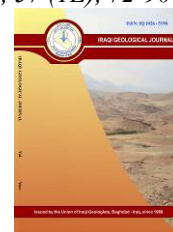




Iraqi Geological Journal

Journal homepage: <https://www.igi-iraq.org>



Analysis Instability of the Riverbank: A Case Study of Tien Riverbank in Cai Be district, Tien Giang Province, Vietnam

Nguyen Hoang Khuyen¹, Nguyen Thi Nu^{2*}, Nguyen Thanh Duong², Bui Truong Son², Bui Van Binh²

¹ Tien Giang Department of Planning and Investment, Tien Giang, Viet Nam

² Hanoi University of Mining and Geology, Ha Noi, Viet Nam

* Correspondence: nhk.skh@gmail.com; nguyenthinu@humg.edu.vn

Abstract

Received: 10 May 2023
Accepted: 19 February 2024
Published: 31 May 2024

Tien riverbank in Cai Be district, Tien Giang province has quite a complex geological structure and human activities, so the riverbanks are frequently instability. The article refers to the instability of the Tien riverbank flowing through Cai Be district, Tien Giang Province. Based on the collected documents, analyzing remote sensing images, and field investigations, two types of riverbank instability with varying severity were identified. The main causes of instability are river flow erosion, influence of waves, geological factors, hydraulic pressure, sand depletion, and human activities. The selection of countermeasures against riverbank erosion in the study area should consider the soft soil ground structure along the riverbank, and the impact of horizontal waves caused by boat activities. Regarding the countermeasures for stability of riverbank, the method of pre-stressed piles exhibit a good solution against riverbank erosion. The research results are the basis for proposing effective prevention solutions to serve sustainable development along this river.

Keywords: Soft soil; riverbank erosion; instability, Tien river

1. Introduction

Riverbank erosion is one of the most common problems faced in many countries (Islam, 2008). The riverbank erosion often occurs every year and not only causes serious devastation to the property and life but also threatens the stability of the buildings. Every year, riverbank erosions affected many people in the world (Naher and Soron, 2019; Rahman and Gian, 2020). For instance, in September 2018 in Naria region of Bangladesh, riverbank erosion led the about 5000 families homeless. The riverbank erosion negatively affects people economic, social, and psychological distress (Radman and Gain, 2020) and causes loss of life and damage to the property and infrastructures (Das et al., 2014).

The riverbank erosion is affected by both natural and anthropogenic factors. The natural factors could be listed as rainfall patterns, flooding, and river morphology whereas anthropogenic factors could include deforestation, land use practices, and infrastructure development near riverbank. The damage mechanisms occurring in two sections of the riverbank along the Arno River, Central Italy, were studied by Dapporto et al. (2001). They employed a series of periodic field observations and riverbank profile measurements. Swanson et al. (1985) indicated that the slope movements on river channels depend on the rate of colluvium delivery from hillslopes. Roslan et al. (2013) indicated the important factor causing riverbank erosion is textural composition along the riverbanks or the level of soil erodibility. Rainfall was also a factor affecting the river bank erosion (Yosoff and Abidin, 2013). In addition, Chang and

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Chuan (2018) studied all factors affected landslide of riverbank such as the slope of riverbank, channel gradient, meander of river, radius of curvature and soil (i.e. brightness, greenness, wetness) and showed that the unstable slope was one of the main causes of riverbank instability. Islam (2008) analyzed the possible causes, mechanisms, prediction methods of riverbank damage, and proposed various prevention measures. Hui (2015) affirmed that the failure of riverbank structures depends on the properties of the soil and the fluctuation of river water level. Rinaldi et al. (2004) used a strain gauge at various depths at a bank of the Sieve River, Tuscany, Italy for pore water pressure measurement in four years from 1996 to 1999 to evaluate the effect of pore water pressure changes on the riverbank instability. The riverbank erosion also was investigated based on Sentinel-2 images (Yang et al., 2021) or observed by the behavior of flow and modeling (Budiyanto et al., 2022).

Tien River plays an important role in providing water and sediment to the Mekong Delta. In recent years, coastal erosion, riverbank erosion and landslides in Mekong Delta are more and more serious (Tho, 2020; Luan et al., 2022). The instability of riverbank in Mekong Delta has been investigated by different authors. Ty et al. (2022) analyzed factors affecting riverbank stability at Cha Va river section, Vinh Long province using theoretical methods combined with surveying, measuring flow rates and remote sensing images. Loc et al. (2020) also determined the cause of landslides on the Cai Xa riverbank, Can Tho City using the field survey method. Bang et al (2021) refer to the influence of geological and hydrological factors on the stability of Cai Vung riverbank, Hong Ngu district, Dong Thap province. The results showed that the prominent causes of erosion have the flow, soft soil along the groundwater level fluctuation. Hai and Trinh (2011) studied the erosion-deposition correlation in some Tien and Hau riverbed areas. Recently, Tri et al. (2021) assessed the stability of the Cai Lan riverbank, Cai Be district, Tien Giang province. Hoai et al. (2019) showed that the bank erosion in Mekong Delta has occurred in many decades, however in the past 10 years, the erosion has occurred seriously and rapidly. Khuyen et al. (2022) indicated that the increase of eroded shore causes the decrease of stability coefficient.

Thus, it can be seen that in the world as well as in Vietnam, there are different studies on riverbank instability. However, due to the characteristics of each river section and the geological conditions of the riverbank, the problem of riverbank instability still occurs every year at different speeds and scales. Moreover, the section of Tien River flowing through Cai Be District, Tien Giang province is one of the most serious problems of riverbank instability, causing huge damage to property as well as the province's budget. Thus, this study aims to investigate the current state of instability of the Tien River in Cai Be District, Tien Giang province and analyze the causes of riverbank instability and propose effective solutions to serve local sustainable development.

2. Study area and methods

2.1 Study area

Tien River is a tributary of the Mekong River system (Fig.1). The section in Cai Be district, Tien Giang province is about 26.5 km long, characterized by the highest shoreline slope with a ratio of 1:1 near the shore and the gentlest 1:6 far from the shoreline in Cu Lao Tan Phong. The study area is a section of the Tien River in Cai Be district, Tien Giang province, Vietnam (Fig. 2) and a typical cross-section is shown in Fig. 3.

Figure 3 indicates a curved, winding, meandering and divided river section. The curve has a radius of about 618 m in Hoa Hung, and 1044 m in Hoa Khanh. The width of the river section continuously changes, and there is a change in flow depth over time.

