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Article

The Validation of XBeach model in Laboratory Experiments: A Study on Hydrodynamics and Morphodynamics in Coastal Zone to Predict the Coastal Erosion

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Abstract: While the XBeach model has been validated for complex coastal processes under storm conditions, its performance in predicting hydrodynamics and morphodynamic changes under controlled, small-scale regular wave scenarios—a critical gap for foundational calibration and understanding—remains less documented. This study addresses this gap by rigorously validating XBeach's capability to simulate regular wave propagation and the consequent coastal erosion in a controlled laboratory environment. The experiment was conducted in a 30 m flume at Kyoto University's UJIGAWA laboratory, using a piston-type wavemaker to generate nine regular wave cases (wave heights: 1.68–3.3 cm; periods: 0.83 s and 1.205 s). Model accuracy was quantitatively assessed using the Mean Absolute Error (MAE). The results demonstrate that XBeach proficiently simulates both hydrodynamic and morphodynamic processes. The validation for significant wave height yielded an MAE of 0.07, while the validation for the eroded area yielded an MAE of 0.05 (5%). Both MAE values are below the 10% sufficiency threshold, confirming the model's reliability in predicting wave transformation and erosion magnitude under regular wave forcing. This study provides a foundational validation benchmark, enhancing confidence in applying XBeach for coastal erosion prediction in scenarios dominated by monochromatic wave conditions.

Keywords: numerical model; Xbeach; coastal erosion; hydrodynamic; morphodynamic

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1. Introduction

The validation of the XBeach model in laboratory experiments has been extensively studied in recent years, with a focus on hydrodynamics, morphodynamics, and coastal erosion prediction. Van Rooijen *et al*. (2022) demonstrated the model's accuracy in simulating wave overtopping and dune erosion under storm conditions using large-scale laboratory data, while Lashley *et al*. (2021) highlighted its capability to model infra-gravity waves and their role in swash zone morphodynamics. De Vet *et al*. (2020) further validated XBeach for wave transformation and run-up on fringing reefs, emphasizing its applicability to complex coastal environments. Splinter *et al*. (2019) and McCall *et al*. (2019) explored the model's effectiveness in remote sensing and hurricane overwash scenarios, respectively, showcasing its versatility in both laboratory and field settings. These studies collectively underscore XBeach's robustness in simulating coastal processes, though they also note challenges such as computational demands and the need for high-resolution input data. Coastal zones globally are facing increasing threats from environmental changes as noted by Kusumadewi (2025). In addition to journal articles, conference papers and reports have contributed valuable insights into XBeach's validation. Roelvink *et al.* (2021) and Williams *et al.* (2020) presented advancements in model validation at international conferences, focusing on barrier island responses and large-scale laboratory experiments. Theses like Van der Lugt (2022) and technical reports such as Gomes da Silva *et al*. (2021) provided detailed analyses of sediment transport and beach profile evolution, further corroborating the model's reliability. Finally, Van Dongeren *et al*. (2023) synthesized these findings in a comprehensive book chapter, offering a holistic view of XBeach's capabilities and limitations. Together, these references highlight the model's growing role in coastal engineering, while also pointing to areas for future refinement, such as improving sediment transport algorithms and expanding validation under diverse hydrodynamic conditions.

The model incorporates various hydrodynamic processes, including shortwave transformation (refraction, shoaling, and breaking), longwave transformation (infragravity waves) (generation, propagation, and dissipation), wave-induced currents, and processes such as wave run-up and overwash inundation. Using a numerical approach based on the Nonlinear Shallow Water Equations (NLSWE) and the wave energy balance model, XBeach can also predict the effects of breakwater construction and the attenuation of wave energy due to mangroves (Merijn Janssen, 2016). Morphodynamic processes modeled include bedload and suspended sediment transport, dune face avalanching, bed evolution, and breaching. The effects of vegetation and hard structures are also accounted for. The model has been validated through a series of analytical, laboratory, and field test cases using standard parameter settings (Bradley, 2023; McCall *et al*., 2023), including for specific environments like mixed-sediment beaches (Martins *et al*., 2022), pebble beaches (Poate *et al*., 2020), and gravel barriers (Xiao *et al*., 2023).

A subsequent laboratory experiment was carried out under the project "Benchmark Test for Harbour Models" at Deltares, as documented in the report by Van der Ven (2016). The first case involved a rectangular basin with only vertical walls and very oblique incident waves, while the second case included a rectangular main basin with an attached side basin and normally incident waves to the main basin. For both cases, the spectral wave heights for shortwaves ($f > 0.04$ Hz) were generally well-predicted by the model. In this study, an experiment will be conducted to validate the XBeach model by calculating wave heights and eroded areas using Mean Absolute Error (MAE) values.

1.1. Hydrodynamics

The short-wave motion is solved using the wave action equation which is a time-dependent forcing of the HISWA. This equation solves the variation of short-waves envelope (wave height) on the scale of wave groups. For the Shortwave action balance, the wave forcing in the shallow water momentum equation is obtained from a time dependent version of the wave action balance equation. Similar to Delft University's (stationary) HISWA model, the directional distribution of the action density is taken into account, whereas the frequency spectrum is represented by a frequency, best represented by the spectral parameter ƒm-1,0. The wave action balance (keyword: swave) is then given by

$$\frac{\partial A}{\partial t}+\frac{\partial c_x A}{\partial x}+\frac{\partial c_y A}{\partial y}+\frac{\partial c_\theta A}{\partial_\theta}=-\frac{D_w+D_f+D_v}{\sigma}$$

In which the wave action A is calculated as

$$A(x,y,t,\theta)=\frac{S_w(x,y,t,\theta)}{\sigma(x,y,t)}$$

where θ represents the angle of incidence with respect to the x-axis, S_w represents the wave energy density in each directional and σ the intrinsic wave frequency. The intrinsic frequency σ and group velocity C_g is obtained from the linear dispersion relation. D_w, D_f and D_v are dissipation terms for respectively waves, bottom friction and vegetation.

1.2. Morphodynamics

In tidal environments, surface erosion strongly depends on the interaction between sand and mud. Sand-mud mixtures are generally characterized by fine sediment fractions and are modelled by the coupling of erosion and deposition formulations, the advection-diffusion equation. Sediment concentrations in the water column are modeled using a depth-averaged advection-diffusion scheme with a source-sink term based on equilibrium sediment concentrations

$$\frac{\partial hC}{\partial t}+\frac{\partial hCu^E}{\partial x}+\frac{\partial hCv^E}{\partial y}+\frac{\partial}{\partial x}\left[D_h h\,\frac{\partial C}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_h h\,\frac{\partial C}{\partial y}\right]=\frac{hC_{eq}-hC}{T_s}$$

In C represents the depth-averaged sediment concentration which varies on the wave-group time scale and D_h is the sediment diffusion coefficient. The entrainment of the sediment is represented by an adaptation time T_s, given by a simple approximation based on the local water depth h and sediment fall velocity W_s. A small value of T_s corresponds to nearly instantaneous sediment response. The equilibrium concentrations of the bed load and suspended load determined separately. There are two transport formulation available for the equilibrium concentration in XBeach. This research will use Formulation of Van Thiel-Van Rijn (XBeach team, 2017).

2. Materials and Methods

This study employed an integrated experimental-numerical approach, where laboratory measurements in a wave flume served as the benchmark for validating the XBeach numerical model. A detailed plan view of the physical model is given in Figure 1. The flume tunnel with a water depth 35 cm – 45 cm has dimensions of 30 m x 0.5 m and high 1.2 m. The wave-maker is of the piston type with plane paddle. The paddle is hydraulically driven and can generate both regular and irregular wave, it can only generate the wave in one direction. A number of measurements carried out prior to the actual test confirmed the high repeatability of generated wave motion to simulate a sandy beach. Sand with grain size diameter 0.2 mm was put on top of Armor broke with a slope of gradient 1:2 is constructed in the tunnel facing the wave maker in order to simulation the erosion rate. However, no significant overtopping of the model was observed under the wave conditions generated during the experiment.

