Vietnam Journal of Marine Science and Technology; Vol. 19, No. 3; 2019: 337–347
DOI: https://doi.org/10.15625/1859-3097/19/3/14058
https://www.vjs.ac.vn/index.php/jmst

Research on wave set-up during storms along the coast of Cua Dai, Hoi An

Nguyen Ngoc The[1,*], Duong Cong Dien[2], Tran Thanh Tung[3]

[1]*Central College of Technology - Economics and Water Resources, Hanoi, Vietnam*
[2]*Institute of Mechanics, VAST, Vietnam*
[3]*Thuyloi University, Hanoi, Vietnam*
[*]E-mail: ngocthe09@gmail.com

Received: 5 May 2019; Accepted: 31 July 2019

Abstract
The central coast of Vietnam is frequently prone to storms and floods. Aside from wind damages during storms, the effect of storm surges, which includes wave set-up, on the coast and coastal infrastructures is very severe. Therefore calculation and prediction of wave set-up and storm surges are significant, both scientifically and practically, to serve as scientific bases for sustainable coastal planning, development and protection. This paper presents the study results on nearshore wave propagation and transformation, as well as the distribution of wave set-up during storms in the coastal area of Cua Dai, Hoi An, using SWAN and SWASH models. The models are thoroughly tested against wave and water level data series collected during a campaign in the project framework. The simulation results show the overall picture of the nearshore wave field and the surge height induced by waves during a storm event along Cua Dai, Hoi An coast. The research output also indicates that wave set-up contributes an important part to the extreme water level of the local nearshore area during storms.

Keywords: Storm surge, wave set-up, SWAN, SWASH, Cua Dai.

Citation: Nguyen Ngoc The, Duong Cong Dien, Tran Thanh Tung, 2019. Research on wave set-up during storms along the coast of Cua Dai, Hoi An. *Vietnam Journal of Marine Science and Technology*, *19*(3), 337–347.

INTRODUCTION

The coast of Cua Dai, Hoi An has a gradually curve shape, aligned in NW - SE direction, facing open sea. Annually, during storm season and northeastern monsoon, the entire Cua Dai coast is severely affected by waves. The local coast has high population density and many important infrastructures, residential buildings, assets, hotels and resorts of Quang Nam province and Hoi An city. Fig. 1 shows some typical damages.

To evaluate the effects of factors such as wave height and wave set-up on the beach, simulation had been performed with specialized numerical models.

a) Large waves completely destroyed coastal buildings of Fusion Alya hotel [*Photo* taken on 16 April 2016]

b) Large waves caused coastline erosion at Tan My beach [*Photo* taken on 18 October 2016]

c) Large waves destroyed the revetment at the main Cua Dai beach [*Photo* taken on 18 October 2016]

d) Large waves eroded the berm of beach in front of Agribank hotel, Cua Dai [*Photo* taken on 26 October 2017]

Fig. 1. Large waves in storms destroyed infrastructure and caused beach erosion at Cua Dai, Hoi An

The simulation results show the overall picture of the nearshore wave field and the surge height induced by waves ("wave set-up") during a storm event along Cua Dai, Hoi An. The results will serve as a scientific basis for local authority and corporations to apply suitable protection measures to stabilize the coastline and beach, as well as to mitigate damages due to storm surges.

THEORETICAL BASIS OF THE WAVE SET-UP NUMERICAL MODEL

In practice, many methods and mathematical models can be used for estimating wave set-up. However, the authors choose SWASH model, which has notable advantages in simulating complex nearshore processes - including wave breaking, non-linear wave-wave interaction, and the propagation of periodic waves, for calculating wave set-up for Cua Dai area.

