Wave Overtopping in the Pre-Design of Coastal Works

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ABSTRACT

Wave overtopping situations, mainly caused by growing coastal erosion processes, directly affect the populations, causing coastal flooding, damages, and losses. Investments required for the construction and maintenance of coastal defence structures are thus expected to increase in the future over social, environmental and economically valuable coastal areas. The high costs incurred through coastal structures lifetime require improved knowledge on their performance, being important to deliver optimal solutions that consider impacts, costs and benefits. XD-Coast model was developed to facilitate pre-design processes of coastal structures and the COAST model was developed to perform subsequent cost-benefits analysis. However, the first version of XD-Coast does not allow forecasting wave overtopping phenomena. Thus, this work aims to improve the understanding of the overtopping impacts by including this valence in the XD-Coast and COAST numerical models, allowing to evaluate the relation between the structure design cost and the consequent costs due to overtopping and flooding hazard in the search for optimized solutions. Throughout this work it will be discussed the design of rocky revetments (slope and crown level) and their construction costs, with the potential benefits of reducing the overtopping and flooding consequences. A real case study on the Portuguese coast (Ovar) is also analysed. Conclusions demonstrate that the overtopping and flooding data recorded by the Portuguese Environment Agency (APA) and the ability to adequately reproduce it by formulations, can represent a step forward in the estimative of coastal overtopping and flooding impacts and to define a correlation between events and related costs.

Key words: COAST, XD-COAST, LTC, wave run-up, numerical modelling, optimization

1. INTRODUCTION

Coastal zones experience increased rates of erosion, mainly due to fluvial sediment supply reduction, as well as coastal areas degradation and transformation due to anthropogenic actions, which are aggravated by climate change effects (Nicholls, R. J., 2002; EEA, 2006; Alves *et al*., 2009; Robinson, 2017). As a coastal erosion consequence, a growing trend of conflicts between shoreline evolution, land use and erosion mitigation measures is observed (Coelho *et al*., 2015). Coastal erosion impacts are confined to coastal areas, which host over 40% of the world population, as well as a wide variety of coastal ecosystems that provide various different services (Martínez *et al*., 2007; Roebeling *et al*., 2011). The increasing urban pressure on coastal areas and the continuous shoreline retreat, allow anticipating significant investments to build and maintain shore protection structures along the coast.

Over the last decades the focus of studies moved from physical effectiveness to a more comprehensive management of coastal zones, evaluating adaptation measures with economic tools such as cost-effectiveness or cost-benefit (Breil *et al.*, 2007). Cost-effectiveness studies provide insight in which adaptation measures achieve coastal protection objectives at least cost (Roebeling *et al.*, 2018). Cost-benefit studies provide insight in which adaptation measures/strategies provide largest net benefits, assessing costs and benefits of engineering measures. In short, coastal zone managers should, amongst others, rely on cost-benefit analyses when defining protection, adaptation and/or retreat strategies (Nicholls and Tol, 2006).

Coastal protection works, like groins and longitudinal revetments, need to be thoroughly evaluated before the intervention, as they represent a particular interference with the coastal environment and, hence, lead to multiple, divergent and location-specific impacts, and imply large investment, as well as maintenance costs. So, improving the knowledge related to design of coastal structures and their performance, considering impacts, costs, and benefits, can helps on searching for optimized solutions.

The improvement of numerical tools developed at Civil Engineering Department of University of Aveiro (COAST software, Lima, 2018, Lima and Coelho, 2019a, Lima *et al*., 2020; which includes XD-Coast, Lima, 2011, Lima et al., 2013, Lima and Coelho, 2019b; and LTC models, Coelho, 2005, Coelho *et al*., 2007) can help to better understand coastal phenomena, giving answers to the major problems of the coastal planning and management, integrating transversal knowledge in risk assessment, physical processes, engineering and economic evaluations. The XD-Coast (Xpress Design of COAstal Structures) model was developed to facilitate calculation processes, allowing a quick comparison between several alternative solutions, and to allow sensitivity analysis about variables involved in the calculations, being a good tool to obtain optimized solutions during the pre-design phase of a structure. In the other hand, COAST (Coastal Optimization ASsessment Tool) software was developed to support decision-making for planning and coastal management with sustainable coastal interventions once it allows costs and benefits analysis. The benefits of a coastal intervention scenario can be estimated through the evaluation of the territory maintained, gained, or lost, over time. For this purpose, COAST encompasses the assessment of the shoreline evolution impacts (with a shoreline evolution model, LTC, Long-Term Configuration). Coastal intervention costs (construction and maintenance) are based on structures dimensions and required material. To define the structure geometry (cross-section and length) and, consequently, the structure volume (knowing local bathymetry and topography), the numerical pre-design tool XD-Coast can be applied. Maintenance costs are heavily dependent on overtopping events. However, first version of the XD-Coast model does not allow to forecast structures overtopping.