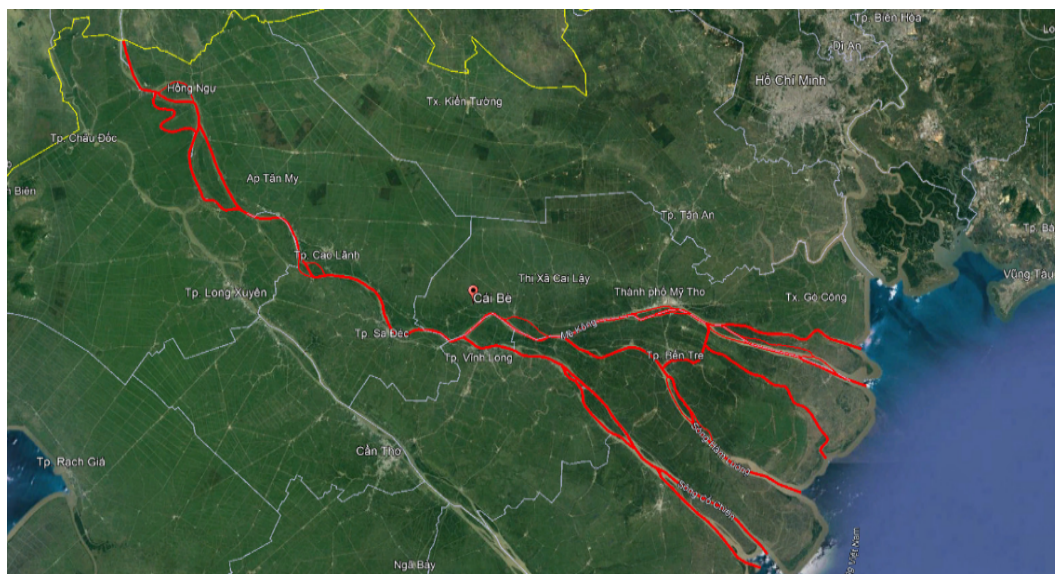


Fig. 1. Tien river in Vietnam



Fig. 2. Tien riverbank in Cai Be district, Tien Giang province, Vietnam

Erosion and sedimentation often occur in curved river sections, distributaries and confluences. According to monitoring and assessment results, when arriving at Tan Chau and Chau Doc, the flow distribution rate in the flood season of Tien River is about 77-78%, and Hau River is about 22-23%. Because the water level in Tien River is higher than that in Hau River, the flood flow on the Tien River before pouring to the sea through 6 estuaries also transfers a significant amount to the Hau River via Vam Nao River.

The section of Tien river flowing through Tien Giang Province has the elevation of river bottom from -6m to -40m with an average of -9m. The bottom slope of the My Thuan - Cai Be section is quite large (10 - 13%) and longer in the downstream section (0.07%). The river has a width of 600 - 1800m, surface section area is about 2500 - 17000m². Figure 4 shows the Tien River section in Cai Be District, Tien Giang Province, Vietnam.

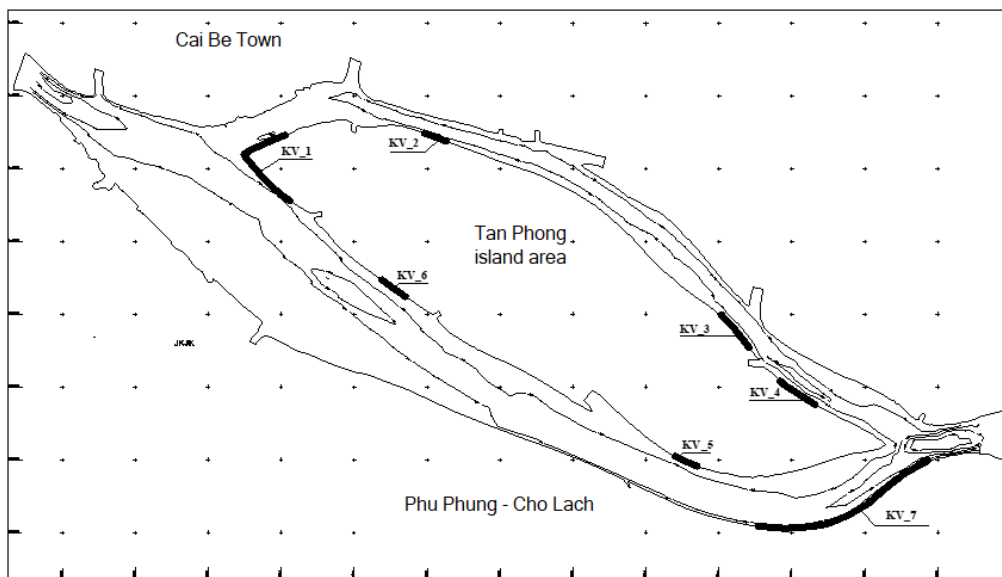


Fig. 3. Map of Tan Phong island area

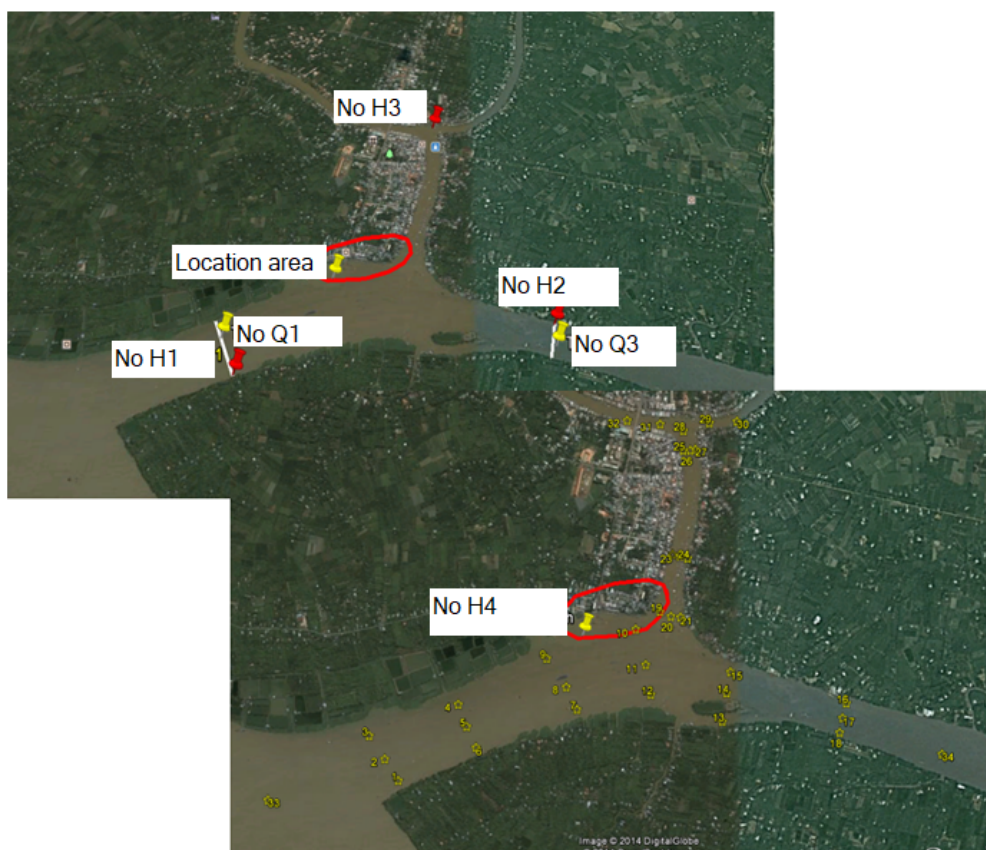


Fig. 4. Cai Be river area and the section of Tien river flowing through Tan Phong island

2.2. Methods

Figure 5 provides a summary of the research methods used in this study. First, the riverbank erosion was validated by collected documents (administrative maps, statistical data), Google Earth images from 2005 – 2021 and the change of river water level from 2005 to 2021. Second, the field investigation and analysis of remote sensing images in the periods from 2005 to 2021 were carried out. After that, the

morphology and scale of instability of the Tien riverbank in Cai Be District, Tien Giang Province was classified and the causes affecting the unstable characteristics of the Tien riverbank was evaluated. Finally, the prevention methods against instability were discussed.