The SWASH was developed (Zijlema and Stelling (2005); Zijlema et al., (2011)) and completed in 2011 at Delft University of Technology, the Netherlands. The basic equations of SWASH include non-linear shallow water equations involving non-hydrostatic pressure and transport equations. Non-hydrostatic free surface flows are described with non-hydrostatic shallow water equations (which originate from Navier - Stokes equations for incompressible fluids), including mass- and momentum-conservation equations:

$$\frac{\partial \zeta}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial hv}{\partial y}=0 \quad (1)$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial \zeta}{\partial x}+\frac{1}{h}\int_{-d}^{\zeta}\frac{\partial q}{\partial x}dz+cf\frac{u\sqrt{u^2+v^2}}{h}=\frac{1}{h}\left(\frac{\partial h\tau_{xx}}{\partial x}+\frac{\partial h\tau_{xy}}{\partial y}\right) \quad (2)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+g\frac{\partial \zeta}{\partial y}+\frac{1}{h}\int_{-d}^{\zeta}\frac{\partial q}{\partial y}dz+cf\frac{v\sqrt{u^2+v^2}}{h}=\frac{1}{h}\left(\frac{\partial h\tau_{yx}}{\partial x}+\frac{\partial h\tau_{yy}}{\partial y}\right) \quad (3)$$

In which: t is time (sec), $d(x, y)$ is the still water depth (m); g is the gravitational acceleration, c_f is the bottom friction coefficient (non-dimensional); τ_{xx}, τ_{xy}, τ_{yx} and τ_{yy} are horizontal turbulent stress terms; $q(x, y, z, t)$ is the non-hydrostatic pressure (normalized by the density); x, y, z are spatial coordinates: x, y are located at the still water level and the z-axis points upwards (m); $\zeta(x, y, t)$ is the water level (or wave set-up); $h = \zeta + d$ is the (total) water depth including the wave set-up; $u(x, y, t)$ and $v(x, y, t)$ are depth-averaged flow velocities corresponding to x and y directions (m/s).

The equations (1), (2) and (3) are solved using FVM (the Finite Volume Method).

SETTING UP MATHEMATICAL MODELS

Data used

Bathymetry data

The bathymetry data of the deep water area is extracted from the nautical map measured by Vietnamese Navy with a scale of 1/100,000.

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 topography data nearshore is extracted from the database of topographic survey in the framework of research project by the Central College of Technology - Economics and Water Resources.

The coastline position, which is digitized from Landsat 8 images 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 from wind by NCEP with the SWAN model [1]. The location to extract wave data is in the deep water area (depth of 60 m), offshore Cu Lao Cham island.

Nearshore wave data for model calibration and verification is taken from measured data in the framework of the project.

Establishing computational domain and grid

Based on bathymetric feature and wave pattern, the authors set up the model domain and grid which are suitable for the wave propagation process from offshore to nearshore, and the wave deformation (including wave breaking and run-up).

The computational domain is divided into two areas:

Area 1: For computing wave propagation from deep water to nearshore Cua Dai, Hoi An with a wave propagation model (SWAN) [2].

Area 2: For computing wave deformation at Cua Dai beach, Hoi An with the wave model SWASH [3].

The computational grid for area 1 is established, containing 421 cells alongshore and 170 cells cross-shore; the smallest grid spacing nearshore is 30 m and the largest one in deep water area (with a maximum depth of 70 m) is 400 m.

The grid in area 2 is rectangular with a cross-shore grid spacing of 5 m and alongshore -25 m, corresponding to 680 grid cells in cross-shore direction (the average depth at the offshore boundary is 18 m) and 400 grid cells alongshore. To compute in detail for each cross-section, 1D grids are also used with grid spacing of 1 m, extending from the shore to locations with a depth of 10 m.

Boundary condition and initial condition

The boundary condition for wave propagation model (zone 1, with coarse grid) is taken from reanalysis wave properties by NCEP wind data. The SWAN model is calibrated and verified against measured data in Oct 2016.

The boundary condition of the detailed wave deformation model (area 2) is extracted from the wave propagation model in area 1.

