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HYBRID FORECAST SYSTEM OF OVERTOPPING WITH INFRAGRAVITY WAVE INCLUDED

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ABSTRACT

The overtopping over a structure is related to the run up, which in turn depends mainly on the wave and the physical characteristics of the structure. However, it is known that there are other oscillations of longer periods (infragravity waves) which, when the incident wave is of the swell type and the product of storms, become relevant because they have a direct influence on the calculation of the overtopping. The aim of this study was to evaluate the non-hydrostatic version of the XBeach model using a one-dimensional scheme to simulate overtopping events. The model was forced in three different ways: free surface data collected in field, wave parameters representing by Hs and Tp, and directional energy spectra generated by an operational wave and infragravitational wave system (SO3). The main results show that XBeach is able to transfer wave energy at low frequencies along the beach profile. In addition, the XBeach model can be coupled with the directional spectra of energy from the operational system to propagate them into the swash zone and generate overtopping in advance. This could potentially serve as an operational overtopping tool to assist the relevant authorities in managing this issue.

KEYWORDS: Caldera, infragravity waves, overtopping forecast, XBeach.

1 INTRODUCTION

Overtopping is defined as flow exceeding the freeboard of coastal structures mainly due to oscillating wave action. This why, the overtopping of structures is a process inherited from the run-up, which depends on various factors such as waves, infragravity waves, instantaneous sea level, and physical characteristics of the structure (e.g. slope, material of protective layers, porosity, apparent friction, and depth at the foot of the structure). However, when the wave reaches the high energies associated with storms, infragravity fluctuations are known to be particularly significant. Therefore, the resulting infragravity wave associated with the swell also oscillates over tens of centimeters.

Traditionally, the evaluation of overtopping on coastal structures is carried out by the combination of meteo-oceanographic information and the analytical evaluation of the variable, through semi-empirical formulae (EurOtop, 2018). Nevertheless, this approach is only associated with waves and sea level, with no considerations given to e.g. wind and infragravity waves effects. Wind and infragravity waves can dramatically modify run up and overtopping values, especially in high waves situations and on reflected beaches (de Beer et al., 2021; Roelvink et al., 2018; McCall et al., 2014). Furthermore, the overtopping may behave differently than predicted by semi-empirical tools due to changes in both flow rate and geometry.

Nowadays, wave propagation models that solve the phase can be used as approximation methods to calculate run up and overtopping processes. They take into account wave dispersivity and non-linear interactions between spectral components, allowing the transfer of incident energy to super and sub harmonics; this makes them suitable for managing coastal run up processes caused by waves and infragravity waves. These models solve the hydrodynamic equations of the flow motion integrated in depth, with time evolution based on the theory of long waves. For example, models based on the Boussinesq equations, models solving the Reynolds-Averaged Navier-Stokes equations (RANS) in simplified form and models solving the Non Linear Shallow Water equations (NLSW).

This contribution does not concentrate on the effect of wind. However, it takes advantage of the SO3 prediction system (Alfaro, 2017), which combines wave and infragravity waves, to couple it to a model that solves the NLSW equations, such as the non-hydrostatic version of the XBeach model (Roelvink et al., 2009), to determine the overtopping. The availability of joint wave and infragravity wave variables provides an opportunity to enhance the comprehension of these processes resulting from the interaction of waves with the beach coastal. It can also provide an improved method for the functional analysis of coastal structures, significantly increasing the overtopping flow rates, allowing more realistic studies to be proposed for the design of protective structures.

The study site is a section of Caldera beach located in Golfo de Nicoya, on the Pacific coast of Costa Rica (see Figure 1A). Over the years, this site has experienced frequent overtopping events over the perimeter of the rubble mount structure that protects a segment of the beach (see Figure 1B). This situation endangers people, a major road running parallel to the beach and access to the main commercial port on the Pacific coast of Costa Rica.