Wave overtopping situations are those that directly affect the populations causing flooding, losses, and damages (in infrastructures, buildings, equipment, etc.). To control and mitigate the consequences of this phenomenon, it is necessary to understand the processes and to evaluate the relationship between the overtopping events, flooding discharge volumes and consequent damages costs. The existence of several calculation methods for the quantification of the overtopping discharges requires a weighing in the evaluation of the results. The relationship between the discharged volumes in flooded areas and their damages costs is site specific. Thus, it becomes essential to perform sensitivity analysis to estimate the influence of each parameter (related to the wave action or coastal structures characteristics) on the final value of the overtopping discharge, flooding, and damaging costs (van der Meer, 2016). To avoid coastal erosion and flooding, and their consequent social, economic, and environmental negative impacts, it is essential to improve the performance and skills of the pre-design of coastal works models.

This work aims to improve the understanding of the overtopping phenomenon, allowing this valence to be included in the XD-Coast and COAST numerical models. With this, it will be possible to evaluate the relation between the structure design cost and the consequent costs due to overtopping and flooding damages, leading to optimized solutions. To better understand the overtopping phenomena, a real case study on the Portuguese coast (Ovar municipality) was analysed, evaluating data recorded by the Portuguese Environment Agency (APA). Note that, Ovar is one of the most serious coastal erosion areas in Portugal (Coelho *et al.*, 2015).

2. OVERTOPPING AND FLOODING PHENOMENA

When the wave runs up the face of the structure, part of its kinetic energy may be dissipated by wave breaking, friction and percolation and part of it is reflected. After the occurrence of these wave-structure interaction processes, the excess wave energy becomes potential energy that flows as run-up; if the runup level is higher than the crest height, then wave overtopping occurs which means there is the transport of water volumes over the structure that might cause flooding.

The maximum run-up level depends, at each point, on the characteristics of the coastline and, at each moment, on the sum of the following vertical components (Silva *et al.*, 2013): 1) sea level - determined by the astronomical tide, plus storm surge; and 2) wave set-up, that causes an increase in water levels due to waves breaking as they travel shoreward, and wave run-up, understood as the extension of the wave by the structure. The run-up height is measured vertically from the still water line (Pullen *et al.*, 2007) and it also depends on the bottom bathymetry, porosity, roughness, permeability of the core and the slope angle.

In this work, to estimate the maximum run-up level (R_{max}), it was considered the empirical formulation developed by Teixeira (2014). The author performed an analysis and categorization of different formulations to calculate the wave run-up based on the characteristics of the northwest coast of Portugal (natural sandy beaches), thus obtaining by linear regression a simplified empirical formulation (see equation 1) that correlates, for each wave, with the Iribarren number:

$$R_{max} = 0{,}41 H_s \xi \tag{1}$$

where H_s represents the significant wave height and ξ represents the Iribarren number.

As for the overtopping, it was considered the mathematical model presented in Burchart and Hughes (2011) - see equation 2, in which the form and coefficients are adjusted to reproduce hydraulic test results for specific geometries. In this equation, Q represents the dimensionless average discharge per meter and R is a dimensionless freeboard.

$$Q = a\, R \tag{2}$$

For the present work, it was considered the resulting formula (Pedersen and Burcharth, 1992; Pedersen, 1996), suitable for rock armoured permeable slopes with a berm in front of a crown wall and irregular, head-one waves (see equation 3). It does not consider reduction factors directly in the equation and a certain conservative bias for small values of q was observed.

$$Q = \frac{q\, T_{om}}{L_{om}^2} \qquad \text{and} \qquad R = 3.2\, \times 10^{-5} \left(\frac{H_s}{R_c}\right)^3 \frac{H_s^2}{A_c\, \mathrm{B} \cot\alpha} \tag{3}$$

where:

- q – average overtopping discharge per unit length of structure
- H_s – significant wave height [m]
- T_{om} – wave period associated with the spectral peak in deep water [s]
- L_{om} – deepwater wave length corresponding to mean wave period [m]
- R_c – crest freeboard [m]
- A_c – berm crest height [m]
- B – front berm width [m]

α – slope angle.

