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Study on the effects of wave-induced setup on coastal evolution of the Cua Dai beach, Hoi An

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Abstract
Over the past years, there have been several studies on the hydrodynamic regime, beach erosion, and accretion at the Cua Dai beach in Hoi An city. However, there is still a lack of in-depth research on the effects of hydrodynamic factors on beach evolution in extreme weather conditions such as a storm event or during the Northeast monsoons, characterized by large waves mainly, especially. The wave set-up directly impacts on the evolution of upper beaches and coastal dunes, consequently causing beach erosion. This paper presents the results of nearshore wave propagation and transformation and the distribution of wave set-up during storms in the coastal area of Cua Dai, Hoi An, using the SWAN model and the XBEACH model. The models have been calibrated and validated using measured wave and water level data observed in the study area in October 2016. The simulation results have shown the overall picture of the influence of wave set-up on the morphology evolution of beach profiles in the study area.

Keywords: Wave setup, beach evolution, SWAN, XBEACH, Cua Dai beach, Hoi An.

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INTRODUCTION

Cua Dai beach, Hoi An is one of the most beautiful beaches in Asia and plays a vital role in the development of the tourism industry in Quang Nam province in particular and in Vietnam in general. In addition to the advantages endowed by nature, every year in the NE monsoon season, the entire northern coastal area of Cua Dai beach suffers from many natural disasters such as storms, tropical depressions, monsoons, storm surges, and wave setup causing coastal erosion, leaving a long-term negative impact on socio-economic development and ecological environmental issues in the region.

There have been several studies [1–7] on the hydrodynamic regime, beach erosion, and accretion in this area to clarify the causes of beach erosion and accumulation in the north of the Cua Dai sea, Hoi An, over the past years. However, there is still a lack of in-depth studies on the effects of dynamic factors in coastal areas on beach evolution in extreme weather conditions such as storms and the NE monsoons causing big waves. The setup due to waves directly impact on the evolution of upper beaches, coastal dunes, causing beach erosion. The authors focus their research on the influence of storm surge on beach fluctuations. The results of the study will contribute to the research process and solve the requirements. Practice in natural disaster prevention, construction of coastal protection works, as well as in management and planning to stabilize the shores and beaches of Cua Dai in the Hoi An city to serve socio-economic development.

SETTING UP MATHEMATICAL MODELS

Data used

The bathymetry data of the shallow water area is inherited from the bathymetric map measured in 2014 by the Institute of Oceanography at Nha Trang, in the framework of the provincial scientific and technological project. The water level measurement data and topography data nearshore are extracted from the database of a topographic survey in the framework of the provincial science and technology research project of Technology-Economics and Water Resources. The coastline position, which is digitized from Landsat 8 images [8] with 15 m resolution and Sentinel-2 images with 10 m resolution, serves as a solid boundary (land boundary) in the model. Deep water wave data is obtained from reanalysis data of wind by NCEP with the SWAN model [9]. The location for extracting wave data is in the deep water area (depth of 80 m), offshore of the Cu Lao Cham island. Nearshore wave data for model calibration and verification is taken from measured data in the framework of the project.

Morphology evolution of the Cua Dai beach

Using synchronous measurement data on the morphological changes of the beach cross section through the SW monsoon, NE monsoon, before and after the storm, and the correlation between wave height and water level in the coastal area of Cua Dai, Hoi An to analyze the change in beach profile under the impact of dynamic factors.

The beach evolution analysis at different stages that correspond to the impacts due to dynamic factors are listed in table 1.

From the analysis results of table 1, generalization of some mechanisms of beach profile evolution at Cua Dai, Hoi An.

The evolution of the beach is quite evident in its seasonal nature. During the NE monsoon season, the beach is severely eroded. The erosion during the southwest (SW) monsoon season the erosion only occurs in unusual weather conditions such as storm events. The extent and rate of beach erosion caused by a storm event is more severe than beach erosion during the NE monsoon. The waves varying from NNE to ENE direction (200–700) cause the most severe shoreline and beach erosion. The range of beach evolution is about 200 m from the shoreline to the sea. The most severe beach erosion is located approximately 70 m from the shoreline. The deterioration at the Cua Dai beach is most significant during the storm season, from September to October. The ENE and ESE waves often cause insignificant damage to the Cua Dai beach due to the effect of wave refraction behind the island of Cu Lao Cham.