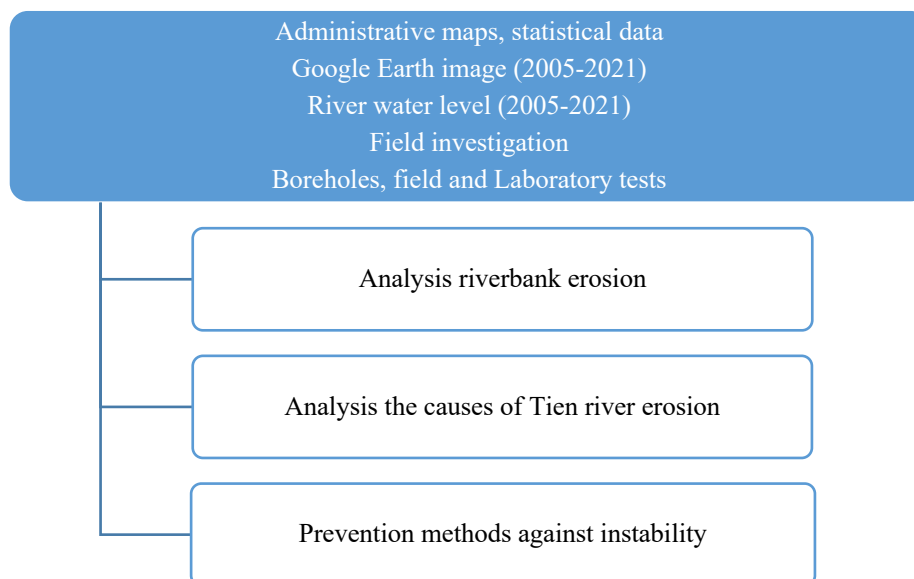


Fig. 5. Methodology used in riverbank erosion

2.3. Geological structure

The geological structure of riverbank (IOE, 2018) was shown as below:

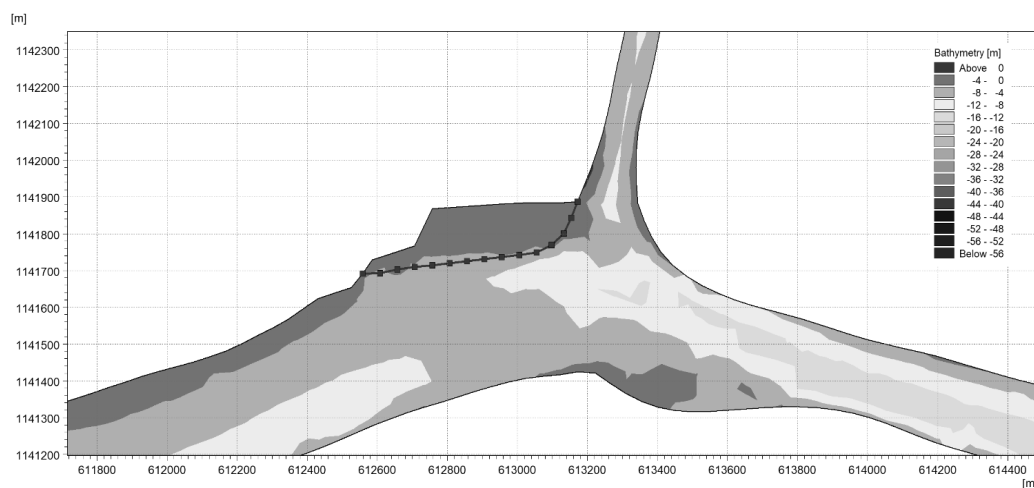
Layer 1: Very soft, greyish black, clayey sand. The SPT values change from 5 to 7. The thickness varies from 3.2m to 5.7m.

Layer 2: Very soft, greyish blue, greyish black, sandy clay. The SPT values varies from 1 to 3. The change of the thickness is from 3.6m to 10.2m.

Layer 3: Firm, greyish, clayey sand. The SPT values change from 5 to 15. The thickness varies from 4.1m to 16.9m.

Layer 4: Firm, greyish blue, greyish black, sandy clay. The SPT values varies from 5 to 9. The change of the thickness is from 4m to 6.0m.

Layer 5: Firm, greyish, clayey sand. The SPT values change from 13 to 27. The thickness varies from 4.7m to 5.5m.



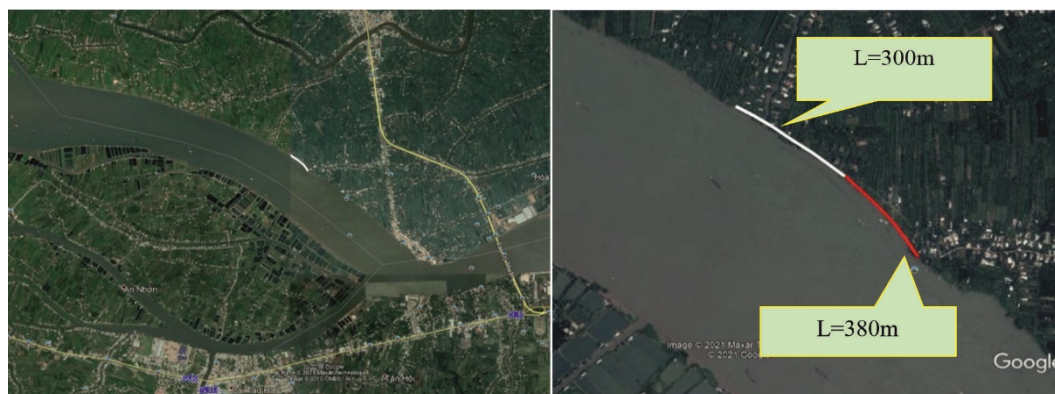


Fig. 6. The location of geological engineering investigation (2021)

Table 1. The Physico – chemical properties of soil layer

No.	Physico – chemical properties	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
1	Gravel, %	0.0	0.0	0.0	0.0	0.0
	Sand,%	61.4	21.3	64.0	27.4	65.0
	Silt,%	28.7	44.7	26.8	40.3	26.5
	Clay,%	9.9	34.0	9.2	32.3	8.5
2	Liquid limit, LL,%	25.8	53.2	25.2	51.7	23.7
3	Plastic limit, PL,%	19.2	27.5	19.0	26.2	18.0
4	Plastic index, IP,%	6.6	25.7	6.2	25.6	5.7
5	Liquidity index, I _s	1.40	0.99	0.96	0.57	0.36
6	Water content, W,%	28.49	52.92	24.93	40.79	20.06
7	Wet unit weight, γ , t/m ³	1.755	1.616	1.838	1.735	1.946
8	Dry unit weight, γ , t/m ³	1.37	1.06	1.47	1.23	1.62
9	Buoyant unit weight, γ_u , t/m ³	0.84	0.65	0.91	0.77	1.01
10	Specific gravity, Δ , t/m ³	2.620	2.583	2.627	2.656	2.643
11	Degree of Saturation, G,%	81.2	94.6	83.2	93.8	84.0
12	Void ratio, e	0.919	1.445	0.787	1.155	0.631
13	Cohesion force unit, C, kG/cm ²		0.070	0.071	0.140	0.080
14	Friction angle, ϕ , degree		5° 10'	15° 29'	8° 58'	19° 39'
15	Compression index	0.047	0.153	0.037	0.064	0.026
16	Modulus compression, E,kG/cm ²	30.44	6.50	37.10	13.59	47.25
17	Load capacity of soil,R, kG/cm ²	0.89	0.53	0.98	0.94	1.17

As show as in the Table 1, it can be seen that the layer 1,2 is very soft soil and it is similar as soft soil in another area in Viet Nam (Nu et al., 2020, Son et al., 2020, Luan et al., 2020). In Vietnam, soft soil is widely distributed in deltas such as Mekong Delta and Red River Delta with thickness drastically changes and can be made different construction.

