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INVESTIGATION OF FAILURE OF RIVERBANK PROTECTION STRUCTURE: A CASE STUDY IN LONG AN PROVINCE, VIETNAM

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Abstract: The riverbank protection structure is an essential structure constructed to protect the riverbank from the natural and human impact. Therefore, ensuring safety for this project is very important. However, this structure can still have technical failures during construction or working stages. The failure of riverbank protection structures poses significant challenges to infrastructure stability and environmental sustainability, particularly in regions with complex geotechnical conditions. Thus, this study aims to investigate the causes of the failure with the case study is the Long Hau riverbank protection project in Long An Province, Vietnam. In doing so, a combination of on-site observations and numerical simulations using PLAXIS 2D was employed to analyze the stability of the structure and identify potential failure mechanisms. The results revealed a displacement of 8.7 cm in the bearing pile and a total structural displacement of 19.2 cm obtained from the numerical analysis, which agree well with those from field observations. Key factor contributing to the failure is the selection of the structure position, consequently leading to insufficient soil compaction, uneven settlement, and underestimated lateral forces during design. The study highlights the critical need for comprehensive site assessments, detailed numerical modeling, and regular maintenance to ensure long-term stability. In addition, the findings provide valuable insights into riverbank protection practices and provide a basis for proposing appropriate solutions for future work.

Keywords: Riverbank erosion; Riverbank protection structure; Structural failure analysis; PLAXIS 2D simulation; Long Hau embankment; Structural displacement; Bearing pile; Lateral earth pressure

АНАЛИЗ РАЗРУШЕНИЯ БЕРЕГОЗАЩИТНОЙ КОНСТРУКЦИИ В ПРОВИНЦИИ ЛОНГ АН, ВЬЕТНАМ

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Аннотация: Сооружения для защиты берегов рек являются важными конструкциями, предназначенными для защиты береговой линии от естественного и антропогенного воздействия. Поэтому обеспечение безопасности для данного проекта имеет первостепенное значение. Тем не менее, эти сооружения могут иметь технические отказы во время строительства или эксплуатации. Разрушение берегоукрепительных сооружений создает серьезные проблемы для стабильности инфраструктуры и экологической устойчивости, особенно в регионах со сложными геотехническими условиями.

В связи с этим данное исследование направлено на изучение причин разрушения на примере проекта защиты берега реки Лонг Хау в провинции Лонг Ан, Вьетнам. Для этого была использована комбинация натурных наблюдений и численного моделирования с использованием PLAXIS 2D для анализа устойчивости сооружения и выявления потенциальных механизмов разрушения. Результаты показали смещение опорной сваи на 8,7 см и общее смещение конструкции на 19,2 см, полученные в результате численного анализа, которые хорошо согласуются с данными натурных наблюдений. Ключевым фактором, способствующим разрушению, является выбор положения конструкции, что приводит к недостаточному уплотнению грунта, неравномерной осадке и недооценке поперечных сил при проектировании.

В исследовании подчеркивается критическая необходимость комплексной оценки площадки, детального численного моделирования и регулярного технического обслуживания для обеспечения долгосрочной стабильности. Кроме того, полученные результаты дают ценную информацию о практике защиты берегов рек и служат основой для предложения соответствующих решений для будущих работ.

Ключевые слова: Разрушение берегов рек; Берегоукрепительное сооружение; Анализ разрушения конструкции; Моделирование в PLAXIS 2D; Стена берегоукрепления Лонг Хау; Смещение конструкции; Опорная свая; Боковое давление грунта

1 INTRODUCTION

Riverbank protection structures are the essential structures that use technical solutions to stabilize and protect riverbanks from the impact of currents, waves, and other impacts. This structure system is especially important in areas prone to erosion. In areas with rapid urbanization and industrialization, such as in many developing countries, riverbank protection becomes extremely urgent because if erosion or bank subsidence is not well controlled, it can lead to serious consequences both economically and ecologically. Therefore, the design of protection structures must take into account the topographic, geological, and hydrological characteristics of the site. Specifically, morphology, soil composition, sediment loading, and flow velocity are factors that significantly influence the stresses and forces acting on the structure. Typical structural components of riverbank protection structures include reinforced concrete, retaining walls, anchor piles, and stone armor layers. These elements work together to resist natural erosional forces while ensuring minimal impact on the surrounding ecosystem. However, engineering challenges can arise when design specifications are flawed or environmental assessments are inadequate, which can compromise the effectiveness of the structure and lead to serious failures.