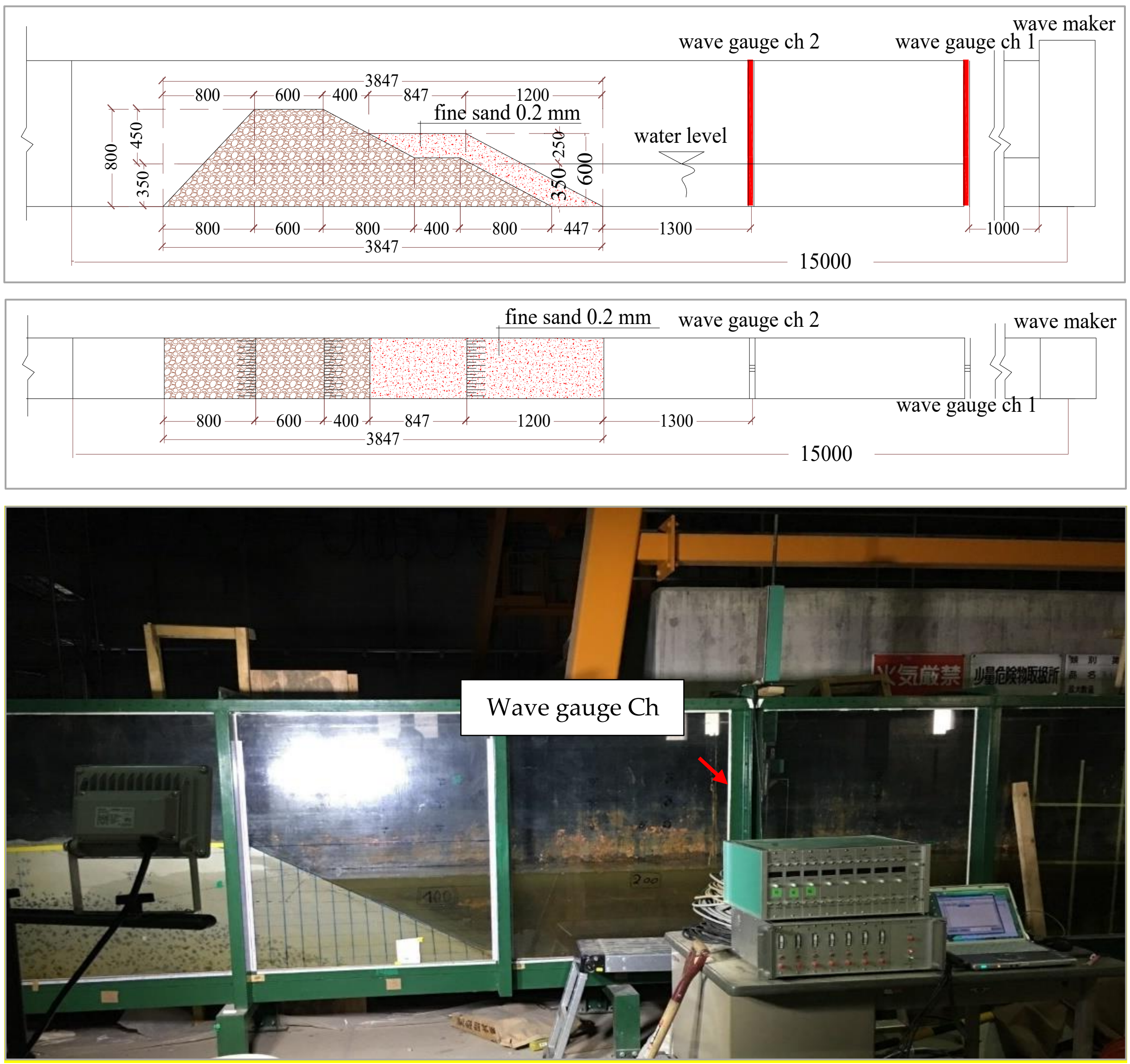


Figure 1. Wave flume tunnel used in the laboratory experiment, showing the side view (top), plan view (middle), and photographic view (bottom)

Two wave gauges are installed on the flume, wave gauge 1 is at a distance of 1 m from the position of the wave maker, while the wave gauge 2 is at a distance of 10 m. data recorded by wave gauge 1 will be used as data for validation of the XBeach model. The recording camera is placed in the side position of the flume, the data obtained from this camera will be used to carry out the digitization process to measure the erosion area during this activity.

2.1. Description of the Hydrodynamic Data

The experimental setup utilized two wave gauges and a velocity-meter to capture 14-minute time series at 0.2-second intervals for nine cases of regular waves. As summarized in Table 1, the cases are grouped by wave period (0.83 s and 1.21 s), with measured wave heights ranging from 1.7 cm to 3.3 cm, and the target wave height for each case was achieved by controlling the wave maker's amplitude.

Table 1. Measured significant wave heights (cm) and corresponding wave periods (s) for all regular wave cases generated in the laboratory flume experiment

Case Id	Hrm (ch 1) (cm)	T 1/3 (sec)	A	WL (cm)
CASE 1	3.3	0.83	3	45
CASE 2	2.6	0.83	2.5	45
CASE 3	2.6	0.83	2.5	35
CASE 4	2.3	0.83	3	35
CASE 5	2.5	0.83	3.3	35
CASE 6	1.7	1.21	2.5	35
CASE 7	2.5	1.21	3	35
CASE 8	2.9	1.21	3.3	35
CASE 9	2.1	1.21	2	35

Wave height data in column 2 is data obtained from experimental results, this wave data is a regular wave generated from a wave maker, to get the wave height as planned by adjusting the amplitude.

2.2. Assumption for Numerical Modelling with XBeach

Assumptions are made to the measurement in order to set-up the XBeach model, XBeach is a numerical model that has limitations, this assumption is made so that the numerical model that is made has a small bias and close to the conditions when physical testing is carried out. When analyzing the model result and measurement, there are number thing to consider the following:

1. The long waves are assumed to be long enough such that it fully reflects off structures. This assumption because in XBeach long waves are also fully reflective. Shortwave energies are assumed to be absorbed or nearly dissipated when they approach the sloping structure.
2. The measured time series of the surface elevation is considered to be correct, although it could be contaminated with re-reflected waves from the wave-maker. The XBeach model show limitations regarding the energy absorption at the offshore boundary.
3. At first, bottom friction of the shortwaves is assumed to be of minor importance because of the smooth flat bed in tunnel. Additionally, the laboratory experiments were carried out in intermediate water depth where friction is less pronounced
4. Wave breaking is not significant, because the characteristic wave height over wavelength is below the steepness-induced breaking

5. Porous structures such as breakwaters are an integrated part of the bathymetry XBeach allows the user to specify non-erodible structures in the model. This option is used to define the breakwater. The location of non-erodible objects was specified as zero.
6. XBeach has limitation in order to assign a porosity or reflection coefficients to the structure which means that everything is impermeable.

2.3. Methodology

A common method is introduced to assess the model accuracy in a more objective way: the error and the Mean Average Error index (MAE). The error of an individual wave gauge is calculated as:

$$error = \frac{(X_{xb}^{1} - X_{lab}^{1})}{X_{lab}^{1}}$$

and the MAE index is computed with

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{(X_{xb}^{1} - X_{lab}^{1})}{X_{lab}^{1}}\right|$$

where N is the number of data points, X_{xb}^{1} and X_{lab}^{1} are the calculated and measured variable, respectively. The error in Equation is the different between the model parameter and measured parameter, normalized with the measured parameter. The *MAE* is the average of error and an index of the model skill. The assessment of the measurement-model and model agreement is as follow:

1. *MAE* index < 0.02 is regarded as good
2. 0.020 $\leq MAE \leq$ .35 is regarded sufficient
3. *MAE* > 0.35 is considered poor

The same holds for the bias of individual wave gauges. The range is based on the uncertainties in the calculation model, absence of various processes and measurement errors.

