Climate Change Impacts in a Large-Scale Erosion Coast of Hai Hau District, Vietnam and the Adaptation

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ABSTRACT: Among the effects of global warming, sea level rise (SLR) and severe typhoons pose the greatest threat to the stability of human settlements along coastlines. Therefore, countermeasures must be developed to mitigate the influences of strong typhoons and persistent SLR for coastal protection. This study assesses climate change impacts on coastal erosion, especially in two projected SLR scenarios of RCP2.6 and RCP8.5. The results show that SLR and severe typhoons lead to the increase of coastal erosion, beach lowering and scour. Moreover, as in projected SLR scenarios, average waves in high tide can cause severe soil erosion at inner slopes and lead to dyke failure by 2060. SLR also increases pore water pressure and causes larger wave attacks on the seadykes making them more unstable in typhoons and storm surges. The paper highlights the need for additional geotechnical engineering measures to protect the coast of Hai Hau district against SLR and severe typhoons. Among the alternatives available for countering these threats, applying soil stabilization and soil improvement combined with geosynthetics are promising strategies for coastal structures. Hybrid structures can be used with earth reinforcement and soil improvement. Additionally, the paper emphasizes the importance of multiple protective adaptations, including geosynthetics and ecological engineering measures against climate change-induced severe erosion on the coast of Hai Hau district.

Keywords: Climate change, Sea level rise, Erosion coast, Representative carbon pathway (RCP), Geosynthetics, Ecological engineering, Coastal protection.

1. INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC 2007) reported that during the 21st century, the sea level will rise another 18 to 59 cm due to global warming. The most recent report of IPCC (Church et al. 2013) has shown that global mean sea level rise for 2081−2100 relative to 1986–2005 will likely be in the ranges of 0.26 to 0.55 m for representative carbon pathway (RCP) 2.6, 0.32 to 0.63 m for RCP4.5, 0.33 to 0.63 m for RCP6.0, and 0.45 to 0.82 m for RCP8.5. Sea level rise (SLR) and climate change pose one of the greatest threats to the stability of human settlements along coastlines (Schleupner 2007; Cong et al. 2009; Molua 2009; Yasuhara et al. 2012a; Macintosh 2013). An average rate of SLR is in the range of 1.75 to 2.56 mm/year in Vietnam (Hanh and Furukawa 2007). Recently, areas along coasts have been affected by SLR, underscoring the need to assess the vulnerability of coasts and the effectiveness of protection measures.

Hai Hau, a district in the coastal zone of Nam Dinh province, in North Vietnam (Figure 1) has suffered from severe erosion. The retreat rate could reach up to 15 to 20 m/year (Martin 2000). In this area, the erosion has caused serious damage to the local infrastructure and even loss of lives (Duc et al. 2007). In the near future, coastal dyke failures may be expected to occur almost annually due to budget constraints, a lack of information on sea boundary conditions, such as water levels and wave heights, and a lack of suitable design methods (Cong et al. 2009). Therefore, countermeasures must be developed to mitigate the influences of extreme weather events and persistent SLR for coastal protection. Among the alternatives available for countering these threats, applying soil stabilization and soil improvement with geosynthetics are promising strategies for coastal structures that must sustain severe wave action and storm surges (Masria et al. 2015).

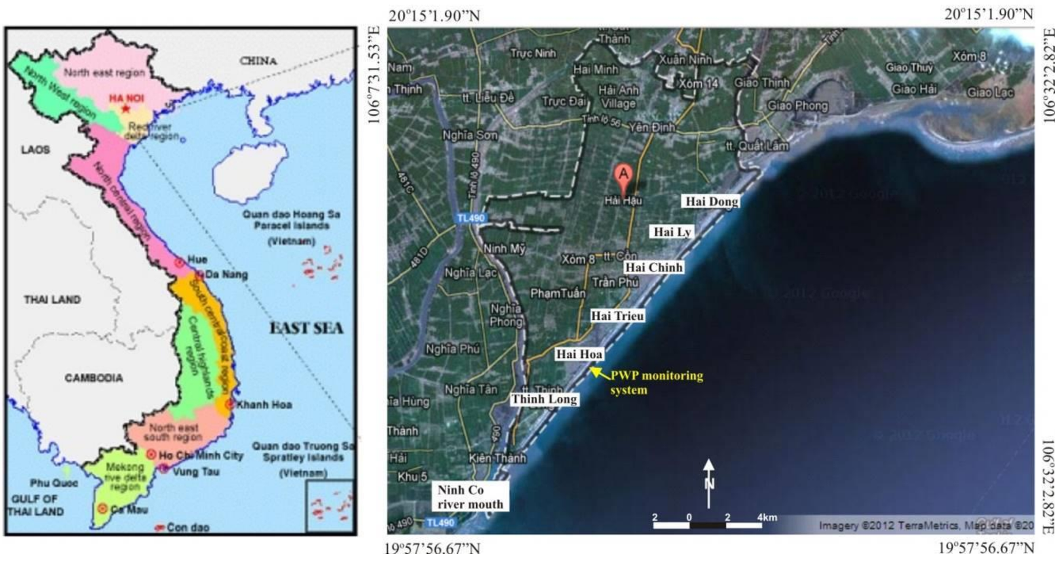


Figure 1 Location of the Hai Hau coast in Vietnam

Furthermore, combinations of those conventionally used techniques are an anticipated geo-technology for reducing climate change-induced disasters. An important issue for this purpose is determining how to reduce costs for construction practices intended to mitigate disasters. Therefore, finding techniques that satisfy engineering effectiveness and cost savings simultaneously is challenging. This paper defines climate change impacts on coastal erosion and outlines the past and then presents current circumstances and future prospects for protecting Hai Hau coastal dykes in the context of climate change.

2. RECENT STATE OF EROSION IN HAIHAU COAST

As one of the most severe coastal erosion in Vietnam, Hai Hau coast has attracted many researches (Vinh et al. 1996; Pruszak et al. 2002; Vu 2003; Duc et al. 2007; Duc et al. 2012).

Changes in the shoreline were assessed by the analysis of topographical maps and satellite images in several time periods. Maps from 1930, 1965, 1985, 1995 and 2001 were used. The shoreline in each map was digitized and then transformed to the same scale and datum (Duc et al. 2012). Recent shoreline change was also investigated by questionnaires and interview with local people (Thuy et al. 2012).

The summarized results from above mentioned scientific papers (Figure 2) show that the most severe erosion is on the coast of five coastal communes (Hai Dong, Hai Ly, Hai Chinh, Hai Trieu, and Hai Hoa) and Thinh Long town. The coastal erosion in Hai Hau was considered to start from the beginning of the 20th century (1905) (Pruszak et al. 2002, Duc et al. 2007). The erosion has a close relation to the degradation of the Ha Lan river mouth (the former main river mouth of the Red River system at that time). Clear evidence of Ha Lan mouth degradation can be found at Giao Long and Giao Phong shorelines, which were continuously accreted with rapid rates (reaching up to 100 m/year in some segments during the period 1905-1930) (Figure 2). However, the main river mouth was then shifted to the Ba Lat mouth and the shoreline in Hai Hau was eroded. Sediment at the coast is dominantly transported south-westward by the northeast and east waves with the volume of 654,078–801,078 m3/year (Duc et al. 2012). During the period 1930-1965, the maximum lateral retreat rate was 22 m/y in the Hai Ly and Hai Chinh communes. The Hai Ly coast was significantly eroded from 1965-1985. The average rate during that period was 21 m/y. In the same period, the rates were 5 m/y on the Hai Dong coast and 11 m/y on the Hai Chinh - Hai Thinh coast. The south part of Thinh Long town was accreted.