The failure of riverbank protection structures is a pressing issue that has garnered significant attention within the disciplines of geotechnical engineering, environmental science, and hydrology. Riverbank failures arise from a multifaceted interplay of natural and anthropogenic factors, including hydrodynamic forces, soil properties, and human interventions. Leng [1] highlights the critical role of geomorphological factors in the failure of riverbank protection structures, emphasizing the necessity for detailed site-specific assessments. Similarly, Akter et al. [2] underscore the importance of understanding hydrodynamic forces acting on geo-bag revetments, noting that these forces significantly influence failure mechanisms. Anthropogenic activities, such as sediment dredging and vegetation removal, exacerbate riverbank instability, as evidenced by Arora [3]. The geotechnical properties of soil play a pivotal role in riverbank stability. Chen and Wen [4] identify soil saturation caused by extreme rainfall and flooding as a primary factor increasing susceptibility to erosion and structural failure. Furthermore, Duong et al. [5] employed numerical modeling to demonstrate how hydraulic conductivity and rainfall intensity interact to destabilize riverbanks. Specific failure mechanisms, such as cantilever collapses resulting from undercutting, are particularly prevalent in cohesive soils [6], [7]. Patsinghasanee et al. [8] reveal through experimental investigations the significance of tension cracks and beam failures in cohesive riverbanks, highlighting the need for tailored engineering interventions to mitigate these risks. Vegetation is a critical factor in enhancing riverbank stability. Research by Abernethy and Rutherfurd [9] shows that even low root densities can substantially improve soil shear strength, thereby reducing failure risks. Conversely, the removal of vegetation contributes to increased erosion and instability, as demonstrated by Docker and Hubble [10], who found a strong correlation between devegetation and mass failure events. The broader implications of riverbank failures extend beyond immediate structural concerns, as they pose significant environmental and economic challenges. Patsinghasanee et al. [11] investigated the fluvial erosion and overhanging failure of cohesive riverbank and reported that this is one of the significant problem of river engineering. Mamun et al. [12] highlights the adverse impact of erosion on agricultural productivity and food security in vulnerable regions. Economic consequences are particularly pronounced in urban settings, where infrastructure and cultural heritage are at risk. Weissgerber et al. [13] note that modifications to riverbanks often disrupt riparian ecosystems Morelli et al. [14] documented riverbank failures affecting historical sites in Florence, Italy, emphasizing the need for integrated management strategies that balance infrastructure protection with environmental sustainability.

In this study, the damage incident of the Long Hau riverbank protection structure in Long An Province is analyzed and evaluated. From there, the cause of the damage will be discussed through the results from observation and numerical simulation. The results of this paper can be a basis for proposing solutions to reinforce this riverbank protection structure in the future.

2 DAMAGE SITUATION OF THE INVESTIGATED RIVERBANK PROTECTION STRUCTURE

Fig. 1 shows the location of the project studied in this paper. The project is located in Long An Province, Vietnam. It aims to prevent riverbank erosion and maintain the stability of nearby infrastructure, which is vulnerable to seasonal fluctuations of the river flow and sedimentation. The project was scheduled to be completed in December 2023.