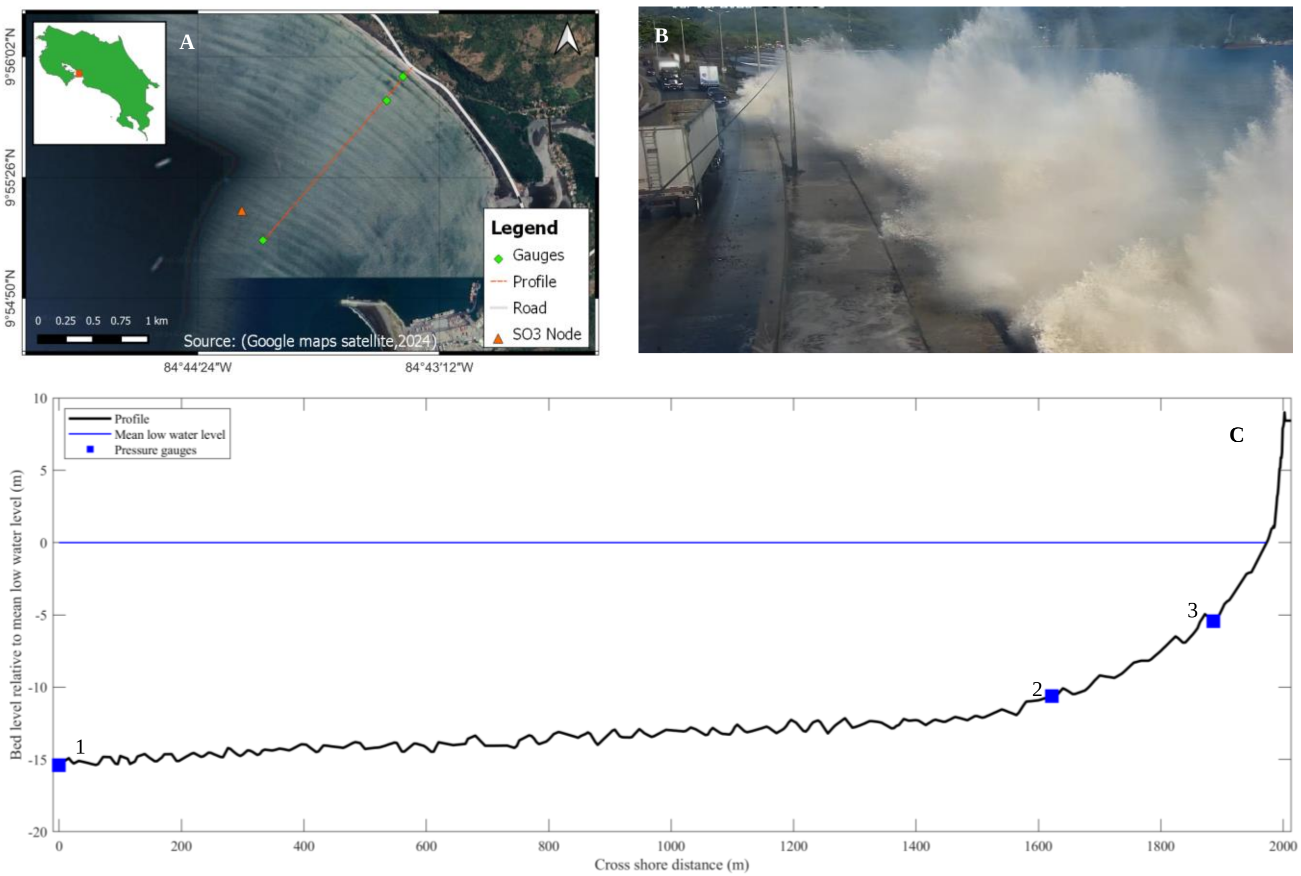

Figure 1. View zone of the study. A) location of profile at Caldera beach; B) Overtopping event in September 2023; C) bathymetry profile along the cross shore transect at Caldera beach and location of pressure gauges (1, 2 and 3).

2 METHODOLOGY

The XBeach model (Roelvink et al., 2009) in its non-hydrostatic module and in its one-dimensional (1D) scheme was used to calculate the overtopping events, specifically, the profile located in front of the Caldera beach section where overtopping on the beach protection structure occurs (Figure 1A). This model was preferred among others due to its low computational cost.

