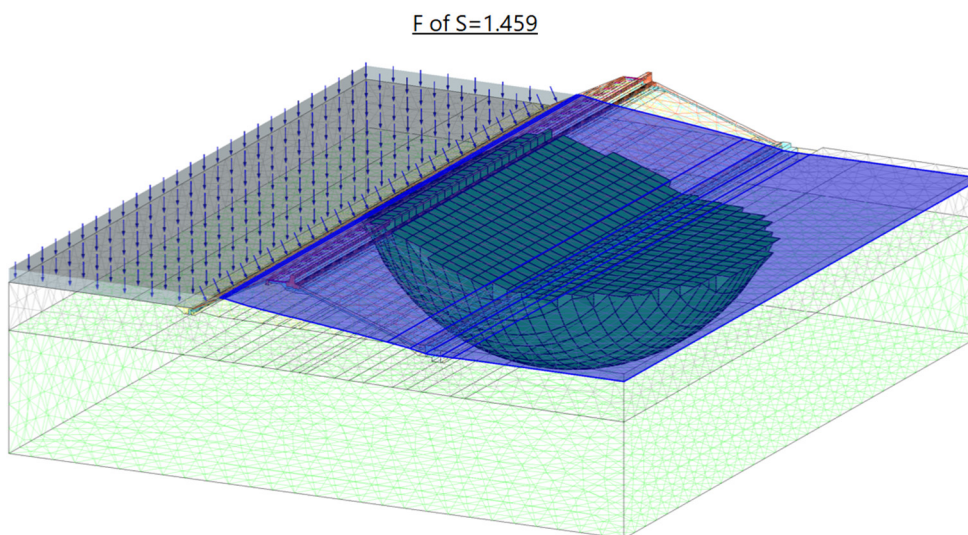


Figure 9. Stability analysis using 2D simulation for basic loading combination

Source: made by H.P. Tran.



a



b

Figure 10. Stability analysis using 3D simulation for basic loading combination:

a — Front view; *b* — 3D view

Source: made by H.P. Tran.