Fig. 2. Model area 1 and area 2

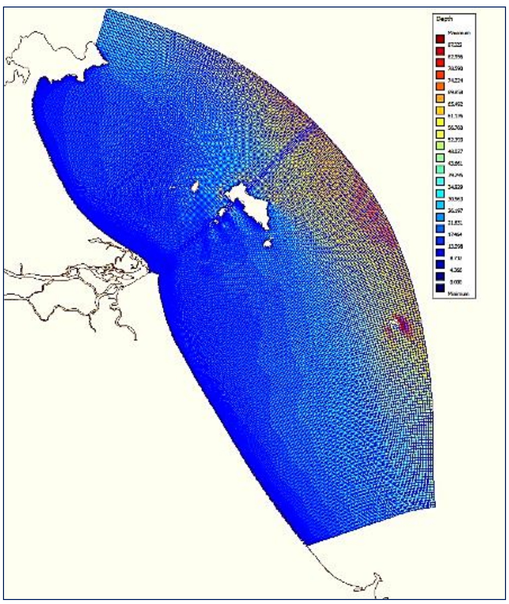


Fig. 3. The computational grid and bathymetry

Model calibration and verification

Result of calibration and verification of the wave propagation model SWAN

The SWAN is used to compute the propagation of wave properties from deep water to shallow water nearshore Cua Dai and produce simulation output, in which spectral wave properties are extracted to be used as boundary condition for the detailed wave deformation model in the surf zone.

To calibrate the SWAN model, the authors use measured wave properties from 11 Oct to 26 Oct 2016 at CD02, CD04 and CD05 gauges, which are located at the nearshore zone of Cua Dai, Hoi An (refer to fig. 4). The results of model calibration are presented in table 1 and fig. 5. It can be seen that the average wave height during simulation period is around 1.5 m, the mean error is 10.6%, which is in the allowable range.

Fig. 4. The location of the wave measurement stations

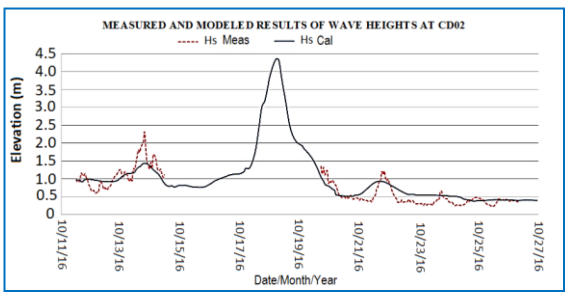


Fig. 5. Comparison of computed and measured wave heights at CD02 (The period from 14 to 19/10 must stop measuring due to very high waves)

Table 1. Errors between calculated and measured wave heights at stations

No.	Gauge	BIAS	RMS
1	CD02	0.04	0.21
2	CD04	0.24	0.37
3	CD05	0.22	0.32
Average		0.16	0.30

Calculation and verification results for the SWASH model

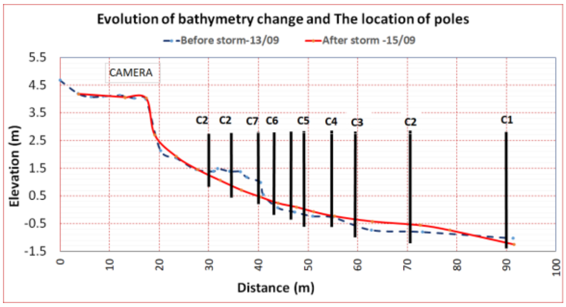


Fig. 6. The bathymetry profile - The location of pole system at Agribank hotel beach from 12th to 15th Sep 2017

Fig. 7. The location of camera

To calibrate the SWASH model, the authors use wave data measured on 14 Sep 2017 for the cross-section at Agribank hotel on the northern coast of Cua Dai (figs. 6–7). The results of SWASH model calibration are presented in table 2.

The comparisons between the computed and measured wave heights, between the computed and measured wave set-ups at this ‘Agribank’ cross-section, 16:00 on 14 Sep 2017 are presented in figs. 8–9.

Table 2. Parameters for model calibration

No.	Parameter	Minimum value	Maximum value	Selected value
1	Manning roughness coeff.	0		0.02
2	Breaking parameter alpha	0	1	0.6
3	Breaking parameter alpha	0	1	0.3

To evaluate the errors in simulating wave height (Hs) and wave set-up (ζ) with SWASH model, the authors use two criteria, BIAS and RMS.

For wave height, BIAS= 0.05, RMS=0.12;
For wave set-up, BIAS= -0.01, RMS= 0.02.