2.4. XBeach Model Setup

The calculation model uses the default settings if the hydraulic/model parameters are unknown. The model setting in a nutshell are as follow:

1. The grid applied is a staggered grid, where the bed levels, water levels, water depths and concentrations are defined in cell centers, and velocities and sediment transports are defined in *u*- and *v*-points. In this case the longshore gradients are ignored and the domain reduces a single gridline with grid number on X = 260 and Y=0, a grid uniform with grid resolution of 0.05 m. A single directional bin will be use, this leads to perpendicular waves always and ignores refraction.
2. The fraction breaking waves Q_b and breaking wave height H_b are calculated differently compared to the breaking formulations used for the non-stationary situation. In α is applied as wave dissipation coefficient, F_{ref} represents a representative intrinsic frequency and y is a calibration factor

$$D_w = \frac{3\sqrt{\pi}\alpha\, f_{rep}\, \rho g\, H_{rms}^{3}}{16h}\, Q_b$$

$$Q_b = 1 + \frac{4}{3\sqrt{\pi}}\left(R^3 + \frac{3}{2}\,R\right)\exp(-\,R^2) - \mathrm{erf}(R)$$

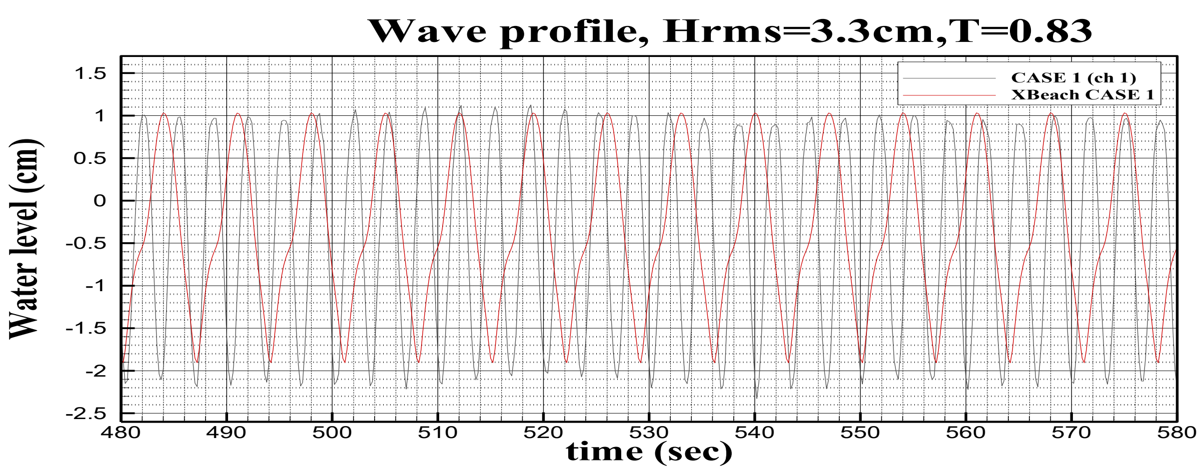
$$R = \frac{H_b}{H_{rms}}$$

3. On the offshore boundary wave and flow conditions are imposed. In the domain waves and currents will be generated which need to pass through the offshore boundary to onshore with minimal reflection. A simple one-dimensional absorbing-generating boundary condition is activated. This option allows for a time-varying water level (surge and/or infragravity waves) to be specified at the boundary while allowing any waves propagating perpendicularly towards the boundary to be absorbed, wall boundary for left and right boundary condition will result in a zero velocity at the lateral boundary.
4. The boundary condition of stationary spectral condition will be used. This means that a uniform and constant wave energy is specified, based on the given values of H_{rms} , T_{m01}, direction and power of the directional distribution function
5. Model is forced at the offshore boundary by imposing a JONSWAP
6. Neumann boundary condition at the lateral boundaries, for both waves and flow. By doing so, there is no lateral gradient (longshore gradients is set to zero).
7. CFL-condition of 0.7 is used (XBeach default).

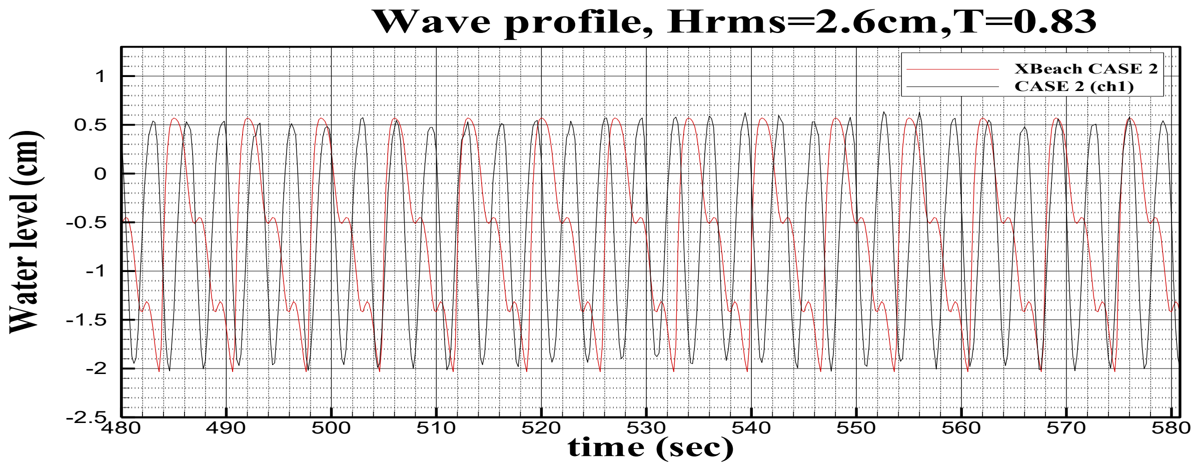
3. Results and Discussion

3.1. Hydrodynamic Validation

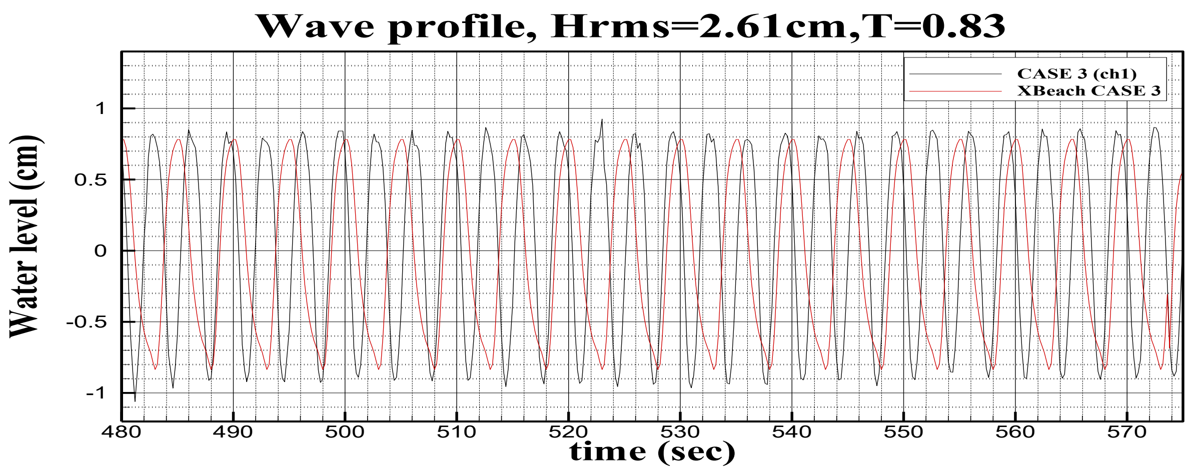
In this session, the hydrodynamic results of XBeach are discussed. The analysis focuses on the wave height and transformation computed by XBeach. The purpose of this test is to check whether the non-linear shallow-water equations (NSWE) numerical scheme is not too dissipative and does not create significant errors in propagation speed. A comparison of wave height data obtained from laboratory activities with the results of calculations from XBeach can be seen in the following figures.