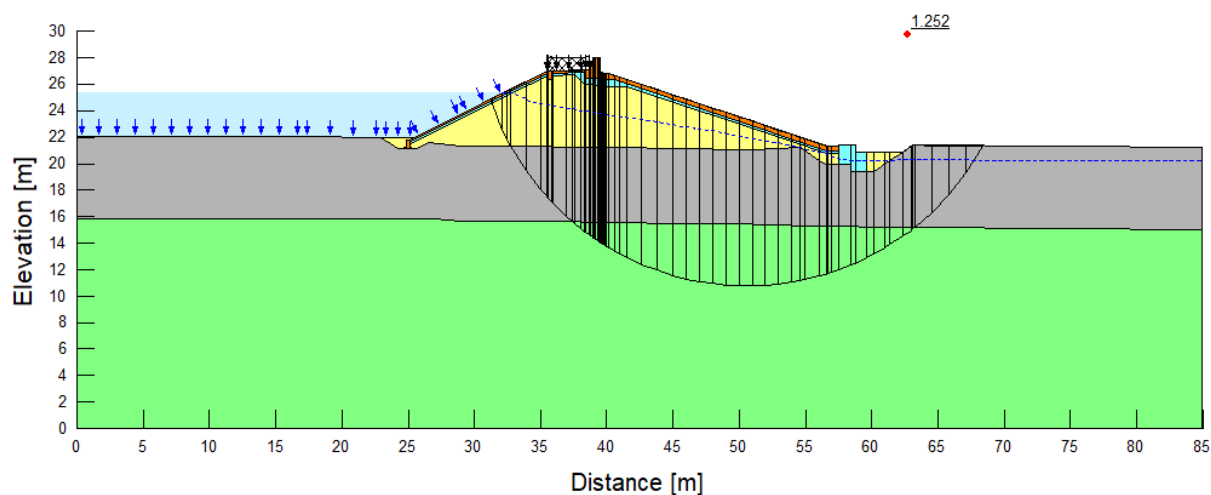
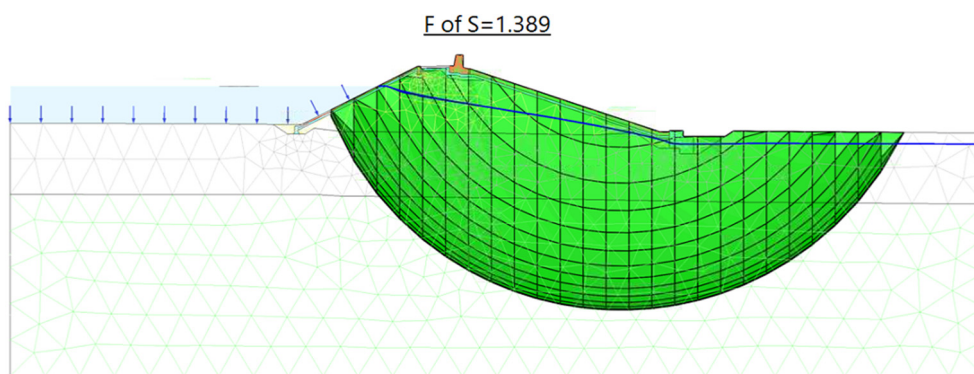
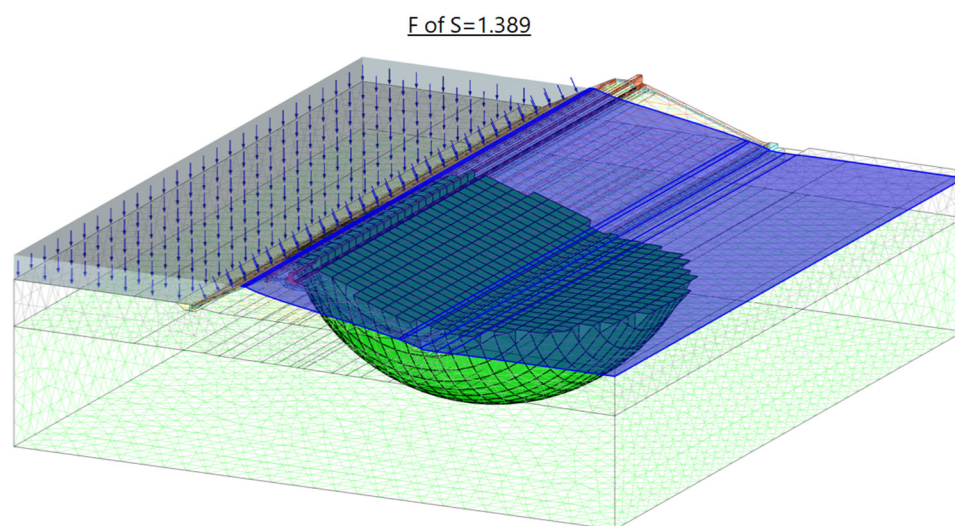


Figure 11. Stability analysis using 2D simulation for extreme loading combination

Source: made by H.P. Tran.



a



b

Figure 12. Stability analysis using 3D simulation for extreme loading combination:

a — Front view; *b* — 3D view

Source: made by H.P. Tran.

4.2. Discussion on the 3D Spatial Effects

Comparing the results between 2D and 3D simulations, it can be seen that the safety factor in the 3D simulation is higher than in the 2D simulation (approximately 11.2%). The observed 11.2% increase in the FS obtained from 2D plane-strain to 3D spatial frameworks is consistent with the established performance of LEM in cohesive soils. This variance is fundamentally driven by the mobilization of lateral shear resistance and interaction forces along the z-axis of the finite sliding mass, which are mathematically omitted in 2D models. Our findings align closely with the empirical benchmarking conducted by Shoffiana, A. et al. (2022) [24], who reported 3D/2D FS ratios ranging from 1.09 to 1.397 (a 9 to 40% difference) for embankments on soft foundations. While some studies, such as those by Bahsan and Fakhriyyanti (2018), have reported higher ratios reaching 1.44 [25], the 11.2% increase in this study is theoretically consistent with the specific geotechnical properties of clay layer 2. According to the variational limit equilibrium frameworks established by Zhang et al. (2024), the magnitude of the 3D effect is highly sensitive to soil cohesion; in purely frictional soils, the 3D effect vanishes, whereas it increases approximately linearly with the dimensionless cohesion parameter $c/(\gamma H \tan \Phi)$ [16].