Before the overtopping calculations, the ability of the 1D model to properly generate and propagate both short waves and infragravity waves along the profile was tested; the 1D model was calibrated and validated with field measurements carried out during different months in the 2019, 2021 and 2022 years (Camacho, 2022; Alfaro-Chavarria & Govaere-Vicarioli, n.d.). The calibrated parameters were the maximum wave steepness parameter (maxbrsteep) and wave steepness criterium to reform after breaking (reformsteep) which were assigned values of 0.7 and 0.6 based on reflective beach; in addition, the White-Colebrook method with a grain size of $D90=9x10^{-4}$ m as estimated by Govaere-Vicarioli et al. (2013) was utilized to calculate bedfriction in the model.

Once the hydrodynamic capability of the model was verified, a series of numerical experiments were performed based on three different wave input configurations: the first one (TS) corresponded to forcing the model through the free surface time series recorded by the pressure gauge 1 (Figure 1C); the second (spcSW) was to force the model with wave parameters (Hs and Tp) associated with the same time series, which the model uses to generate a JONSWAP-type spectrum and then a random free surface time series; the third configuration (spcSW+IGW) consisted of forcing XBeach with a directional spectrum generated by the operational system SO3 (Alfaro, 2017). All configurations used the same bathymetric-topographic profile.

Beach profile and free surface data were collected during a 7-day field survey between August 31 and September 6 of 2023, which overlapped with one of the major storms that caused overtopping at the study site during 2023 (Piña, 2023) (Figure 1B). The profile was measured with an echo sounder in the water and on the dry beach with topography, extending from 15 m depth to the surf and swash zones (Figure 1C). Free surface data were measured by three pressure gauges placed along the profile, which were set at 1 Hz to measure 1048 samples hourly to represent the sea states; and significant wave height and peak period (Hs and Tp) wave parameters were calculated for each sea state.

The SO3 forecasts directional spectra with their respective wave parameters (Hs, Tp and Dir) and infragravity wave parameters (H_{IG} y T_{IG}), every 3 hours for the next 7.5 days, at different sites (nodes) distributed inside the Gulf of Nicoya; the SO3 has one of its nodes near pressure gauge 1 (Figure 1A). The SO3 was calibrated and validated by Alfaro (2017), is based on a hybrid downscaling model derived from a Production Hindcast reanalysis (Tolman and Chalikov, 1996).

In each of the three configurations, two numerical experiments were conducted: the first (Exp 1) was to simulate a sea state measured at 16:00 hours on September 2, 2023, which is known to have generated overtopping but not in an excessive manner; the second (Exp 2) was a sea state measured at 5:00 hours on September 3, 2023, which according to people from the community was when most overtopping occurred. Each experiment had a duration of 1 hour to comply with the sea state concept; this time was considered sufficient to have an adequate randomness of the generated wave phases, an adequate statistical significance, and a proper energetic integration of the wave. The spcSW and spcSW+IGW configurations were repeated a total of 100 times each, to evaluate the effect of the randomization of the phases performed by the model. The 100 simulations lasted approximately 2.5 hours, on a computer with a Xeon W-2133 CPU @ 3.6 GHz, with 6 cores and 128 GB of RAM.

The tide level corresponding to the time when the sea state was measured was associated with Exp 1 and Exp 2, which were 3m and 3.2m respectively. Table 1 gives a summary of the information on the experiments carried out in each configuration.

Table 1. Numerical experiments information simulated in XBeach model.