Currently, the shoreline in Hai Dong has been accreted. However, the erosion continues to increase in other segments. The most severe erosion segment is now shifting to the southwest. The erosion is very significant on the coast of Thinh Long town. The shoreline was retreating up to 40-50 m/y from 2003 to 2005 (Duc et al. 2012). Beach relief in the south part of Thinh Long town was lowered by approximately 1.7 m in the period from July 2010 to September 2011 (Figure 2).

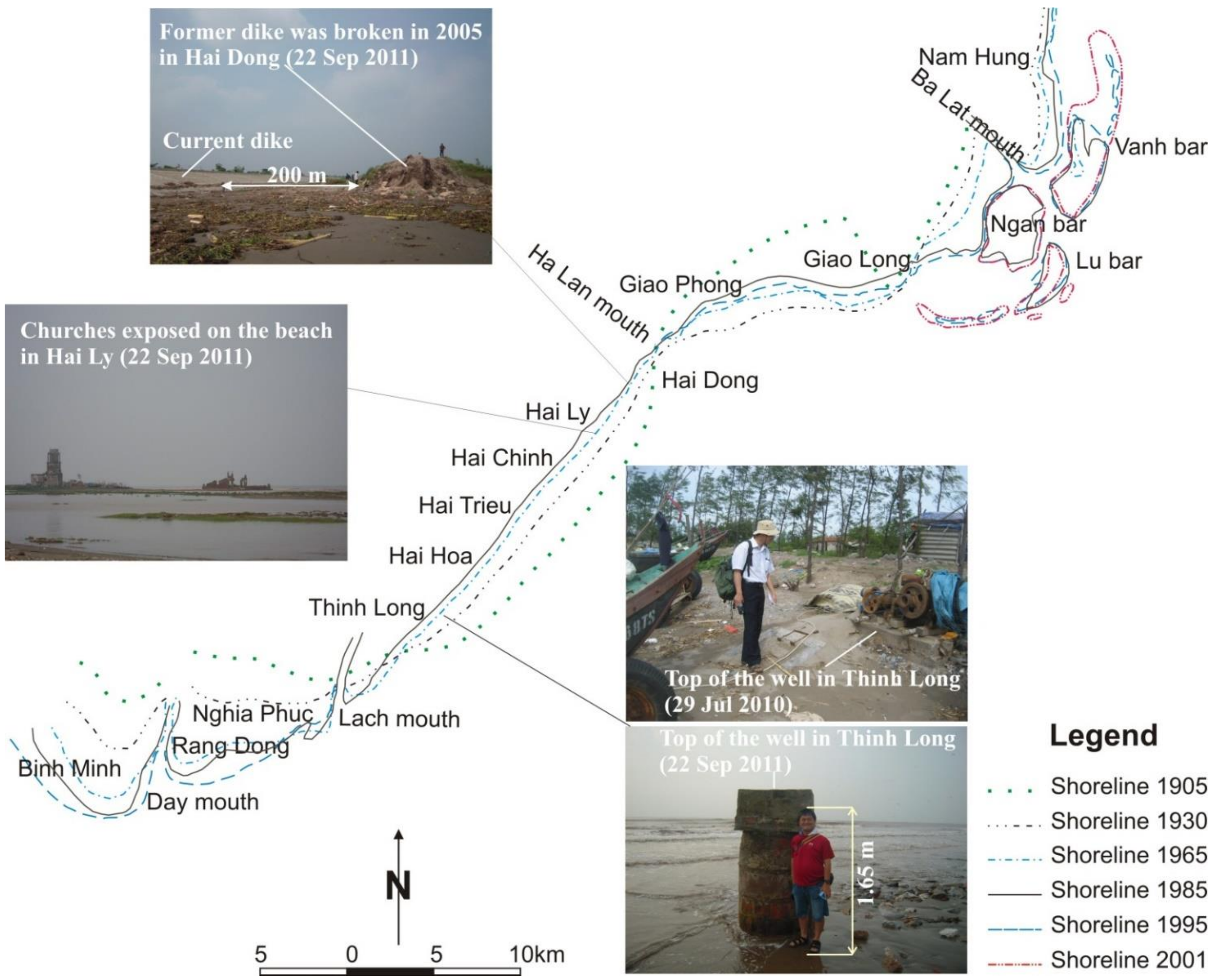


Figure 2 Coastal erosion in the Hai Hau coast (shorelines taken from Duc et al. 2012)

Because of the severe retreat, coastal dyke collapse has occurred frequently, about once every 7–10 yr. (Cong et al. 2009), as depicted in Figure 3. The figure shows that using old churches as symbolic monuments might illustrate the destruction caused by the progressive retreat of the Hai Hau coast. Unfortunately, the remaining symbolic churches finally collapsed in 2010.

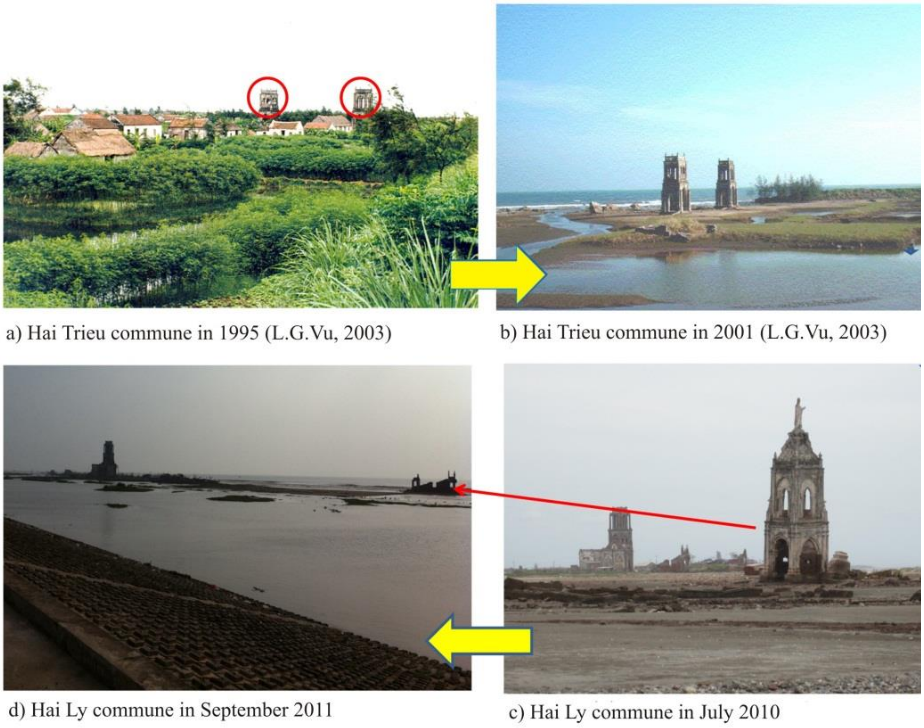


Figure 3 History of erosion process in the Hai Hau coast

3. IMPACTS OF CLIMATE CHANGE ON THE HAI HAU COAST

3.1 Recognition of climate change

According to the report of the Ministry of Natural Resources and Environment (MONRE 2009), during the 50 years from 1958-2007, the annual average temperature in Vietnam increased by approximately 0.5-0.7°C. The annual average temperature during four recent decades (1961–2000) was higher than that of three prior decades (1931–1960). Annual temperatures for 1991–2000 in Hanoi were 0.8°C higher than the average for 1931–1940.

The relative sea level rise in Vietnam has been calculated mainly from tide-gauge data collected at four stations: Hon Dau (Quang Ninh province – northern Vietnam), Da Nang, Qui Nhon (central Vietnam) and Vung Tau (southern Vietnam). Thuy (1995) analysed two tidal gauges in the northern coast at Hon Dau and at Hai Hau. The result shows that from the 1950s to the 1990s, the average rate of SLR was 2.24 mm/y. The longest tide data series was taken at Hon Dau station during the 1960–2000 period, during which a sea level rise of 1.9 mm per year was recorded (Hanh and Furukawa 2007).