3. Results and discussion

3.1. Tien riverbank erosion

Tien riverbank erosion is becoming increasingly serious in Cai Be district, irregularly and frequently occurring at any time of the year. However, the high risk of riverbank erosion often occurred before and after each annual flood season. According to statistical data from 2016-2020 (ID, 2020; Việt Nam News, 2023), the province has handled 547 riverbank erosion with a total length of about 51,139

m. In 2019, the landslides occurred in the western watershed districts with a total length of nearly 4,700m, with an estimated investment cost of over 48 billion VND. Among them, in Cai Be district, there are 42 segments of riverbank erosions with a total length of 2,550m. In 2020, there were 132 erosion segments with a total length of 8,527m, with an estimated treatment cost of about 114.4 billion VND. Up to now, there are still 39 erosion segments from previous years that have not been treated, with a total length of over 2,255 m and cost estimated at over 39.6 billion Vietnamese Dong (VND).

For instance, in 2020, the riverbank erosion in Hau Thanh commune, Cai Be district (Figs. 7, 8, and 9), affecting the lives and travel of local people. Along canal No. 07, in Hau Vinh hamlet, Hau Thanh commune, Cai Be district, the dike was destroyed more than 60m long and 3m wide. Although this incident did not cause any loss of life, but the dike which is a key traffic route in this area was cut off; many houses along the dike are unsafe. The Tien River sections have complex terrain, so riverbank is a high risk of erosion. According to the detailed planning, this area will be used to built the infrastructure for a commercial and service area connecting to the Tien River.



Fig.7. "Frog jaw" landslide point in Hau Thanh commune, Cai Be district (2020)



Fig. 8. People's travel and goods transportation face difficulties (2020)



Fig. 9. Landslide creating a cleft deep into roadbed 54C (2022)

Analyzing the characteristics of shoreline images using Google Earth images from 2005 to 2021 shows that the riverbank erosion width is widened up to 90 m in 16 years, although countermeasures have also been implemented in some river sections.

Period 2005 - 2008: On the left bank, about 4 km upstream from My Thuan bridge, the riverbank was eroded, the largest erosion width was about 67m (average erosion per year is about 22.3 m).

Period 2008 - 2017: Although some sections have protection works, the maximum erosion width is about 48m, and the erosion rate has decreased compared to the period 2005-2008.

Period 2017 - 2021: the shoreline continues to erode at an increasing rate. In just 4 years, the largest eroded width of the river section in Tan Thanh and An Huu communes has reached 38 m, an average of 9.5 m/year. In the section of Hoa Hung commune, close to My Thuan bridge, the largest eroded width has reached 40 m at the beginning of the river with an average of 10 m/year.

3.2. Classification of Tien riverbank erosion

The section of Tien riverbank in Cai Be District is a sharp curved section, causing the flow to suddenly change direction, increasing the risk of landslides. The width of the river bed changes continuously from 1278 m, then narrows to 741m, the smallest is 447 m in Hoa Hung, then expands and branches again. The Ham Luong branch has the widest width of 1244 m, and the narrowest of 201m. Co Chien branch has the smallest width of 396m. Statistics on landslide area in Tien Giang show that there is a very fast rate of riverside erosion, the highest speed in the period 2000-2005 (90.2 hectares/year).

Table 2. Classification of erosion rates in coastal areas (Diep et al., 2019)

Riverbank erosion area	Area of riverbank erosion by stages (ha)				
	1989-2000	2000-2005	2005-2009	2009-2014	2015-Present
Tien Giang	304.98	451.01	151.87	243.40	110.13

The status and speed of riverbank erosion is clarified according to the levels which presented in Table 3. The average erosion rate in Cai Be District, Tien Giang province from 2005 to 2021 is 5 m/year. However, in the period from 2005 to 2008, it was 22.3 m/year, and the period from 2017 to 2021, it was 10 m/year.

Table 3. Classification of landslide rates in coastal areas (Hong and Thoa, 2007)

Evaluation criteria	Level	Parameter
Rate of accretion/erosion	Slow	< 5 m/year
	Medium	5 - 10 m/year
	Fast	10 - 30 m/year
	Very fast	> 30 m/year

The Tien riverbank erosion can be clarified into two types:

- Riverbank erosion occurs due to the erosion process causing riverbank collapse, mainly occurring at the top of the riverbank or where the river section is not very deep. The dynamic factors are mainly due to the activity of currents on the surface as well as the impact of waves originating from the activities of ships and a part of the waves created by the wind at certain locations. The scale of development of this type is often small and can be directly observed in many cases.
- Riverbank erosion occurs due to deep erosion at the base of the riverbank, causing bank collapse and slippage. The dynamic factors are mainly due to the activity of deep currents, due to eddies arising near the foot of the shore as well as due to sand mining activities that increase the flow depth, leading to an increase in riverbank elevation. This type of damage often has a large scale of riverbank erosion and is often manifested by the appearance of large cracks extending along the river bank, causing slumping, sliding or a mixture of both processes.

3.3. Cause of riverbank erosion

3.3.1. Effects of river flow

During the impact of the flow on the channel, if the flow velocity is greater than the allowable non-erosion velocity of the soil constituting the channel, the erosion will occur. The degree of erosion and sedimentation depends more or less on two factors of the flow. One is the magnitude of the flow velocity compared to the allowable non-eroding velocity, and the other is the time to maintain a high velocity value.

The general morphology of the river section in Cai Be area is that of a curved river section in the delta, divided into many creeks, with many floating islands, and is in the process of complex evolution. Therefore, this river section is unstable and the sedimentation and erosion are manifestations of the natural process of change and interaction between the flow and the channel. According to the law of flow, in the curved river section, the process of bank destruction occurs on the concave bank and accretion on the convex bank (Fig.10).



Fig. 10. The riverbank erosion in a curved river section in Cai Be District (2020)

A typical landslide along the banks of Cai Be canal in Dong Hoa Hiep commune, Cai Be district, occurred at the end of June 2017, with a length of 32 m, reaching dozens of meters deep inland, causing a section of road to be lost, threatening the safety of life and property of two households in An Thanh hamlet, and Dong Hoa Hiep commune (Fig. 11).



