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Simulating Erosive and Accretive Conditions in the Swash: Applications of a Nonlinear Wave and Morphology Evolution Model

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Abstract: This work presents a new model for surf and swash zone morphology evolution induced by nonlinear waves. Wave transformation in the surf and swash zones is computed by a nonlinear wave model based on the higher order Boussinesq equations for breaking and non-breaking waves. Regarding sediment transport, the model builds on previous research by the authors and incorporates the latest update of a well-founded sediment transport formula. The wave and morphology evolution model is validated against two sets of experiments on beach profile change and is afterwards used to test the performance of a widely-adopted erosion/accretion criterion. The innovation of this work is the validation of a new Boussinesq-type morphology model under both erosive and accretive conditions at the foreshore (accretion is rarely examined in similar studies), which the model reproduces very well without modification of the empirical coefficients of the sediment transport formula used; furthermore, the model confirms the empirical erosion/accretion criterion even for conditions beyond the ones it was developed for and without imposing any model constraints. The presented set of applications highlights model capabilities in simulating swash morphodynamics, as well as its suitability for coastal erosion mitigation and beach restoration design



Citation: Samaras, A.G.; Karambas, T.V. Simulating Erosive and Accretive Conditions in the Swash: Applications of a Nonlinear Wave and Morphology Evolution Model. *J. Mar. Sci. Eng.* **2024**, *12*, 140. <https://doi.org/10.3390/jmse12010140>

Academic Editors:
Theocharis Plomaritis and Daniel C. Conley

Received: 17 November 2023

Revised: 24 December 2023

Accepted: 28 December 2023

Published: 10 January 2024



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Keywords: numerical model; boussinesq equations; coastal morphology; erosion; accretion; swash zone

1. Introduction

Coastal erosion is nowadays among the most intensively investigated topics in coastal research. This is justified by the expected impact of climate change on the intensity of the drivers behind it (both natural- and human- induced; [1–6]), as well as on its direct association to the inundation of low-lying areas [7–10]. Since building coastal resilience against erosion and flooding is based on the effective design of coastal protection and adaptation measures [11,12], numerical models have become indispensable tools for scientists, engineers and policymakers. As such, their accuracy and reliability are continuously tested in both research and engineering applications [13–18].

The study of coastal morphology evolution is particularly demanding. Its accurate representation by numerical models depends on the scales in space and time over which the interplay between various codependent processes is to be taken into consideration. General discussion and valuable insights on the topic can be found in [19–26]. Regardless, though, the fundamentals of coastal morphodynamics lie in a beach profile's response to wave action.

The swash, i.e., the part of the beach where the sediment bed is submerged and alternatively exposed, due to uprush and backwash, plays a key role in coastal morphology evolution through both cross-shore and longshore processes. Regarding longshore transport and its modelling in the swash, useful insights can be found in [15,27–31]. Focusing on cross-shore processes, it is documented that waves acting upon a beach profile which is not

in equilibrium will redistribute sediment across it as the beach adjusts towards equilibrium shape. Cross-shore transport will be predominantly directed either onshore or offshore, the former leading to accretion at the foreshore (berm formation) and the latter to erosion at the foreshore with the eroded sediment forming a notable bar near the breaker line (hence the typical distinction between accretive and erosive profiles).

The above processes in the swash can be broken down and modelled through understanding the interplay between swash flow velocities, bed shear stress, bore collapse-induced turbulence, wave-swash interactions, infragravity waves, in-/ex-filtration and pressure gradients (horizontal and vertical). Chen et al. [32] present a thorough review on the dynamics of sand transport in the swash and on the use of practical models to simulate it. Reference is also made to works that delve into the intricacies of swash zone dynamics, like the experimental work of [33,34], the modelling works of [35–37] and the combined experimental—numerical works of [38,39]. Modelling attempts in relevant literature are typically based on the reproduction of sets of seminal experiments, like the ones collected and presented by [40]. It is noteworthy, though, that profiles with prominent accretive patterns at the foreshore are scarcely studied compared to erosive ones.

This work presents a new advanced phase-resolving nonlinear wave, sediment transport and bed morphology evolution 2DH model, that builds on previous research by the authors [13] and incorporates the latest update of a well-founded sediment transport formula [41]. The model is validated against two sets of experiments on beach profile change, namely the U.S. Army Corps of Engineers (CE) experiments and the Central Research Institute of Electric Power Industry (CRIEPI) experiments [40], with particular focus on prominent accretive profiles, and is afterwards used to test the performance of a widely-adopted erosion/accretion criterion. Section 2 in the following presents the components and theoretical background of the wave and morphology evolution model. Section 3 presents the characteristics of model applications. Section 4 presents and discusses model results, and Section 5 presents the conclusions drawn from this work, along with insights for future research.