Tropical cyclones are a common climatic event in northern Vietnam. The so-called typhoon season often starts in June and ends in October. Approximately 13% of all tropical cyclones strike the northern coast. The most recent data for the annual number of tropical cyclones, as released on the website of National Centre for Meteorology and Hydrology (www.thoitietnguyhiem.net) (Figure 4) show no clear trend in the number of cyclones between the 1960s

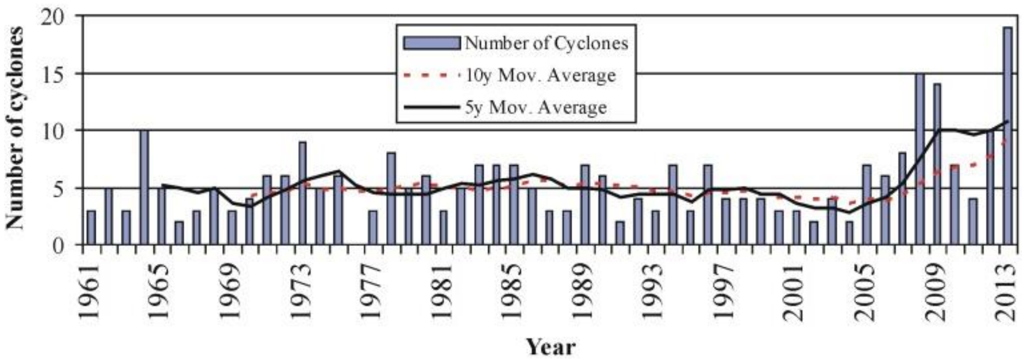


Figure 4 Number of tropical cyclones landed on Vietnamese coast (1961-2013) (Data source: Website of Vietnam National Center for Meteorology and Hydrology)

3.2 Impacts of sea level rise

3.2.1 Increase of erosion

To estimate the future increase of coastal erosion, the formula from Bruun (1962) was used. The formula shows the relation between SLR and the increase of coastal erosion as follows:

$$R_{\infty} = S\frac{L_{*}}{h_{*}+B} \quad (1)$$

where S is SLR, R_{∞} is the accelerated rate of erosion due to SLR, and L_* and (h_*+B) are the width and vertical extent of the active cross-shore profile, B is the height of the berm, h_* is the depth of closure.

The results (Table 1) show that the accelerated rate can reach 0.17-0.25 m/y along the coast of Hai Hau. As a raw estimation, SLR can cause 10-50% of the exceeding rate during the periods 1985-1995 and 1995-1999 (Duc et al. 2012).

Based on formula (1) and mean SLR curves of IPCC (Church et al. 2013), impacts of SLR on future erosion for low (RCP2.6) and high (RCP8.5) scenarios are shown in Figure 5. Accumulative amounts of erosion by 2020 are 6.4, 6.8 and 9.4 m in Giao Phong, Hai Dong and Thinh Long, respectively. They are similar in both low and high scenarios. By 2100, amounts of erosion reach to 34-50 m for low scenario and 56-83 m for high scenario.

Table 1 Accelerated rates of coastal erosion due to SLR

Section	SLR (mm/y)	h* (m)	B (m)	L* (m)	Accelera-ted rate (m/y)
Giao Phong	2.24	5.4	2.0	556.7	0.17
Hai Dong	2.24	7.0	2.0	821.6	0.20
Hai Hoa-Thinh Long	2.24	10.4	2.0	1377.6	0.25

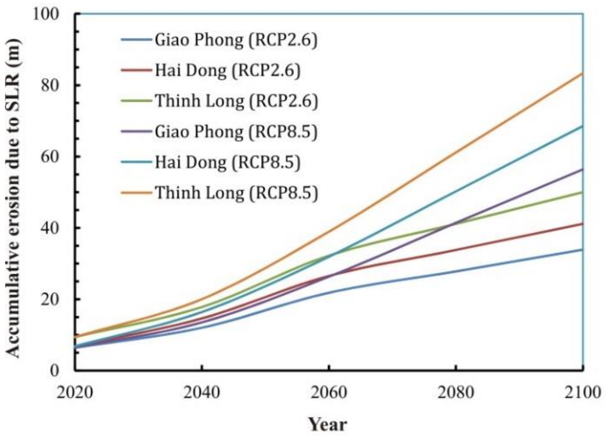


Figure 5 Erosion in Hai Hau coast due to SLR of RCP2.6 and RCP8.5 scenarios

3.2.2 Scour

The shoreline cannot keep lateral movement in front of the coastal dykes. A large amount of sediment on the beach of Hai Hau was washed away, which lowered the beach profile and scour at the toe of coastal dykes. The rate of beach lowering is estimated by the physical model of Barnett and Wang (1988). Assuming the volume of sediment transported is similar to the value before the construction of the dyke, the relation between the erosion rate and rate of beach lowering is as follows:

$$\Delta h = \Delta Y \times B / l \quad (2)$$

where Δh is the rate of beach lowering, ΔY is the erosion rate, l is the width of the beach from the shoreline to the depth of the mean sea level (m), and B is the height of the berm.

Rates of beach lowering were high at Hai Ly, Hai Chinh, Hai Trieu, and Hai Hoa (Table 2) with values of 15-25 cm/y in the period from 1985 to 1995. The current concrete coastal dykes have foots placed at the depth of 1.5 m. Therefore, assumed same rate of lowering, the current dyke's foot may be destroyed in only 6-10 years. Recently, beach lowering has been very serious in Thinh Long town, where the rate was up to 156 cm/y. The situation is more serious with the impacts of SLR. As shown in Figure 6, SLR causes 8-12 cm of beach lowering in Hai Hau by 2020 in both low and high scenarios. By 2100, the beach is lowered from 41-65 cm for low scenario to 68-108 cm for high scenario. Therefore, lowering of beach profile is the most serious threat to the long-term stability of coastal dykes.

Table 2 Rates of beach lowering at Hai Hau coast

Location	Beach slope	Height of berm (m)	Width of beach (m)	Erosion rate (m/y)	Rate of beach lowering (cm/y)
Hai Dong	0.015	2.5	200	5	6.3
Hai Ly	0.015	2.5	180	12	16.7
Hai Chinh	0.015	2.5	250	15	15.0
Hai Trieu	0.015	2.5	225	20	22.2
Hai Hoa	0.010	2.5	210	21	25.0
Thinh Long (2001)	0.010	2.5	260	7	6.7
Thinh Long (2010)	0.010	2.5	80	50	156

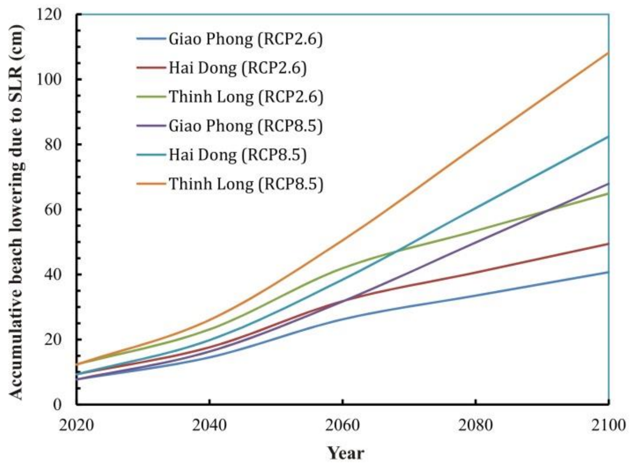


Figure 6 Beach lowering in Hai Hau coast due to SLR of RCP2.6 and RCP8.5 scenarios

