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Study on the stable behavior of the river embankment system considering climate change impacts and pressure wave

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ABSTRACT

Understanding the behavior of working conditions of the embankment structural system on reinforced concrete pile foundations is very important in design, construction, operation exploitation, and use. This study assessed the adaptive performance of the Hau River landslide protection embankment in regard to climate change scenarios, specifically the impacts of more extraordinary groundwater table drawdown conditions including pressure waves. The study uses Plaxis 2D V.22 software to simulate and calculate the safety factor of the stability of landslide protection embankment on the right bank of Hau River in the area of Binh Duc Ward, Long Xuyen City, An Giang Province. Simulation. The research results on the effectiveness of shore protection works by the seawall system show that the impact of rising water levels as forecasted by climate change projections (+2.8m elevation) is still within the safe limits. Besides, the dangerous scenario of lowering water levels from the design elevation of -1.0 m (M_{sf} = 1.114) down to the climate change water level of -1.5m elevation (M_{sf} = 1.113)) affecting the protected shoreline also has a minor influence on the stability of the structure. Moreover, the impact of waves on the protection works, which is negligible, is also reduced by the shore protection seawall.

1. INTRODUCTION

Vietnam possesses an expansive and diverse fluvial and coastal system, containing over 2,360 primary and minor rivers and canals. The nation's coastline extends approximately 3,300 km, with a river mouth every 23 km on average. Presently, 112 river mouths discharge into the sea along the coast. This extensive network of rivers and coastline generates favorable conditions for various economic sectors, including fisheries, aquaculture, tourism, and transportation.

However, coastal erosion presents a complex and escalating challenge. This erosional trend threatens the safety and assets of coastal inhabitants and engenders adverse economic and environmental repercussions. Therefore, providing appropriate construction solutions is essential. Accordingly, several solutions have been implemented to decrease coastal landslide conditions, including constructing coastal protection works such as walls and pile systems. Furthermore, the research and application of advanced technologies in coastal management and protection also play essential roles.

The current state of shore reinforcement embankments in Vietnam is diverse typologies, categorized into three primary classes: permanent, semi-permanent, and simple-scale. Over recent decades, constructing thousands of these systems has partially fulfilled practical riverbank armoring necessities. However, notwithstanding successes, some projects have experienced damage, loss of shoreline stabilization functionality, and even adverse impacts to upstream and downstream reaches. The failure mode in embankment structures can be classified into types, such as damage to the top of the embankment, a part of the revetment roof to reinforce the shore peeling off, and the foot of construction collapsed and sliding (Cuong, 2016).

Additionally, the extent of protection work is limited due to funding constraints, which hinders the stabilization of entire hydrodynamic reaches. Determining optimal armoring length along riverine environments subject to bidirectional flows represents a complex challenge, lacking robust theoretical calculation methods. Furthermore, the survey of the current status, geology, and hydrological conditions must ensure and meet reliability. Using physical model experiments or 2-dimensional and 3-dimensional mathematical models is necessary to ensure reliability. Recent research by scientists has focused on analyzing and evaluating the stability of the embankment system and providing solutions, applying technology in coastal protection, as Kham (2013), Hajiazizi and Heydari (2019), Li et al. (2020), Linh et al. (2021). However, these analyses generally exclude climate change impacts and pressure waves which unfold rapidly and impart growing multifaceted effects.

Integrating climate change projections may become vital for developing adaptive, sustainable bank protection strategies. The studies of Pk et al. (2021) and Johnston (2021) both indicate climate change can significantly impact embankment stability through various interconnected failure mechanisms related to increased moisture and degradation of foundation soils. Quantitative, scenario-based assessments using advanced numerical modeling are critical to guide proactive adaptation strategies and ensure embankment safety and performance over the long term as the climate changes.

The current situation shows that climate change is an important factor causing a significant impact on shore reinforcement works in Vietnam and globally. Climate change encompasses phenomena including rising mean temperatures, sea level rise, intensified storm frequency and severity, droughts, floods, and additional hydroclimatic shifts. Rising sea levels amplify storm intensity and frequency, heightening coastal erosion and landslide risks (Ministry of Natural Resources and Environment 2016; Chi et al. 2017).