Table 1. Results of the analysis of beach evolution through various stages

Stages		Occurrence, characteristics of storms or monsoon	H_{smax} (m)	H_{Ndmax} (cm)	Wave direction	Beach evolution and the extent of impacts
From	To					
23/3/2016	17/8/2016	Not available	2,69	21,15	ENE-SE	Low-intensity accretion
17/8/2016	12/9/2016	Impacts of typhoon on 12/9/2016	2,70	38,90	ENE	Erosion of beach edge, high beaches
1/10/2016	30/12/2016	Impacts of typhoon on 17/10/2016	4,98	45,04	NE	Erosion of beach edge, high beaches, dune toes
		Impacts of NE monsoon on 2/11/2016	4,0	37,53	NE	Erosion of beach edge, high beaches, dune toes
		Impacts of NE monsoon on 30/11/2016	3,63	21,30	NE	Erosion of beach edge, high beaches
		Impacts of NE monsoon on 15/12/2016	3,77	29,43	NE	Erosion of beach edge, high beaches
		Impacts of NE monsoon on 27/12/2016	3,79	23,67	NE	Erosion of beach edge, high beaches
1/1/2017	30/3/2017	Impacts of typhoon on 26/3/2017	3,44	38,84	ENE	Erosion of beach edge, high beaches

Mathematical models will be used to analyze and clarify the effects of wave-induced setup on the beach evolution in the study area to clarify the mechanism of coastal erosion and quantitative assessment of factors that drive erosion in bars and coastal dunes, in the following section.

Model setup, computing region, grid and boundary conditions

The computational domain is divided into two areas (figure 1): Domain 1: used for computing wave propagation from deepwater to nearshore of the Cua Dai, Hoi An, SWAN model has been used for computing. Domain 2: used for computing wave propagation in the nearshore area and at Cua Dai beach, XBEACH model has been used for this domain.

The computational grid of the SWAN model in domain 1 (figure 2) is established, containing 421 cells alongshore and 170 cells cross-shore; the smallest grid spacing located nearshore is 30 m and the largest one in the deep water area (with a maximum depth of 70 m) is 400 m. The rectangular computing grid of the XBEACH model in domain 2 (figure 2) is nested inside the SWAN model grid with a grid step of 5 × 25 m, corresponding to (310 × 481) grid cells.

Figure 1. Computational domain 1 and 2

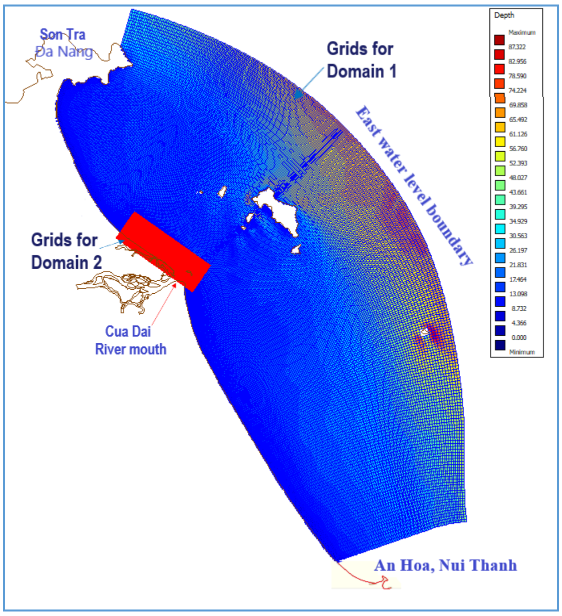


Figure 2. Computing grids of domain 1 and 2

Boundary condition and initial condition

The boundary conditions of the SWAN model (domain 1, with coarse grid) are taken from reanalysis wave properties by NCEP wind data [9]. The SWAN model was calibrated and verified against measured data in Oct. 2016.

The boundary conditions of the XBEACH model (domain 2) are extracted from the SWAN model, which is used in the larger domain.

Model calibration and verification

Calibration and verification of SWAN model

SWAN model has been calibrated using measured wave data in October 2016. The simulating wave heights and wave periods are closely similar to measured wave data. Deviation and average square error of simulating wave heights, wave periods, and wave directions compared to measured data in October 2016 are listed in table 2. The detail of model calibration shows in.

The SWAN model was validated using measured wave data in March 2017. The model calibration and validation results indicated that the model could accurately simulate wave propagation from deep water to the nearshore area of the Cua Dai beach. The simulating of the wave heights and wave periods at the SMS01 station and SMS02 station agrees with the measured data in March 2017. The results of deviation and average square error are calculated and listed in table 3.

