Implementation of the SWASH model into HIDRALERTA system

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Abstract: Early warning systems are an important tool for local authorities to detect emergency situations in advance and initiate the necessary safety measure. These systems often depend on numerical models to estimate wave overtopping in the affected areas. The SWASH model has shown to deliver good results in recent overtopping studies. The To-SEAlert project has the aim of increasing the efficiency, robustness and reliability of the HIDRALERTA early warning system. This study shows a first intent to implement the SWASH model to simulate wave overtopping for the Ericeira prototype. SWASH was implemented for one breakwater profile used to simulate the overtopping discharge and evaluate the associated risk levels. It was compared to the current approach used in HIDRALERTA, which resorts to a neural network trained with a physical modeling database, NN_OVERTOPPING2. Finally, both approaches were compared with previously analyzed video images of the breakwater. The results showed that SWASH generally overestimates overtopping and is not in good agreement with the video images. NN_OVERTOPPING2 has a better agreement with the video images. A possible reason for the overestimation might be the wave direction, which cannot be included in one-dimensional simulations in SWASH.

Keywords: Early Warning System, Wave Overtopping, Risk Reduction, SWASH model.

I. Introduction

Early Warning Systems (EWS) are fundamental tools for local authorities to prevent damage and loss of lives due to coastal flooding during storms. Among the different early warning systems dealing with coastal hazards, there is a variety of systems aiming at forecasting wave-induced overtopping, relying on accurate wave overtopping estimations by numerical models.

As wave overtopping at coastal structures is a complex phenomenon and depends on different parameters, the existing methods that can be used to estimate and simulate it are diverse. The parameters considered for the estimation of overtopping include, for example, the incident significant wave height, the spectral wave period at the toe of the structure (the spectral wave period is preferred to either the peak period, or the average period, as it gives more weight to the longer periods in the spectrum), the crest freeboard and the slope of the structure, as well as other geometrical features [1].

While the application of (semi-) empirical formulas is restricted to specific geometries, structure configurations and wave conditions, the prediction of wave overtopping under different or more complex conditions can be a challenge. Therefore, in cases where those formulae fail to give accurate estimations, numerical models can be used to model overtopping at coastal structures. As overtopping is a nonlinear, highly dynamic and stochastic phenomenon, the focus of the efforts of engineers and researchers lies on the modelling of the entire process that leads to the wave-induced overtopping [2].

A recent approach to model wave overtopping is based on the dispersive nonlinear shallow water (NLSW) equations, which allow non-hydrostatic pressure, as well as a resolution of the vertical flow and its structure. The SWASH model [3] numerically simulates non hydrostatic, free-surface, rotational flows in one or two horizontal dimensions. As the governing equations are NLSW equations and include non hydrostatic pressure, they can describe complex and rapidly changing flows in detailed topo-bathymetries that are often found in coastal flooding events. Therefore, the model is able to simulate shallow water flows and nearshore processes, including wave propagation, breaking and runup, wave transmission through structures, non-linear interaction and wave-induced circulation [3].

Several studies on wave overtopping have been carried out using the SWASH model in past years, e.g. [2], [4]–[6]. Zhang et al. [7], for example, computed mean overtopping discharge over a breakwater with an armour layer of Accropode and compared their results with the physical model results of the CLASH database. The authors discovered the necessity to properly calibrate the model to obtain the apparent friction coefficient of the armour layer and to meet the physical model results for the mean overtopping discharge. In the calibration process, they found that the friction coefficient is correlated with the relative crest freeboard Rc/Hs and the wave steepness Sop and developed an empirical equation to be used for the determination of the friction coefficient of Accropode in future studies.

The performance of SWASH was also compared with two numerical models based on the full Navier-Stokes equations, namely DualSPHysics and FLOW-3D [8]. For the estimation of wave overtopping and the impact on a seawall, reasonable predictions were observed from all three models, with SWASH having a significantly lower computational cost than the other two.

Although the development of EWS is still in early stages, efforts have been made to implement these systems in Europe, e.g. through the iCoast [9] and RISC-KIT project [10], where the latter uses the numerical models XBeach (for open beaches) and SWASH (for harbors, pocket beaches and revetments) to simulate overtopping and flooding.