Strong support from the government and authorities is needed to solve these difficulties. Investing in scientific research and applying advanced technologies in managing and designing embankments is also necessary to increase the efficiency and sustainability of irrigation infrastructure in Vietnam. This study implements Plaxis software 2D V.22 to analyze the behavior of the embankment and its stability in preventing landslides in the downstream river, taking into account the scenario of forecasting climate change impacts which is considering the water levels exceeding the original design levels based on climate change scenarios as projected in reports.

2. METHODOLOGY

Research on solutions for treating soft ground using reinforced concrete piles and geotextiles is essential in the construction and geotechnical industry. Many studies have used numerical calculation and simulation methods to evaluate the effectiveness and sustainability of the embankment to prevent river bank erosion. Among them, the finite element method is a powerful tool used to simulate problems related to embankment to prevent river bank erosion. The research used Plaxis 2D V.22 software to simulate soil properties and embankment history (stage of construction, completion, and use) which allows assessment of the impact of vehicle live load, wave pressure load and water level changes on the load-bearing capacity, stability of the embankment structure. Specifically, by considering the climate change scenarios, the water level changes exceeded the design levels, reaching a high of +2.8 meters and a low of -1.5 meters instead of the originally designed -1.0 meters.

Stability Factor

The stability coefficient of the structure is calculated according to the force balance equation, defined as the ratio between the anti-slip force and the sliding force. This calculation method was proposed by Bishop (1995). Alan Wilfred Bishop's method of calculating the stability coefficient according to the force balance equation is used in geotechnical and construction to evaluate stability and propose improvement measures for sloping roof structures such as dams, embankments, ramps, maintenance holes, and other sloping structures. The diagram for calculating sliding stability using the Bishop method is shown in Figure 1, the slope stability coefficient Kat is determined as follows:

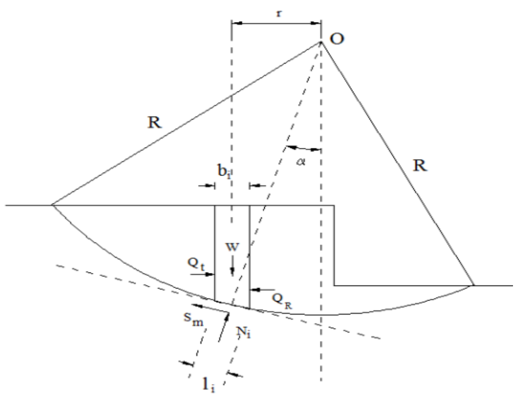


Figure 1. Diagram of sliding stability using the Bishop method

$$K_{at} = \frac{\sum cl_i \cos\alpha + Wtg\varphi}{\sum W \sin\alpha} \quad \text{(Eq.1)}$$

In which: c is the cohesion of the soil within the length of the sliding arc l_i (Kg/cm^2); l_i is the fragment length (cm); α is the inclination angle of the distributed sliding surface with the horizontal surface (degree); W is the weight of each fragment (Kg).

Plaxis software provides numerical calculation and simulation tools to evaluate the stability coefficient of structures, loads, and other factors. Evaluating the stability coefficient using this software is valuable and essential in designing and constructing geotechnical works such as embankments, dams, tall buildings, and landslide-resistant structures. In Plaxis software, the stability factor is expressed as "Factors of Safety" abbreviated as FOS. This is an essential parameter in geotechnical analysis and soft-ground treatment. The coefficient of stability (FOS) is calculated to evaluate the safety level of the building and ensure that the building has enough strength to withstand loads and forces from the surrounding environment. The stability coefficient is determined by comparing the soil's resistance to slide with the force acting on the structure. When FOS > 1, it means that the soil's sliding resistance is strong enough to resist the impact force, and the structure is safe. On the contrary, if FOS < 1, there is a risk that the impact force is greater than the sliding resistance, and the structure may collapse or be damaged.