2. The Wave and Morphology Evolution Model

The wave and morphology evolution model used in this work is an improved version of the model presented by [13], with regard to its essential sediment transport module.

The advanced phase-resolving wave model is based on the higher-order Boussinesq-type Equations for breaking and nonbreaking waves, expressed as:

$$\zeta_t + \nabla \cdot (h\mathbf{U}) = 0 \quad (1)$$

$$\mathbf{U}_t + \frac{1}{h} \nabla \mathbf{M}_u - \frac{1}{h} \mathbf{U} \nabla \cdot (\mathbf{U}h) + g \nabla \zeta + G = \frac{1}{2} h \nabla [\nabla \cdot (d \mathbf{U}_t)] - \frac{1}{6} h^2 \nabla [\nabla \cdot \mathbf{U}_t] + \frac{1}{30} d^2 \nabla [\nabla \cdot (\mathbf{U}_t + g \nabla \zeta)] + \frac{1}{30} \nabla [\nabla \cdot (d^2 \mathbf{U}_t + g d^2 \nabla \zeta)] - d \nabla (\delta \nabla \cdot \mathbf{U})_t - \frac{\tau_b}{h} + \mathbf{E} \quad (2)$$

where $\mathbf{M}_u$ is defined as:

$$\mathbf{M}_u = (d + \zeta) \mathbf{u}_0^2 + \delta (c^2 - \mathbf{u}_0^2) \quad (3)$$

and G as:

$$G = \frac{1}{3} \nabla \left\{ d^2 \left[(\nabla \cdot \mathbf{U})^2 - \mathbf{U} \cdot \nabla^2 \mathbf{U} - \frac{1}{10} \nabla^2 (\mathbf{U} \cdot \mathbf{U}) \right] \right\} - \frac{1}{2} \zeta \nabla [\nabla \cdot (d \mathbf{U}_t)] \quad (4)$$

where ζ is the wave surface elevation, d is the water depth and h is the total water depth ($h = d + \zeta$); the subscript “t” denotes differentiation with respect to time; $\mathbf{U}$ is the horizontal velocity vector $\mathbf{U} = (U, V)$; $\tau_b = (\tau_{bx}, \tau_{by})$ is the bed friction term calculated according to [42,43]; δ is the roller thickness, determined geometrically according to [44]; $\mathbf{E}$ is the eddy viscosity term, calculated according to [45]; and $\mathbf{u}_0$ is the bottom velocity vector $\mathbf{u}_0 = (u_o, v_o)$, with u_o and v_o being the instantaneous bottom velocities along the x- and y-

directions respectively. Following [43], wave breaking is initiated using breaking angle $\varphi_b = 30^\circ$, which then gradually changes to its terminal value $\varphi_b = 10^\circ$.

The model is capable of simulating the phenomena of shoaling, refraction, breaking, diffraction, reflection and wave-structure interaction, as well as nonlinear wave-wave interaction. Regarding model capabilities in simulating the non-linear evolution of unidirectional or multidirectional wave fields in the nearshore, one can refer to [46] (see also [47] on the issue). Regarding wave-structure interaction and energy transmission, one can refer to [48]. The model is analysed in detail in [13] and description is not repeated here. The model's implementation to diverse coastal engineering applications can be found in [16,43,49].

Regarding the sediment transport module, this work builds on the improvements introduced by [13] and adopts the latest update of the transport formula of [50,51] proposed by [41]. Bed load and sheet flow transport is accordingly simulated using [41]:

$$q_{sa} = a_w \sqrt{\frac{f_w}{\tan \Phi_m}} d_{50} \hat{u} K_n^{1/2} \left| \frac{dd_e}{dx} - d_x \right|^{1/2} \text{sign} \left(\frac{dd_e}{dx} - d_x \right) \theta_{cw,m} \exp \left(-b \frac{\theta_{cr}}{\theta_{cw}} \right) \quad (5)$$

where:

$$K_n = \hat{q}_c + \hat{q}_t = \frac{u_c u_t}{\hat{u}^2} = \frac{u_c}{\hat{u}} \left(1 - \frac{u_c}{\hat{u}} \right) \quad (6)$$

$$\frac{dd_e}{dx} = \tan \Phi_m \left(\frac{\hat{q}_c - \hat{q}_t}{\hat{q}_c - \hat{q}_t} \right) \quad (7)$$

$$\hat{q}_c = \frac{u_c^2}{\hat{u}^2} \left(1 - \frac{u_c}{\hat{u}} \right) \quad (8)$$

$$\hat{q}_t = \frac{u_t^2}{\hat{u}^2} \left(1 - \frac{u_t}{\hat{u}} \right) \quad (9)$$