Numerical Experiments	Time and date of sea state	Source of input wave	Wave inputs format	Configuration label
Exp 1	16 hr. Sep 2 2023	Pressure gauge 1	Free surface time series	TS
			Hs=1.7 m, Tp=19 s	spcSW
		SO3 node	Directional spectrum (Hs=1.75 m, Tp=18 s, H_{IG}=0.08 m y T_{IG}=73 s)	spcSW+IGW
Exp 2	5 hr. Sep 3 2023	Pressure gauge 1	Free surface time series	TS
			Hs=2.5 m, Tp=19 s	spcSW
		SO3 node	Directional spectrum (Hs=2.7 m, Tp=19 s, H_{IG}=0.2 m y T_{IG}=86 s)	spcSW+IGW

3 RESULTS

The skill of the XBeach model in its 1D numerical scheme to generate and propagate waves and infragravity wave along the profile was teste; the XBeach model was forced with the free surface time series measured by pressure gauge 1 during the field campaign carried out between August and September 2023. The results were compared with the data measured by the pressure gauges at the three locations where they were deployed (see Figure 1C), using free surface time series plots. Figure 2 compares the modelled and measured free surface time series at the three locations, corresponding to a sea state with a noticeable grouping wave characteristic of swell.

Figure 2A demonstrates a good fit between the model and the data measured by pressure gauge 1, in both amplitude and phase. Figure 2B shows a fit of the phases generated by the model, with a slight increase in amplitude. Figure 2C corresponds to the site where pressure gauge 3 was placed, and shows some time lags between the time series, as well as a slight decrease in amplitude according to the model. The validation process confirmed the capability of the XBeach model for wave propagation along the beach profile.

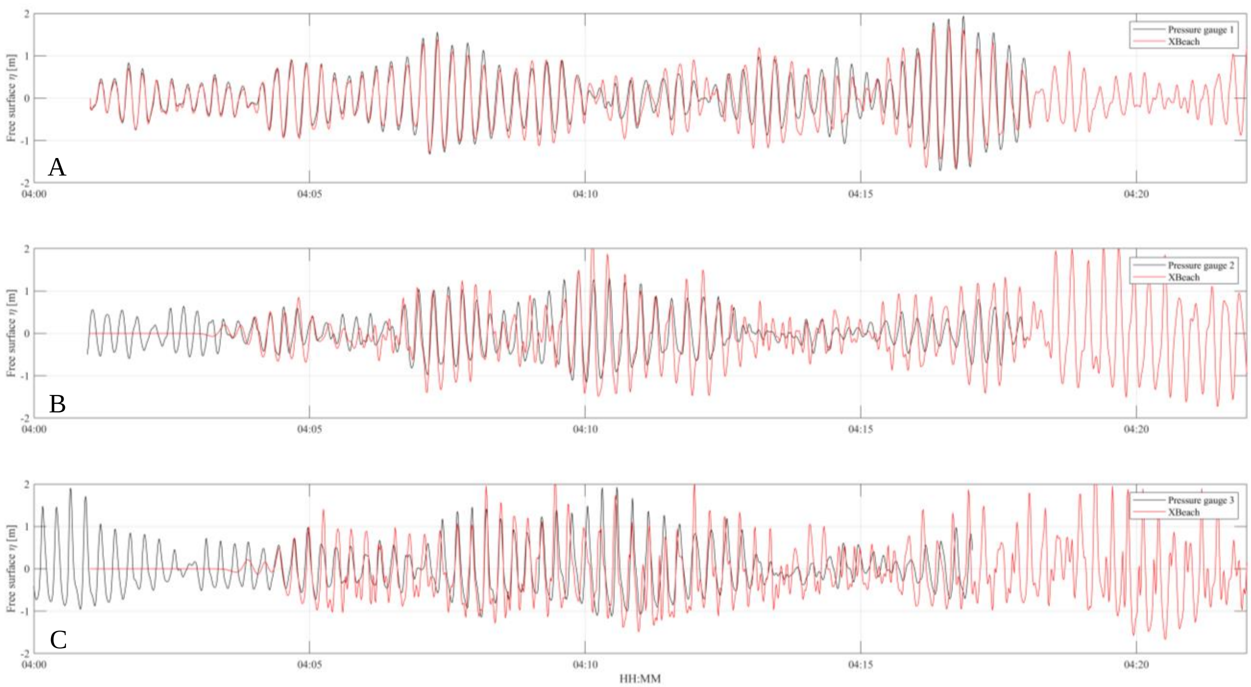

Figure 2. Free surface time series measured and modeled in three locations along the beach profile. A) pressure gauges 1, B) pressure gauges 2 and C) pressure gauges 3.