Pressure waves

The Vietnamese Standard TCVN 11736:2017 (2017) focuses on the structures that protect the seas. This standard is applied in the design, construction, or renovation. The aim of the standard is to determine the standard values of loads caused by waves and vessels on coastal protection structures, ensuring their safety, durability, and stability under environmental conditions. The maximum wave pressure (P_d, kPa) was calculated according to Eq. 2 and showed in Fig. 2.

$$p_d = k_s k_f k_{rel} \rho g h \quad \text{(Eq.2)}$$

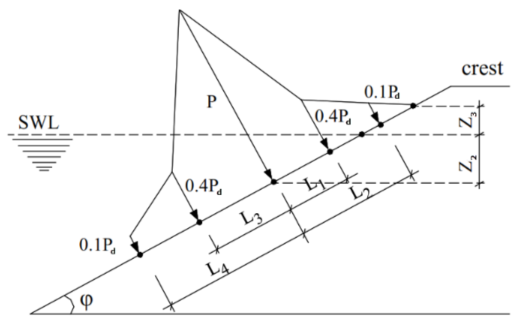


Figure 2. Wave pressure distribution on embankment slope roof

In which: k_s and k_f are coefficients; k_{rel} is the maximum relative wave pressure on the sloping roof (Kg/m^2); ρ is the density of water (Kg/m^3); g is the gravitational acceleration (m/s^2); and h is the wave height (m).

However, this method requires significant details of wave data and is complicated for the engineer in calculation. Therefore, the lengths L_1, L_2, L_3, and L_4 are calculated using the linear function of the total length (L_φ, m) affected by wave pressure, as shown in Fig.2 and Eq.3 (TCVN 8421:2010). In addition, because of the fewer properties data, this study ignored the crest (Z_3) of the wave when considering the wave pressure.

$$\begin{aligned} L_1 &= 0.0125 L_\varphi \\ L_2 &= 0.0325 L_\varphi; \\ L_3 &= 0.0265 L_\varphi; \\ L_4 &= 0.0675 L_\varphi \end{aligned} \quad \text{(Eq.3)}$$

Plaxis modeling

The landslide protection embankment in this study is on the right bank of Hau River, in Binh Duc ward, Long Xuyen City, An Giang Province, with a total length of 1141 meters. There are 17 geological survey boreholes. Hydrological data were collected and investigated from 2000 to 2021, and water resource data was collected from bulletins announcing and forecasting and presented as the following. The project has geographical coordinates of 10°24’25’’ North latitude and East longitude, the West border Highway 91, and the East borders Hau River. Based on the geological survey results, in this study, we proposed 02 characteristic Cross-Sections to build the model, as showed in Fig. 3.

The average general geological characteristics in Cross-Section 1-1 are showed in Table 1 and Table 2, including Layer 1: Dusty clay, hard plastic state, thickness 3.80 meters, good load-bearing capacity. Layer 2: Brown gray clay, soft plastic state, thickness 2.00 meters, good load-bearing capacity. Layer 3: Clay mud, gray brown, plastic-flowing state, thickness 21.70 meters, very poor bearing capacity. Layer 4: Mixed sand, plastic state, thickness 11.00 meters, good load-bearing capacity. Compared to the soil layer properties at Cross-Section 1-1, the subsurface characteristics at Cross-Section 2-2 exhibit better geotechnical properties, as shown in Table 3, including Layer 1: Dusty clay, hard plastic state, thickness 5.31 meters, good load-bearing capacity. Layer 2: Clay mud, gray brown, plastic-flowing state, thickness 17.00 meters, very poor bearing capacity. Layer 3: Fine sand, dark-brown gray, thickness 16.19 meters, good load-bearing capacity.

Both cross-sections have a quite thick weak soil stratum, with a 21.7m deep stratum for Cross-Section 1-1 and 17 m deep stratum for Cross-Section 2-2. Comparing the bottom sand layers (layer 4 of Cross-Section 1-1 and layer 3 of Cross-Section 2-2) between the two cross-sections, the sand properties at Cross-Section 2-2 exhibit better geotechnical properties than at Cross-Section 1-1.