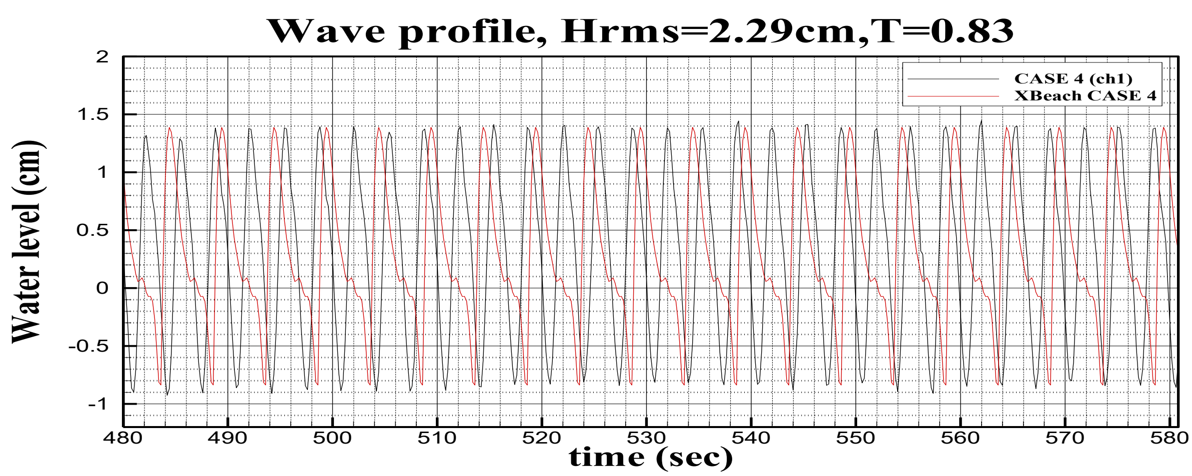
(a)


Wave profile, Hrms=2.6cm,T=0.83
XBeach CASE 2
CASE 2 (ch1)
Water level (cm)
time (sec)

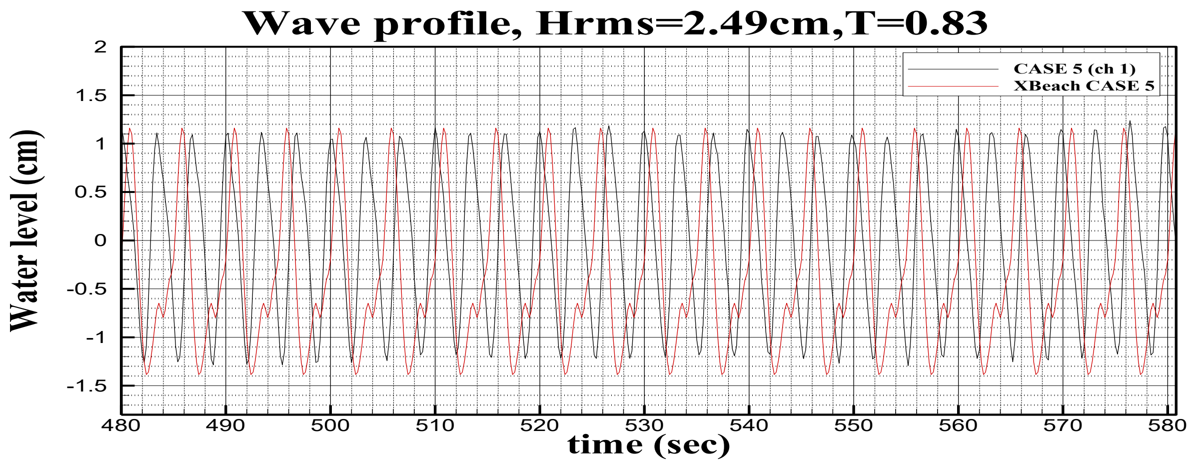
(b)


Wave profile, Hrms=2.61cm,T=0.83
CASE 3 (ch1)
XBeach CASE 3
Water level (cm)
time (sec)

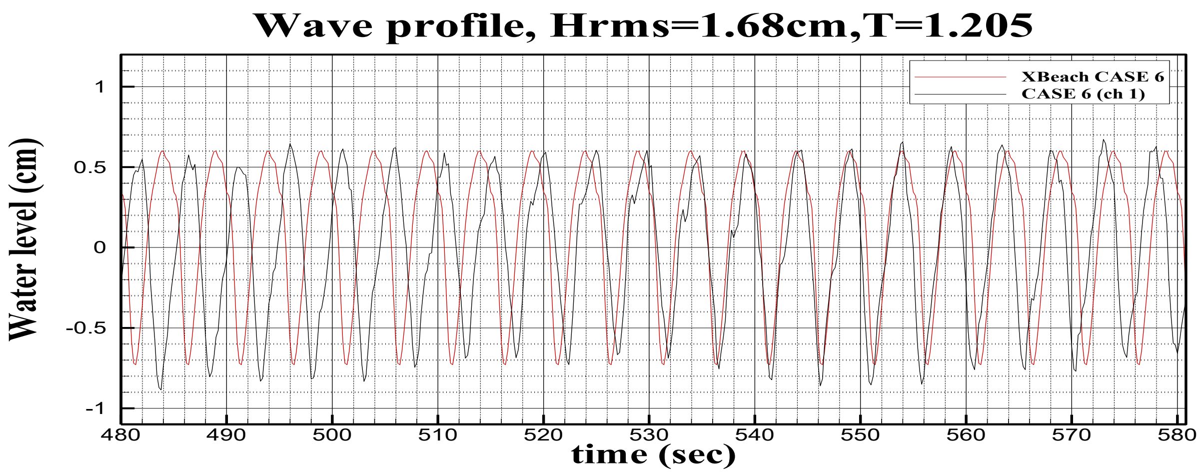
(c)


Wave profile, Hrms=2.29cm,T=0.83
CASE 4 (ch1)
XBeach CASE 4
Water level (cm)
time (sec)

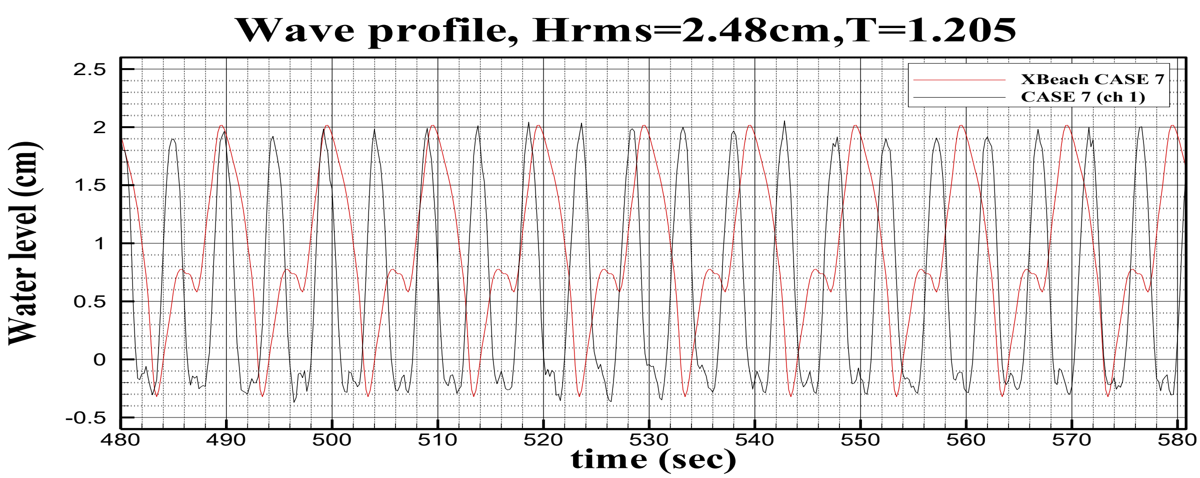
(d)