In Equations (5)–(9): a_w and b are empirical coefficients (set to 6 and 4.5, respectively); f_w is the wave friction factor; Φ_m is the friction angle for a moving grain (set to 30 deg); d_{50} is the median grain size; d_x is the local bottom slope; d_e is the depth (for equilibrium conditions); $\theta_{cw,m}$ and θ_{cw} are the mean and maximum Shields parameters due to wave-current interaction, respectively; and θ_{cr} is the critical Shields parameter for incipient motion of the sediment. It is noted that c and t are indices that refer to the wave crest and wave through, respectively, with peak velocities u to be perceived accordingly and $\hat{u}$ calculated following the approach of [52]. Both the phase-lag and acceleration effects are introduced in the calculation of $\theta_{cw,net}$ that is used for the derivation of Equation (5), as in [50,51].

Suspended load and bed morphology evolution are simulated as in [13], based on the combined formulation of [50,51,53,54] and the equation of [55], respectively. Regarding the connection to the nonlinear wave model, specifically, it is noted that breaking wave-induced turbulence and the generated undertow (as a return flow due to surface roller effects of broken waves) lead to offshore-directed suspended load. On the other hand, under non-breaking waves or under relatively weak breaking/undertow conditions the time-averaged bed load and sheet flow transport (Equation (5)) is usually directed onshore, due to near-bottom velocity asymmetry together with the acceleration effects. The difference of the two quantities (i.e., the total load), along with runup/backwash flow effects, determine the direction of the total sediment transport rate and consequently dictate the erosion/accretion process.

The methodology adopted for the series of model applications can be encoded into the steps also described in [13], and is repeated in the following for reasons of completeness. First, the initial bathymetry is inserted into the wave model in order to estimate the wave and current fields. These fields are afterwards used by the sediment transport module to calculate the sediment transport rates. Finally, bathymetry is updated by the sediment transport module solving the equation of the conservation of sediment transport [55]

for the transport rates calculated in the previous step. The procedure is repeated for a user-specified time period or until a state of morphologic equilibrium is reached.

3. Model Applications

3.1. Validation for Experimental Data

Two sets of experiments are used in this work for the validation of the wave and morphology evolution model: The US Army Corps of Engineers experiments and the Central Research Institute of Electric Power Industry experiments [40], referred to as CE and CRIEPI experiments in the following, respectively.

The CE experiments were conducted in 1956/1957 and 1962 in the 221.0 m long, 5.2 m wide and 7.0 m deep Large Wave Tank of the US Army Corps of Engineers Beach Erosion Board (henceforth referred to as LWT). The LWT was at the time of the experiments located at Dalecarlia (Washington DC, US; see [56] for facility details). The full dataset comprises two series of movable-bed model experiments on beach profile change, mainly distinguished by the grain size of the bed material used. Tests of monochromatic waves of varying steepness were run for the different grain sizes in order to produce either accreting or eroding profiles. Nineteen (19) cases are documented in [40,56]: all but two started from a plane slope of 1:15; water depths (at the flat section of the flume) ranged from 3.5 m to 4.6 m; grain sizes with median diameters of 0.22 mm and 0.40 mm were used; wave heights ranged between 0.55 m and 1.68 m; wave periods ranged between 3.75 s and 16.0 s. Tests were continued until the establishment of stable beach profiles in all runs (i.e., until no significant profile changes were detected). This work focuses on tests that resulted in prominent erosive and—most importantly—accretive profiles at the foreshore; these are Tests no. 300 and 301 from the CE experiments. The specific tests conditions are presented in Table 1, in which d_{50} is the median grain size, H is the wave height, T is the wave period, d is the water depth and Dur is Test duration.

Table 1. Test conditions for the CE and CRIEPI experiments reproduced in this work (eros. = erosive test; accr. = accretive test).