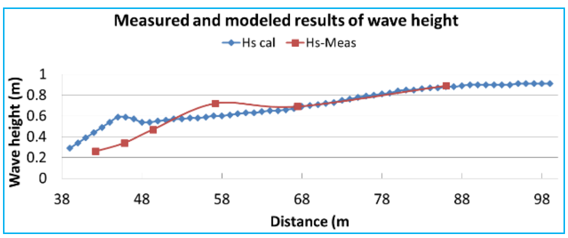


Fig. 8. Comparison of computed and measured wave heights at Agribank profile, Hoi An

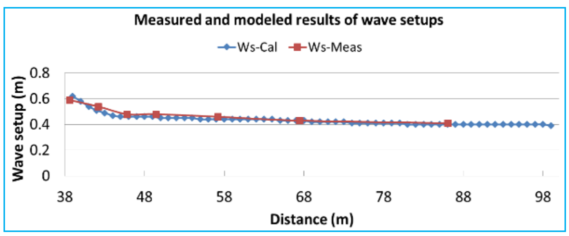


Fig. 9. Comparison of computed and measured wave set-ups at Agribank profile, Hoi An

Simulation errors in both BIAS and RMS are in the allowable range; therefore the SWASH model can be used to calculate for selected typical typhoons affecting the Cua Dai beach, as well as for hypothetical scenarios.

COMPUTING WAVE SET-UP FOR CUA DAI BEACH

Simulation scenarios

Scenarios

In recent years, extreme weather events are more evident and tend to increase in both frequency and intensity. Additionally, erosion and accretion in many coastal zones along the Central provinces are increasing at an alarming rate. To establish simulation scenarios for predicting the variation of wave set-up during storms at Cua Dai in future, with NE incoming waves, the authors base on simulations with deep water wave properties corresponding to various return periods [4]. The wave heights (Hsig) and wave periods (T) are listed in table 3.

Table 3. Wave parameters and scenarios

No.	Scenario	Returning period (years)	Parameter	
			Hsig (m)	T (s)
1	KB 1	10	11.79	13.3
2	KB 2	50	13.19	14.2
3	KB 3	100	13.79	14.6
4	KB 4	200	14.39	14.9

Locations along Cua Dai beach where wave simulation is carried out

The Cua Dai beach is located on the northern side of the Dai river mouth, where the Vu Gia - Thu Bon river system discharges into the sea. The presence of Cu Lao Cham island adds complexity to wave propagation and deformation processes. Thus, to obtain accurate results in calculating wave propagation, the authors choose six representative locations along the Cua Dai beach (fig. 10). These locations experience severe coastal erosion recently.

Fig. 10. The location of wave properties extracted at Cua Dai beach, Hoi An

Results in wave set-up simulation along Cua Dai during storms

Results in wave propagation computing for scenarios

Based on the results in wave field at the local nearshore zone, the authors extracted the wave parameters at the six chosen locations along the coastline. These wave parameters are listed in table 4 for every scenario.

The wave properties in table 4 show that:

For each location, the wave heights calculated in various scenarios do not differ much.

Regarding the distribution of wave height alongshore, it can be seen that the wave height at An Bang beach is largest, and wave heights tend to decrease southward (the Cua Dai area). Due to the influence of Cu Lao Cham island, the wave height at Vinpearl hotel beach is smallest.

Scenario 4, corresponding to a 0.5% exceedance frequency of deep water wave, shows highest waves with longest period. However, the difference between wave height and period among the scenarios is not remarkable.

Table 4. Wave parameters at the model boundary in various scenarios

Beach location	Parameter	Scenario			
		KB1	KB2	KB3	KB4
An Bang	Hsig (m)	6.71	6.75	6.78	6.83
	T (s)	13.41	14.62	14.62	14.62
Agribank hotel	Hsig (m)	6.09	6.16	6.21	6.27
	T (s)	13.41	14.62	14.62	14.62
Tan My beach	Hsig (m)	5.98	6.02	6.05	6.11
	T (s)	13.41	14.62	14.62	14.62
Cua Dai beach	Hsig (m)	5.94	5.90	5.89	5.90
	T (s)	13.41	14.62	14.62	14.62
Revetment	Hsig (m)	5.37	5.33	5.30	5.29
	T (s)	13.41	13.41	14.62	14.62
Vinpearl hotel	Hsig (m)	5.13	5.20	5.25	5.28
	T (s)	13.41	14.62	14.62	14.62