Wave profile, Hrms=2.49cm,T=0.83
CASE 5 (ch 1)
XBeach CASE 5
Water level (cm)
time (sec)

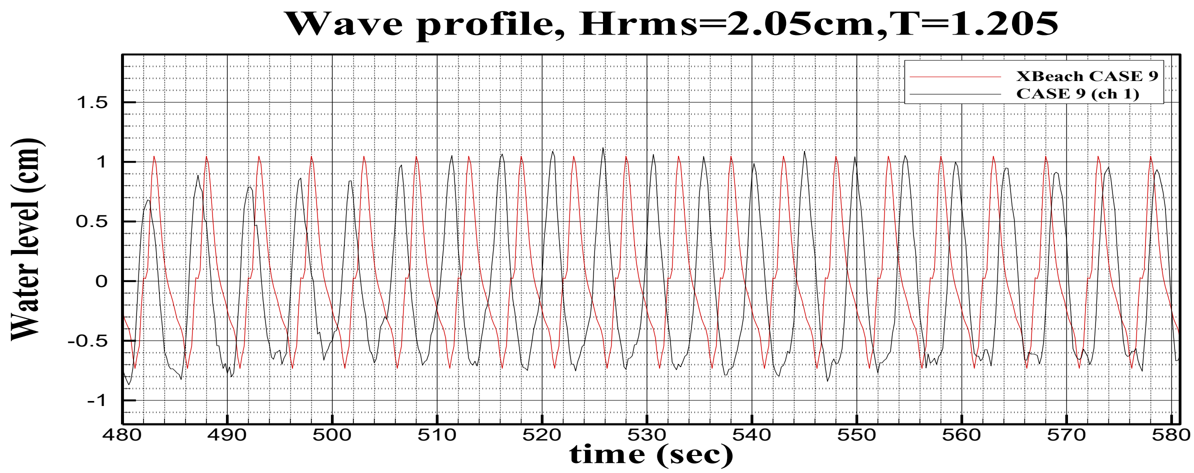
(e)


Wave profile, Hrms=1.68cm,T=1.205
XBeach CASE 6
CASE 6 (ch 1)
Water level (cm)
time (sec)

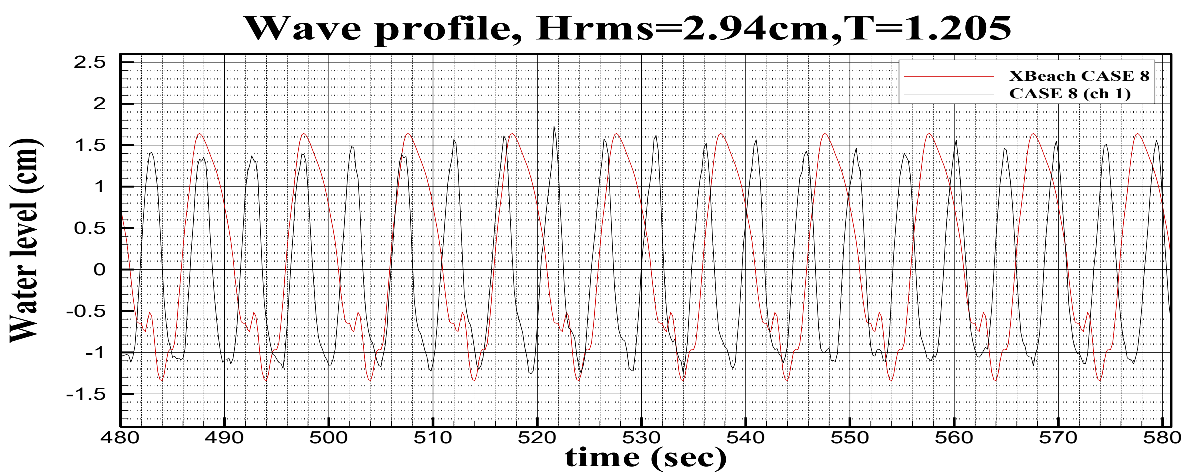
(f)


Wave profile, Hrms=2.48cm,T=1.205
XBeach CASE 7
CASE 7 (ch 1)
Water level (cm)
time (sec)

(g)



(h)



(i)

Figure 2. Results of the wave height validation run with default XBeach model for every case and laboratory experiment, black lines indicated wave high recorded wave gauge (Ch 1) and red lines indicated XBeach model (HRMS) measured results for compounds a (3.3), b (2.6), c (2.61), d (2.29), e (2.49), f (1.68), g (2.48), h (2.05), and i (2.94)

The averaged significant wave heights are recorded in Table 2 and visualized along with the measurements, it should be noted that, due to the averaging of the wave heights, some information is lost and that the possible differences between the measurements and model result cannot be retrieved unambiguously.

Table 2. Statistical error metrics demonstrating low prediction error and good agreement between laboratory measurements and XBeach model results for significant wave heights

Case ID	Hrms (lab) (cm)	Hrms (XBeach) (cm)	Error
CASE 1	3.3	3.1	0.06
CASE 2	2.6	2.6	0.02
CASE 3	2.6	1.6	0.05
CASE 4	2.3	2.2	0.04
CASE 5	2.5	2.5	0.01
CASE 6	1.7	1.4	0.19
CASE 7	2.5	2.3	0.08
CASE 8	2.9	2.9	0.01
CASE 9	2.1	1.8	0.15
	MAE		0.07

Table 2 show some statistical information of the calculated wave heights. of the value of error contained in column 4, MAE value shows 0.07, it can be concluded that overall relative error is less than 10 % which is regarded sufficient. The performance of XBeach is compared to results obtained from physical model tests performed under a variety of wave heights. From all validated cases, it can be seen from the profile illustrations that XBeach's ability to simulate bed profiles shows positive results. The error values for each case are summarized in Table 2. For instance, De Vet *et al.* (2020) reported a normalized root-mean-square error (nRMSE) of approximately 10-15% for wave transformation over fringing reefs using irregular waves. The lower MAE (5%) achieved in this study can be attributed to the controlled, simplified conditions of regular wave forcing in a laboratory flume, as opposed to the complex bathymetry and irregular wave spectra in reef environments. This favorable comparison underscores that for fundamental regular wave interactions with a sandy slope, XBeach demonstrates excellent predictive skill, providing a reliable benchmark for its core sediment transport algorithms before their application to more intricate field scenarios.

3.2. Morphodynamic

To validate XBeach's capacity to simulate coastal erosion, a comprehensive morphodynamic analysis was conducted. Beyond hydrodynamic agreement, accurately predicting changes in bed profile—specifically the erosion area under varying wave conditions—is critical for assessing the model's practical utility in coastal management. This analysis first involved a sensitivity study to identify key parameters influencing bed-level change, followed by a quantitative comparison of predicted and measured erosion areas. The expected outcome is a calibrated model setup that reliably reproduces observed morphodynamic changes, thereby reinforcing confidence in XBeach's application for erosion prediction under controlled regular wave scenarios. The performance of XBeach is compared to result obtained from physical model test performed in a variety of wave height. The purpose of this activity is to see the ability of XBeach in calculating the eroded area. To obtain maximum results, the XBeach model will first do a sensitivity analysis, that is, changing the parameters that affect the model to determine the effect of these changes on bed profile.