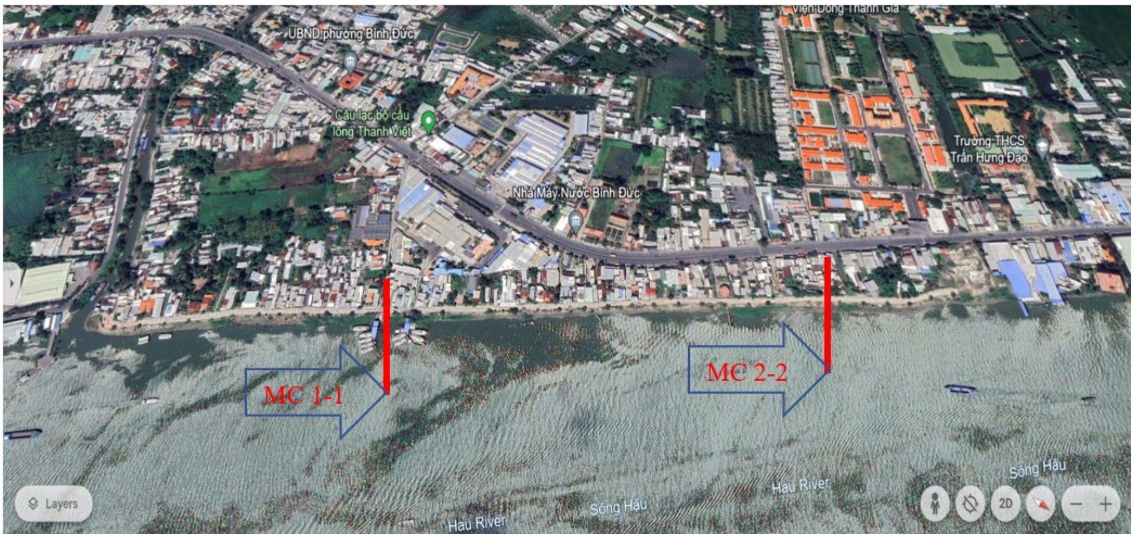


Figure 3. Cross-Section 1-1 and 2-2

Table 1. Reinforced concrete material parameter

No	Material	EA (kN/m)	EI (kN.m²/m)	W (kN/m/m)	ν
1	Reinforced concrete pile 25x25cm, L = 5.25m	1.88E+06	9.77E+03	1.56	0.20
2	Reinforced concrete pile 30x30cm, L=28.5m	2.70E+06	2.03E+04	2.25	0.20
3	Reinforced concrete beam 20x30cm, L=6.62m	1.80E+06	1.35E+04	1.50	0.20

Table 2. Properties of Soil Layers at Research Location - Cross-Section 1-1

Thickness	**Layer 1**	**Layer 2**	**Layer 3**	**Layer 4**	**Filling Sand**	**Unit**
	H=3.80	H=2.00	H=21.70	H=22.60	-	m
Model	MC Undrained	MC Undrained	MC Undrained	MC Undrained	MC Drained	
γ_{unsat}	19.85	19.69	16.15	18.29	17	kN/m^3
γ_{sat}	19.94	19.75	16.30	18.90	20	kN/m^3
E_{oed}	5775	6704	3370	12370	40380	kN/m^2
ν	0.30	0.30	0.35	0.30	0.30	
k_x	5.88x10^{-2}	0.1020	1.32x10^{-3}	1	1	m/day
k_y	2.35x10^{-2}	0.0409	5.129x10^{-4}	1	1	m/day
c	16.60	19.70	8.82	8.30	1	kN/m^2
φ	11.20	12.40	12.00	14.70	32	degree

Table 3. Properties of Soil Layers at Research Location - Cross-Section 2-2

Thickness	**Layer 1**	**Layer 2**	**Layer 3**	**Filling Sand**	**Unit**
	H=5.31	H=17.00	H=16.19	-	m
Model	MC Undrained	MC Undrained	MC Undrained	MC Drained	
γ_{unsat}	21.01	16.02	17.94	17	kN/m^3
γ_{sat}	21.20	16.15	18.60	20	kN/m^3
E_{oed}	4980	2360	9450	40380	kN/m^2
ν	0.30	0.30	0.25	0.30	
k_x	0.0406	0.1720	5	1	m/day
k_y	0.0184	0.0689	5	1	m/day
c	21.10	8.96	4.08	1	kN/m^2
φ	15.70	11.50	30.50	32	degree

Hydrological conditions are recorded in according to data provided from the statistical of the highest water level of the year and the lowest water level of the five hydrological stations Long Xuyen – An Giang in (2021). The data provided at the survey location reflects the impact of climate change, resulting in the highest projected water level of +2.8 meters and the lowest of -1.5 meters.

The Plaxis modeling for proposed scenarios. Implement historical and constructive conditions across 16 phases, as presented below. It notes that this study aims to analyze and evaluate the stability of the embankment under the lowering water level conditions due to the impact of climate change forecasts and wave pressure. Figure 4 shows the Plaxis model at the last phase.