3.3 Impacts of extreme weather events

3.3.1 Typhoon-induced erosion

Hai Hau coast experienced an erosion rate of approximately 100 m in a severe typhoon in 1999 on the Nghia Phuc coast (Duc et al. 2007). According to a formula from Kriebel and Dean (1993), the retreat distance caused by extreme wave heights can be estimated as follows:

$$R(t) = R_{\infty}\left(1 - e^{-t/T_s}\right) \quad (3)$$

in which

$$R_\infty = \frac{S(W_b - h_b/m_o)}{B + h_b - S/2} \tag{4}$$

$$W_b = \left(\frac{h_b}{A}\right)^{3/2}$$

$$T_s = 320\frac{H_b^{3/2}}{g^{1/2}A^3}\left(1 + \frac{h_b}{B} + \frac{m_o W_b}{h_b}\right)^{-1}$$

S - wave height; h_b - depth of the breaking wave
m_o - beach slope; B - height of the berm
W_b - width of the breaking wave zone
A - experimental coefficient;
H_b - height of the breaking wave

The recorded wave heights during typhoons at Hai Hau tide station (1976-1994) were 3.2-4.25 m (Pruszak et al. 2002). Table 3 indicates that the erosion rate can reach up to 7.1 m when the wave height is 4.25 m and the duration is 2.4 hours. As mentioned above, climate change leads to stronger variability in the frequency and intensity of tropical cyclones on the Vietnamese coast (Thanh 2014). As a consequence, the extreme erosion rates can become more frequent and severe in the future.

Table 3 Erosion rate caused by an extreme wave height

Section	**S (m)**	**h_b (m)**	**H_b (m)**	**B (m)**	**m_o**	**D_{50} (mm)**	**A ($m^{1/3}$)**	**t (h)**	**R(t) (m)**
Giao Phong	4.25	6.96	3.15	2.00	0.0040	0.143	0.0798	2.4	3.9
Hai Hoa	4.25	9.23	4.10	2.00	0.0150	0.143	0.0798	2.4	7.1
Thinh Long	4.25	8.18	3.78	2.00	0.0100	0.147	0.0840	2.4	3.1
Lach mouth	4.25	8.83	3.23	2.00	0.0045	0.157	0.0872	2.4	2.2

3.3.2 Wave overtopping and soil erosion

In the current design, the heights of the coastal dykes in Hai Hau can only stand typhoons in the lower tenth of intensity (Beaufort scale) in the mean tide. Another problem with the instability of the dykes is admissible wave overtopping. The situation becomes much more serious during typhoons as the Hai Hai coast has experienced severe storm surges, which were up to 0.8-2.6 m high (Table 4). When the wave run-up distance is higher than the crest freeboard (the vertical distance between the mean sea level and the top of the structure), the water will overtop the structure in a continuous sheet of water. The possibility of crest and inner slope to resist erosion and local sliding triggered by overtopping water in Hai Hau (Figure 7) must seriously be considered.

Table 4 Heights of storm-surge in representative typhoons in the last five decades

Typhoon	**Date of formation**	**Landing place**	**Storm surge height (m)**
Phillis	02 Jul. 1966	Nam Dinh, Ninh Binh	1.10
Rose	08 Sep. 1968	Nam Dinh	2.56
Ruth	10 Dec. 1973	Thanh Hoa	2.50
Joe	18 Jul. 1980	Hai Phong	1.94
Warren	16 Aug. 1981	Thai Binh, Nam Dinh	1.15
Pat	18 Oct. 1988	Hai Phong	0.78
Dot	16 May 1989	Hai Phong	1.92
Damrey	19 Sep. 2005	Nam Dinh, Hai Phong	2.50

To estimate the amount of overtopping water under the normal wave condition at high tide level in Hai Hau coast, the following formula from van der Meer (1998) was used:

$$\frac{q}{\sqrt{gH_s^3}} = \frac{0.06}{\sqrt{\tan\alpha}}\gamma_b\xi_{op}\exp(-4.7\frac{R_c}{H_s}\frac{1}{\xi_{op}\gamma_b\gamma_f\gamma_\beta\gamma_v}) \tag{5}$$

Where

$$\xi_{op} = \frac{\tan\alpha}{\sqrt{S_{op}}} \quad \text{and} \quad S_{op} = \frac{2\pi H_s}{gT^2}$$

q is the average overtopping rate (m^3/s per m width), g is the acceleration due to gravity (9.81 ms^{-2}), H_s is the significant wave height (m), α is the average slope angle, γ_b is the reduction factor for a berm, ξ_{op} is the breaker parameter, R_c is the crest freeboard (m), γ_f is the reduction factor for slope roughness, γ_β is the reduction factor for oblique wave attack, γ_v is the reduction factor due to a vertical wall on a slope, S_{op} is the wave steepness, and T is the period of the wave (s).

The data acquired from average wave condition was used in the equation (5). The input parameters are H_s = 1.5 m, T = 6 s, α = 15 degrees, γ_b = 1, γ_f = 0.9, γ_β = 1, and γ_υ = 0.65. Based on Chezy's equation, the velocity of the water flow on the surface of the inner slope is calculated as follows:

$$v = C\sqrt{Ri} \tag{6}$$

$$C = \frac{1}{n}R^{1/6} \tag{7}$$

$$R = \frac{bh}{b + 2h} \tag{8}$$

where: v is the mean flow velocity (m/s), C is the Chezy coefficient, R is the hydraulic radius, i is the slope of the channel bed, n is the roughness coefficient (after Julien 2002), set to be 0.016 in the calculation, b is the width of flow (m), and h is the depth of flow (m).

a) Destruction of outer slope by wave attacks, Thinh Long 22 Feb 2012

b) Destruction of inner slope by overtopping, Thinh Long 4 Dec 2013

Figure 7 Destruction of current coastal dyke slopes on the Hai Hau coast

Geometrical characteristics of coastal dykes in Hai Hau are shown in Figure 8. According to the Unified soil classification system (ASTM 2001), the materials used to build the coastal dyke on the Hau Hau coast are mostly clayey sand (SC) with medium compaction and low plasticity (Table 5). Based on empirical relations between water velocity and erosion rate for various types of soils (Figure 9) of Briaud (2008), erosion rates at the inner slopes of the Hai Hau dykes are shown in Table 6.