3.2.1. Sensitivity Analysis of XBeach Morphodynamic Response

To determine which model parameters were of importance for the model calibration a sensitivity analysis was performed, four model parameter were selected for the sensitivity analysis, these parameters were "hmin", "facua","eps" and "hswitch". More detail of these parameters will be described in table 3. The model runs with the short computational time span equal to the duration 3600 second. Specific parameters were varied once at a time to keeping the other parameters at fixed value. In this way, the differences that occurred were solely caused by change in the parameter of interest.

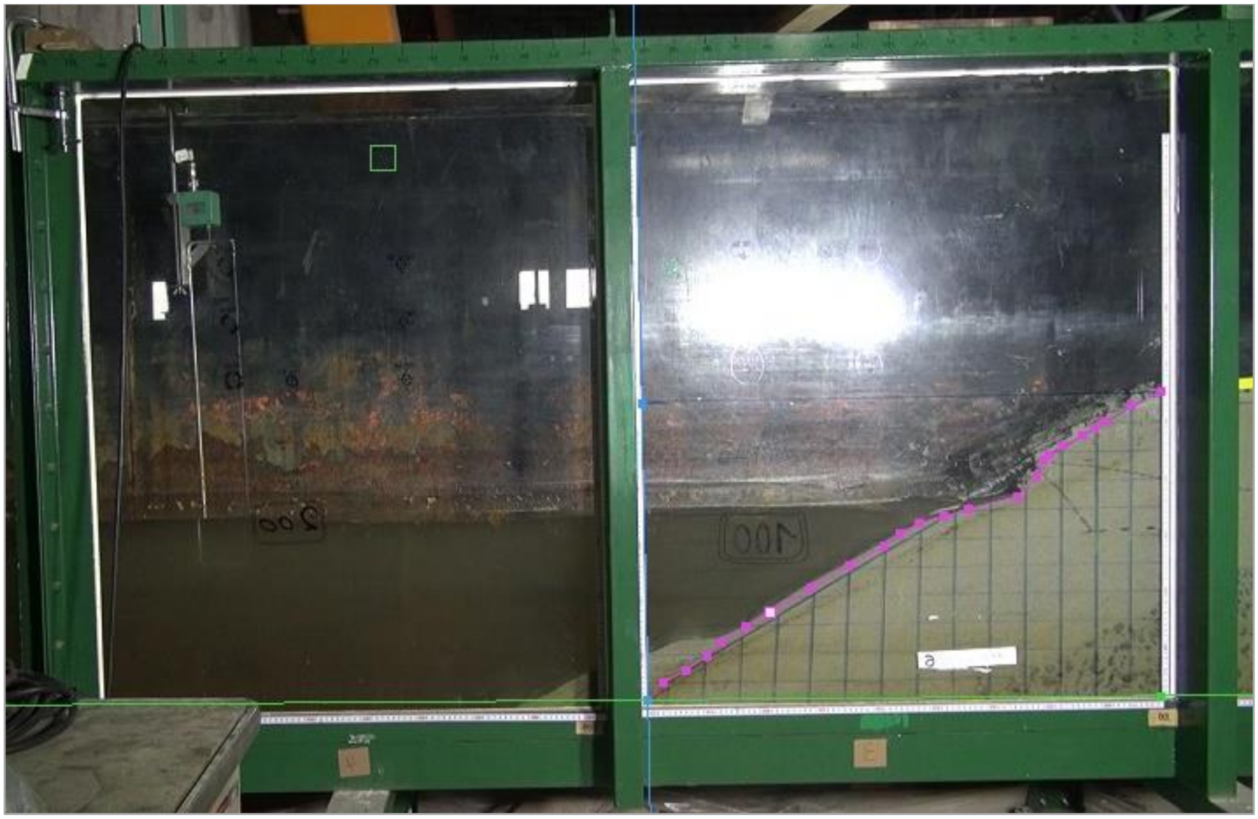


Figure 3. The results of the experiment activity will be the benchmark for determining the value of analysis sensitivity for parameters of "hmin", "facua", "eps" and "hswitch". (This figure 3 is not referenced anywhere)

The results of the experiments that will be the benchmark are taken from the results of laboratory experiments with the hydrodynamic parameters of case 4 (see Table 3). The value of each parameter used is taken from the highest value, the middle value and the minimum value, with the expected value representing the parameters analyzed.

Table 3. The value of the parameter to be used to carry out sensitivity analysis

Parameters	Definition	Default value	Range	Assigned value for sensitivity analysis
hmin	Threshold velocity difference to determine conservation of energy head versus momentum	0.2 m	0.001-1 m	0.001, 0.1, 1
facua	Calibration factor time averaged flows due to both wave skewness and wave asymmetry	0.1	0-1	0.1, 0.5, 1
eps	Threshold water depth about which cells are considered wet	0.005	0.001-0.1 m	0.001,0.01, 0.1
hswitch	Water depth at which the grid cell is switched between wetslp and dryslp	0.1 m	0.01-1m	0.01, 0.1, 1

3.2.2. Sensitivity Parameter of "hmin"

The description of "hmin" is Threshold velocity difference to determine conservation of energy head versus momentum, which stokes drift is included. It prevents very strong return flows or high concentrations close to the waterline. the results obtained from the simulation by entering the value of hmin 0.001, 0.1 and 1, show the pattern of odd bed level changes, if viewed from the experimental profile bed patterns, erosion occurs in the range of a distance of 12.55 m to 12.75 m and the addition occurs at a distance 12.55 to 12.15, on the contrary the results of XBeach simulation with variations in "hmin" values actually show the occurrence of two erosion patterns, the results of the sensitivity of the model to changes in "hmin" can be seen in Figure 4.

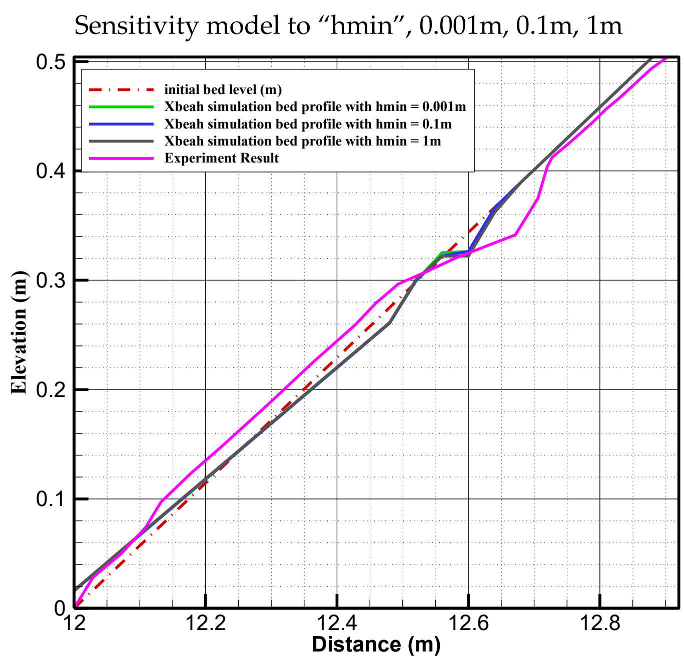


Figure 4. Sensitivity of "hmin" input variations to the bed level experimental results, the green line shows the XBeach simulation results with a "hmin" value of 0.001m, blue line indicated "hmin" 0.1m, black line indicated "hmin" 1m

3.2.3. Sensitivity Parameter of "facua"

"Facua" is the calibration factor for short-wave averaged sediment transport due to both wave skewness and wave asymmetry, the default value of this parameter is 0.1m.