Furthermore, the study by Xue et al. (2025) utilized a 3D Finite Difference Method (FDM/FEM) and reported a relatively small safety factor increase, from 1.27 in the 2D analysis to 1.311 in the 3D analysis, for their reinforced slope [26]. This narrower margin of increase is mechanistically attributed to the fundamental differences between FEM/FDM and LEM. Finite Element and Finite Difference frameworks inherently calculate complex stress-strain redistributions, localized volumetric yielding around structural reinforcements (such as piles), and capture massive reductions in spatial displacement. These strain-based mechanics often result in more conservative scalar safety factors for reinforced structures. In contrast, the 3D Limit Equilibrium Method (LEM) utilized in this current study focuses purely on statics, directly integrating the lateral boundary resistance of the highly cohesive natural clay matrix into the force-balance equations. By recognizing these distinct mechanical functions and methodological behaviors, the 11.2% variance is validated not as a numerical inconsistency, but as a mathematically precise evaluation of spatial confinement within a pure LEM framework.

As of 2026, the majority of engineering design standards in Vietnam still require a 2D simulation to verify the stability of the coastal revetment. However, the 2D simulation seems to underestimate the stability of the protective structure system compared to reality. It implies that using 2D simulation in practice design can be safer but inefficient in terms of the economic aspect. The question of using 2D or 3D simulation in practice design should be discussed more in future research.

5. Conclusions

This paper conducted the stability analysis for the coastal revetment, which aims to protect the shoreline located in Vinh Long province, Vietnam, from erosion, using 2D and 3D simulations. The results can be stated as follows:

1. The implementation of the Long Huu — Hiep Thanh revetment geometry successfully mitigates macroscopic slope instability on highly cohesive, low-bearing-capacity foundations. Deterministic analyses confirm that the structural configuration maintains safety factors of 1.252 (2D) and 1.389 (3D) under extreme conditions featuring a 1.5-meter simulated water level increase. These values strictly satisfy the high-stress threshold requirements ($[K] \geq 1.05$) mandated by the Vietnamese national standard TCVN 9901:2023, validating the design's resilience against severe climate-induced storm surges.

2. Three-dimensional slope stability modeling, utilizing the column method framework, yields safety factors approximately 11.2% higher than equivalent 2D plane-strain simulations for the same critical slip surfaces. This numerical divergence is theoretically sound and mechanistically attributed to the mobilization of lateral shear resistance and interaction forces along the z-axis of the finite sliding mass, which are artificially omitted in 2D assumptions but become highly pronounced in the cohesive clays characterizing the Mekong Delta.

3. For linear coastal infrastructure lacking complex concave or convex topographical geometries, 2D and 3D numerical seepage models exhibit negligible variance in calculated piezometric flow lines and pore water pressure distributions. Under these specific, straight-axis longitudinal conditions, 2D steady-state seepage analyses remain quantitatively robust, indicating that computationally expensive 3D groundwater flow modeling is unwarranted unless significant lateral foundation inhomogeneities or sharp coastal curvatures are present.

4. While traditional 2D Limit Equilibrium Methods serve as a highly conservative benchmark ensuring maximum structural safety, the routine mathematical omission of lateral boundary effects systematically suppresses the perceived structural capacity of the slope. Consequently, this over-conservatism inevitably leads to the specification of over-engineered, excessive physical reinforcements. The application of 3D spatial stability analysis presents a mathematically validated pathway for cost-effective design refinement, allowing engineers to safely optimize material allocation in massive, capital-intensive coastal infrastructure projects without compromising regulatory safety thresholds.

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