Fig. 11. The riverbank erosion in My Duc Dong, Cai Be District (2021)

The Co Co riverbank area in Thai Hoa hamlet, An Thai Dong commune, Cai Be district, also has many erosion segments of which the most dangerous is the landslide near Co Co market. This landslide is more than ten meters long, penetrates deep into the mainland, threatening rural roads and 3 households along the road.

The flow of the Tien River is also changing mainly due to the continuous climate of drought years from 2002 to 2010 and major floods in 2011, and a series of years of drought and heavy rain in 2011-2016. It can be seen that the impact of hundreds of dams on the Mekong River along with climate change led to a decline in the amount of mud and sand sediments in the Mekong River. Tides have continuously increased since 2005, increasing the flow speed on the main stream.

Based on survey documents on riverbed mud and sand and the geology of the Tien river section passing through the beginning of Tan Phong island, the rate of sediment flow ranges from 0.2 to 0.4 m/s.

3.3.2. Effects of waves and currents caused by waves

Among the causes of erosion, currents and waves generated by ship activities also increased the erosion rate and level. In which, the reverse flow causes erosion at the toe of the canal bank, while horizontal waves and turning waves cause landslides at the upper part of the canal bank.

The impact of channel erosion caused by the reverse flow speed of boats, most types of ships from 5 tons to 30 tons in both left and right branches have reverse flow speed ($U_r < 0.11$ m/s) compared to the starting velocity of the sediment and sand in the channel ($V_{o_xoi} = 0.32$ m/s) is quite small. Therefore, the reverse flow does not cause deep erosion of the channel;

However, for boats of 300 tons or more, the reverse flow in the left branch ($U_r \geq 0.631$ m/s) and right branch ($U_r \geq 0.426$ m/s) are both greater than the starting speed of sand and mud sedimentation. Therefore, in this area, the channel erosion caused by the impact of ships of greater than 300 tons;

The impact of horizontal erosion (erosion on the riverbank surface) caused by the flow velocity of the ship's stern waves. For ships from 5 tons to 30 tons, the current speed caused by the ship's stern waves ($U_{max} = 0.344$ m/s - 0.545 m/s) $>$ ($V_{o_xoi} = 0.32$ m/s) causing river bank erosion but not much. For ships of greater than 300 tons, when traveling in this area, the river bank erosion is relatively large, because of the ship's stern wave speed ($U_{max} > 3.583$ m/s) is more than 10 times larger than the starting velocity of sand and mud.

When there are waves, a current will be created due to the waves and the force of the waves hitting the shore. The flow speed due to the waves is greater than the allowable non-eroding speed of the sand and mud particles on the shore, causing erosion and at the same time, the wave force acting on the shore will break soil structure. The mechanism of shore erosion caused by waves is shown in Figure 10. The section focuses on flow speeds but other factors can influence erosion, such as channel geometry, water levels, and vegetation cover.



Fig.12. The riverbank erosion caused by boat activities (2021)

There are 2 main causes of waves in this area:

- Waves caused by wind: waves in both the southwest and northeast monsoon seasons during high water periods are one of the causes of shore erosion. Especially, the wave influence during the monsoon season (Northeast season) causes landslides in the southern shore of the island.

- Waves caused by activities of boats: the density of boats operating on the river with high frequency and large capacity cargo ships, although not close to the shore, it still cause horizontal waves with heights ranging from $(0.3 \div 0,5)\text{m}$ which is the cause of bank erosion.

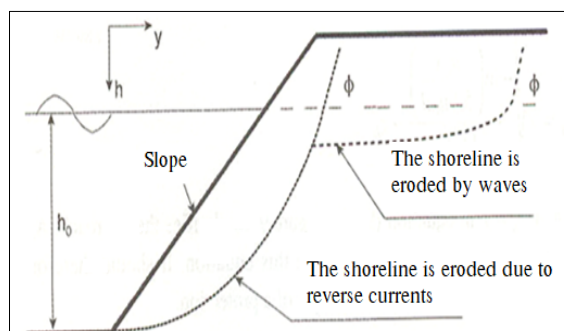


Fig. 13. Diagram analyzing some causes of bank erosion

The impact of water transport vehicles with increasing trends in both density and weight is also one of the factors that increase the risk of riverbank landslides. Along with that, the water transportation system is growing rapidly and strongly in terms of number, load and speed of boats. The volume of goods transported by inland waterway vehicles reaches 51.5 million tons/year. Through calculations in some rivers in the Mekong Delta, boats of over 5 tons when running on the river cause a reverse flow with a flow speed greater than the mud and sand starting speed of sedimentation. For reverse flow, ships with a load of more than 15 tons have a maximum speed near the shore that is 1.5 - 5.0 times higher than the starting speed of mud and sand in the channel (Hung, 2004; Hoanh, 2014).

3.3.3. Due to weak soil in the riverbank structure

The study area's soil has a soft soil (Table 1), the riverbank has a high height and steep, so the riverbank is very susceptible to erosion and landslides and cannot withstand the load in coastal areas. Therefore, if there are no structural measures to control the impact, this area is at very high risk of bank erosion due to coastal load, threatening the lives and property of the state and people in the future. The river banks composed of soft clay, dust and sand layers will be susceptible to erosion, causing instability of the riverbank, especially in conditions of changes in flow.



Fig.14. Canal bank erosion due to weak geology (2020)



Fig.15. The riverbank erosion in Hau Thanh commune, Cai Be district (2020)



Fig.16. Some landslide recovery works in Tien Giang completed in a short time have subsided.

In addition, due to weak geological conditions, the construction of riverbank and riverside protection works here needs to be carefully researched to improve the design condition so that it is stable after construction or right during the process of construction. Landslides still occur during the construction process. Even if the lifespan of these structures is significantly reduced, it is necessary to have solutions for calculations that are close to reality and suitable for the weak soil conditions here.

3.3.4. Effects of hydrostatic pressure and turbulent flow in rivers

The appearance of underground flows in the Mekong Delta and along the Tien River in Cai Be District, Tien Giang Province is due to the terrain tilting towards the flow direction of the Tien and Hau rivers (Northwest - Southeast) and along these two large rivers are interconnected networks of canals with almost perpendicular flow directions. At that time, the water force at the river confluence creates very strong underground vortices. According to Bernoulli's law, the greater the speed of the vortex, the lower the pressure inside the vortex. Therefore, if eddies appear near the shore zone, in addition to causing erosion, they also create a pressure drop zone on the slope surface of the river bank, increasing the possibility of riverbank landslides. These underground vortices move, they will create "frogs" at the river's junction and intersection and penetrate deeply into both banks until the riverbank slumps.

In curved river sections with concave banks, it is easy to see that when the main stream has high velocity hitting the concave bank at a certain angle, causing the liquid particles to be pushed to the bottom and move towards the high velocity region. This pressure flow erodes the channel, creating a local erosion hole. Over time, the erosion hole grows in width and depth and increasingly presses closer to the shore, causing mechanical instability of the shore soil, especially in cases where the lower soil layer is weaker than the upper soil layer. When the unstable bank soil mass falls, the local erosion hole is filled, the flow cannot immediately carry it all away and after a while the channel returns to an unstable state. Erosion of curved river banks with local scour holes often occurs intermittently. Landslides have the shape of circular sliding arcs, each landslide block is very large, the level of danger and damage level of each landslide is very high. Ali et al. (2023) indicated that the infiltration rate gradually decreases as the shallow groundwater rises to the surface of unsaturated soil regardless of the hydraulic conductivity value. So, it is affected in the stability of river bank.