Dataset	Test no.	Slope	d_{50} [mm]	H [m]	T [s]	d [m]	Dur [h:m]
CE experiments	300 (eros.)	1:15	0.22	1.68	11.33	4.27	50:00
	301 (accr.)	1:15	0.40	1.68	11.33	4.27	50:00
CRIEPI experiments	3-1 (eros.)	1:20	0.27	1.07	9.10	4.50	71:00
	1-3 (accr.)	1:20	0.47	1.05	9.00	4.50	69:30

The CRIEPI experiments were conducted between 1979 and 1983 in the 205.0 m long, 3.4 m wide and 6.0 m deep Large Wave Flume of the Central Research Institute of Electric Power Industry in Japan (see [57,58] for facility details). Similar to the CE experiments, tests of monochromatic waves of varying steepness were run for different grain sizes in order to produce either accreting or eroding profiles. Twenty four (24) cases are documented in [40,57,58]: initial plane slope varied between 1:50 and 1:10, although for some tests the profile from the previous test was used as initial profile; water depths (at the flat section of the flume) ranged from 3.5 m to 4.5 m; grain sizes with median diameters of 0.27 mm and 0.47 mm were used; wave heights ranged between 0.30 m and 1.80 m; wave periods ranged between 3.0 s and 12.0 s. As mentioned in the previous, this work focuses on tests that resulted in prominent erosive and—most importantly—accretive profiles at the foreshore; these are Tests no. 3-1 and 1-3 from the CRIEPI experiments, whose conditions are also presented in Table 1.

3.2. Investigation of an Erosion/Accretion Criterion

Criteria for distinguishing profile response under wave action have always been of interest in relevant research, as their utility extends from practical reasons (e.g., quickly estimating the expected profile response for large datasets) to enriching our understanding of the interplay between wave conditions and profile characteristics (profile shape and

sediment properties) that leads to sediment redistribution patterns in the surf zone and in the swash.

In the process of developing and presenting the profile evolution model SBEACH, Larson and Kraus [59] present previous research on criteria for identifying profile response (e.g., [60–65]) and eventually propose the criterion expressed as:

$$\frac{H_o}{L_o} \begin{cases} < M \left(\frac{H_o}{wT} \right)^3 \rightarrow \text{eros.} \\ > M \left(\frac{H_o}{wT} \right)^3 \rightarrow \text{accr.} \end{cases} \quad (10)$$

where H_o , L_o is the deep water wave height and wavelength, respectively, w is the sediment fall speed and M is an empirical parameter set to 0.0007 for regular waves in the lab or mean wave height in the field. The criterion implies predominant sediment transport offshore that leads to erosion at the foreshore for $H_o/L_o < 0.0007(H_o/wT)^3$, and predominant sediment transport onshore that leads to accretion at the foreshore for $H_o/L_o > 0.0007(H_o/wT)^3$. The respective profiles are typically referred to as “erosive/bar” or “accretive/berm” profiles, since erosion at the foreshore leads to the formation of a prominent bar near the breaker line and accretion at the foreshore leads to berm buildup. These two types of profiles are also referred to as winter-summer, storm-normal or dissipative-reflective profiles in literature. The criterion of [59], formally presented in [66,67], has been established as the most widely used since, although variations of its formulation have also been proposed and discussed in future research by [68–75], based on the same or different experimental datasets.

This work focuses on expanding the set of conditions tested during the CE and CRIEPI experiments (see Section 3.1 and [40,56–58]), using the wave and morphology evolution model presented Section 2 and validated in Section 3.1. This is done in order to investigate the performance of the Larson and Kraus criterion in predicting erosive/bar and accretive/berm profiles. A total of 22 New Tests were run, with the set of combinations of wave conditions and profile characteristics used in each one presented in Table 2 (slope for all runs was set equal to 1:20; New Tests are henceforth denoted as NT).

Table 2. Test conditions for the investigation of the erosion/accretion criterion of Larson and Kraus [59] (NT = New Test; slope for all runs equal to 1:20).

Test No.	d_{50} [mm]	H [m]	T [s]	Test No.	d_{50} [mm]	H [m]	T [s]
NT01	0.20	1.00	12.0	NT12	0.40	1.50	8.0
NT02	0.20	0.50	3.0	NT13	0.40	1.00	6.0
NT03	0.25	1.00	4.5	NT14	0.40	1.00	8.0
NT04	0.30	1.00	8.0	NT15	0.42	1.00	8.0
NT05	0.30	0.75	3.0	NT16	0.45	0.75	4.5
NT06	0.30	0.75	8.0	NT17	0.45	1.00	14.5
NT07	0.30	1.50	14.0	NT18	0.50	0.75	4.5
NT08	0.35	1.00	5.5	NT19	0.50	0.75	9.5
NT09	0.35	1.25	5.0	NT20	0.50	1.00	7.5
NT10	0.40	1.00	12.0	NT21	0.55	1.00	8.0
NT11	0.40	0.50	8.0	NT22	0.80	1.50	8.0