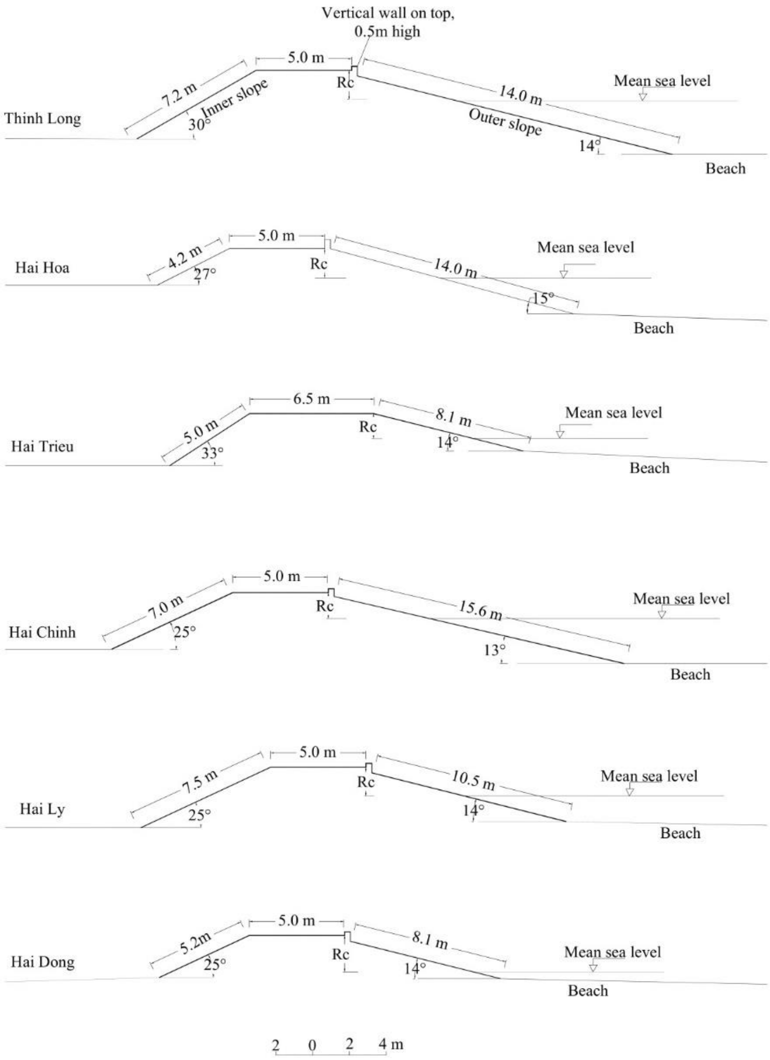


Figure 8 Typical cross sections of coastal dykes on the Hai Hau coast

Properties		North Hai Dong	South Hai Dong	Hai Ly	Hai Chinh	Hai Trieu	Hai Hoa	Thinh Long
Grain sizes	Sand	61.7	63.8	63.1	61.2	59.8	62.6	
	Silt	12.0	10.4	12.3	9.8	12.4	11.4	
	Clay	26.3	24.2	24.6	25.3	26.1	23.5	
Natural water content (%)		29.8	30.1	30.4	30.3	30.1	30.5	30.4
Unit weight (g/cm^3)		1.81	1.81	1.80	1.80	1.81	1.82	1.83
Dry unit weight (g/cm^3)		1.47	1.45	1.47	1.48	1.42	1.44	1.40
Specific gravity (g/cm^3)		2.70	2.72	2.69	2.71	2.67	2.68	2.72
Void ratio		0.832	0.821	0.827	0.821	0.824	0.923	0.827
Porosity (%)		45.4	45.2	44.9	44.8	45.1	48.0	44.9
Degree of saturation (%)		74.0	73.7	72.7	72.6	72.4	88.7	74.4
Liquid limit (%)		44.5	42.7	41.7	41.5	41.7	42.5	42.1
Plastic limit (%)		31.9	30.6	28.7	29.5	28.2	28.7	28.6
Plasticity index (%)		12.6	12.1	12.0	12.0	13.5	13.8	13.5
Effective cohesion (kPa)		13.0	12.5	9.3	10.1	11.0	9.0	8.0
Effective internal friction angle (degree)		24.5	23.0	23.3	24.2	24.1	25.0	23.1
Soil type (after ASTM 2001 - D2487)		SC	SC	SC	SC	SC	SC	SC

Table 5 Geotechnical properties of soils in coastal dykes in Hai Hau coast

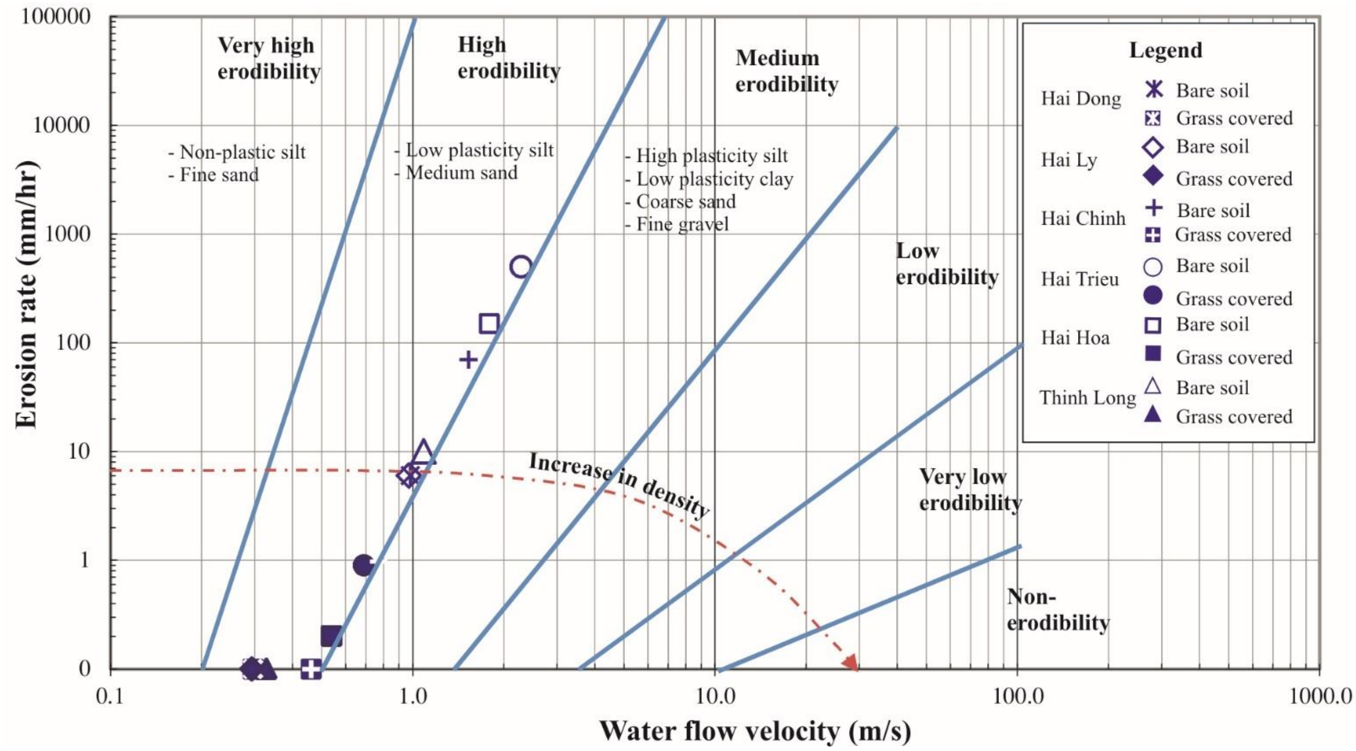


Figure 9 Estimation of soil erosion rates at inner slopes of the coastal dykes in Hai Hau coast

Table 6 Erosion rates at dyke inner slopes caused by waves at high tide

Section	Outer slope (deg.)	Crest freeboard (m)	Length of inner slope (m)	Inner slope (deg.)	Overtopping flow (l/s per m)	Water flow velocity (m/s)		Erosion rate (cm/hr)	
						Bare soil	Grass covered	Bare soil	Grass covered
Hai Dong	14	1.0	5.2	25	20	0.98	0.30	1	Very low
Hai Ly	14	0.9	7.5	25	28	0.97	0.30	1	Very low
Hai Chinh	13	0.65	7.0	25	52	1.53	0.46	7	Very low
Hai Trieu	14	0.7	5.0	33	56	2.29	0.70	50	Very low
Hai Hoa	15	0.9	4.2	27	38	1.79	0.54	15	Very low
Thinh Long	14	0.9	7.2	30	28	1.09	0.30	1	Very low

Erosion is ignorable at Hai Dong, Hai Ly and Thinh Long. However it is severe at Hai Hoa, Hai Trieu, especially in Hai Trieu, where the inner slope was bare soil with no vertical concrete wall to prevent waves from running up. The erosion rate at Hai Trieu was estimated up to 50 cm/h. In the cases of vegetated inner slope, velocities of overtopping water flows were significantly reduced. Erosion rates at inner slopes were negligible (Table 6).