Results in wave set-up simulation in the scenarios

Estimating the wave height at chosen locations for the scenarios

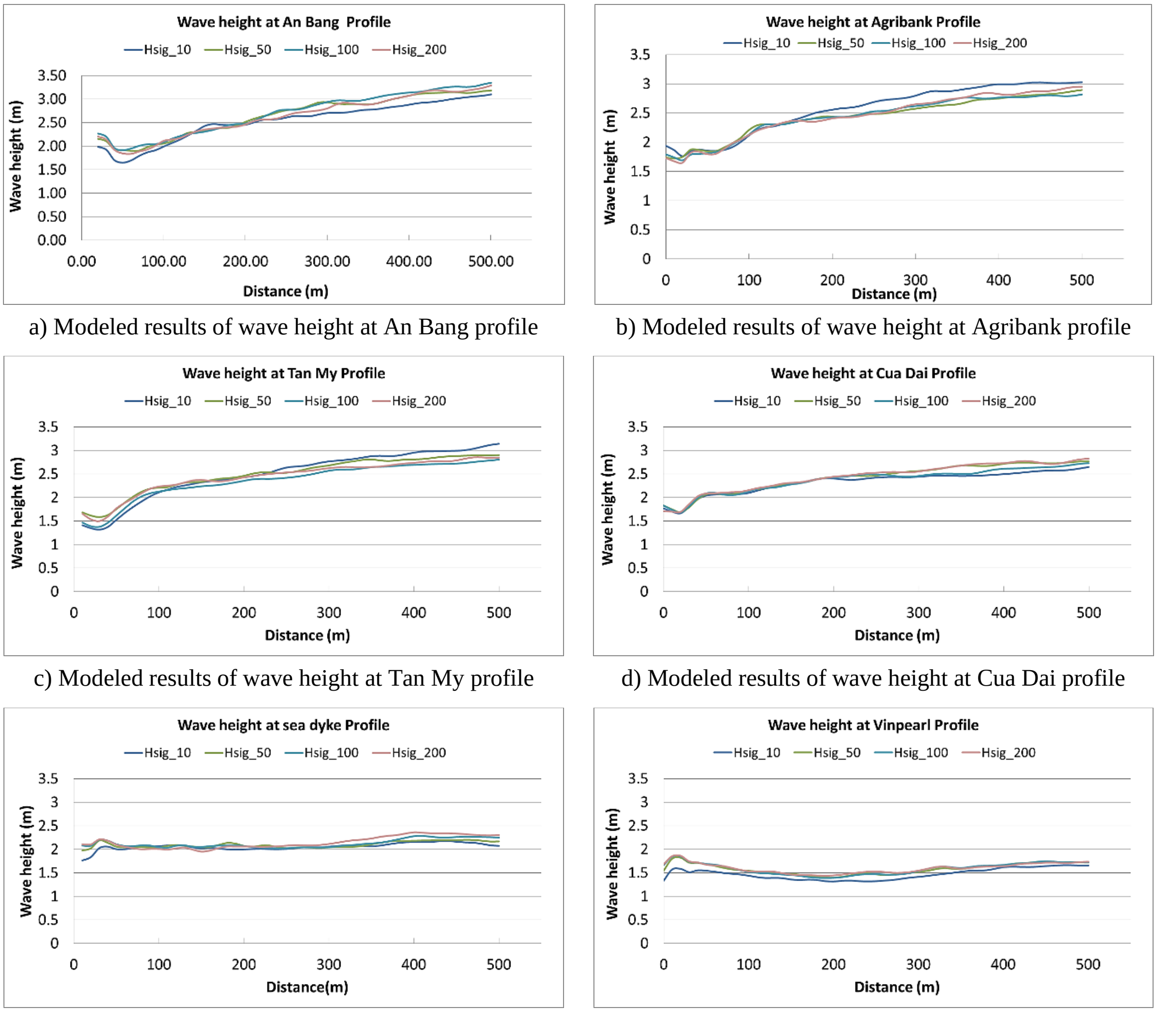
Using the calibrated parameters for the SWASH nearshore wave model mentioned in Section 3, the authors simulate wave height for the entire northern nearshore zone of Cua Dai.