Figure 1. Location of Long Hau embankment

As shown in Fig. 2, this riverbank protection structure consists of a reinforced concrete retaining wall approximately 1.1 meters high and an average thickness of 20 cm. The retaining wall is designed to withstand significant lateral forces exerted by the river, especially during rainy seasons. Behind the wall, a compacted sand layer with a compactness K of 90% provides a support layer to minimize movement and displacement by evenly distributing the pressure load on the retaining wall. The retaining wall is connected to a series of 400 mm diameter and 28 m long prestressed concrete piles, which form the foundation of the structure, ensuring both vertical and horizontal stability. The piles are arranged in a grid pattern, with 3.0 m spacing both vertically and horizontally, each sector consisting of two vertical piles and one inclined pile. This configuration is intended to maximize load distribution and to counteract forces caused by land subsidence, flow, and sediment movement.

The foundation of the structure is reinforced with a layer of geotextile fabric under the sand layer to increase stability and prevent erosion phenomena, along with a series of tightly packed PVC-coated gabions at a depth of -6 meters along the riverbed. These gabions, dimensions of 200 cm x 100 cm x 50 cm, act as a protective barrier against erosion, creating a buffer zone that protects the foundations from direct hydrodynamic impact.

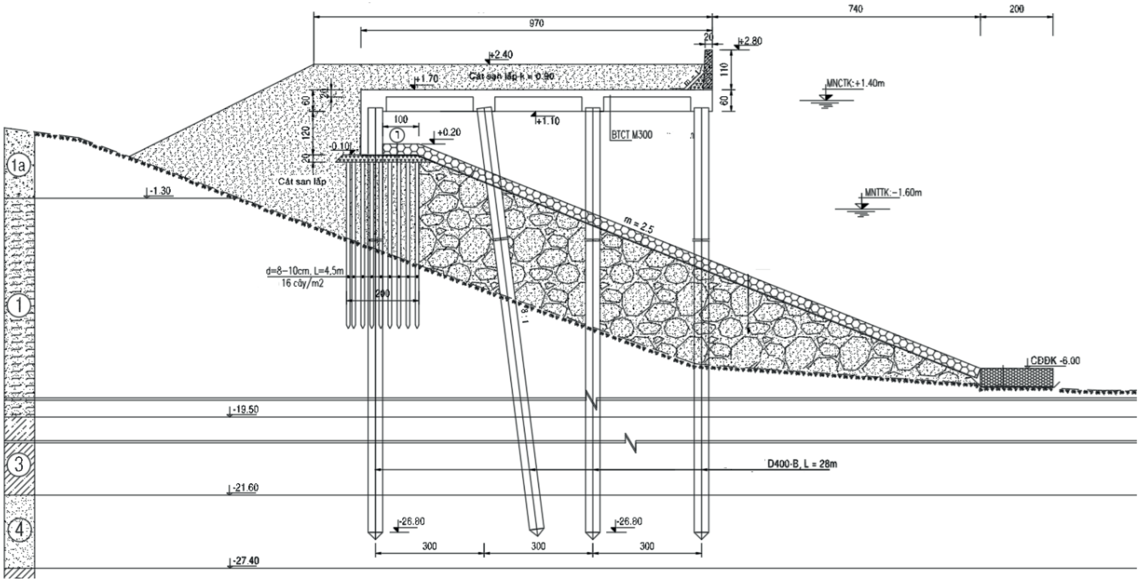

Figure 2. Long Hau embankment cross-section

As shown in Figs. 3 and 4, the Long Hau embankment began to show signs of failure soon after completion. Major issues included a displacement of approximately 20cm toward the river, visible cracks in the concrete piles, and settlement of the compacted sand layer behind the wall. These issues raised concerns about the long-term stability and resilience of the structure and posed potential risks to adjacent infrastructure and the ecosystem if not addressed promptly.

Figure 3. Settlement of the compacted sand layer after construction completion

Figure 4. Cracks on piles

These failures may be due to design or construction method deficiencies. The presence of cracks may indicate that the piles are not sufficiently resistant to surcharge load and lateral force. Similarly, lateral displacement towards the river may indicate a deviation in the safety system or a lack of force components in the calculation. The settlement of the sand layer behind the wall is due to uneven compaction. Solving these problems requires a comprehensive analysis of design and construction factors, focusing on soil interactions and material selection. Therefore, a safety assessment analysis for this structure is required to find the main causes that may lead to displacement and subsequent pile cracking.