4. Results and Discussion

4.1. Results for Model Validation

Figure 1 presents results for Test 300 from the CE experiments (see Table 1). Figure 1a shows the comparison of the measured and computed (by the model) profiles (including model results for $t = Dur/2$), Figure 1b shows the difference between measured and computed profiles, and Figure 1c shows the net sediment transport rate (positive values = onshore transport, negative values = offshore transport). Figures 2–4 present the respective results for Test 301 from the CE experiments and Tests 3-1, 1-3 from the CRIEPI experiments (also see Table 1).

For the accretive tests CE 300 and CRIEPI 3-1 the Equilibrium Beach Profiles (EBPs) according to [76] are also presented in Figures 1a and 3a, respectively; so are the differences between measured and EBP/Dean profiles in Figures 1b and 3b. Equilibrium Beach Profiles follow equation $d = Ay^{2/3}$, where d is the depth, y is the cross-shore distance measured from the shoreline and A is a parameter associated to the median grain size according to [77].

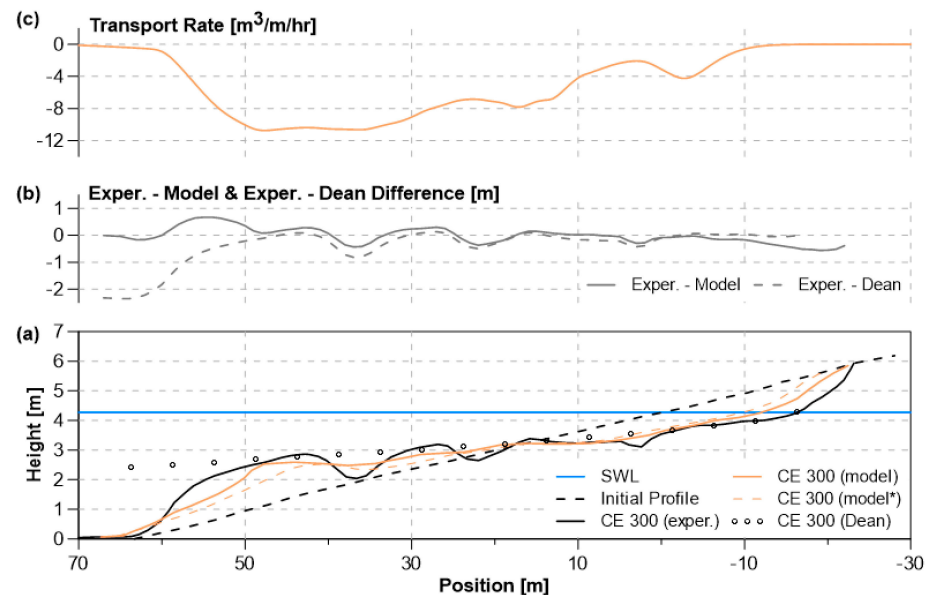


Figure 1. Results for Test CE 300 (see Table 1): (a) comparison of measured and computed profiles (* denotes model results at $t = Dur/2$) and respective Dean EBP; (b) difference between measured and computed/Dean profiles; (c) computed net sediment transport rate (positive values = onshore transport, negative values = offshore transport).