Note that the notational permeability of the core is considered 0.4.

Due to random nature of many variables in coastal engineering, most of the parameters are uncertain, and so are the empirical formulae. Therefore, when the formula does not cover the actual range of the structure geometry and sea states, preliminary designs should be model tested before actual construction (Burchart and Hughes, 2011).

3. NUMERICAL MODELING

To design a coastal structure, four fundamental steps must be followed. Firstly, it is very important to define a correct load setting, represented by the wave height. Then, the structure pre-design is developed, based on empirical formulations. Thereafter, a physical model at reduced scale should be built and tested in laboratory, to understand the real performance of the structure. Finally, the design of the structure is carried out, considering the pre-design and the laboratory tests results. For the pre-design step, the existence of numerical tools such as XD-Coast facilitates calculation processes, allowing a quick comparison between several alternative solutions and to carry out sensitivity analysis about variables involved in the calculations.

3.1 COAST numerical tool

The COAST was developed to perform cost-benefit analysis applied to coastal interventions (namely groins, longitudinal revetments, artificial nourishments and sand by-pass systems) with the aim of optimizing solutions, decreasing costs and increasing the associated benefits (Lima, 2018). It encompasses three stages (Figure 1) to evaluate the physical and economic performance of the different types of coastal interventions: 1) projection of the shoreline evolution in a medium-term horizon (using LTC numerical model), that leads to estimate the benefits of the intervention; 2) pre-design of the coastal structure and its material volumes (with the support of XD-Coast, that allows to estimate the construction and maintenance costs c; and finally, 3) according to the previous results, a cost-benefit assessment of each intervention scenario is made.

The benefits of a coastal intervention scenario are estimated through the numerical modelling evaluation of the territory maintained, gained, or lost over time. For this purpose, the shoreline evolution numerical model LTC was considered. LTC was developed to support coastal zone planning and management in relation to coastal erosion problems (Coelho *et al.*, 2013; Lima and Coelho, 2017). The estimation of coastal intervention costs is based on structures dimensions and required material and comprises construction and maintenance works. Thus, it is necessary to define the type of blocks and geometry of the structure (cross-section and length) and, consequently, the structure volume (knowing local wave climate, and bathymetry and topography from the shoreline evolution assessment). XD-Coast is a program that evaluates the cross-section characteristics of coastal structures, allowing the calculation of armour layer blocks unit weight and the determination of the main geometric cross-section characteristics. In the cost-benefit module, monetary values are assigned to the materials volumes and structures maintenance requirements (Lima, 2018; Lima and Coelho, 2019a; Lima *et al*., 2020).

To compare and assess the economic viability of different coastal intervention scenarios in COAST, a cost-benefit analysis is performed (following Roebeling *et al*., 2011) considering the net present value and the benefit-cost ratio evaluation criteria (Zerbe and Dively, 1994). Costs and benefits are compared to the non-intervention scenario, where costs are defined as the initial investment and recurrent maintenance costs (in €/year) and benefits are defined as territory maintained, gained, or lost due to the intervention (in €/m^2/year). Initial investment and recurrent maintenance costs are based on XD-Coast design, and erosion/accretion areas are based on LTC shoreline evolution results.

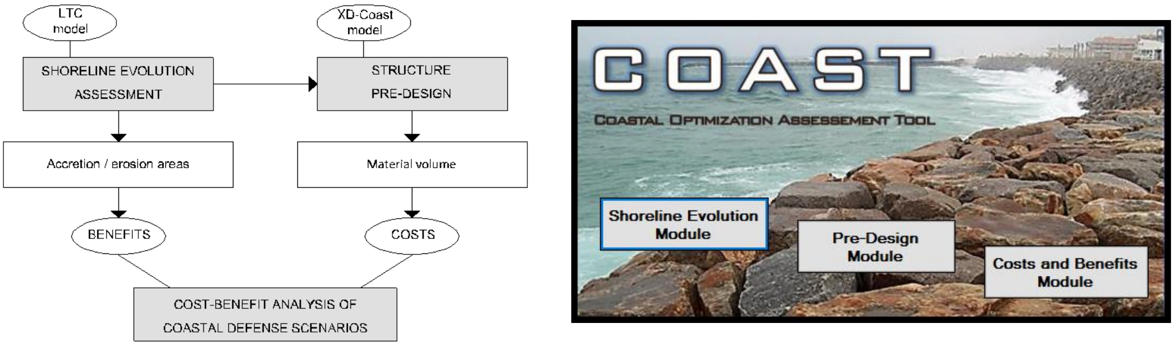


Figure 1: COAST numerical tool.