Table 2. Calibration results of SWAN model using measured data in October 2016

No.	Station	Wave height		Wave period		Wave direction	
		BIAS (m)	RMS (m)	BIAS (s)	RMS (s)	BIAS (deg)	RMS (deg)
1	SMS01	-0,04	0,11	0,46	2,80	5,20	19,68
2	SMS02	0,08	0,15	-0,78	2,86	-3,36	19,40

Table 3. Verification results of SWAN model using measured data in March, 2017

No.	Station	Wave height		Wave period		Wave direction	
		BIAS (m)	RMS (m)	BIAS (s)	RMS (s)	BIAS (deg)	RMS (deg)
1	SMS01	-0,02	0,09	0,70	1,56	-11,71	21,68
2	SMS02	0,03	0,07	-0,10	0,82	-7,41	0,87

Calibration and verification of the XBEACH model

The parameters used to calibrate the XBEACH model are listed in calibration parameter table for wave height and wave surge [10]. The XBEACH model calibration process is a trial-and-error process of many combinations of parameters and The simulation results were verified using the analyzed wave heights, wave-induced setup, and bathymetry change data to measure the scene during the DOKSURI storm from September 12 to 15, 2017 [11]. Figures 3 and 4 present computed and measured wave heights and wave setup at the Agribank beach profile. Figure 5 shows the simulated and measured beach profile changes at the Agribank beach on September 14, 2017. The average statistical error of BIAS deviation and the mean-squared statistics of RMS were used to evaluate the agreement between the calculated results and the measured results. The results of deviation and mean square error are presented in table 4.

Table 4 shows that simulation errors in both BIAS and RMS parameters are within the allowable range. Therefore, the XBEACH model can be used to calculate the evolution of the beach profile at Cua Dai beach under some specific storm events, as well as for some hypothetical scenarios.

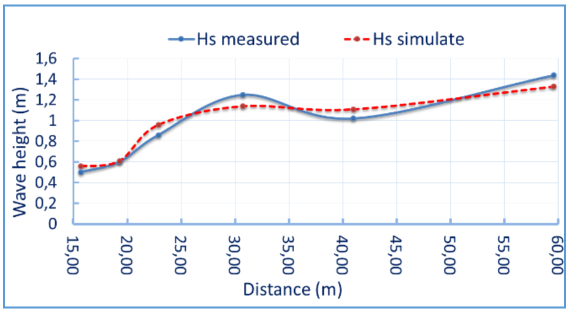


Figure 3. Comparison of computed and measured wave heights at Agribank profile, Hoi An

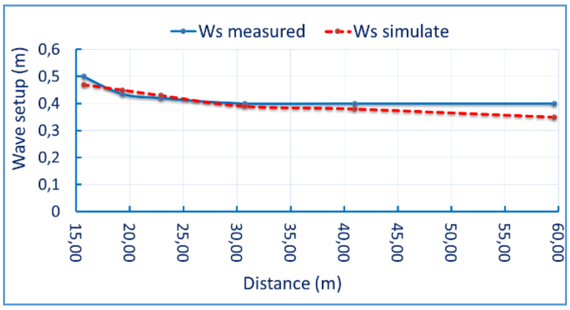


Figure 4. Comparison of computed and measured wave set-ups at Agribank profile, Hoi An

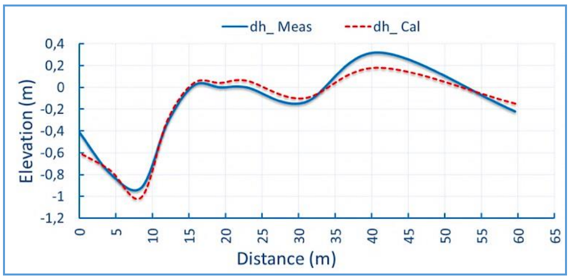


Figure 5. Comparison of calculated and measured topography at Agribank beach, Hoi An

Table 4. Results of the verification of wave height, wave-induced current and bathymetry changes in the XBEACH model

No.	Parameter	BIAS (m)	RMS (m)
1	Wave height	0,01	0,09
2	Wave-induced setup	-0,02	0,03
3	Bathymetry change	-0,014	0,09

STUDY ON THE EFFECTS OF WAVE-INDUCED SETUP ON BEACH EVOLUTION USING THE MATHEMATICAL MODEL

Simulation scenarios and location of computational cross-sections

Simulation scenarios: Four simulation scenarios have been used in this study (table 5) to clarify the mechanism of beach evolution caused by hydrodynamic factors during a storm event and provide a scientific basis for proposing solutions to cope with beach erosion caused by storm events. Location of computational cross-sections: the Cua Dai beach has a specific geographical factor, geomorphology, heterogeneous coastal morphology and is significantly driven by the Cu Lao Cham Island. Consequently, the simulation must consider the effect of the Cu Lao Cham island on wave propagation from deep water to the nearshore area. Four cross-sections have been selected to ensure the simulation results represent the distinct characteristics of each coastal section in the study area–the location of 4 cross-sections presented in figure 6.