A typical example of this statement is that the bank of the Vam Nao River in My Hoi Dong commune suddenly collapsed on the morning of April 22, 2017, causing dozens of houses to be washed into the river, 106 households had to be urgently relocated. Because this river section connects the Tien River and the Hau River, the collision between the two water flows has created many whirlpools along the river, accompanied by big waves and can easily cause boat sinking.

In the studied river section, the average speed can reach more than 1.00 m/s while the riverbed and riverbank geology can only prevent erosion at speeds less than 0.40 m/s. When the river bed is continuously eroded, large erosion holes are created and expand close to the river bank. The current strong landslide location is the narrowest section of the right branch, so the average annual velocity, especially in the flood season, will be much larger and the channel in this area is highly likely to be eroded.

3.3.5. Impact of silt and sand depletion

More than a hundred hydroelectric dams on the Mekong River have reduced the amount of sediment deposited in the Mekong Delta. According to research published by Milliman & Syvitski (1992), the Mekong River's sediment load before 1990 was up to 160 million tons/year, ranking 10th in the world in terms of sediment load (Meade, 1996). According to monitoring results announced by the Mekong River Commission (MRC) in 2013, from 2003 to 2009, the average sediment load at Chiang Saen station (Thailand) decreased from 10 to 60 million tons (reduced 83%); in Pakse (Laos) decreased from 60 to 120 million tons/year (down 50%) and in Kratie (Cambodia) decreased from 90 to 160 million tons/year (down 43%). Experts from the World Wide Fund for Nature (WWF) (Jean-Paul et al., 2013) warn that if all hydropower construction plans on the Mekong mainstream and tributaries are implemented, the total of only 20% of alluvium, mud and sand returning to the Mekong Delta remains compared to before.

Excessive sand exploitation on this river also causes the Mekong Delta to shrink and gradually sink. Previously, landslides and sedimentation activities were intertwined, with more sedimentation than landslides, so the Mekong Delta was raised and gradually encroached into the sea. Nowadays, alluvium and sedimentation has decreased, so landslides have increased.

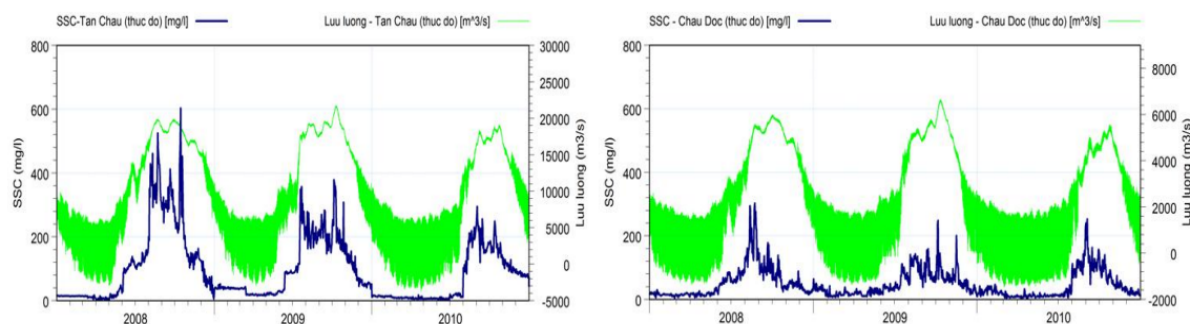


Fig.17. Flow process and suspended sediment content actually measured at Tan Chau station (left) and Chau Doc in the period 2008 - 2010 (Hung et al., 2013)

The distribution chart of suspended sand and sediment content at Tan Chau and Chau Doc stations (Fig. 17) shows clear seasonal fluctuations of sand and sediment on the main stream of the Mekong river. The concentration of suspended sand and sediment in Tan Chau during the flood season ranges from 200-500 mg/l and reaches the largest value during the flood peak, while in the dry season it is only about 30-100 mg/l. The concentration of suspended sand and sediment in Chau Doc during the flood season is much lower than that in Tan Chau, only from 100 ÷ 300 mg/l. The average total amount of sand and mud in the three years 2008 - 2010 at Tan Chau and Chau Doc stations is 46.2 and 5.6 million m³, respectively, equivalent to about 76.2 and 9.2 million tons (Hung et al., 2013).

3.3.6. Human activities

In addition to the natural factors, there are also factors of socio-economic activities such as surface load of structures (transportation works, housing), water transportation, illegal sand mining, building

houses to encroach on river banks, encroaching on river banks, digging fish ponds, anchoring fish rafts... these are human-caused causes. Waterway traffic activities lead to further erosion of the shoreline due to ship waves. Houses on river banks, digging fish ponds and anchoring fish rafts which increases the load and narrows the river flow. Illegal sand mining at the wrong location, at the wrong time and with the wrong mining method has aggravated bed fluctuations and is very difficult to predict and assess.

In addition, the appearance of dams upstream has blocked a huge amount of silt and water flow from flowing into the Mekong Delta every year. This not only causes a shortage of sediment sources to build up and expand the coastline, but also causes a shortage of water flowing from the Tien and Hau rivers, not enough to push coastal currents away to reduce intrusion. saltwater intrusion and limit the water's impact on the coast. Faced with increased encroachment from rising sea levels while alluvial sources for compensation are increasingly depleted, coastal retreat in the Mekong Delta is inevitable (Quang, 2017).

In recent years, aquaculture (especially raising tiger prawns, giant freshwater prawns, mud crabs, molluscs, etc.) has developed strongly in most coastal districts. This profession has become a key economic sector of many provinces. There have been many aquaculture areas in mudflats and fish raft anchorage areas that were not planned properly, narrowing and shifting the flow, causing river bank erosion. This spontaneous, widespread, unplanned development has destroyed many hectares of coastal mangrove forests, has shown signs of causing environmental degradation, causing ecological imbalance, increasing the risk of disrupting the development process. sustainable socio-economic development in the region. The immediate consequence is an imbalance in geodynamics in the coastal area, which is also a factor causing serious bank erosion in many places.

The construction of illegal structures encroaching on the river surface hinders flood drainage, leading to local erosion behind the structures; The construction of roads with elevations exceeding the 2000 flood and dikes in recent times has also reduced the amount of flood water flowing into the field, while increasing the flow speed and flood volume into the two streams. mainly causes river bank erosion.

River sand mining activities are one of the causes that directly impact channel changes. Massive and indiscriminate sand mining changes the flow and causes shoreline erosion, affecting people's lives. According to research by Bravard (University of Lyon, France) and Goichot (Truong, 2016), from 1998 to 2008 Tien River lost about 90 million tons of river bottom material. But in the period 2008-2012, the exploitation speed skyrocketed to 57 million tons/year, 20 times the amount of sand transported annually by the Mekong River, calculated in Kratie, Cambodia. Excessive sand exploitation creates holes up to 15m deep in rivers in Cambodia. On the Vietnamese side, many holes are recorded that are tens of meters deep, in some places up to 45 meters deep from the natural river bottom. Coarse sand and medium sand from the upper Mekong River have become less trapped in deep holes and do not move downstream.