– Phase 1: Analyze effective stress of ground under natural conditions

– Phase 2: Construction of reinforced concrete pile systems, cap beams, anchor beams, and sloping roof beams.

– Phase 3: Lining with geotextile fabric and filling with sand.

– Phase 4: Lining with geotextile fabric and filling with sand.

– Phase 5: Considering vehicle load.

– Phase 6: Safety factor corresponding to design water level ±0.00 meter, taking into account wave pressure

– Phase 7: Safety factor with design water level +0.00 meters.

– Phase 8: Analyzing behavior at the maximum water level of +2.80 meters according to climate change, taking into account wave pressure.

– Phase 9: Safety factor with the maximum water level of +2.80 meters according to climate change.

– Phase 10: Analyzing of behavior at design water level ±0.00 meters, taking into account wave pressure.

– Phase 11: Safety factor at design water level ±0.00 meters.

– Phase 12: Analyzing of behavior at minimum design water level of -1.00 meter, taking into account wave pressure.

– Phase 13: Safety factor at minimum design water level of -1.00 meter.

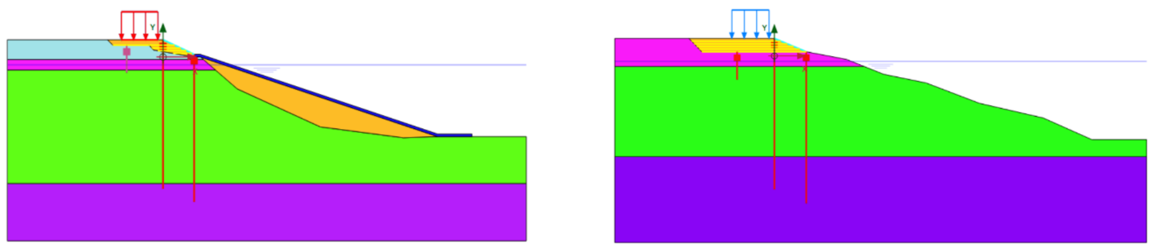
– Phase 14: Analyzing of behavior at the water level of -1.50 meters according to of climate change forecasts, taking into account of wave pressure

– Phase 15: Safety factor at the water level of -1.50 meters according to climate change forecasts.

This study employs two typical cross-sections for investigation, then four models are proposed in the cases of considering wave pressure and cases not considering wave pressure, their symbols are denoted as CS1.NWP, CS1.WP, CS2.NWP, CS2.WP, and presented in Table 4.

Table 4. Plaxis model

No	Cross-Section	Name	Considering wave pressure
1	Cross-Section 1-1	CS1.NWP	No
2		CS1.WP	Yes
3	Cross-Section 2-2	CS2.NWP	No
4		CS2.WP	Yes



Cross Section 1-1 Cross Section 2-2

Figure 4. Plaxis models of 02 Typical Cross-Sections

3. RESULTS AND DISCUSSION

The stability analysis results are shown in Figures 5, 6. The analysis results in Figure 5 show that the performance of the reinforced concrete piles (RCP) as designed is relatively suitable for the deformation model of the subsoil. Two rows of piles with the 27.50m length are completely outside the lateral ground deformation zone. However, the solution of a row RCP with a length of 5m still falls within the deformation zone of the subsoil, especially in the weak soil, which limits the ability of the piles to work both in terms of side friction and pile toe resistance.

The safety factor M_{sf} of the structure varies from 1.113 (Phase 15) to 1.359 (Phase 9) for Cross-Section 1-1, the specific range (1.113, 1.359) is from model CS1.NPW and the range (1.113, 1.354) is from model CS1.PW. Meanwhile, the factors are from 1.388 (Phase 15) to 1.709 (Phase 9) for cross-section 2-2, more details, the range (1.418, 1.709) is from model CS2.NPW and the range (1.388, 1.709) is from model CS2.PW.

The results indicate that cross-section 2-2 meets the safety requirements according to TCVN 9902-201 (2013) which specifies a permissible safety factor value of $M_{sf} \geq 1.15$. Otherwise, the 3rd layer with the weak soil is quite thick at cross-section 1-1, to lower stability analysis results. Specifically, at the lowest water level according to the design (-1.0m) with M_{sf} = 1.114, it is close to the permissible limit, and at the water level of -1.50m (according to the climate change scenario) with M_{sf} = 1.113, it does not meet the permissible limit. The analysis results do not satisfy the safety requirements for both SC2.NPW and SC2.PW models.