3 ASSESSMENT OF THE CURRENT STATUS OF THE PROJECT

3.1 Project Position

Fig. 5 shows the clear transformation of the regional riverbank from 2014 to 2024. The colored contours represent the positions of the riverbank in a specific timeline, such as 2014 (blue line), 2020 (red line), and 2024 (yellow line). These lines represent the progress of the riverbank movement through each stage. The 2014 riverbank is located close to the riverbed, representing the initial state of the riverbank before being greatly impacted by natural or human factors. The blue line shows that the extent of the riverbank remains relatively stable, without significant changes, indicating that the level of erosion or artificial intervention is still very limited. By 2020, the riverbank changes became more evident as the red line moved toward the landside compared to that observed in 2014. This can be explained by natural erosion or interference from construction and land exploitation activities near the riverbank area. This shift suggests a possible reduction in natural land area and also shows the impact of hydrological or human factors on the topographic structure of the area. The shoreline in 2024 (represented by the yellow line) is currently the newly designed embankment line. Noticeably, the position of the project is about 23.68 m from the shoreline. Choosing the centerline position far from the existing shoreline with this distance can create certain deviations in the calculation of loads and pressures on the embankment, especially the soil pressure from the backfilling foundation (highlighted in red color) after the completion of the project. The observation also shows that the incident occurred mostly in this area. It might be due to the fact that, during the design process, the impact of the backfilling foundation may not have been considered carefully, leading to the omission or underestimation of important impact forces. Specifically, the earth pressure and displacement of the foundation after backfilling are likely to put great pressure on the embankment, requiring additional reinforcement measures or appropriate structural solutions to maintain the stability of the structure. Therefore, it is necessary to carefully analyze the cause of this incident, from which appropriate solutions can be proposed to reinforce the structure at this location.

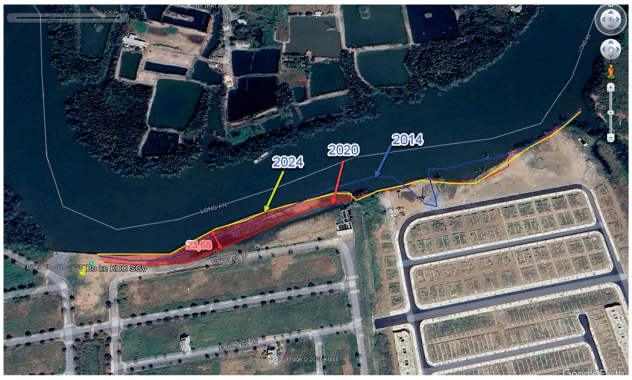

Figure 5. Location of shoreline in 2014 and 2020 and embankment in 2024

3.2 On-Site Observation

The field observation, which took place from August to September 2023, included 29 specific locations illustrated by the red area in Figure 5 and the red spot illustrated explicitly in Figure 6. The main objective of the observation was to systematically collect and observe at each location after the backfilling work, thereby assessing the actual condition of the project during construction. From there, it is possible to assess the safety level or detect the damage of the Long Hau embankment project.