With similar data, in Thinh Long, as an example of Hai Hau coast, erosion rates at inner slopes increase sharply due to future SLR (mean SLR curves as in Figure 13.11 of Church et al. 2013). The rates are serious after 2040 in both RCP2.6 and RCP8.5 scenarios (Figure 10). The difference in erosion rates between RCP2.6 and RCP8.5 scenarios is only significant after 2060. However, erosion rates in bare soils for RCP8.5 scenario are about ten times as those for RCP2.6 scenarios by 2080 and 2100. It is significant to note that erosion rates by 2100 are still not so serious in both scenarios if the inner slopes densely covered by grass.

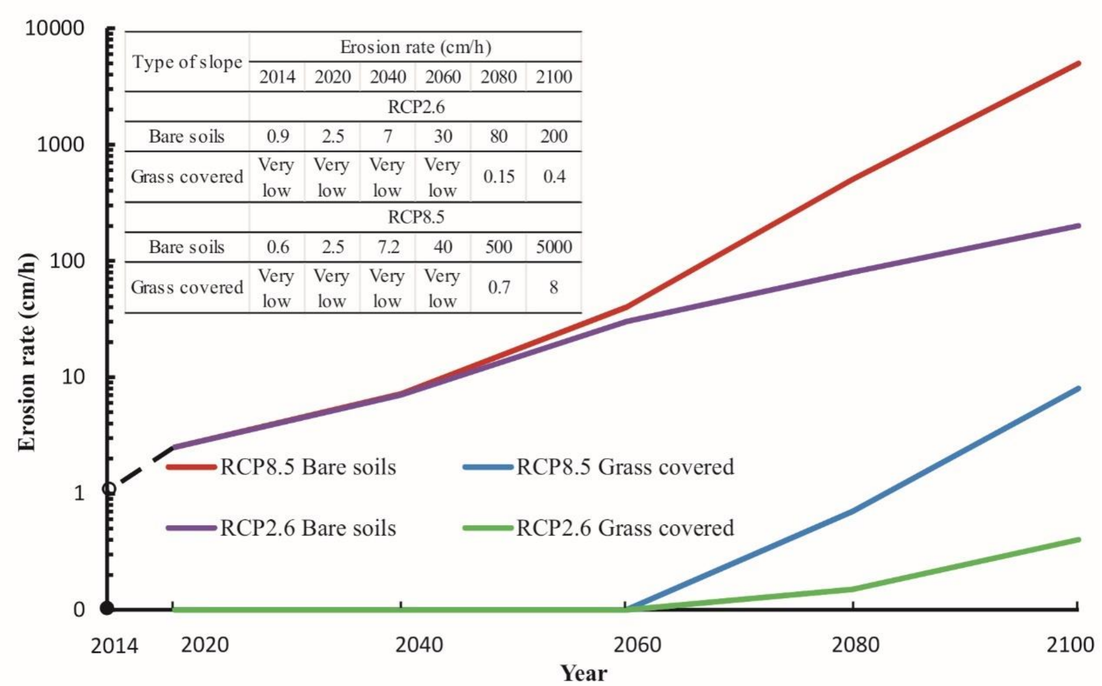


Figure 10 Erosion rates at dyke inner slopes of Thinh Long town in RCP2.6 and RCP8.6 scenarios (geometrical parameters of dykes, beach slope were measured in 2012, and assumed to be constant in the calculation)

4. GEOTECHNICAL ENGINEERING MEASURES FOR CLIMATE CHANGE ADAPTATION

4.1 Current coastal protection

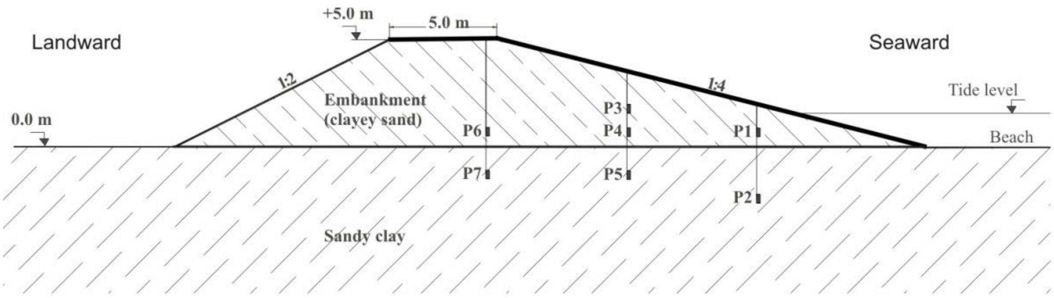
Coastal dykes, mainly made of soils, were very commonly constructed in the 1980s. The construction of these dykes is simple. Therefore, the dykes are easily eroded and severely damaged in a typhoon (Vinh et al. 1996). Dykes of such type are still used in some parts of the Hai Hau coast, including the Hai Chinh and Hai Dong communes. To reinforce the dykes, groins are used. The groins are built of concrete reinforced with concrete tubes, which are 10-cm-thick and 1 m in diameter, and placed continuously at a depth of 0.5

m under the tidal flat and a height of 1.5 m with sandbags inside. The distance between the links is 80 m (Figure 11a). Mangrove forest is being replanted in Hai Dong (Figure 11b) where coastal sediments are now accreting. With investments from PAM (Programme Alimentaire Mondial) and the government from 1998 to the present, the coastal dyke system in Hai Hau has been intensively reinforced (Figure 11c). The coastal dyke height has been improved by 4.5–5.5 m. Footings were placed at 1.5 m depth, and the dyke was reinforced by lines of tripods and covered by polygonal pre-cast concrete of 100-kg mass, even reaching 200 kg on the slope of 1: 2.2–3 (Figure 11d). In segments of the soil dykes, standby blocks of limestone are disposed nearby for emergency rehabilitation in bad weather conditions.

Figure 11 Conventional coastal protection in Hai Hau coast

4.2 Pore water pressure monitoring

In order to have a precise insight into changes of pore water pressure (PWP) in the dyke body and foundation, a PWP monitoring system was installed. Equipment used for the system was purchased from Slope Indicator. Sensors are vibrating wire type which posse a high accuracy in a range of pressure from 0.7 bar to 35 bar. Totally, 7 piezometers were installed in January 2013 (Figure 12). The piezometers were installed at different depths and isolated from each other to form a net of multi-level PWP inside and under the dyke. The data is recorded every 10 minutes. Recorded PWP have different values depending on depths and locations. Tide levels of lower than 0.5 m have no impacts on PWP changes (Fig. 13a). PWP at piezometers 1, 3 and 6 showed negative values because these were put above the groundwater table, meanwhile piezometers 2, 4, 5 and 7 showed positive values. High conductivity zones near the coast lead to similar curves of fluctuation between daily tide levels and PWP in all piezometers with positive values (Figure 13a). It is well known that the response to harmonic fluctuation of tide level decreases exponentially with distance inland (Slooten et al. 2010). Therefore changes of PWP at piezometer 7 (the most landward site) proves high potential of seawater intrusion through dyke bodies which will seriously affect landward rice fields. Northeast monsoon induces 2-5 kPa higher in PWP even in low tide level conditions (Figure 13b). Fluctuation in tide levels changes PWP distribution in the dykes, and therefore changes seadyke stability, which can be more detail analysed in another study.