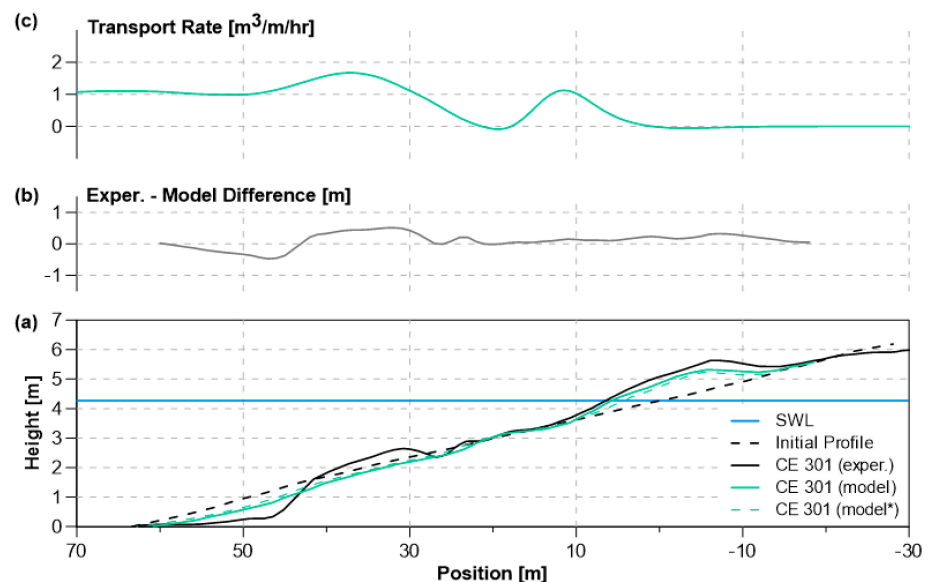


Figure 2. Results for Test CE 301 (see Table 1): (a) comparison of measured and computed profiles (* denotes model results at $t = Dur/2$); (b) difference between measured and computed profiles; (c) computed net sediment transport rate (positive values = onshore transport, negative values = offshore transport).

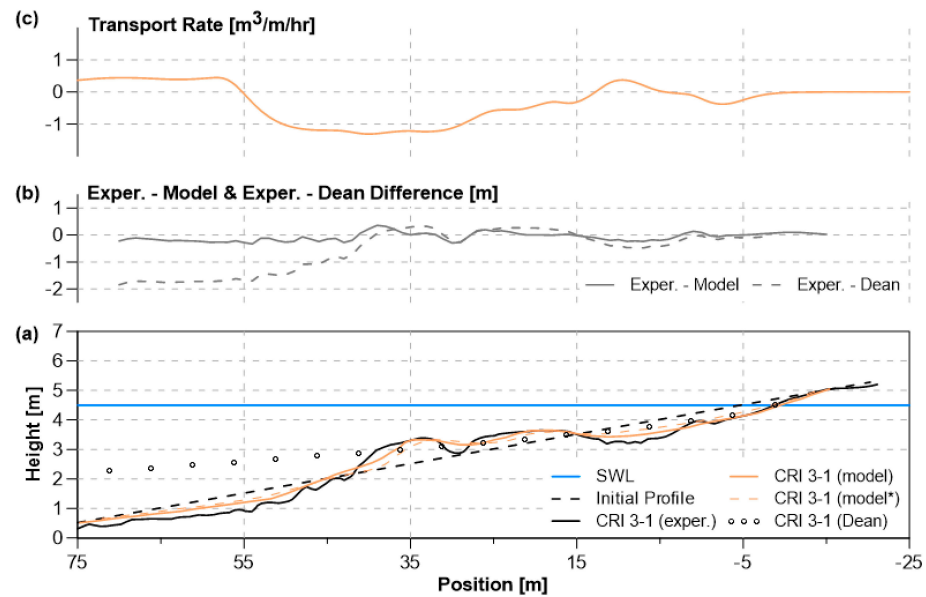


Figure 3. Results for Test CRIEPI 3-1 (see Table 1): (a) comparison of measured and computed profiles (* denotes model results at $t = Dur/2$) and respective Dean EBP; (b) difference between measured and computed/Dean profiles; (c) computed net sediment transport rate (positive values = onshore transport, negative values = offshore transport).