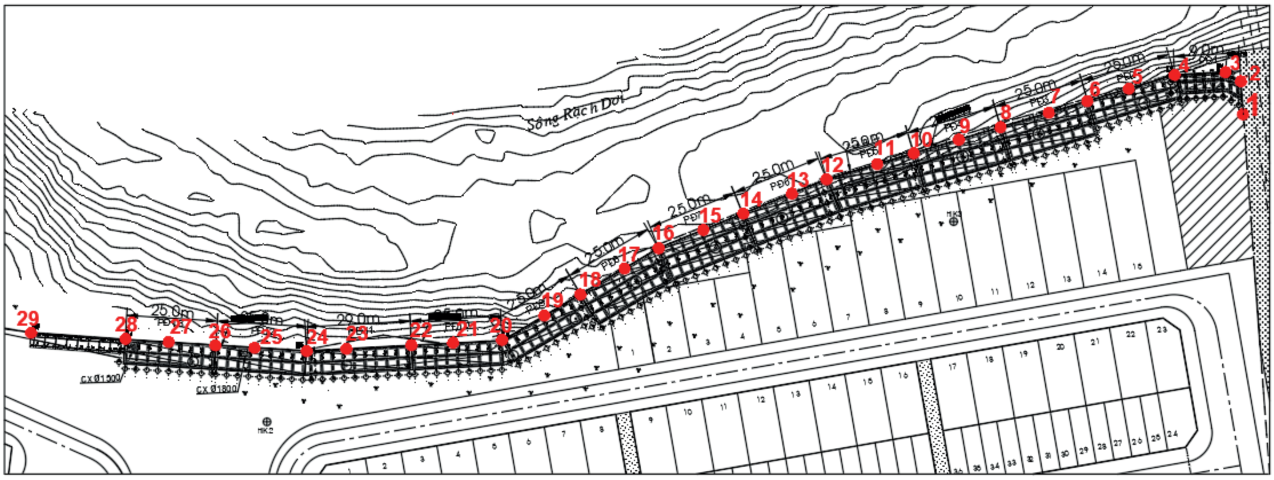

Figure 6. Locations for displacement observation

The results collected from the field observation have been summarized and presented in Fig.7. It can be seen that, after the backfilling on August 16, 2023, the project experienced displacement at 29 measurement points for the first observation. Especially at positions 10-16, the displacement value is quite large, about 11-16cm. After that, there were 10 more observations and the displacement value continued to increase to about 20cm for measurement positions 12 and 13. In addition, cracks have gradually appeared on the concrete piles and can cause unsafety for the project. From this, it can be seen that the design and construction work were not proper when not fully assessing the impact of backfilling on the project. This displacement may be due to horizontal soil pressure as well as the increased load of machinery and equipment during the backfilling process. In addition, the displacement is great at positions 10-16 due to the considerable area of backfilling compared to the other positions. Thus, the impact of the lateral active earth pressure at these positions is more significant. To verify the cause of this problem, numerical simulation analysis needs to be performed, as shown in the following section.