HIDRALERTA [11]–[15] is an EWS for forecast and risk assessment of wave overtopping in coastal zones. It provides forecasts 72 hours in advance and with a 3#hour interval, of wave characteristics and the risk levels associated with specific port activities and coastal receptors. The system uses datasets of several years of sea-wave/water level characteristics and/or pre-defined scenarios, to evaluate wave overtopping and flooding risks of the protected areas.

Eight prototypes are operational in the HIDRALERTA system, five in mainland Portugal (Ericeira and Sines harbours, and Costa da Caparica, Praia de Faro and Quarteira coastal zones) and three in the Azores archipelago (Praia da Vitória, S. Roque do Pico and Madalena do Pico harbours). Presently, HIDRALERTA is being extended to the port of Peniche. The system gets the offshore boundary conditions (wind an wave characteristics) from ECMWF forecasts for the north Atlantic region, which are then propagated to the shore using the wave propagation models SWAN [16] and DREAMS [17]. The astronomical tide is obtained with the XTIDE model [18]. In harbor areas (Fig. 1), the neural network NN_OVERTOPPING2 [19] computes the estimated mean overtopping discharge, q, at each cross-section of the structure. As input conditions, the results of the DREAMS and XTIDE models are used. Warnings are triggered when pre-set thresholds for q are exceeded.

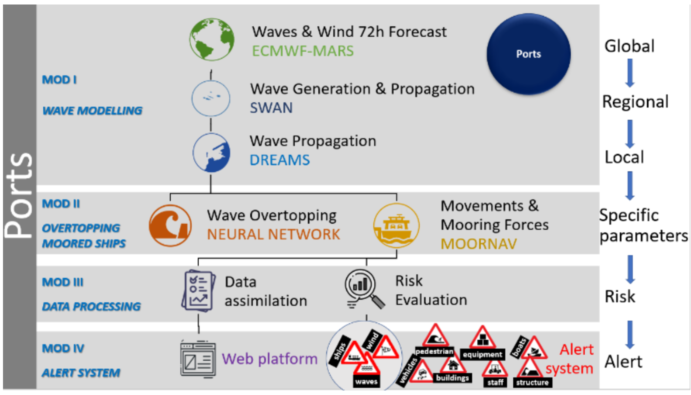

FIG. 1 .

Structure of the HIDRALERTA system for the harbour prototypes

This study describes a first effort to implement the numerical model SWASH [3] to replace NN_OVERTOPPING2 in the HIDRALERTA system for the Ericeira harbor prototype. SWASH is a numerical model that simulates the wave propagation and transformations nearshore and in shallow waters and is also capable of computing the amount of water that overtops the coastal structure in the sea-land interface. Several non-linear physical phenomena are present in its formulation, some explicitly and others are parameterized, thus needing an adequate calibration in order to achieve good results. On the other hand, NN_OVERTOPPING2 is a tool that estimates the mean overtopping of a structure based on a set of data obtained from physical models. The SWASH model is considered a robust process-based model with high accuracy of simulating wave propagation in shallow water [20]. As any point in the numerical domain can be specified in the output of the model, it allows to estimate the inland incursion of overtopping discharges or, in the case of two-dimensional models, the flooded area, and the wave propagation along the domain, which the neural network tool NN_OVERTOPPING2 is not capable of.

Within the scope of the To-SEAlert project, SWASH was applied for one of the cross-sections of the structure to compute the mean overtopping discharge for a range of test cases and to compare the results and the associated risk levels with NN_OVERTOPPING2.

II. Methodology

A. Model Setup

Ericeira harbor is located on the west coast of Portugal and is sheltered by a 430 m long breakwater, oriented to the south-west, with a quay in the rear side (Fig. 2). The profile chosen for the implementation of the SWASH model has an orientation of 309°N, it has an armor layer of tetrapods (Fig. 2) and is in the vicinity of a quay on the lee side of the breakwater.