Figure 3 presents the results of Exp 2 in three configurations: TS (figure 3A), and one of the 100 simulations performed in spcSW and spcSW+IGW (figures 3B and 3C, respectively). Each figure displays the number of overtopping over the crest (+8.8 m) of the beach profile during the simulation. TS configuration produced the highest number of overtopping events, spcSW generated the minimum number of overtopping in comparison to TS and spcSW+IG. This behavior was consistent in the two experiments (Exp 1 and Exp 2), and all simulations.

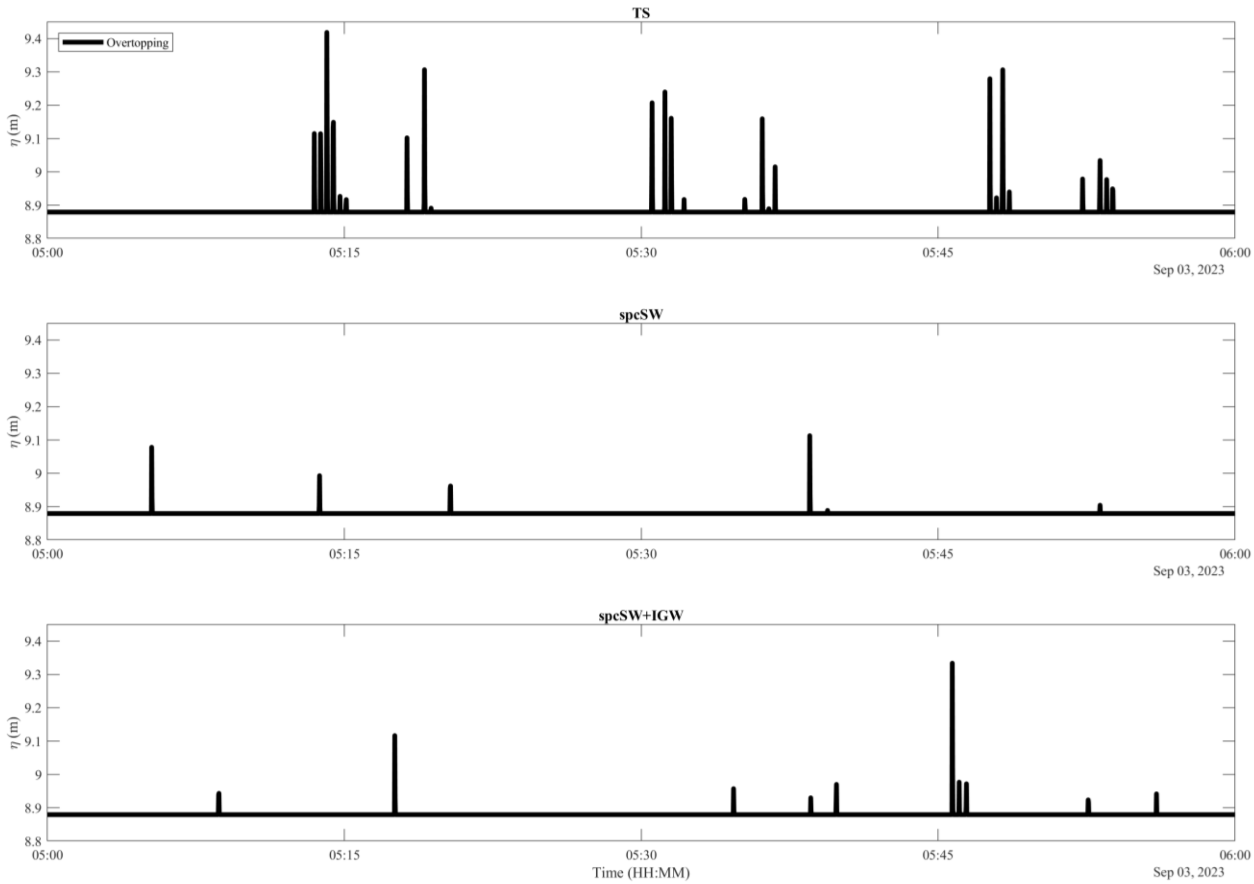

Figure 3. Amount of overtopping calculated in experiment Exp 2. A) TS, B) spcSW and C) spcSW+IGW.