Currently, there are about 82 companies licensed to exploit 28 million tons of river sand each year. However, the reported volume of sand and the actual amount of sand exploited are difficult to control, and illegal sand mining still occurs regularly. Currently in An Giang, there are 11 sand mines licensed to exploit about 5.3 million m³/year. Can Tho currently has only 3 mining mines, Vinh Long has 37 mines, Dong Thap has 19 mines, An Giang has 11 mines and 7 dredging areas. Sand bank (is the difference between the volume of river sand transported from (upstream with the amount of sand exploited throughout the delta, as well as the amount of sand dumped into the sea) of the Mekong Delta has shown an annual sediment deficit of about 25 million tons due to sand mining and being retained by hydropower plants. electricity was built. From 2005 to present, sand has been mined in increasing quantities, of which more than 70% of mined sand is used for backfilling.

According to the Southern Inland Waterways Branch (Truong, 2016), the rate of deepening of the Tien and Hau rivers from 2008 to present has been faster, on average from 3-7 m. This situation occurs on the entire route, not just any section.

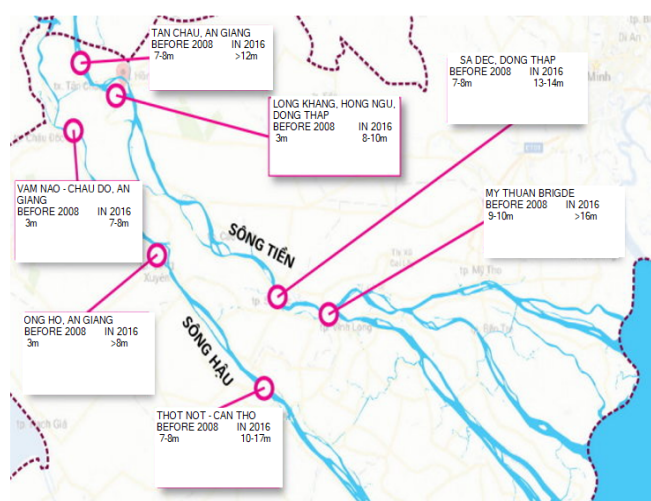


Fig.18. Diagram of some areas of the Tien and Hau rivers appearing deeper than before (Truong, 2016)

The population explosion and the expansion of the construction infrastructure network (roads, factories, industrial parks.) along the Tien River increase the rate of land subsidence. When building foundations, they will create isolation from the surrounding soil. If there is an impact from other factors, such as sand mining, for example, here, "hungry" swirling lakes will form. Alluvium will tend to move and quickly form "frog jaw" at the depth of tens meters below the riverbank.

In recent years, the regional transportation system has also made clear progress. In the period from 2010 to 2015, many traffic routes were built, upgraded and expanded, including many sections close to the river banks, canals, especially inter-district and inter-commune routes. Investment in the construction of regional dikes and embankments has also developed very well in recent years. Especially the construction of unplanned dikes to grow third-crop rice has narrowed the flood drainage space, causing a significant impact on channel stability and increasing the risk of landslides. In addition, the dumping of waste and scrap materials and construction of works that encroach on riverbanks and riverbeds have also increased the risk of river bank erosion (Thuong, 2011).

In addition, a series of connecting road traffic projects are built along the river to link and develop regional and inter-regional economies, requiring the selection of appropriate structures. Projects along the banks of Tien River in Cai Be District are mentioned as: Project to upgrade provincial road 864 along Tien River, starting point connecting National Highway 30, Cai Be district, ending point connecting provincial road 862, Go Cong Dong district. The project also passes through My Tho City and Cai Lay, Chau Thanh, Cho Gao, and Go Cong Tay districts.



Fig.19. Road and Tien River embankment project in My Tho City, Tien Giang in 2015

4. Desining the countermeasures against riverbank erosion

The embankment section is 300m long, with a structure of 26m long SW600A pre-stressed piles alternating with 20m long SW600A piles anchored by reinforced concrete (0.35x0.35)m, is 26.8m long with load-reducing slabs and interconnecting beams connected to the embankment cap beam. The embankment crest elevation is +2.7m, the outside of the river bank is prevented from erosion by stone mats on the geotechnical layer.

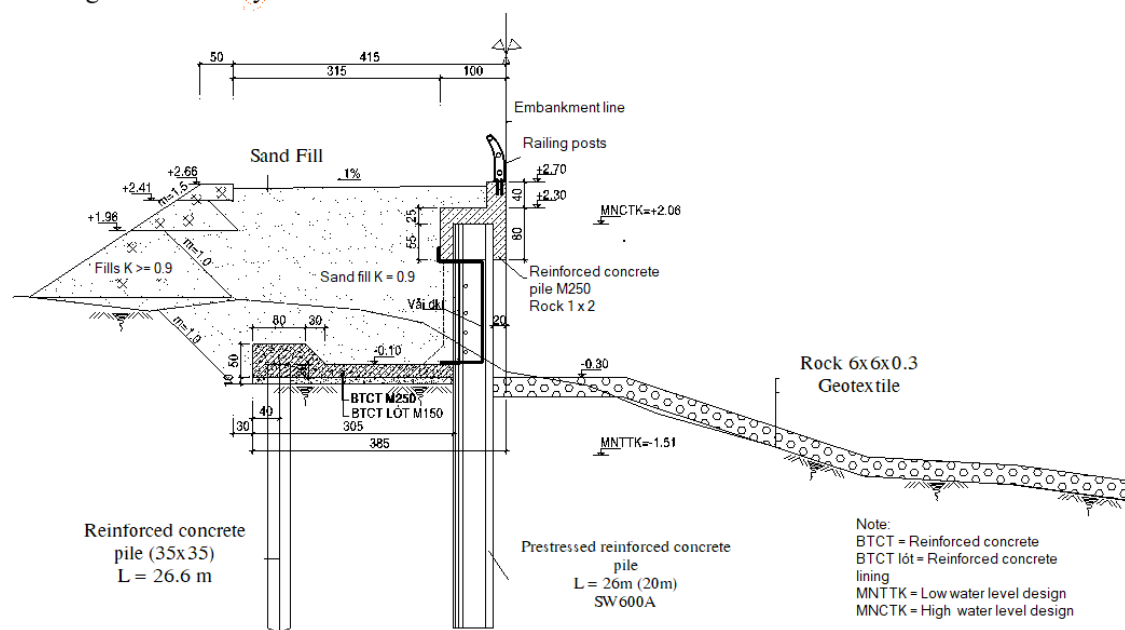


Fig.20. Cross-sectional structure of embankment

The stability of the Tien riverbank section through Cai Be district, Tien Giang province was used by GEO-SLOPE software.. In particular, the SLOPE/W module - in GEO-SLOPE software is used to calculate the stability of natural slopes, slopes of embankments, slopes of excavated roads, earth dams, breakwaters, types of retaining walls as well as such as the stability of slopes or slopes in the case of reinforcement such as reinforced soil such as anchors, reinforced soil with geotextiles and steel mesh.. The selected calculation method is the Bishop method. When calculating stability, the sliding surface is

assumed as a cylindrical arc, the sliding block was divided into many different pieces and the coefficient of stability (FOS) was calculated by equal to the ratio between anti-slip force and sliding force. If $FOS = 1$, the slope is in limit equilibrium, $FOS > 1$, the slope is stable and $FOS < 1$, the slope is unstable. The input parameters for the soil layers are shown in Table 1. The stability coefficient of the embankment is shown in figure 21 and 22. The results show that the embankment is stable.