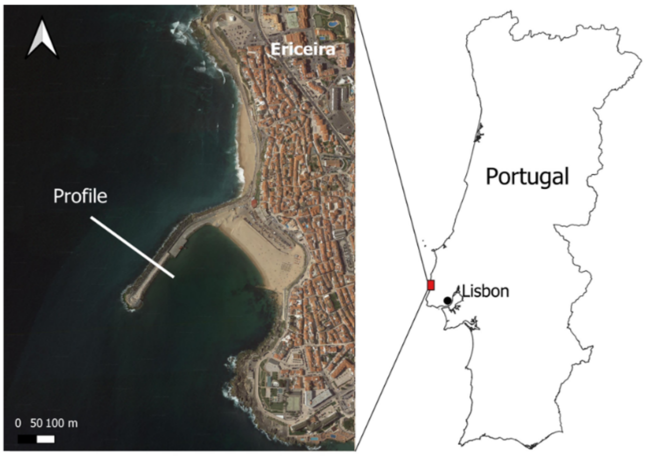

FIG. 2 .
Ericeira breakwater and the profile that was chosen for simulations

Overtopping simulations with SWASH were performed in a one-dimensional mode for a computational period of 131 minutes with an additional spin-up period of 15% of the computational period and an initial timestep of 0.01 seconds. An automatic time step control was implied with a maximum Courant number of 0.5 and a minimum Courant number of 0.1. The recommended number of vertical layers was checked, following the instructions of the user manual, which resulted in one vertical layer for all simulations. To account for bottom roughness, a different Manning friction coefficient was applied to the offshore area (0.019 s/(m1/3), the user's manual default Manning friction coefficient for wave simulations over large distances) and to the armor layer of tetrapods (0.078 s/(m1/3)). The latter is as an average value that was chosen based on the results of [21], where the Manning coefficient was calibrated for the same breakwater profiles for SWASH simulations.

The length of the numerical domain was 419 m, where 334.5 m corresponded to the area offshore, 48 m to the breakwater and 36.5 m to the lee side of the structure (Fig. 3). The bathymetry was constructed with data acquired from EMODnet (150 m grid spacing) and DGTerritorio (LiDAR survey of 2011, 2 m spacing). The profile had a constant grid spacing of 0.5 m.

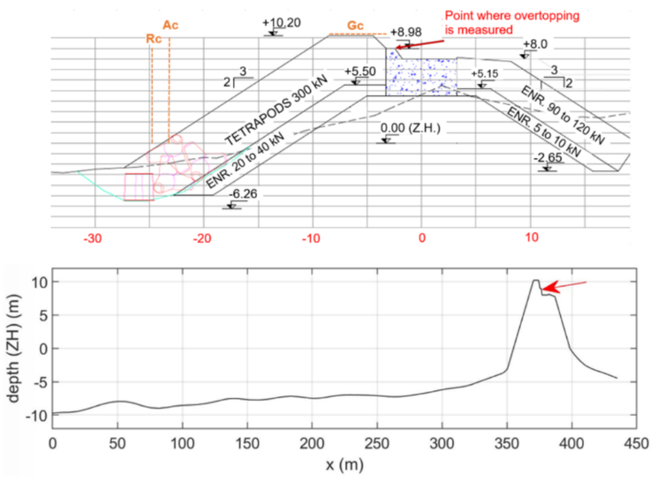

FIG. 3 .
Cross-section of the breakwater profile used for the simulations (top) and bathymetry used in SWASH, with the cross-shore distance referred to the wavemaker boundary and red arrow indicating where overtopping results were extracted (bottom)

At the offshore boundary, a JONSWAP wave spectrum defined the shape of the irregular waves, with a peak enhancement parameter γ=3.3 and a weakly-reflective boundary was imposed. A sponge layer of 100 m was applied at the end of the domain to prevent the reflection of outgoing waves that would give rise to instabilities within the numerical domain. The boundary conditions were chosen based on existing overtopping studies, e.g. [2], [5]. For the non-hydrostatic pressure term a Keller-Box scheme with ILU preconditioner was used to increase the stability of the model.

B. Validation

HIDRALERTA was used to generate overtopping discharge and the associated risk levels for three past storms that covered overtopping and no-overtopping events. Four risk levels (no risk, low risk, moderate and high risk) were produced for five coastal receptors (Table 1).