Location of computational cross-sections

Cua Dai beach, Hoi An, has geographical factors, geomorphology, and heterogeneous coastal morphology. Offshore is covered by Cu Lao Cham island, so when calculating, not considering these issues will greatly affect the accuracy of the calculation results. Therefore, the study has selected 4 calculated cross-sectional positions (fig. 6, table 6) representing the distinct characteristics of each coastal area of the study area.

Table 5. Wave parameters in deep-water [12] corresponding to each simulation scenario

No.	Scenario	Return period (year)	Frequency (%)	Parameter	
				H_{sig} (m)	T (s)
1	TH1	10	10	11,79	13,30
2	TH2	20	5	12,39	13,60
3	TH3	50	2	13,19	14,20
4	TH4	100	1	13,79	14,60

Table 6. Location, coordinates, water depth at computational points at the boundary

No.	The point at the boundary of computation cross-section	X	Y	Water depth (m)
1	CD01	221643	1760720	-19,53
2	CD02	219986	1761870	-19,21
3	CD03	218793	1762716	-18,57
4	CD04	217128	1763875	-18,57

Fig 6. Location of computational points at the coastal area of the northern beach of Cua Dai, Hoi An

Study on the effects of wave-induced setup on the evolution of Cua Dai beach, Hoi An

Scenarios

The dissertation offers three scenarios, including Scenario 1 (KB1): beach evolution during storms during the mid-tide period considering the effects of wave-induced setups; Scenario 2 (KB2): beach volatility during storms during high-level periods taking into account the effects of wave-induced setups; and Scenario 3 (KB3): beach evolution during storms during the mid-tide period does not take into account the effects of wave-induced setups. The dissertation compared the results of the simulation of the sea cross-sectional topography of the scenarios: Scenario 1 (KB1) & Scenario 2 (KB2); Scenario 1 (KB1) & Scenario 3 (KB3) to analyze and evaluate the effects of wave-induced setup on the beach evolution in the study area.

Results of the study on the effects of wave-induced setup on beach evolution in the study area

When conducting convolutional cross-sections of the scenarios: Scenario 1 & Scenario 2; Scenario 1 & Scenario 3 under the calculated cases, we will get a picture of the beach topographic change in the study area (see the representative images in below figs. 7–14).

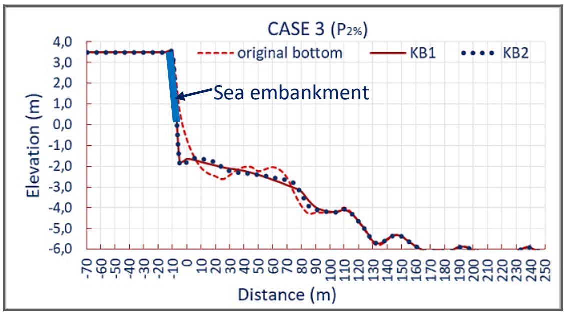


*Figure 7.*Comparison of beach evolution at the cross-section CD01 to scenarios KB1&KB2

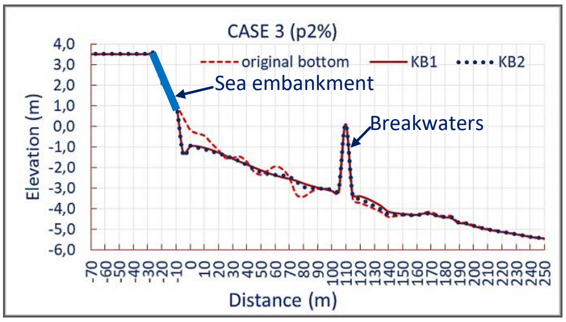


Figure 8. Comparison of beach evolution at the cross -section CD02 to scenarios KB1 & KB2

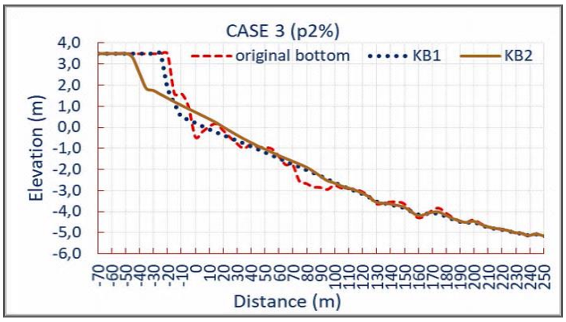


Figure 9. Comparison of beach evolution at the cross -section CD03 to scenarios KB1 & KB2