Table 2 shows that the TS configuration produced the highest number of overtopping events in the two experiments, with a total of 1 and 25 for Exp 1 and Exp 2 respectively. This makes sense because the wave magnitude of Exp 1 was smaller than the wave of Exp 2. The spcSW and spcSW+IGW of Exp 1 generated on average 0.01 and 0.03 overtopping after the 100 simulations. In comparison, spcSW and spcSW+IGW in Exp 2 generated an average of 8 and 9 overtopping events respectively in the 100 simulations performed for each; in this experiment spcSW+IGW generated 12.5% more overtopping events than spcSW, but this only represents 36% of the overtopping events generated by TS, meanwhile spcSW generated 32% of the overtopping with respect to TS.

Table 2. Main results of overtopping events in each experiment and wave input configurations

Numerical Experiments	Configuration label	Amount of Overtopping	Percentage of sea state with overtopping (%)	Percentage of overtopping in relation to TS (%)
Exp 1	TS	1	100	-
	spcSW	0.01*	1	0
	spcSW+IGW	0.03*	3	0
Exp 2	TS	25	100	-
	spcSW	8*	100	32
	spcSW+IGW	9*	100	36

Note: The values marked with asterisks (*) indicate the average of overtopping obtained in 100 simulations.

The two experiments presented in Table 1 have been repeated using the same methodology as before. However, the XBeach model was used with default and uncalibrated parameters. After running the simulations (1 simulation for TS, 100 simulations for spcSW and 100 simulations for spcSW+IGW), none of the evaluated configurations resulted in an overtopping events.

4 CONCLUSIONS

The numerical experiments and their results confirm that the non-hydrostatic version of the calibrated XBeach model is capable of transferring wave energy at low frequencies along the surf and swash zones, as well as generating overtopping events on a stretch of Caldera beach. However, there is no overtopping under any of the configurations used in this study if the model is not calibrated.

The overtopping events produced by the spcSW and spcSW+IGW configurations have been validated with TS, reports from inhabitants near the study site, and press articles of extreme events (Piña, 2023). It has been found that the XBeach model produces the most amount of overtopping when forced with free surface time series (TS). When it is forced only with the energy content of the waves generated by parameters (spcSW), it generates the least amount of overtopping, while when it is forced with a directional spectrum containing energy in both the wave frequency bands and infragravitational waves (spcSW+IGW), the number of overtopping events increases but is still less than the results in TS.

The Exp 1 represents a sea state with an energy level close to the average, the overtopping generated in the spcSW and spcSW+IGW after 100 simulations each, only reaches 1% and 3% respectively. On the other hand, Exp 2 which represents a sea state with more energy generates overtopping in the 100 simulations performed in each spcSW and spcSW+IGW configuration; furthermore, both present similar values in terms of the average amount of overtopping events obtained, but less than half of those achieved in TS. The spcSW configuration underestimates the number of overtopping events by 68% while spcSW+IGW underestimates it by 64%.

Coupling the XBeach model with SO3 directional spectra, which contain both wave and infragravity wave energy, allows wave propagation from deep to shallow water, which is considered more realistic at sites where the incident wave is mainly swell. It is known that this type of wave carries energy related to infragravity oscillations; when these waves reach the coast, they can significantly impact sediment transport, alter beach morphology, and affect run up and overtopping. In addition, forcing the XBeach model with directional spectra generated by the SO3 and then performing multiple simulations is considered a computationally low-cost technique.

At present, the system is working properly, and it predicted appropriately the overtopping events, that's way is a good first approximation to reproduce overtopping events. This work could serve as the basis for a future operational overtopping system to help authorities manage this issue, mitigate material risks, and prevent emergencies.

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