Piezometer	Elevation (m)
P1	0.7
P2	-2.4
P3	1.8
P4	0.7
P5	-1.3
P6	0.7
P7	-1.3

Figure 12 Sketch of the PWP monitoring system

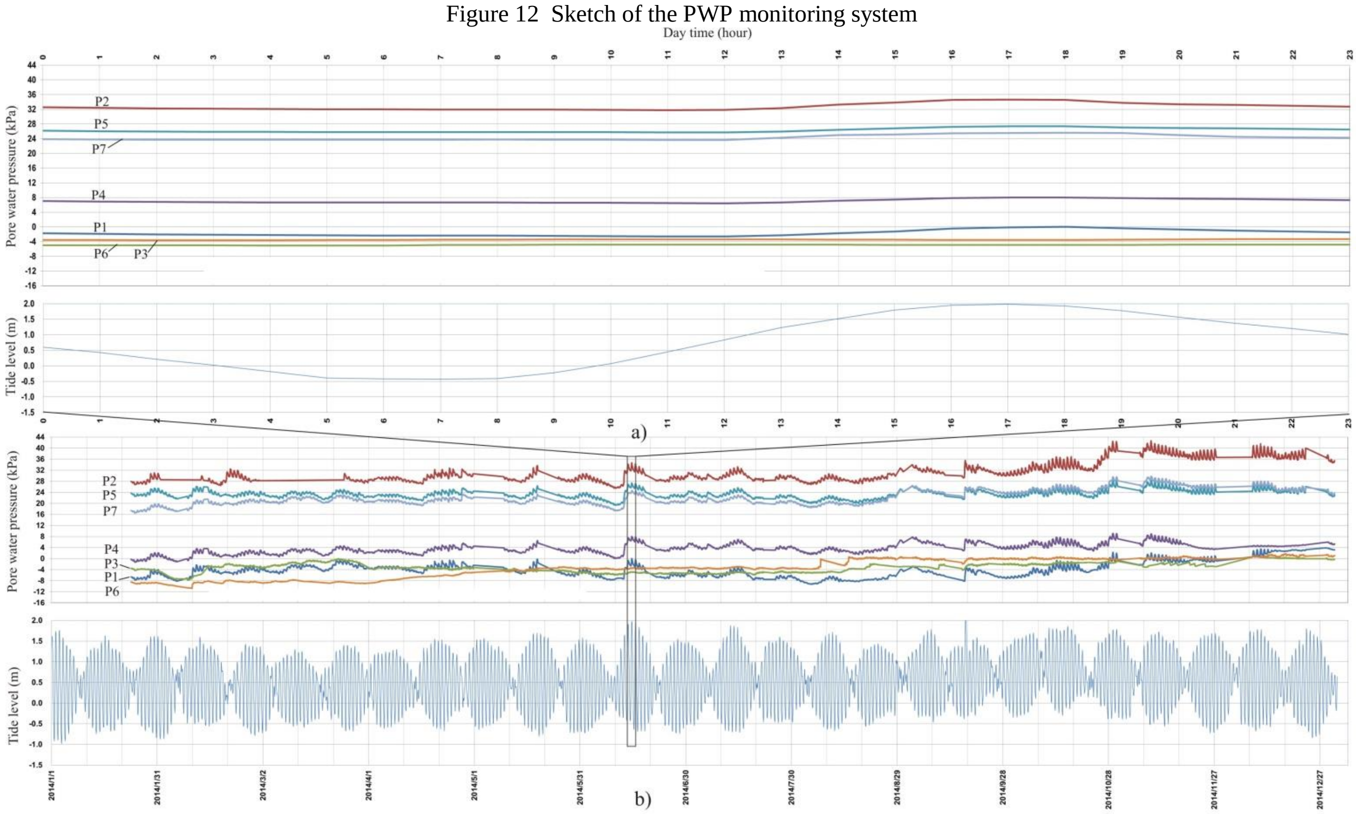


Figure 13 Relationship between tide level and PWP in Hai Hoa (a. A daily record on 14 June 2014, b. Long-term record)

4.3 Advanced protective measures

In recent years, because of SLR, some of the existing coastal protection structures need to be rehabilitated and new, stronger or taller coastal structures have to be built (Chu et al. 2012). The use of combinations of conventional techniques is anticipated in geo-technology to reduce climate change-induced disasters, as shown in Table 7. In the case of Hai Hau coast, advanced measures should focus on two main threats of climate change to dyke stability, which are the increase of scour and potential more intensive erosion at the inner slopes of dykes (Yasuhara et al. 2016).

Table 7 Improvement of coastal dykes (modified from Yasuhara et al. 2013)

Improvement/Reinforcement	Example of technique	Remarks
Mechanical improvement/Reinforcement	Well-graded soils Well-compacted soils Inclusion of fiber materials	Inexpensive Durable Locally available material or traditionally used material
Mechanical-chemical improvement/reinforcement	Admixture of fiber materials with cement Sandwich-structure using non-woven fabrics with quicklime Placement of geosynthetics with soils stabilized by cement	Hybrid Cost/benefit and analysis
Mechanical/ecological reinforcement	Grass with geocell and mangrove Geotube and gabions	Inexpensive Friendly to the environment

4.3.1 Application of geosynthetics

Instead of conventionally used adaptation against climate change, use of geosynthetics was proposed around 1970 and has been adopted in Vietnam for protecting river dykes and coastal levees under severe storm and inundation (Trinh 2010). However, for coastal areas, few case histories illustrate so-called good practices (Yasuhara et al. 2012c). For a geosynthetics application to function correctly, geosynthetics and traditional measures must be combined in accordance with the levels of driving forces. Furthermore, locally available natural geosynthetics should be included in the development of adaptive measures. Sato et al. (2013) and Yasuhara et al. (2013) attempted the combination of palm tree fibres with sandy soils to reinforce dykes, which is currently under laboratory investigation.

Matsushima et al. (2011) presented a case study of the successful use of jute inclusions in soils used for local agricultural road embankments to resist climate change events as depicted in Figure 11. From the perspective of cost savings, several measures can be used for reinforcement dykes, including the usage of locally available materials. Adequate compaction is fundamentally important but sometimes difficult, particularly when aiming for high compaction, such as 90–95% of maximum dry density of soil (Figure

14a). Compaction can be improved with natural (coconut, bamboo) or artificial (i.e., plastic) fibres (Figure 14b) (Sato et al. 2013). Sandwich structure dykes (Figure 14c) are suitable for the construction of dykes using cohesive soils. Therefore, locally available granular materials are promising for the formation of sandwich layers among cohesive soil layers (Yamazaki et al. 2007; Yasuhara et al. 2012b).

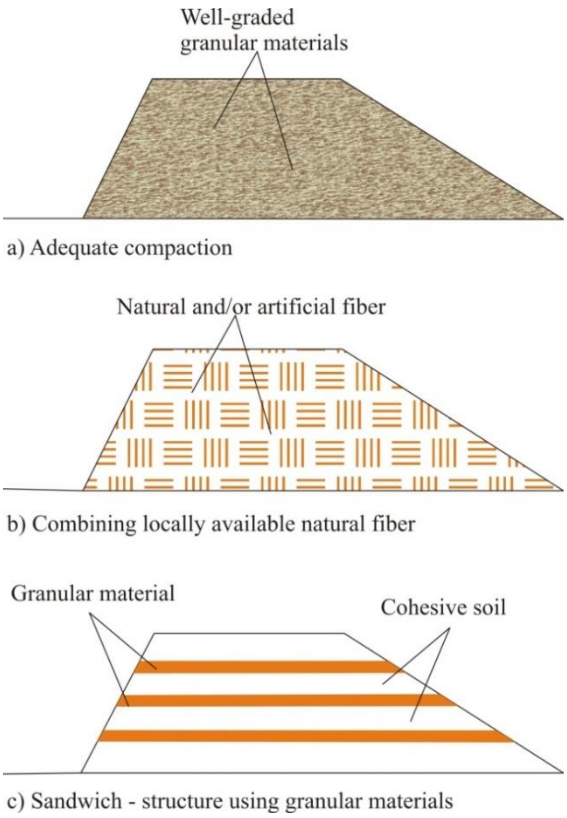


Figure 14 Several options for reinforcement for coastal dykes (after Yasuhara et al. 2012c)

4.3.2 Hybrid earth structures by combining earth reinforcement and soil improvement

A necessary issue is the construction of countermeasures against inundation caused by the combination of storm surge and SLR. For the successful execution of countermeasures, the authors propose reinforcement techniques combining soil bags with geosynthetics, as presented in Figure 15, which belongs to a permanent countermeasure. To upgrade the reinforced sea walls with geosynthetics, other work such as the injection of cement mortar into soil bags can be undertaken, as presented in Figure 16.