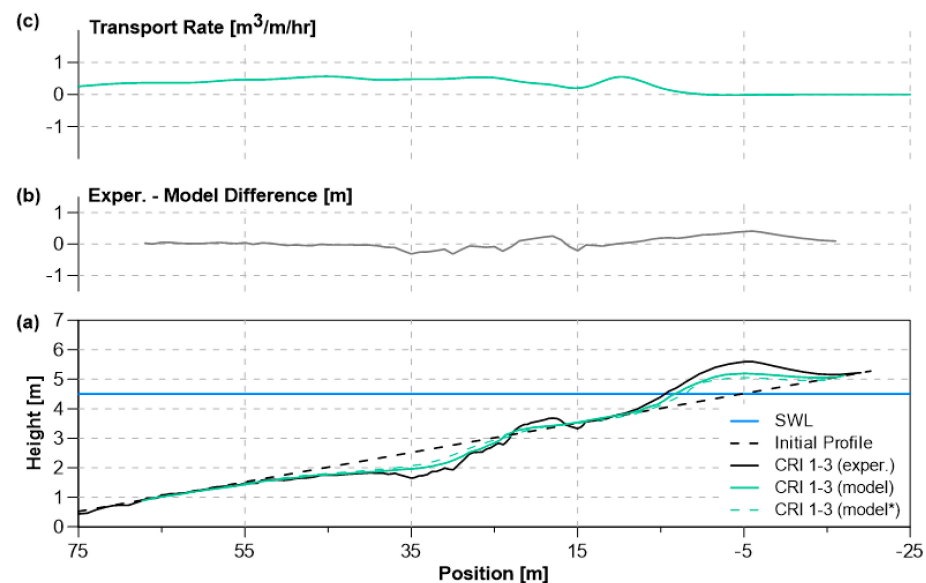


Figure 4. Results for Test CRIEPI 1-3 (see Table 1): (a) comparison of measured and computed profiles (* denotes model results at $t = Dur/2$); (b) difference between measured and computed profiles; (c) computed net sediment transport rate (positive values = onshore transport, negative values = offshore transport).

Model results compare very well with the experimental data, overall. Regarding the erosive tests (i.e., Tests CE 300—Figure 1 and CRIEPI 3-1—Figure 3) the model simulates accurately the loss of sediment from the shoreface and the gradual formation of the longshore bar, as well as the erosion-accretion transitions along the profile, in both cases. Model results for the computed profiles at half the Tests' durations (denoted as "Model*" in Figures 1 and 3) are indicative of the evolution of erosive profiles as simulated by the presented model. Between Tests, results are comparatively better for Test CRIEPI 3-1; however, absolute differences between measured and computed profiles are significantly below 0.5 m for both Tests and exceed this value only locally. The mean, variance and standard deviation of said absolute differences are calculated to be equal to 0.22 m, 0.032 m and

0.17 m, respectively, for Test CE 300, and equal to 0.14 m, 0.009 m and 0.09 m, respectively, for Test CRIEPI 3-1.

On the other hand, the EBPs according to [76] (denoted as “Dean” in Figures 1 and 3) do not simulate profile evolution with comparable accuracy, especially seaward of the erosion-accretion transitions. Absolute differences between measured and EBPs/Dean profiles exceed 1 m along large parts of the profiles. The mean, variance and standard deviation of said absolute differences are calculated to be equal to 0.49 m, 0.52 m and 0.72 m, respectively, for Test CE 300, and equal to 0.75 m, 0.48 m and 0.69 m, respectively, for Test CRIEPI 3-1.

Regarding the—more significant in the context of this work—accretive tests (i.e., Test CE 301—Figure 2 and CRIEPI 1-3—Figure 4), the model simulates accurately the accumulation of sediment at the foreshore and the gradual formation of the berm, in both cases. The significance of the specific feat should be particularly acknowledged, especially considering the size of the berm, in terms of both shoreline advance at SWL and accreted volume. Morphology evolution in the subaerial parts of the profiles is captured satisfactorily, although there appears to be a relative weakness in capturing erosion-accretion transitions underwater that needs to be further investigated. Model results for the computed profiles at half the Tests’ durations (denoted as “Model*” in Figures 2 and 4) are indicative of the evolution of accretive profiles as simulated by the presented model. Absolute differences between measured and computed profiles are significantly below 0.4 m for both Tests and approach this value only locally. The mean, variance and standard deviation of said absolute differences are calculated to be equal to 0.20 m, 0.021 m and 0.14 m, respectively, for Test CE 301, and equal to 0.13 m, 0.013 m and 0.11 m, respectively, for Test CRIEPI 1-3.

It is important to highlight that the wave and morphology evolution model presented in this work achieved the results of Figures 1–4 without any modification of the empirical coefficients of the transport formula of Equation (5). The values of these coefficients were set to $a_w = 6$ and $b = 4.5$ in all model runs, exactly as proposed by Zhang and Larson [41].

4.2. Results for the Investigation of an Erosion/Accretion Criterion

Table 3 presents results for the test conditions presented in Table 2 (NT = New Test). It is noted that Erosion (E) and Accretion (A) classifications in Table 3 refer to model results regarding the equilibrium profile at the end of each simulation. After calculating the respective H_o/wT and H_o/L_o sets of values, results are also presented in Figure 5, along with all data for CE and CRIEPI experiments presented in [40].

Table 3. Model results for the test conditions presented in Table 2 (NT = New Test). Erosion (E) and Accretion (A) classifications refer to model results regarding the equilibrium profile at the end of each simulation.