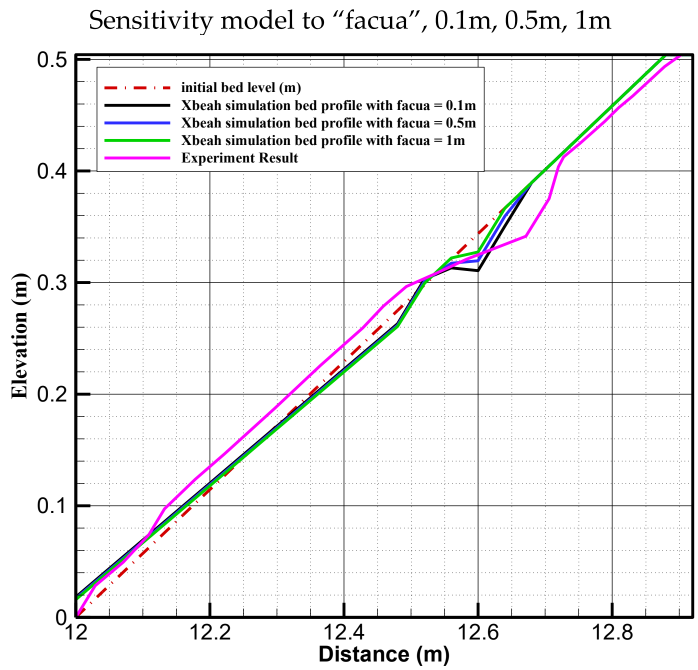


Figure 5. Sensitivity of "facua" input variations to the bed level experimental results, pink line indicated the bed profile from experimental result, the green line shows the XBeach simulation results with a "facua" value of 1m, blue lines indicated "facua" 0.5m, and black lines indicated "facua" 0.1m

Variations in the value of these "facua" parameters will be input into the XBeach model of 0.1, 0.5 and 1, the result can be seen in figure 5 From the results of the figure above it can be seen that, by entering the value of the variation of the "facua" parameters, the results do not significantly affect to the change in bed level, the pattern of bed level changes resembles the pattern that occurs with variations in the "hmin" parameter.

3.2.4. Sensitivity parameter of "eps"

Parameter of "eps" is the threshold water depth at which cell is considered wet or dry. In very shallow water some processes need to be limited to avoid unrealistic behavior, the parameter of "eps" determines whether points are dry or wet and can be taken quite small. for variations in the value of these "eps" parameters will be input into the XBeach model of 0.1, 0.01 and 0.001, the result can be seen in Figure 6.

Sensitivity model to “eps”, 0.001m, 0.01m, 0.1m

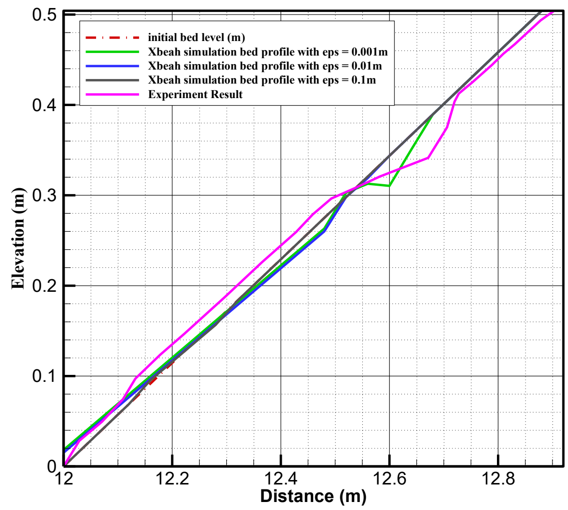


Figure 6. Sensitivity of “eps” input variations to the bed level experimental results, pink lines indicated the bed profile from experimental result, the green lines indicated eps 0.001m, blue line indicated “eps” 0.01m, black line indicated “eps” 0.1m

3.2.5. Sensitivity Parameter of “hswitch”

The “hswitch” parameter in the XBeach model is described as the water depth at which the grid cell is switched between wetslp and dryslp. The default value is 0.1 m, by entering a variation of 0.01, 0.1 and 1, in order to see the effect of switch parameters on changes in the bed profile. The result can be seen in figure 4.8. from the bed profile that is generated by entering the “hswitch” parameter of 0.01m shows positive results, the profile approaches the results of the experiment.

Sensitivity model to “hswitch”, 0.001m, 0.1m, 1m

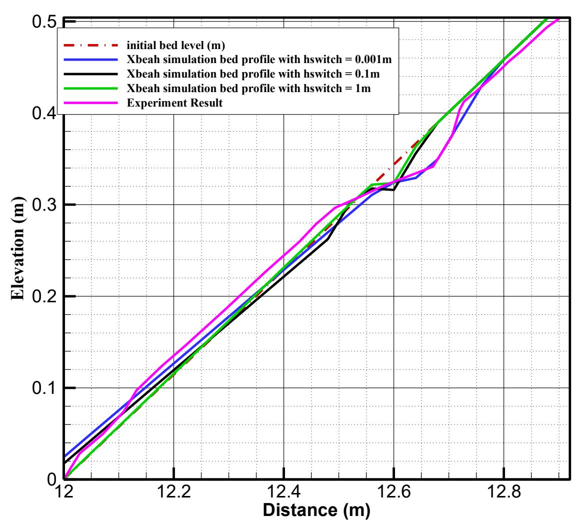


Figure 7. Sensitivity parameter of “hswitch” to the bed level experimental results, pink line indicated the bed profile from experimental result, the green line shows the XBeach simulation results with a “hswitch” 1m, blue line indicated “hswitch” 0.001m, black line indicated “hswitch” 0.1m

3.2.6. Result of the Sensitivity Analysis

Bed profile result from sensitivity parameter of "hmin", "form", "turb" and "facua" did not affect to the results much, vice versa by entering a value of "hswitch" 0.001 give results that are close to the results condition of laboratory experiment. The results of the sensitivity analysis will be summarized in the Table 4.

Table 4. Summary of sensitivity analysis results for key XBeach morphodynamic parameters and their effects on bed profile simulation

Parameters	Definition	Default value (m)	Range (m)	Value to be use
hmin	Threshold velocity difference to determine conservation of energy head versus momentum	0.2	0.001-1	Default
facua	Calibration factor time averaged flows due to both wave skewness and wave asymmetry	0.1	0-1	Default
eps	Threshold water depth about which cells are considered wet	0.005	0.001-0.1	Default
hswitch	Water depth at which the grid cell is switched between wetslp and dryslp	0.1	0.01-1	0.001m

3.3. Result of the Morphodynamic Validation

The results of comparison of bed profile obtained from laboratory activities and the results of calculations from XBeach can be seen in the following Figures 8, 9, 10 and Figure 11.

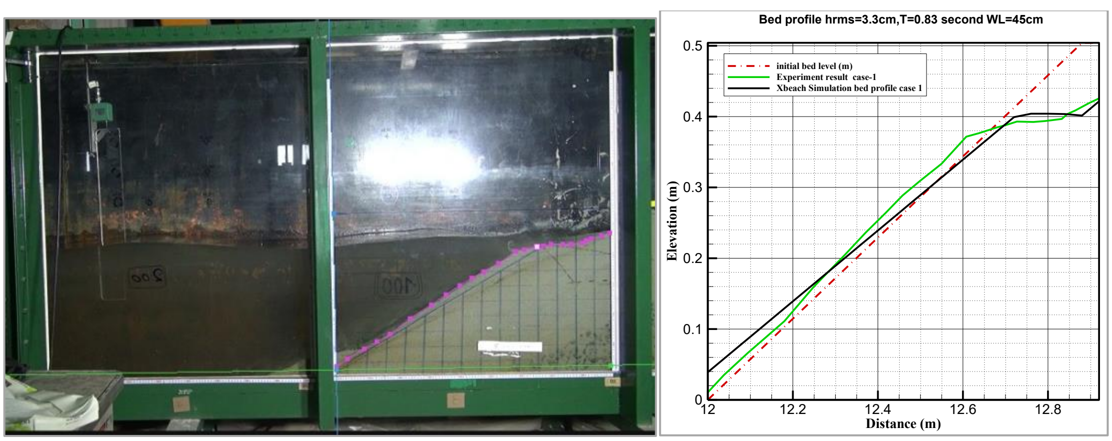


Figure 8. Case 1, photo image from left view (left), bed profile from XBeach model and laboratory experiment (right), red lines indicate initial bed profile, green lines indicated experiment result, black lines indicated XBeach model