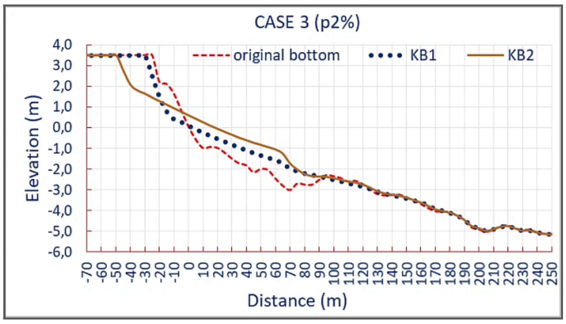


Figure 10. Comparison of beach evolution at the cross -section CD04 to scenarios KB1 & KB2

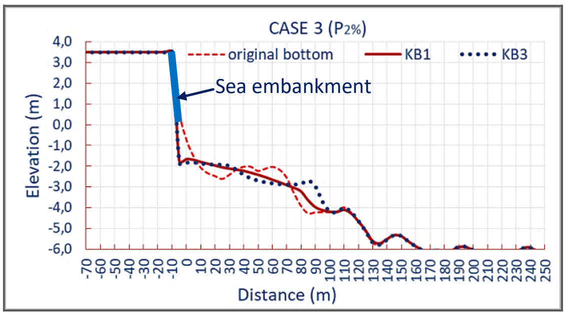


Figure 11. Comparison of beach evolution at the cross -section CD01 to scenarios KB1&KB3

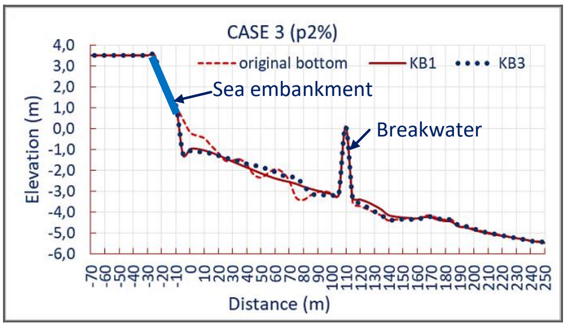


Figure 12. Comparison of beach evolution at the cross -section CD02 to scenarios KB1 & KB3

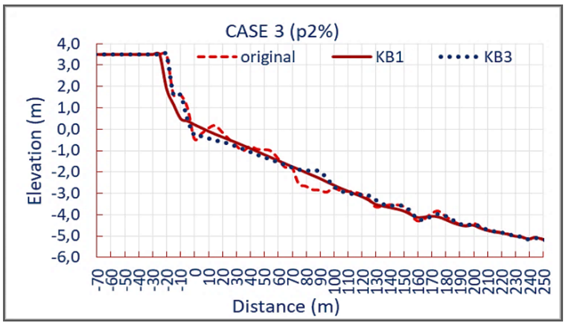


Figure 13. Comparison of beach evolution at the cross -section CD03 to scenarios KB1 & KB3

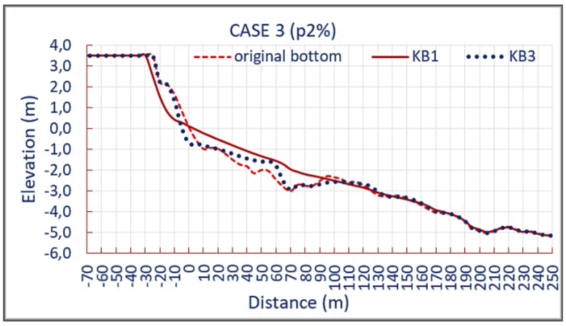


Figure 14. Comparison of beach evolution at the cross -section CD04 to scenarios KB1 & KB3

Analysis of effects of wave-induced setup on beach evolution

In analyzing the effects of wave-induced setup on beach evolution, this paper defines a general convention of representative symbols of the range and rate of topographic change across the beach profile of each selected simulation scenario (figures 15 and 16).

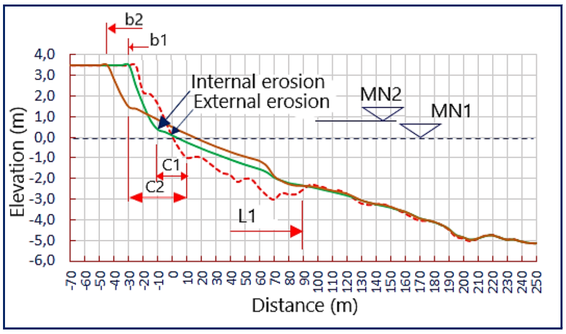


Figure 15. Designation of extent and intensity of the evolution of beach cross-section corresponding to scenarios KB1 & KB2