Test No.	Model Result	Test No.	Model Result
NT01	E	NT12	E
NT02	E	NT13	E
NT03	E	NT14	E
NT04	E	NT15	A
NT05	E	NT16	A
NT06	E	NT17	A
NT07	E	NT18	A
NT08	E	NT19	A
NT09	E	NT20	A
NT10	A	NT21	A
NT11	A	NT22	A

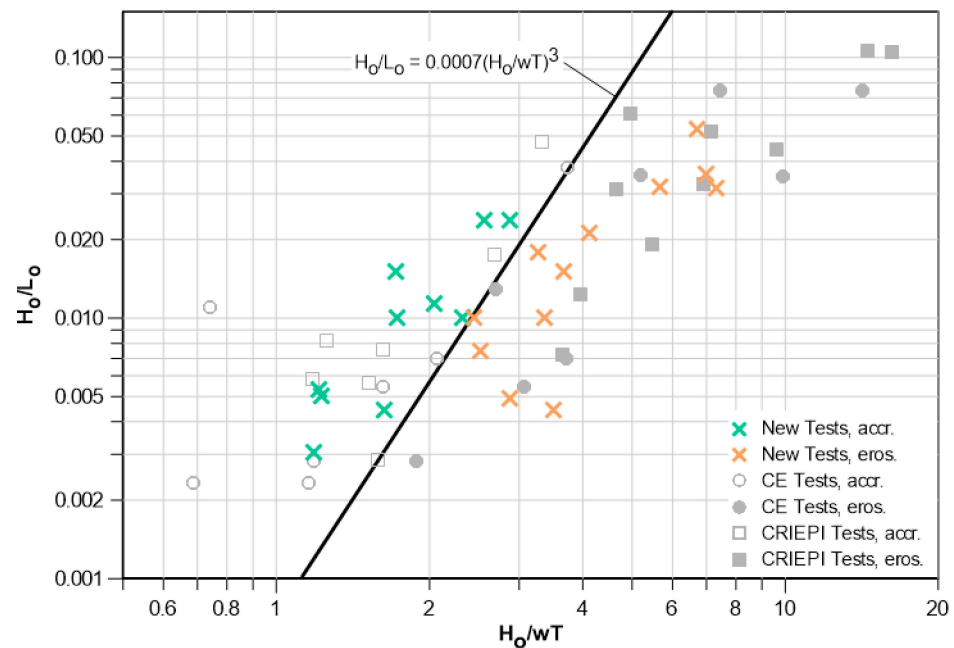


Figure 5. Profile response with regard to accretion (accr.) or erosion (eros.) as simulated by the wave and morphology evolution model of this work for the New Test conditions of Table 2 (see also Table 3), along with the observations in the CE and CRIEPI experiments [40]. The solid line represents the limit of the Larson and Kraus criterion [59], i.e., $H_o/L_o = 0.0007(H_o/wT)^3$.

Figure 5 shows that the wave and morphology evolution model's results and the Larson and Kraus criterion agree in predicting erosive/bar and accretive/berm profiles for a wide range of test conditions, even beyond the CE/CRIEPI experiments regarding both wave conditions and profile characteristics. It is noted again, as for the validation tests of Sections 3.1 and 4.1, that all model runs were setup without modifying the empirical coefficients of the transport formula of Equation (5) from the values sets by Zhang and Larson [41].

5. Conclusions

The new wave and morphology evolution model presented and used in this work builds on previous research by the authors and adopts a new formula for the calculation of sediment transport. Model applications were designed in order to, first, validate the model against experimental data (with particular focus on prominent accretive profiles which are rarely examined in relevant research), and then use it to test the performance of one of the best-known erosion/accretion criteria. The results presented in Section 4 are deemed to highlight the innovative aspects of this work, namely: (a) the accurate simulation of accretive conditions at the foreshore (with a particular note on the relative magnitude of the phenomenon in the selected tests); (b) the fact that the model reproduces experimental data very well for both accretive and erosive profiles with no modification of the empirical coefficients in the sediment transport formula proposed by Zhang and Larson [41]; and (c) the confirmation of the empirical criterion of Larson and Kraus [59] even for conditions beyond the ones it was developed for, without imposing any model constraints.

This work is deemed to provide useful insights on the modelling of morphology evolution in the swash for both research and engineering applications. Along with complementary authors' work on the integrated modelling of coastal wave dynamics, hydrodynamics and morphodynamics [13,15,16,20,77], it is furthermore considered as a step towards research on the combination of advanced numerical models and machine learning methods in coastal engineering.

Author Contributions: Conceptualization, methodology, model development, model validation, model applications, formal analysis, visualization, writing, A.G.S. and T.V.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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