Based on the simulation result of wave heights for different scenarios, the authors extract wave height distribution along six chosen cross-sections of Cua Dai beach. The output is represented in fig. 11.

The simulation results show that the wave height distribution at Cua Dai beach has two distinctive features:

In the offshore zone, the wave height decreases from the North to the South of Cua Dai, conforming to the distribution of wave height along the offshore boundary for modelling.

In the nearshore zone, the wave height no longer conforms to the distribution of wave height along the offshore boundary; but is largely influenced by the local bathymetry and some sheltering effect by Cu Lao Cham island.



a) Modeled results of wave height at An Bang profile
b) Modeled results of wave height at Agribank profile
c) Modeled results of wave height at Tan My profile
d) Modeled results of wave height at Cua Dai profile
e) Modeled results of wave height at the ‘revetment’ profile
g) Modeled results of wave height at Vinpearl profile

Fig. 11. Modeled results of wave height at Cua Dai beach

Simulation of wave set-up for various scenarios

The results of simulation, showing distribution of wave set-up for the chosen scenarios, are presented in fig. 12.

Based on the simulation results (fig. 12), the authors extract wave set-ups on six selected cross-sections on Cua Dai beach. The output is shown in fig. 13.

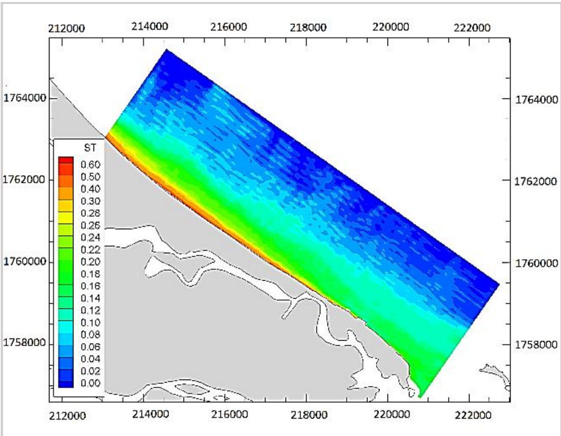
From this result, it is possible to find the largest set-up, close to shoreline, according to four scenarios; these are presented in table 5.

The above results show that:

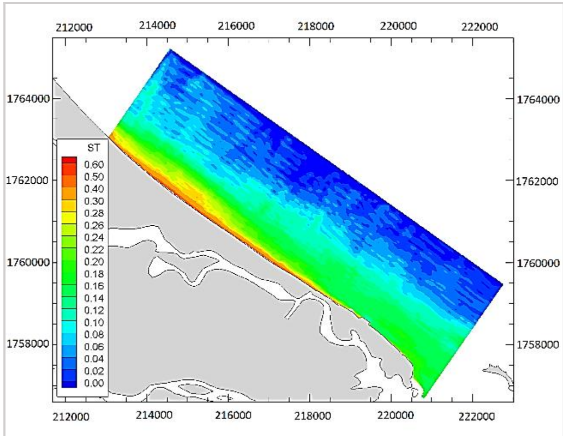
At the same location, the wave set-up values calculated for various scenarios do not differ much; possibly because Cu Lao Cham may act as a barrier to reduce high waves. The effect of this island is to make the wave fields nearshore almost similar among the scenarios. However, in case of a larger return period, the nearshore band experiencing wave set-up would be wider.

The wave set-up along Cua Dai, Hoi An varies remarkably among the selected locations alongshore. The location with largest wave set-up is An Bang beach (north of Cua Dai river mouth); smallest wave set-up occurs at Vinpearl hotel beach adjacent to the river mouth.