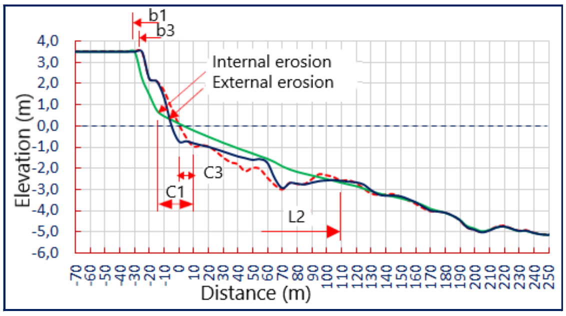


Figure 16. Designation of extent and intensity of the evolution of beach cross-section corresponding to scenarios KB1 & KB3

Explanation of the symbols in figs. 15, 16:

C1, C2 and C3 are the width of the upper beach according to scenario KB1, KB2, KB3.

b1, b2, b3 are shoreline erosion widths from the original shoreline to the shoreline according to KB1, KB2 and KB3.

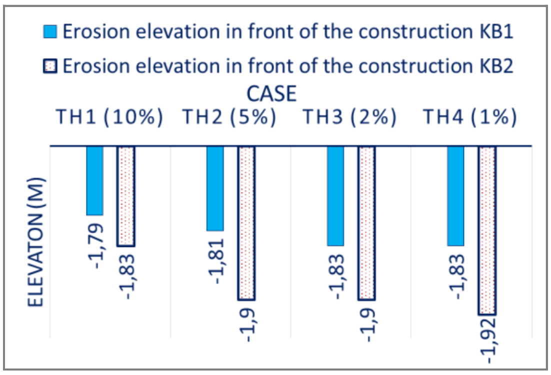
L1, L2 and L3 are the range of areas with strong evolution according to KB1 & KB2 and KB1 & KB3.

MN1 is the water level that includes medium tide level and wave-induced setup, MN2 is the water level including high tide and wave-induced setup; MN3 is the medium tide level.

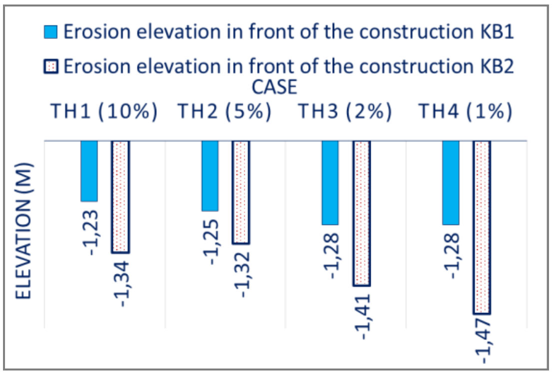
Analysis of effects of wave-induced setup on beach evolution in scenarios KB1 & KB2

From the simulating results of beach profile change corresponding to each simulation scenario, we have analyzed and evaluated the range and rate of changes in shoreline and beach profile evolution at the Cua Dai. Statistical values are presented in table 7.

The results in figs. 17, 18 and table 7 show that the evolution of shoreline and beach profiles due to the influence of wave-induced setups is significant when a storm hits land coincident with spring and medium tide periods, but the most severe beach erosion occurs when a storm event hits land coincident with high tide. During a high tide period (KB2), the beach erosion was three times larger than when a storm landed during a mid-tide period (KB1). The beach extent and rate of change vary significantly between simulation scenarios and the calculated locations along the coast. The beach area has coastal protection work (cross-section CD01, CD02). The shoreline is relatively stable, but the foreshore is severely eroded, including erosion at the toe of the revetment. The shoreline and beach are severely eroded in the natural beach area (cross-section CD03 to cross-section CD04).

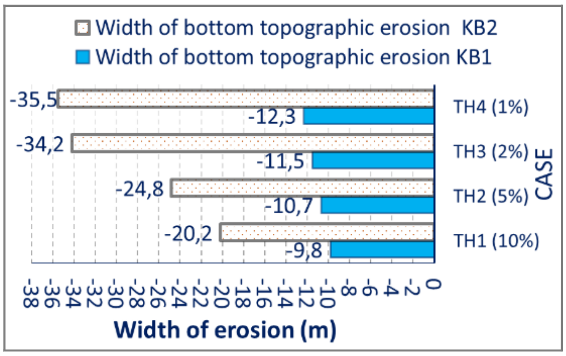


Elevation and erosion depth of KB1 & KB2 works at CD01

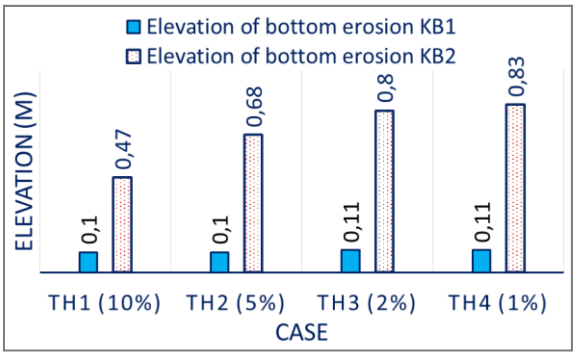


Elevation and erosion depth of KB1 & KB2 works at CD02

Figure 17. Comparison of elevation, depth of toe erosion KB1 and KB2 for calculation cases at CD01, CD02 (beach has protected works)