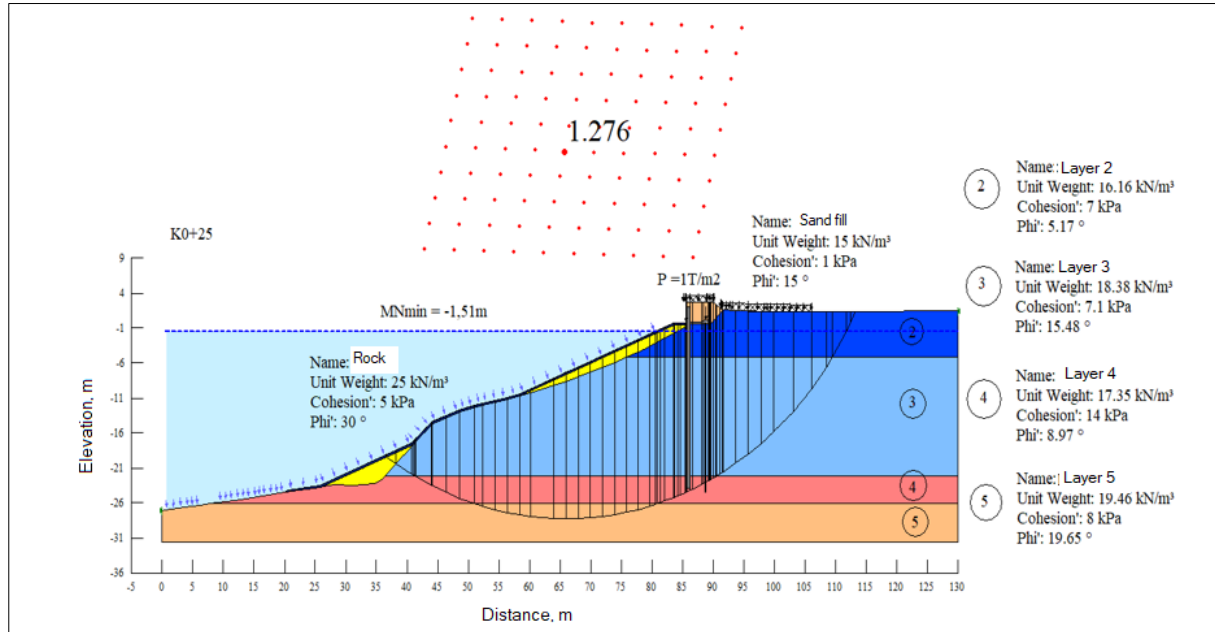


Fig. 21. Calculation results at section K0+25

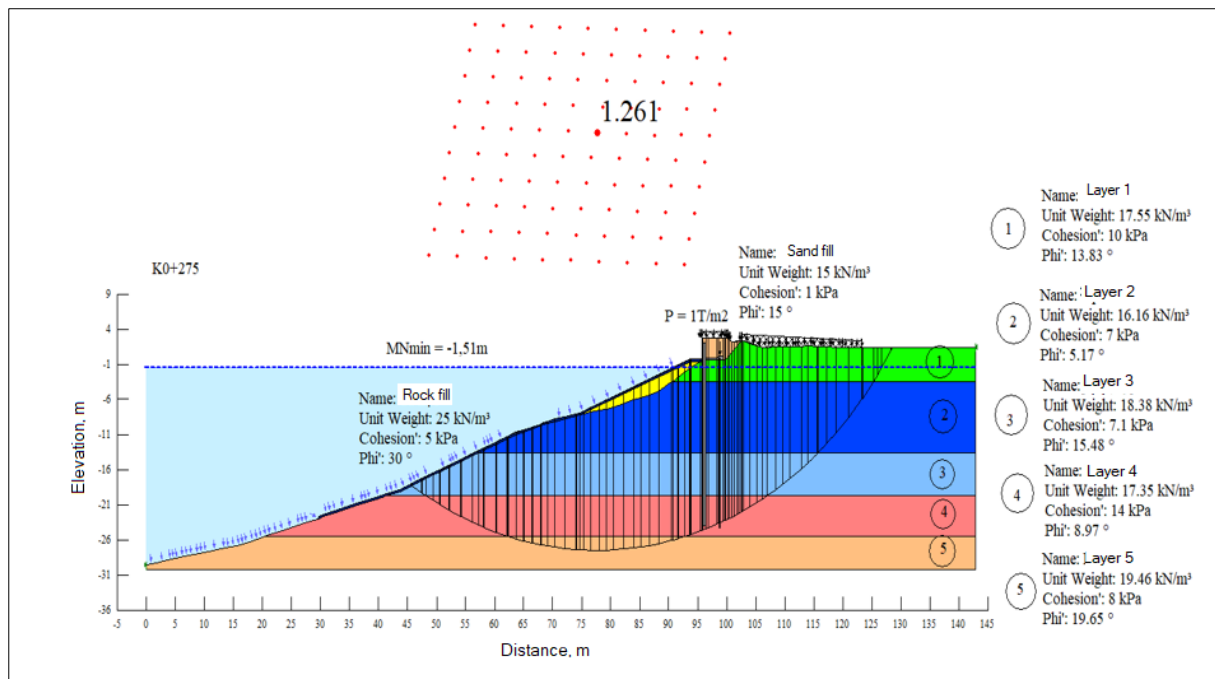


Fig. 22. Calculation results at section K0+275

5. Conclusions

From the research results, the following main conclusions can be drawn:

Since the river flow is enhanced by climate change as well as tidal regime and construction activities in general, the riverbank is mainly formed on soft soil. The complex changes in river valley morphology have caused strong riverbank instability on the Tien river, especially the section of the Tien river through Cai Be district.

The destabilization process mainly occurs in curved river sections, distributaries and confluences of the flow as a general rule located on the concave banks. However, due to the impact of tides changing the hydraulic regime of the flow, the process of bank destruction can occur on both convex and concave banks, contrary to normal rules.

There are two types of Tien riverbank erosion include the riverbank erosion occurs due to the process of bank erosion, causing bank collapse, and the bank erosion occurs due to the process of erosion deep into the foot of the bank, causing collapse and bank slippage.

Causes of instability include the erosion impact of river flow, the influence of waves and currents caused by waves, the geological structure of weak ground, the impact of hydraulic pressure, static and eddy currents in rivers, the effects of sediment and sediment depletion, as well as anthropogenic activities.

Regarding the countermeasures for stability of riverbank, the selection of countermeasures should consider the weak soil structure, the impact of horizontal waves causing by boat activities. In this study, the method of pre-stressed piles exhibit a good solution against riverbank erosion. The limitations of this study has not mentioned comprehensive solutions to prevent bank erosion.

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