3.2 Improvement of numerical tools

Numerical tools can help to better understand coastal phenomena, giving answers to the major problems of the coastal planning and management, integrating transversal knowledge in risk assessment, physical processes, engineering, and economic evaluations. Due to the importance of overtopping and flooding events in maintenance costs of longitudinal rocky revetments along these structures time life, this work aims to improve the modelling capability of the overtopping and flooding phenomena and, consequently, allowing these valences to be included in COAST numerical tool. To include overtopping effects in COAST integrated methodology, it is necessary to intervene in all the 3 integrated modules, as follows:

1) **LTC (shoreline evolution module):**

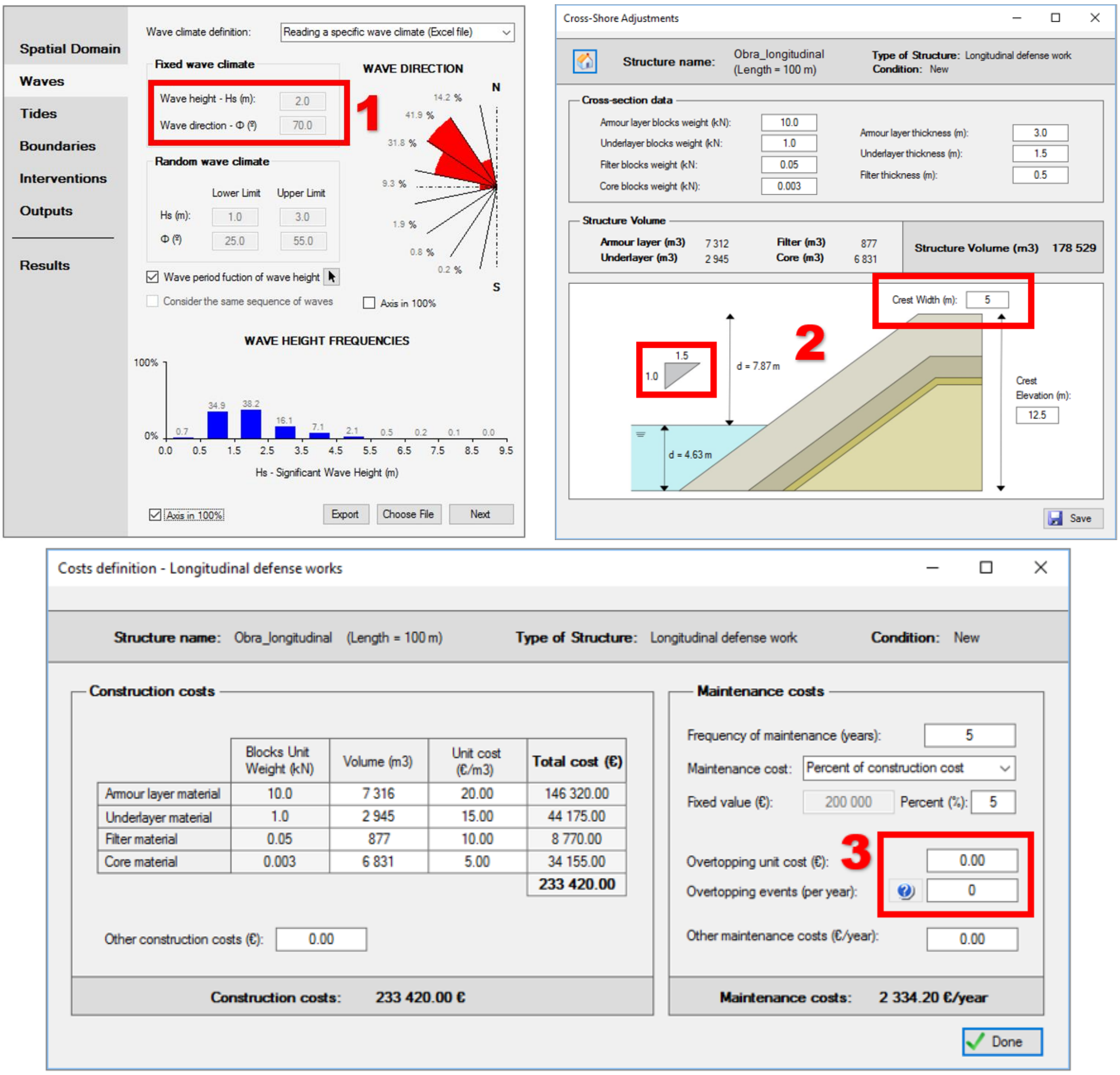
The wave transformation by refraction, diffraction and shoaling is modelled in a simplified manner (Lima and Coelho, 2017), always taking into consideration the updated bathymetric data of each time step. The refraction effects in LTC are estimated through Snell's law, while the shoaling effect is calculated assuming that Airy's linear theory of sinewaves is valid. The diffraction effects are only calculated for beach extensions located downdrift the groins, considering a simplified method. LTC outputs are used in XD-Coast model the propagated wave climate considering the local bathymetry of the structure site.