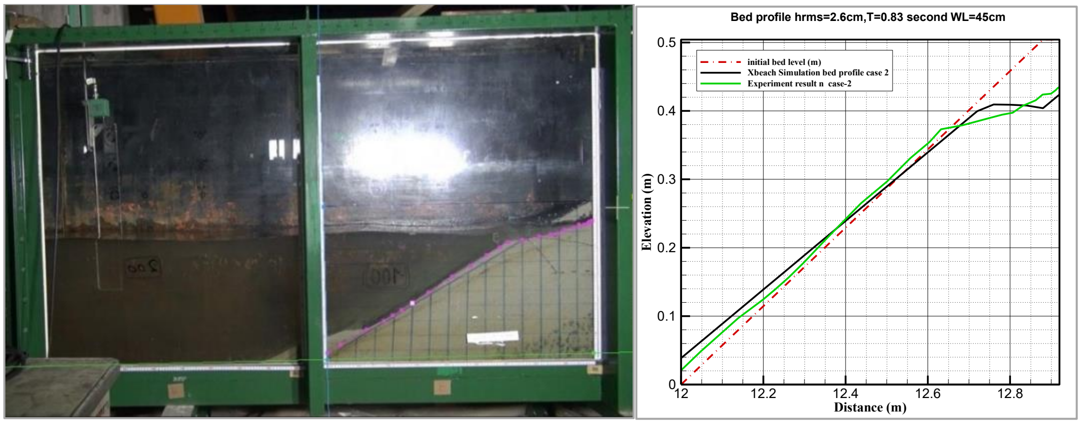


Figure 9. Case 2, photo image from left view (left), bed profile from XBeach model and laboratory experiment (right), red lines indicate initial bed profile, green lines indicated experiment result, black lines indicated XBeach model

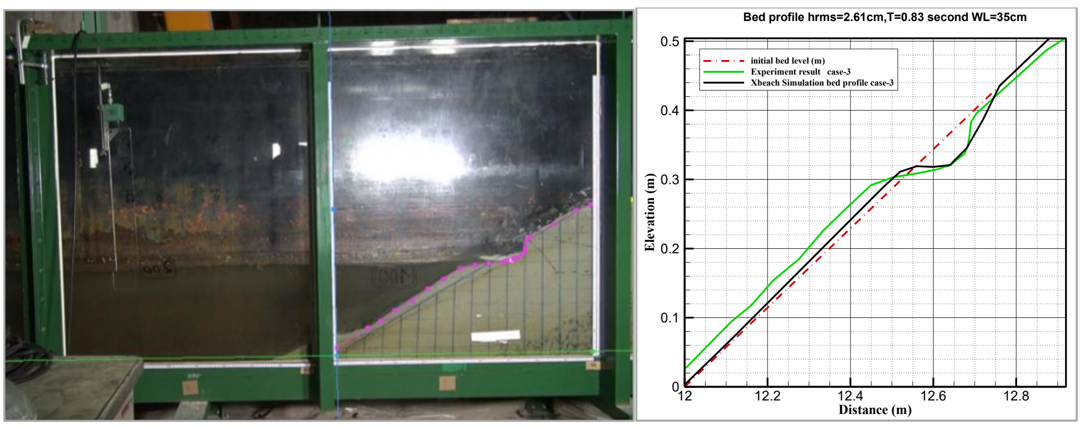


Figure 10. Case 3, photo image from left view (left), bed profile from XBeach model and laboratory experiment (right), red lines indicate initial bed profile, green lines indicated experiment result, black lines indicated XBeach model

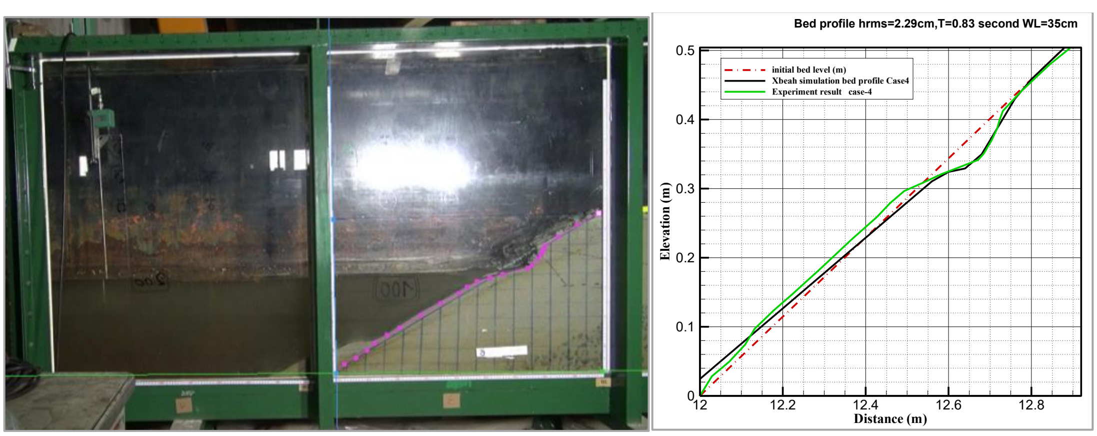


Figure 11. Case 4, photo image from left view (left), bed profile from XBeach model and laboratory experiment (right), red lines indicate initial bed profile, green lines indicated experiment result, black lines indicated XBeach model

From all validated cases, it can be seen from the profile illustrated that XBeach ability to simulate bed profiles in terms of the resulting bed profile shows positive results, the error values of each case can be seen in the Table 5.

Table 5. Morphodynamic validation outcomes for each experimental case with associated statistical error metrics, indicating low relative error and strong agreement between laboratory measurements and XBeach bed profile simulations

Case ID	Eroded area (lab) (m^2)	Eroded area (XBeach) (m^2)	Error
CASE 1	0.0114	0.0110	0.03
CASE 2	0.0113	0.0103	0.09
CASE 3	0.0053	0.0056	0.07
CASE 4	0.0048	0.0052	0.08
CASE 5	0.0083	0.0086	0.03
CASE 6	0.0046	0.0048	0.03
CASE 7	0.0081	0.0085	0.04
CASE 8	0.0125	0.0120	0.01
CASE 9	0.0093	0.0104	0.11
	MAE		0.05

Table 5 shows some statistical information of the calculated error number for morphodynamic validation, the results of the MAE show the value 0.05 or equivalent to 5 %, from this result it can be concluded that overall relative error is less than 10 % which is regarded sufficient.

4. Conclusions

This study provides a rigorous validation of the XBeach numerical model for simulating hydrodynamic and morphodynamic processes under controlled, regular wave conditions using laboratory flume experiments as a benchmark. The results demonstrate that XBeach can reliably reproduce wave transformation and associated bed profile changes, indicating strong predictive capability within acceptable error limits for engineering and research applications.

Sensitivity analysis showed that several morphodynamic parameters had minimal influence on bed profile evolution, whereas adjustment of the hswitch parameter was essential for accurately capturing the observed erosion pattern. This finding emphasizes the importance of appropriate parameter calibration, even under simplified wave forcing conditions.

The main scientific contribution of this work is the establishment of a foundational validation benchmark for XBeach under regular wave forcing, which strengthens confidence in its core sediment transport formulations. Practically, the results support the application of XBeach in controlled environments or coastal settings dominated by simplified wave conditions prior to deployment in more complex scenarios.

Nonetheless, the validation is constrained by its simplified design, including the use of regular waves, a one-dimensional flume configuration, and uniform sediment characteristics. Future studies should therefore extend the validation to irregular wave conditions, higher-dimensional domains, and more diverse sediment and beach configurations, as well as apply the calibration insights from this study to field-scale coastal erosion cases.

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