Evolution of beach erosion width KB1 & KB2 at CD04



Evolution of beach erosion elevations KB1 & KB2 at CD04

Figure 18. Comparison of elevation, scour width of KB1 & KB2 for calculation cases at MCCD03, MCCD04 (beach without protection works)

Table 7. Variation of elevation, dimension, and extent of beach erosion between scenarios KB1 & KB2

Cross-sections	Scenario	Elevation of the beach erosion in the outside and inside regions corresponding to various scenarios				Width of coastal erosion		Width of beach erosion		L_1 (m)
		Outside of KB1	Inside of KB1	Outside of KB2	Inside of KB2	b1 (m)	b2 (m)	C1 (m)	C2 (m)	
CD01	1	-0,70	-1,79	-0,70	-1,83	-10,5	-10,5	0	0	100
	2	-0,70	-1,81	-0,70	-1,90	-10,5	-10,5	0	0	100
	3	-0,70	-1,83	-0,70	-1,90	-10,5	-10,5	0	0	102
	4	-0,70	-1,83	-0,70	-1,92	-10,5	-10,5	0	0	102
CD02	1	-0,93	-1,23	-0,94	-1,34	-10,5	-10,5	0	0	145
	2	-0,95	-1,25	-0,97	-1,32	-10,5	-10,5	0	0	145
	3	-0,98	-1,28	-0,96	-1,41	-10,5	-10,5	0	0	145
	4	-0,98	-1,28	-0,96	-1,47	-10,5	-10,5	0	0	145
CD03	1	0,20	0,40	0,60	1,30	-6,80	-15,2	-4,8	-14,4	105
	2	0,22	0,43	0,70	1,42	-7,30	-24,2	-5,2	-19,5	105
	3	0,23	0,45	0,88	1,75	-8,10	-29,7	-6,4	-24,6	105
	4	0,23	0,45	0,92	2,05	-8,50	-34,8	-8,8	-32,7	105
CD04	1	0,10	0,40	0,47	1,34	-9,80	-20,2	-2,8	-14,7	95,0
	2	0,10	0,40	0,68	1,47	-10,7	-24,8	-4,8	-17,8	95,0
	3	0,11	0,43	0,80	1,80	-11,5	-34,2	-5,6	-23,3	95,0
	4	0,11	0,74	0,83	2,04	-12,3	-35,5	-7,2	-25,2	95,0

Analysis of effects of wave-induced setup on beach evolution in scenarios KB1&KB3

The simulation results and beach profile changes in each scenario have been analyzed and evaluated the shoreline and beach profile's range and rate of change. The statistical results are shown in table 8.

The results are presented in table 8 and figs. 19–22 show that at the beach section, which has coastal protection works such as revetment (cross-section CD01, CD02), the influence of wave-induced setups mainly causes erosion at the foreshore. Erosion occurs at the toe of the revetment at cross-section CD01 and may reach an elevation of -1.83 m and a height of -1.23 m at cross-section CD02. Coastal dunes with natural shoals (cross-sections CD03, CD04), beach profile change, is located mainly on the foreshore without considering the composition of wave-induced setup. But when considering the wave-induced structure in the simulating, the beach profile change occurs at the lower part of the beach profile, including shoals, and affects the upper beach to the foot of the coastal dune. The erosion rate, in this case, was two times larger than when not considering the wave-induced structure in the simulation scenario KB3. The range of beach evolution is about 95 m to 145 m seaward from the edge of the coastline.

Table 8. Variation of elevation, dimension and extent of beach erosion between scenarios KB1 & KB3