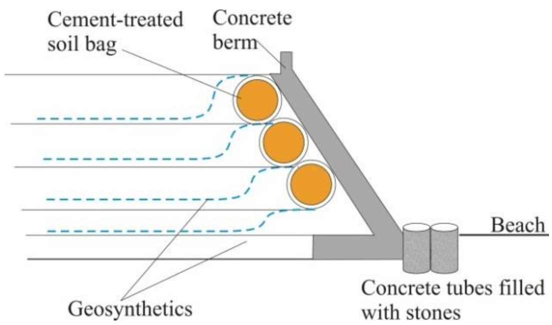


Figure 15 From single to hybrid use of reinforcement and improvement (modified from Yasuhara et al. 2013)

Regarding these techniques, although combined reinforcement of this type against severe storms has proved valid in laboratory tests (Yasuhara and Juan, 2007), it should be combined with other techniques, particularly for use against extreme weather events.

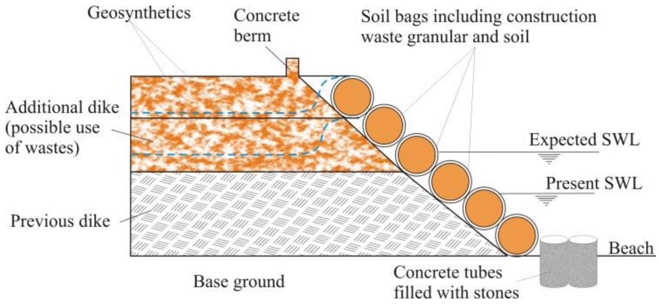


Figure 16 An example of reinforcing reconstruction using soil bags and geosynthetics (modified from Yasuhara et al. 2013)

4.3.3 Multiple protection mechanisms to respond to climate change

The use of only a single countermeasure such as the dyke reinforcement described above is insufficient for long-term protection, particularly against severe weather conditions following storm surges or typhoons (Duc et al. 2015). One proposed multiple protection solution for climate change adaptation is shown in Table 8, which depicts three combined countermeasures: an off-shore wave-eating facility (geotube), near-shore measures (mangrove plantation is popular in developing countries), and a dyke reinforced with vetiver grass and locally available techniques and materials. Concrete tubes filling by rock boulders (as shown in Figure 10b) are installed to prevent the scour of dykes trough.

Due to a lack of investment, the current coastal dykes still suffer from overtopping seawater. In such a case, vetiver grass is a suitable application for the protection of the inner coastal dyke slope. The vetiver hedgerows reduce soil loss on a slope by 62–86% in comparison with the case without vetiver hedgerows (Donjadee and Tingsanchali 2013). Recent field tests (Akkerman et al. 2007; Van der Meer 2008) have shown that grass slopes can resist a significant high overtopping rate of approximately 75 l/s/m or more for a moderate grass cover. The root system of a grass cover in the sub-surface soil layer of approximately 20 cm is the main factor controlling the resistance to wave topping (Quang and Oumeraci 2012). Vetiver can also be used in combination with other traditional engineering solutions (Truong 1998; Truong et al. 2008). For example, the lower part of the dyke can be covered by the combination of rock riprap and geo-textile, while the upper half is protected with vetiver hedge. Garcia (2007) presented an analysis for stability of the dyke slope with reinforced grass revetments with geosynthetics on the inner slope during an overtopping event. The results showed that using geocell or geomat strengthens the grass layer due to the increase in the cohesion of the soils.

To reinforce the inner slopes of the coastal dykes in Hai Hau against soil erosion, vetiver grass can be built with the following layout specifications:

- o Vetiver should be planted in two directions: For stabilization of the coastal dyke inner slope, vetiver should be planted in rows parallel to the flow direction (horizontal), on approximate contour lines 0.8-1.0 m apart (measured down slope).
- o The first horizontal row should be planted at the crest of the slope, and the last row should be planted at the trough of the inner slope.
- o Vetiver should be planted on the contour along the length of the dyke between the top and bottom rows at the spacing specified above.
- o Because of loose sandy soils at the sub-surface of the inner dyke slopes, vetiver grass growth is enhanced by using a cell with denser compacted soils and fertilizer.

Mangrove is used as an additional reinforcement on the coast for weak erosion (erosion rate lower than 2 m/y). One hundred metres of mature mangrove can reduce 0.1 m of wave height (Mazda et al. 1997 and Quartel et al. 2007). In cases of stronger erosion, mangrove forest must be planted behind wave breaking measures such as geotubes (Duc et al. 2016).

The application of geotubes is now popular worldwide due to advantages such as ease, cost-effectiveness, rapidity of installation and durability (Koffler et al. 2008; Lee and Douglas 2012). Recently, owing to the high cost of rubble mound coastal structures, the application of geotube technology has become a serious consideration (Shin and Oh 2007). The advantage of geotube technology as a cost-saving measure compared to traditional technologies for coastal structures was shown in a study by Sheehana and Harrington (2012). Various materials can be used for filling the geotube, including sand or sandy soils, which are dominant on the Hai Hau coast. Geotubes are installed as submerged breakwaters and work as an efficient and environmentally friendly solution to protect the shoreline from erosion (Sheehana and Harrington 2012, Duc et al. 2016).

Table 8 Preventive measures against erosion in Hai Hau coast under the context of SLR

Objective	**Required measures**	**Supporting measures regarding the current erosion rate**		
		< 2 m/y	2-5 m/y	> 5 m/y
Protection of dyke surface from erosion	Raising height of dykes Concrete revetment with geotextile (seaside) Vetiver plantation (inner side) Natural and artificial fiber for better compaction of dyke materials	Mangrove	Geotube breakwater Mangrove	Geotube breakwater
Mitigation of accelerated erosion and scouring due to SLR	As current design, dyke trough needs to be installed at least 1.5 m below the current beach surface	Mangrove	Geotube breakwater Mangrove	Geotube breakwater Protection of coastal dyke toe by groynes (concrete tubes filled with stone boulders)

5. CONCLUSIONS

Coastal erosion has been a serious threat to the coast of the Hai Hau district. In the long term, SLR and severe typhoons may lead to the increase of coastal erosion, beach lowering and scour. In the current time, dykes can fail due to typhoon and storm surges, but as in projected SLR scenarios, average waves in high tide can cause severe soil erosion at inner slopes and lead to dyke failure by 2060.

Accumulative amounts of erosion by 2020 are 6.4, 6.8 and 9.4 m in Giao Phong, Hai Dong and Thinh Long, respectively. They are almost similar in both low and high SLR scenarios. By 2100, amounts of erosion reach to 34-50 m for low scenario and 56-83 m for high scenario.

Lowering of beach profile is the most serious threat to the long-term stability of coastal dykes. SLR causes 8-12 cm of beach lowering in Hai Hau by 2020 in both low and high scenarios, and 41-65 cm for low scenario, 68-108 cm for high scenario by 2100.

The erosion rates at inner slopes increase sharply due to future SLR, which become seriously after 2040 in all scenarios.

From the perspective of engineering adaptive measures, a combination of geosynthetics with soil improvement using cement can be used for coastal protection in the context of climate change in Hai Hau. Multiple protective measures, including conventional structures (i.e., dykes, revetments, and groins) with geotubes and ecological engineering solutions (i.e., mangrove forests and vetiver grass), are good solution against climate change-induced severe erosion.

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