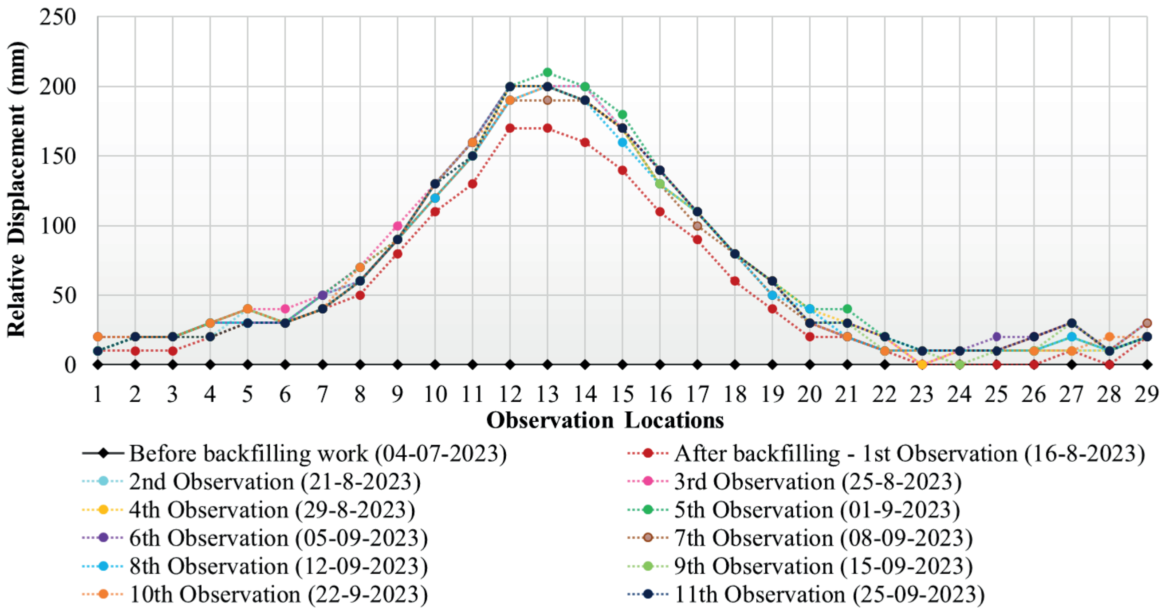

Figure 7. Relative displacement of the riverbank protection structure from the observation

3.3 Numerical analysis

Numerical analysis is widely employed to solve the engineering problem by various researchers [15, 16]. In this study, PLAXIS 2D software – a tool widely used by engineers and researchers to solve geotechnical problems [17, 18, 19] – was applied as a design tool to analyze the stability and determine the cause of geotechnical failures. The mechanical properties of the embankment together with the geotechnical properties of the embankment and foundation, were collected for analysis using the finite element method. To ensure the accuracy of the simulation, the boundary conditions were specifically set as follows: the bottom of the model was assumed to be completely fixed (fixed boundary), while the longitudinal boundaries only allowed vertical displacement to reflect the actual conditions at the site, as shown in Fig. 8.

The soil parts are modeled using six-node triangular isoperimetric elements with three Gaussian points per element as presented in Fig. 8. The Mohr-Coulomb (MC) model, an elastic-plastic model commonly used to simulate the general behavior of soils, requires five parameters: Young's modulus (E′), friction angle (φ'), Poisson's ratio (ν′), cohesion (c′), and dilatation angle (ψ′). For the case $\varphi' > 30^o$, dilatation angle (ψ′) is approximately $\varphi' - 30^o$ [20]. The material parameters are based on field data collected from geotechnical surveys and previous studies at the study site. The typical geological layers at the site include filling sand, silty clay, and soft clay. Field tests such as SPT (Standard Penetration Test) and laboratory tests, including triaxial compression and direct shear, are performed to determine important geotechnical parameters.

The Mohr-Coulomb model was chosen because of the relatively homogeneous geological characteristics in the study area. This model is simple but still meets the analysis requirements. However, to increase accuracy, the parameters were calibrated through comparison with field observations, ensuring that the model fully reflects actual conditions.

The connection between the embankment and the filling soil was also taken into account in the analysis by the rectangular interface elements, which consist of six nodes used between the soils and the structural elements [21]. The material properties used in the finite element simulation are detailed in Tables 1 and 2.