TABLE 1 .
COASTAL RECEPTORS AND OVERTOPPING THRESHOLDS (l/s/m) IN HIDRALERTA ACCORDING TO EACH RISK LEVEL

Risk level	Trained staff	Aware pedest-rian	Unaware pedest-rian	Vehicles (low speed)	Vehicles (moderate/ high speed)
No risk	[<1[	[<0.1[	[<0.01[	[<10[	[<0.01[
Low risk	[1-5[	[0.1-0.5[	[0.01-0.02[	[10-25[	[0.01-0.03[
Moder-ate risk	[5-10[	[0.5-1[	[0.02-0.03[	[25-50[	[0.03-0.05[
High risk	[≥10	[≥1]	[≥0.03]	[≥50]	[≥0.05]

The results of HIDRALERTA with the newly implemented SWASH model were compared to the approach currently used in HIDRALERTA, where NN_OVERTOPPING2 is used to compute overtopping discharges. Additionally, both approaches were compared to previously analyzed video images of the breakwater. For that, a video-monitoring system was used and it had been implemented in Ericeira within the To-SEAlert project (Fig. 4 top). As that system had some problems (namely the damage of the video-camera during a storm), the project NAVSAFETY (Fundo Azul program, FA_04_2017_013) has provided some images from another video-monitoring system placed in Ericeira (Fig. 4 bottom). However, this latter system was placed at some distance of the breakwater, making the video images analysis more difficult. As not for every event of this study video images were available, only a total of 46 images were analyzed.

FIG. 4 .
Video-systems installed in Ericeira: To-SEAlert project (top) and NAVSAFETY project (bottom)

FIG. 4 .
Video-systems installed in Ericeira: To-SEAlert project (top) and NAVSAFETY project (bottom)

The comparison with the video images was only undertaken for two of the above-mentioned receptors: “Aware pedestrian” and “Vehicles (low speed)”. The videos were categorized into the same risk levels as presented in Table 1 for these two receptors. For the definition of risk levels, possible impacts of the overtopping occurrences in the video images were analyzed according to Table 2.

TABLE 2 .
Risck level definition for video images based on impacts for each receptor

Risk level	Aware pedestrian	Vehicles low speed
No risk	No injuries	Safe to drive
Low risk	Minor injuries	Light motorbikes or bicycles become unstable
Moderate risk	Multiple minor injuries or some serious injuries	Serious damage that affects its use, but without temporary stoppage
High risk	Multiple serious injuries and/or loss of lives	Serious damage that doesn’t allow its use

III. Results

The overtopping discharge computed by SWASH and by NN_OVERTOPPING2 in HIDRALERTA showed significant differences (Fig. 5). While the SWASH model performed well at no-overtopping events, which mainly resulted in the same discharge (0 l/s/m), SWASH generally presented higher overtopping values when compared to NN_OVERTOPPING2. The Root-Mean-Square-Error (RMSE) was 5.47 l/s/m, which is a large error considering the average overtopping discharge of the test cases estimated by SWASH was 0.73 l/s/m.