Cross-section	Scenario	Elevation of the beach erosion in the outside and inside regions corresponding to various scenarios				Width of coastal erosion		Width of beach erosion		L_2 (m)
		Outside of KB1	Inside of KB1	Outside of KB3	Inside of KB3	b1 (m)	b3 (m)	C1 (m)	C3 (m)	
CD01	1	-0,70	-1,79	-0,70	-1,73	-10,5	-10,5	0	0	100
	2	-0,70	-1,81	-0,70	-1,73	-10,5	-10,5	0	0	100
	3	-0,70	-1,83	-0,70	-1,75	-10,5	-10,5	0	0	105
	4	-0,70	-1,83	-0,70	-1,76	-10,5	-10,5	0	0	105
CD02	1	-0,93	-1,23	-1,03	-1,19	-10,5	-10,5	0	0	130
	2	-0,95	-1,25	-1,04	-1,20	-10,5	-10,5	0	0	130
	3	-0,98	-1,28	-1,07	-1,23	-10,5	-10,5	0	0	135
	4	-0,98	-1,28	-1,09	-1,26	-10,5	-10,5	0	0	135
CD03	1	0,20	0,40	-0,24	-0,24	6,80	0,00	4,80	0,00	100
	2	0,22	0,43	-0,30	-0,30	7,30	0,00	5,20	0,00	100
	3	0,23	0,45	-0,30	-0,30	8,10	0,00	6,40	0,00	100
	4	0,23	0,45	-0,30	-0,30	8,50	0,00	8,80	0,00	100
CD04	1	0,10	0,40	-0,75	-0,67	9,80	4,70	1,80	0,00	105
	2	0,10	0,40	-0,76	-0,70	10,70	4,90	4,80	0,00	105
	3	0,11	0,43	-0,85	-0,82	11,50	5,40	5,60	0,00	105
	4	0,11	0,74	-0,89	-0,85	12,30	5,80	7,20	0,00	105

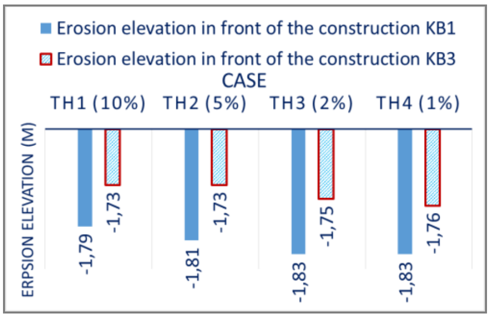


Figure 19. Evolution of elevation, depth of toe erosion KB1 & KB3 at CD01

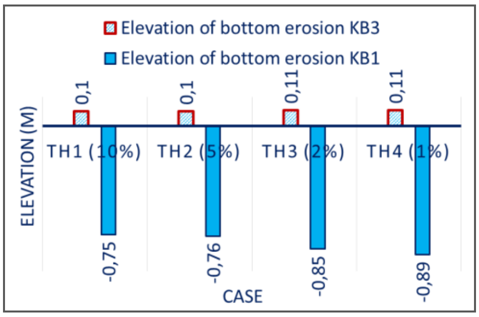


Figure 21. The evolution of the erosion elevations of KB1 & KB3 at the CD04

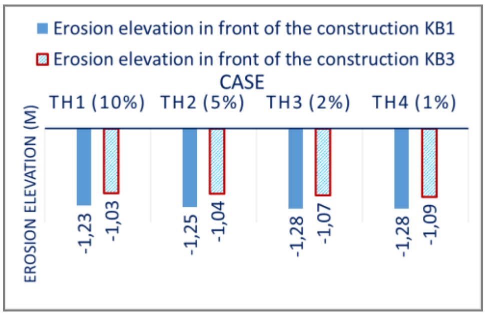


Figure 20. Evolution of elevation, depth of toe erosion KB1 & KB3 at CD02

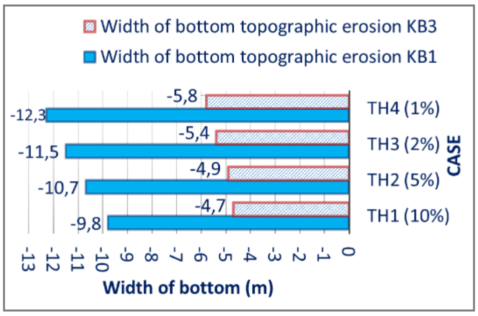


Figure 22. Evolution of erosion width of KB1 & KB3 at the CD04

CONCLUSION

This study uses two coastal hydrodynamic models to simulate wave propagation and deformation on the beach profile and compute wave-induced setup during storm events in different simulation scenarios for the Cua Dai Beach in Hoi An city. Good agreement has been achieved in calibration and verification of both mathematical models, which provide the best fit between computed and measured wave parameters, with good BIAS and RMS indices. Therefore, the XBEACH model is reliable for simulating wave-induced setup for the Cua Dai beach.

The paper also presents results from simulating the effects of wave-induced setup on beach evolution in the study area. The simulation results also clarified the extent and level of the impact of wave-induced setup on shoreline and beach erosion for a natural beach and a protected beach where coastal revetment has been built. It implies that it is necessary to have a structural solution to minimize the impact of waves-induced setup on the upper part of the beach at Cua Dai to stabilize.

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