As the Safety factor shown in Figure 6 shows, when the water level rises to elevation +2.80m (Phase 8), the results show higher safety factors than when the water level drops, indicating that a rising water level corresponds to increased wave pressure against the embankment to reduce the loading from the landside.

This is clearly evidenced when the water level sequentially drops from +2.80m down to elevations 0.00m (Phase 10), -1.00m (Phase 12) and -1.50m (Phase 14). The highest predicted water level reached +2.8m, with a safety factor (M_{sf}) of 1.354 and 1.709, while at the water level of 0.0m, the safety factor ranged from M_{sf} = 1.212 to 1.543. Therefore, lateral hydrostatic pressure of the water also plays a role as a proactive effect in some cases, not always posing a hazard to the embankment. This is entirely consistent and explains the mechanism of pressure both within and outside the embankment, aligning well with the results reported in several studies.

The investigation assessed the impact of lowering the water level to the lowest designed level of -1.0

meters, which achieved a safety factor of M_{sf} = 1.144 to 1.452. However, at the lower water level as per the climate change scenario, the safety factor only reached M_{sf} = 1.113 to 1.418. Comparing the results between the model with the lowest design water level of -1.00m and the model with a decrease of -1.50m in water level due to climate change predictions, the stability factor decreases by an average of 2.71% for cross-section 1-1. For cross-section 2-2, when the SC2.NPW model does not consider the influence of wave pressure, the average stability factor decreases by 3.99%, and for the SC2.PW model, which is affected by wave pressure, the average stability factor decreases by 11.67%.

Figure 6 shows that the influence of wave pressure on the safety factor of the embankment is negligible. When comparing the safety results of models affected by wave pressure and those not affected by wave pressure, the results indicate that wave pressure affects the stability of the structure in cases of lowering water levels and actively contributes in cases of rising water levels (elevation +2.80m). Compared to models (SC1.NPW, SC2.NPW) that do not consider this influence, the change ranges from (0%, 0.37%) and (0%, 2.1%) for cross-sections 1-1 and 2-2, respectively.