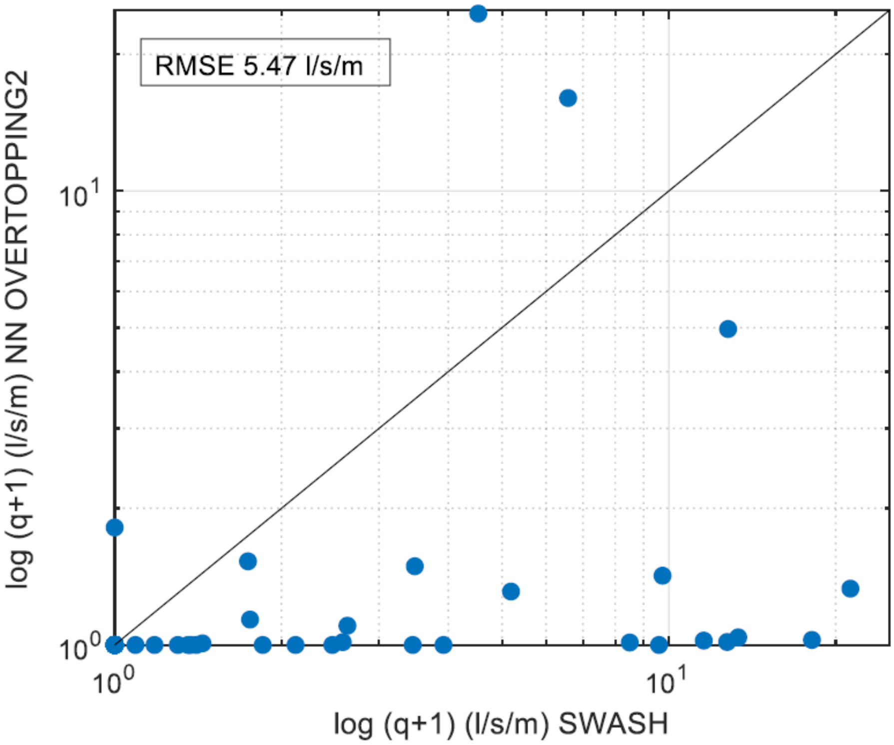

FIG. 5 .

Comparison of q estimated by HIDRALERTA using SWASH and using NN_OVERTOPPING2

As a consequence, the risk levels generated by HIDRALERTA based on the overtopping discharge resulted in higher alerts when using SWASH than when using NN_OVERTOPPING2. Fig. 6 shows the differences in risk levels computed by HIDRALERTA with SWASH and NN_OVERTOPPING2 for the five receptors. It could be observed that the majority of the cases resulted in the same risk level for all five receptors. This majority included 38 of the 63 total cases which were no-overtopping events.

Once overtopping occurs, however, especially for the receptors with lower thresholds for q, the SWASH simulations resulted in higher risk levels than NN_OVERTOPPING2. For aware pedestrians, the risk level was higher in SWASH in 38% of the cases and a maximum difference of three risk levels was found. For trained staff the thresholds for q are slightly higher than for pedestrians and high speed vehicles, which is why the risk levels are mainly surpassed by one risk level (13%) and only 6% and 8% by two and three risk levels, respectively. For vehicles at low speed, which have high thresholds for q compared to the other receptors, a maximum difference of one risk level was found.

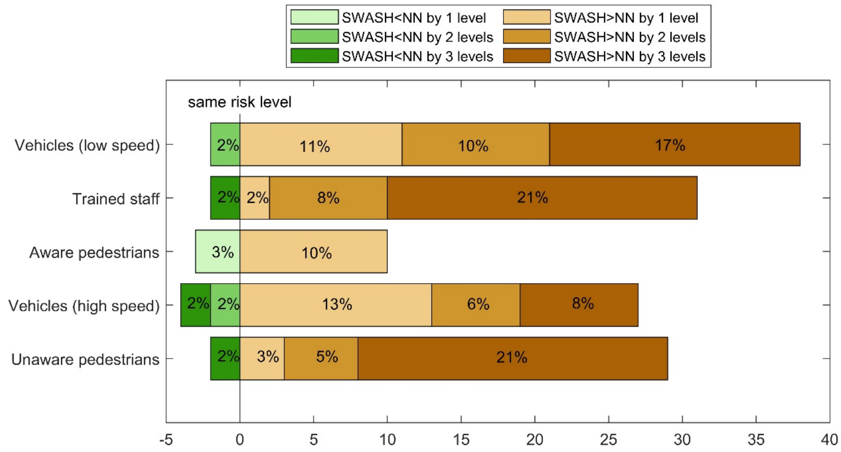

FIG. 6 .
Risk levels generated for the five receptors by HIDRALERTA.
Comparison between results of SWASH and NN_OVERTOPPING2

The validation with video images revealed an overall better performance of NN_OVERTOPPING2 when compared to video images of the breakwater (Fig. 7). For aware pedestrians and low speed vehicles the neuronal network generates the same risk level for the majority of cases (69% and 92%, respectively). Again, for low speed vehicles, a maximum difference of one risk level was found due to the higher thresholds. SWASH showed good results for vehicles, with 85% of consensus and 4% and 11% of one level under- and one or more levels over, respectively. For the lower thresholds of the pedestrians, in 42% of the cases it presents a higher risk level, whereas 46% resulted in the same risk level and 13% were lower by one risk level .