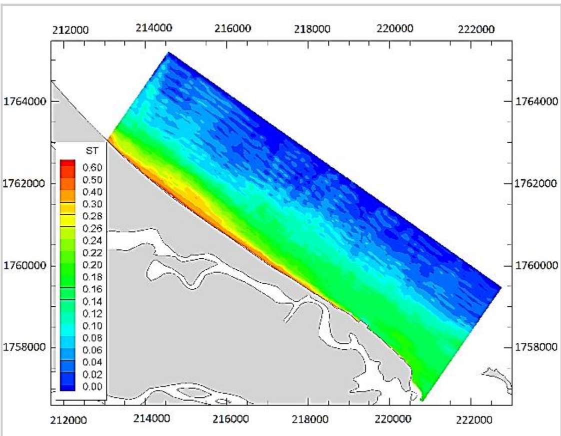
The computed wave set-ups for various scenarios range from 24 cm to 60 cm, whereas the spring tidal range is 110 cm and storm surge is 188 cm (corresponding to a 200 year return period) [5]. The wave set-up contributes about 20% of the tide and storm surge. Therefore the role of wave set-up in storms is important in the extreme water level of the study area.



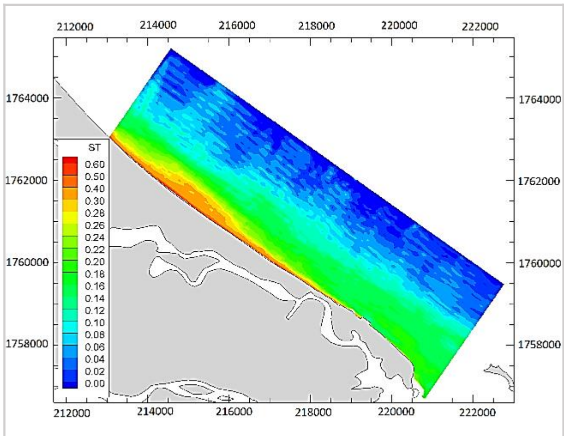
a) Scenario 1 (10 year return period)



b) Scenario 2 (50 year return period)



c) Scenario 3 (100 year return period)

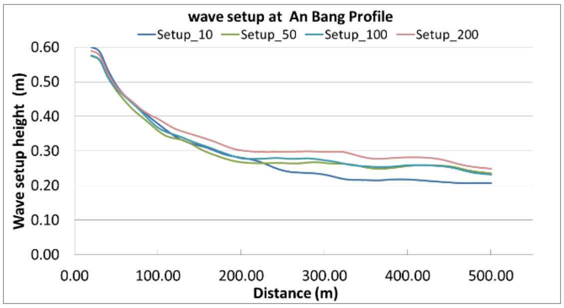


d) Scenario 4 (200 year return period)

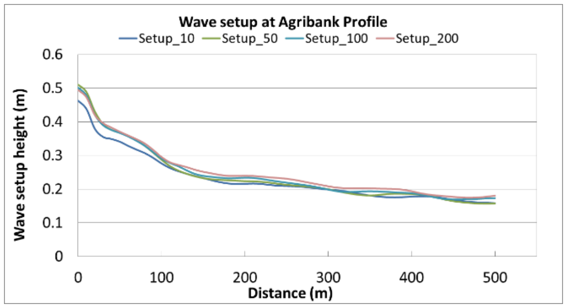
Fig. 12. The results of wave set-ups for scenarios

Table 5. Wave induced set-ups in various scenarios

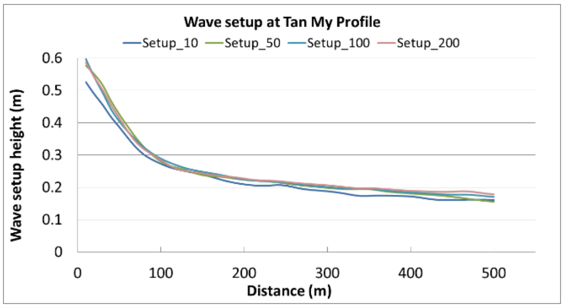
No.	Location	Scenario			
		1	2	3	4
1	An Bang beach	0.59	0.60	0.60	0.60
2	Agribank hotel beach	0.46	0.50	0.50	0.50
3	Tan My beach	0.53	0.58	0.58	0.58
4	Cua Dai beach	0.55	0.57	0.58	0.58
5	Beach with revetment	0.36	0.36	0.36	0.36
6	Vinpearl hotel beach	0.24	0.30	0.30	0.32