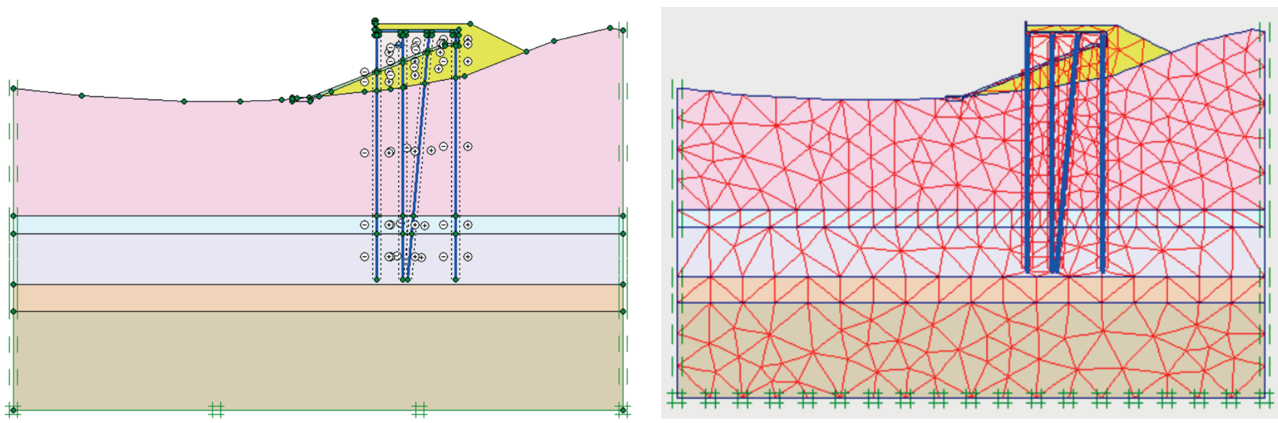

Figure 8. Numerical analysis in Plaxis 2D

Table 1. Parameters of the soil used in PLAXIS 2D

No.	Parameters	Units	Value							
1	Name		Fill sand	Rockfill	Layer 1	Layer 3	Layer 4	Layer 5	Layer 6	Concrete
2	Describe				Clayey silt	Silty clay	Sandy	Clay	Sandy	
3	Material model		MC	MC	MC	MC	MC	MC	MC	LE
4	Type of material behaviour		Drained (D)	Non porous	D	D	D	D	D	Non porous
5	Unsaturated weight	kN/m³	17.0	22.0	15.3	20.3	20.8	19.2	20.4	25.0
6	Saturated weight	kN/m³	18.0		15.5	20.8	21.1	19.6	20.8	
7	Horizontal Permeabilities	m/day	1.0		1.0	1.0	1.0	1.0	1.0	
8	Vertical Permeabilities	m/day	1.0		1.0	1.0	1.0	1.0	1.0	
9	SPT (N)	-			0÷3	5÷10	11÷22	13÷25	19÷26	
10	Stiffness	kN/m²								
	E_{50}^{ref}		7500.0	7500.0						2.15E+07
	E_{SPT}				678.9	3237.1	9723.8	3112.0	9293.3	
11	Poisson's ratio		0.3	0.3	0.4	0.4	0.4	0.4	0.3	0.2
12	Cohesion	kN/m²	1.0		5.6	14.6	6.2	34.1	5.7	0.2
	Friction angle	Deg.	30.0	45.0	3.4	10.1	24.0	14.2	24.2	
13	Angle of dilatancy	Deg.			0.0	0.0	0.0	0.0	0.0	
14	R_{int}			1.0	0.7	0.7	0.8	0.7	0.8	1.0

Table 2. Parameters of plate elements

Ord.	Parameters	Symbol	Units	D400-B
1	Material grade			*M800*
2	Young's Modulus	E_{ref}	kN/m²	4.00E+07
3	Dimension	h	m	0.40
4	Section area	A	m²	0.1257
5	Moment of inertial	I	m^4	1.26E-03
6	Spacing	s	m	3
7	Axial stiffness	EA	kN/m	1.68E+06
8	Flexural rigidity	EI	kNm²/m	1.68E+04
9	Equivalent plate thickness	d'	m	0.346
10	Weight	w	kN/m/m	1.19
11	Poisson's ratio	ν (nu)		0.2
12	Length	L	m	13.00
13	Allowable displacement	[d]	cm	-
14	Crack bending moment	$[M]_{kn}$	KN.m	75.00

The results of the pile displacement and the overall displacement are shown in Figure 9. It can be seen that the simulation results are quite close to the results from the field observations. The overall displacement value from the numerical analysis, which is 19.2 cm, agrees well with that from the field observation, which is 20.1 cm. The relative difference is only about 4.5%. This proves that the PLAXIS 2D model, with the calibrated material parameters and boundary conditions, is capable of reflecting the actual conditions in the study area quite accurately. However, a larger error was recorded in the pile displacement, which is 8.7 cm from the numerical analysis compared to 7.5 cm from the field observation. This may be due to the inaccuracy in simulating the connection between the pile and the ground or other nonlinear factors that have not been included in the model.