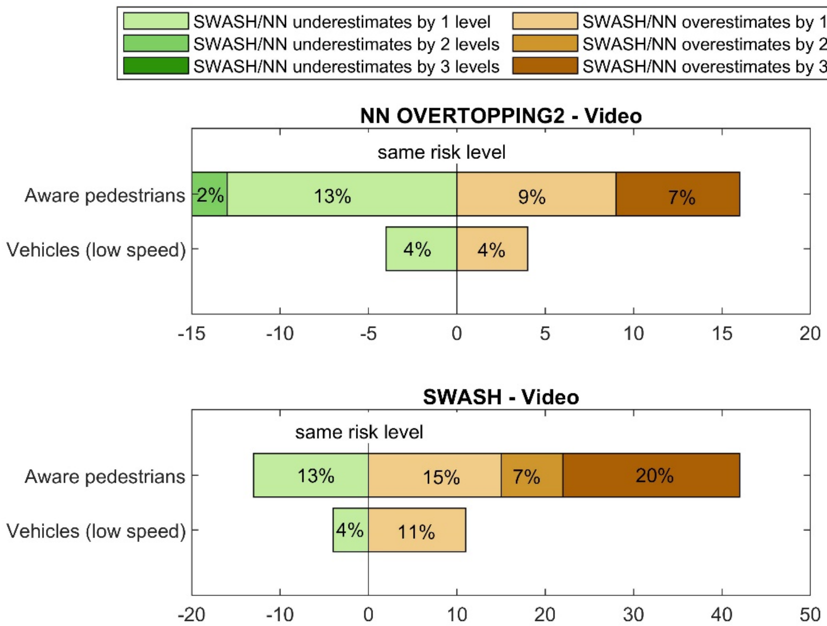

FIG. 7 .
Risk levels generated for aware pedestrians and slow driving vehicles. Comparison between results of NN_OVERTOPPING2 and video images (top) and SWASH and video images (bottom

There are several factors that may influence the performance of SWASH within HIDRALERTA. While NN_OVERTOPPING2 accounts for wave obliquity, it is not possible to include the wave direction in one-dimensional simulations in SWASH and wave obliquity affects the amount of wave overtopping at a coastal structure, e.g. [20]. More specifically, waves attacking a structure perpendicularly cause higher overtopping discharges than oblique approaching waves. Consequently, SWASH assumed in each case that waves approached the structure normally and the results for q may have been particularly high due to this assumption.

Furthermore, in this first test phase, a constant Manning coefficient for the armour layer of the breakwater was applied for the overtopping simulations of SWASH. Previous studies have shown (e.g. [7], [22]) that the performance of SWASH improves when the Manning coefficient is calibrated for a particular breakwater material and that it is correlated with the dimensionless crest freeboard and wave steepness. In [22], several empirical equations have been developed to define the Manning coefficient based on the wave direction, dimensionless crest freeboard and wave steepness, and the results of the SWASH model could be improved when compared to NN_OVERTOPPING2.

While the neural network NN_OVERTOPPING2 is a commonly used tool to estimate overtopping discharge, it does not reflect real data. Although the video images implied an opportunity to compare the simulated discharges and risk levels against qualitative data, it must be considered that the analysis of the videos and categorization of risk levels is partially subjective and furthermore dependent on the visibility and quality of the material. In general, however, the video validation confirmed what the comparison of the two approaches had shown: an overall overestimation of discharge (and thus, of risk) by the SWASH model.

IV. Conclusions

This study demonstrated that the implementation of the SWASH model into HIDRALERTA for the chosen profile was successful but did not deliver good results. The results outlined that SWASH computes significantly higher overtopping discharges than NN_OVERTOPPING2, expect in cases of no overtopping, where it mostly agreed with the neuronal network.

It can be concluded that the wave direction, which is not considered in one-dimensional simulations of SWASH, might play a role in causing these discrepancies, as well as the definition of the Manning friction coefficient of the breakwater material and the video analysis. Although delivering qualitative data to assess the performance of the two methods in terms of risk level predictions, the video analysis does not allow for the quantitative assessment of the two methods performance.

Future work will include implementing of the empirical equations developed by [21] for the definition of the Manning friction coefficient, which considers the angle of wave attack and material of the breakwater. The use of 2D SWASH simulation is also a goal to consider the wave direction. However, a set of simulations should be made a priori to obtain in real time the results of overtopping for the HIDDRALERTA system. Also, efforts must be undertaken to develop low-cost methodologies to deliver quantitative overtopping data in prototype conditions.

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