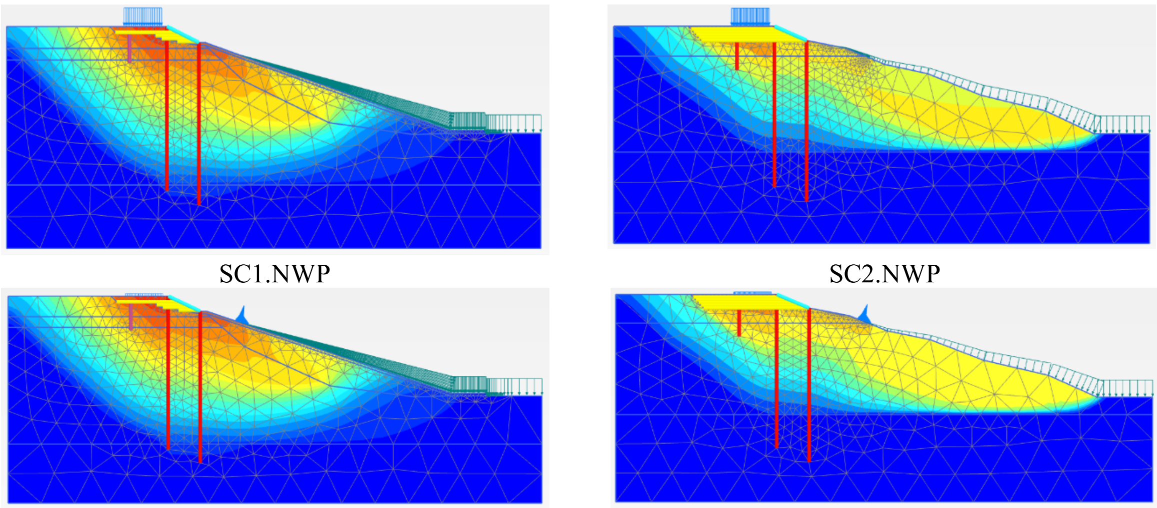


Figure 5. Total deformation at Phase 15

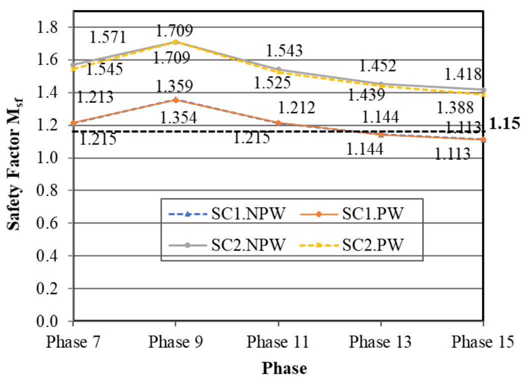


Figure 6. Safety factor

4. CONCLUSIONS

The study takes into account the impact factor due to changes in the water level based on hydrological data of maximum and minimum water levels measured at Long Xuyen – An Giang station from 2001 to 2021. On the other hand, the topic also focuses on analyzing vehicle live load's influence on the embankment structure. From the simulation results to find the critical state of the embankment structure, this study conducts stability assessments under projected climate change impacts on water levels and wave pressure. Specifically, the results analyze the impact when considering changes in water levels from the design level of +0.0 meters to the climate change scenario's projected level of +2.8 meters, followed by the lowering of the water level to the designed level of -1.0 meters and the projected level of -1.5 meters as per the climate change scenario. Simultaneously, there is a comparison of the effects of wave and no-wave impacts. The following conclusions can be considered from this study:

– From the analysis results using Plaxis 2D V.22 software according to vehicle live load 5 tons acting on structure for each case of water level. The stability factors range from 1.113 to 1.359 for Cross-Section 1-1 and from 1.388 to 1.709 for Cross-Section 2-2. For the models of Cross-section 2-2, the safety factors are within the permissible limits per TCVN 9902-2013 standards. Otherwise,

– With regard to water level rise, specifically as per the climate change prediction, when the water level rises to +2.8 meters surpassing the embankment level. Analyzing results corresponding to climate change scenarios shows that when water levels rise, the balance between earth pressure from the inside and wave pressure ensures the stability of the structure with a high safety factor. This is due to the omission of considering the impact of vortexes on the embankment foot and river bed due to the impact of waves and boats.

– On the contrary, comparing the impact of lowering the water level to -1.5 meters as per the climate change scenario with the impact at the design water level of -1.0 meters. The lowered water level scenario (lowering water level) shows a decrease in the stability of the structure due to the loss of the balancing effect of general wave pressure on the embankment. Specifically for the analysis results under the -1.50m scenario of lowered water level, at Cross-Section 1-1, the stability factors M_{sf}=1.113 is lower than the allowable value per standards. Therefore, routine monitoring and surveillance should be conducted at locations with topography similar to this cross-section to promptly propose solutions if water levels tend to fall below the -1.00m design level.

– The limitations of the study did not delve deep into the analysis of subsoil deformation, as the research focused solely on the impact of sea level rise due to climate change and considered the influence of wave pressure. In future studies, it is possible to further develop this research method to assess subsoil deformation more comprehensively under the influence of both factors presented.

– Furthermore, when determining the stability and deformation of the embankment system, further research is needed on the influence of factors such as waves from ships and boats, soil erosion at the bottom of pile walls, erosion in the form of frogs, and changes in flow due to mining. sand waterfall.

– The project needs to have results of monitoring the horizontal displacement of the top of the embankment structure at the cross-section locations of the research and simulation. Having specific comparison results, this study only provides predictive conclusions so that agencies and units can have reference data. From there, there are plans to propagate, warn, and limit the loads operating on the embankment and ensure the safety of the irrigation project's exploitation corridor when operating and using the project to achieve satisfactory results and highest efficiency.

– Besides, The Mohr–Coulomb model is an approximate model of the relationship of soil. This is a purely elastic model based on Hook's law combined with the Mohr–Coulomb sabotage standard. In the elastic-plasticity model, deformation and deformation rate are analyzed into two components: the elastic part and the pure plasticity part. Hook's law is used to express the relationship between stress increase and strain. The model consists of five basic parameters: elastic module E, Poison ν coefficient, soil adhesion force c, friction angle in φ and expansion angle of soil ψ. Therefore, it is recommended to conduct three-axis compression experiments for the ground area of the construction to have sufficient data for more accurate calculation.

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