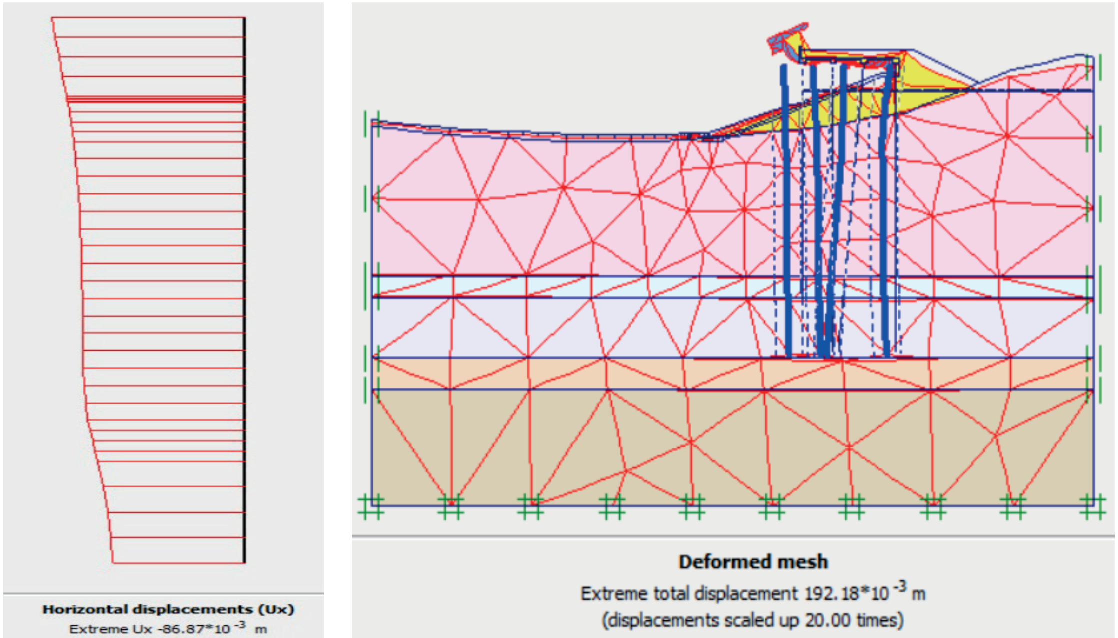

Figure 8. Pile displacement and total displacement.

The findings from this study provide important information to guide future design and maintenance practices for riverbank protection structures in Long An province, Vietnam. The detection of excessive displacement at critical locations, such as the center area of the embankment, indicates that additional reinforcement measures, such as increasing the cushion sand or using piles with higher resistance to lateral loads, are needed. At the same time, field observations demonstrate the importance of periodic inspections to detect early signs of deterioration and take corrective action before serious problems occur.

4 CONCLUSIONS

This study aims to assess the damage status of the embankment protection structure through observation and numerical analysis. In addition, this study also aims to detect the causes of the observed damage. From the analysis results, some conclusions can be drawn as follows:

The integrated approach of field observations and numerical simulations, as in this study, can become powerful methods to evaluate design performance and detect potential problems early in riverbank protection works.

The selection of the structure system position far away from the existing shoreline is one of the significant causes of failure. Because the great lateral force from the backfill soil might not be carefully considered in the design stage or due to a not proper construction process. Thus, the structure is displaced by around 20 cm toward the riverside and the cracks patterns occur on the bearing piles as shown by the observed results. This result was confirmed by the numerical analysis using PLAXIS 2D.

In the context of globalization and climate change, increasingly affecting riverside areas, expanding similar studies internationally will provide more diverse data, helping to develop new design standards that are more suitable for different natural and economic conditions. This is a potential research direction and should be further developed in the future.

Future research should focus on integrating advanced simulation techniques and eco-engineering solutions to enhance the resilience of riverbank protection systems.

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