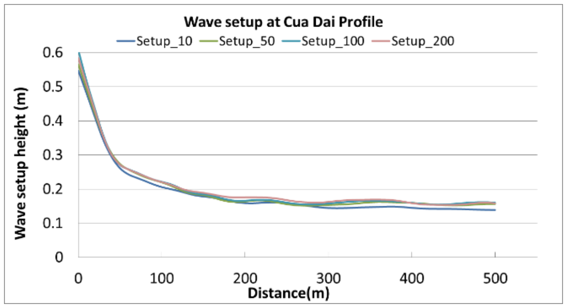
a) The result of wave set-ups at An Bang profile



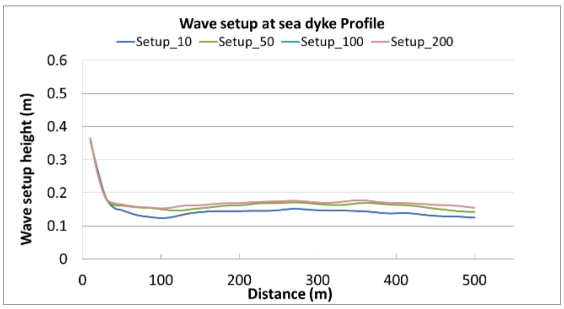
b) The result of wave set-ups at Agribank profile



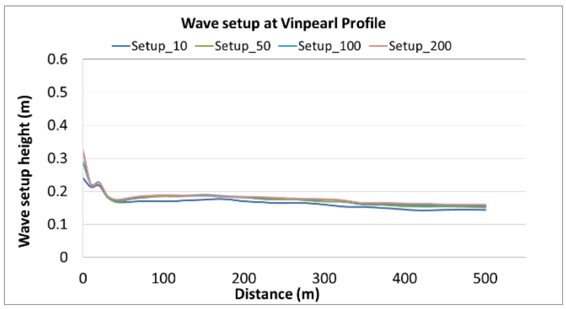
c) The result of wave set-ups at Tan My profile



d) The result of wave set-ups at Cua Dai profile



e) The result of wave set-ups at the ‘revetment’ profile



g) The result of wave set-ups at Vinpearl profile

Fig. 13. The result of wave set-ups for scenarios at several profiles along Cua Dai Beach, Hoi An

CONCLUSION

In this study, two specialized models are combined for simulating wave propagation and deformation toward the shore, and computing wave set-up during storms in different scenarios for the Cua Dai, Hoi An beach. Good performance had been achieved in calibration and verification, which is demonstrated through the fit between computed and measured wave heights, with good BIAS and RMS indices. Therefore the wave set-up model (SWASH) is reliable for simulating wave set-up in the surf zone.

The simulation output of storm wave set-up for selected scenarios provides an overall picture about the distribution of wave set-up with remarkable difference along the coast of Cua Dai. On the other hand, the simulation results also show that the storm wave set-up contributes an important part in the extreme water level of the study area.

It is recommended, when designing coastal protection structures, to consider adding the wave set-up so that the construction can perform more effectively against coastal disaster, for the safety of inland assets.

REFERENCES

[1] Duong Cong Dien et al., 2016. Simulation wind wave characteristics in East Sea base

on SWAN wave model forced with NCEP wind. *Proceedings of the 19th Fluid Mechanics Conference, Hanoi University of Science and Technology*.

[2] SWAN manual 41.01, 2014. TU DELFT.

[3] The SWASH team, 2014. SWASH user manual, Delft University of Technology.

[4] Ministry of Agriculture and Rural Development, 2012. Technical standards apply to the program of strengthening, protecting and upgrading sea dykes. *Hanoi*.

[5] Dinh Van Manh, 2014. Calculation of sea level elevation for designing coastal projects in Vietnam. *Publishing House for Science and Technology*.