2) **XD-Coast (pre-design module):**

On XD-Coast model, it is possible to define the most important characteristics of the structure related to overtopping phenomena, namely the crest elevation and the slope angle. By changing these parameters, it is possible to evaluate the consequences of the overtopping events on total costs of the structure, in conjunction with the cost-benefit module. Considering the structure characteristics and the wave climate from LTC model, XD-Coast model estimates the wave run-up (according to equation 1) and the average overtopping discharge per unit length of structure (according to equation 2 and 3).

3) **Cost-benefit module:**

With the information given in the two previous modules, in cost-benefit module it is possible to assess the monetary consequences of overtopping and flooding events, considering the defined structure cross-section. The new features incorporated in the 3 modules allow to carry out the sensitivity analysis that led to an optimized solution in terms of costs, considering the crowning and slope of the structure.
Figure 2 shows COAST's windows considering the new features related to inclusion of overtopping effects where the red numbers in the figure correspond to the previous items, 1), 2) and 3).



Wave climate definition: Reading a specific wave climate (Excel file)

Fixed wave climate

Wave height - Hs (m): 2.0

Wave direction - Φ (º): 70.0

Random wave climate

	Lower Limit	Upper Limit
Hs (m):	1.0	3.0
Φ (º)	25.0	55.0

☑ Wave period fuction of wave height

☐ Consider the same sequence of waves

☐ Axis in 100%

☑ Axis in 100%

Structure name: Obra_longitudinal (Length = 100 m)

Type of Structure: Longitudinal defense work

Condition: New

Cross-section data

Armour layer blocks weight (kN): 10.0

Underlayer blocks weight (kN: 1.0

Filter blocks weight (kN: 0.05

Core blocks weight (kN): 0.003

Armour layer thickness (m): 3.0

Underlayer thickness (m): 1.5

Filter thickness (m): 0.5

Structure Volume

Armour layer (m3)	7 312	**Filter (m3)**	877
Underlayer (m3)	2 945	**Core (m3)**	6 831

Structure Volume (m3) 178 529

Crest Width (m): 5

Crest Elevation (m): 12.5

Structure name: Obra_longitudinal (Length = 100 m) **Type of Structure:** Longitudinal defense work **Condition:** New

Construction costs

	Blocks Unit Weight (kN)	Volume (m3)	Unit cost (€/m3)	**Total cost (€)**
Armour layer material	10.0	7 316	20.00	146 320.00
Underlayer material	1.0	2 945	15.00	44 175.00
Filter material	0.05	877	10.00	8 770.00
Core material	0.003	6 831	5.00	34 155.00
				233 420.00

Other construction costs (€): 0.00

Construction costs: 233 420.00 €

Maintenance costs

Frequency of maintenance (years): 5

Maintenance cost: Percent of construction cost

Fixed value (€): 200 000 Percent (%): 5

Overtopping unit cost (€): 0.00

Overtopping events (per year): 0

Other maintenance costs (€/year): 0.00

Maintenance costs: 2 334.20 €/year

Figure 2: COAST's windows, considering overtopping and flooding effects: LTC (top left), XD-Coast (top right) and cost-benefit (down).

4. STUDY CASE – OVAR (FURADOURO)

The municipality of Ovar, with a total area of about 147.70km² (DGT, 2021) and more than 55000 inhabitants (INE, 2012), belongs to the Aveiro district and is located on the Northwest coast of Portugal (Figure 3). Its coastal system is characterized by being mostly sandy and is exposed to the Atlantic Ocean in a shore extension of about 15km, presenting important coastal erosion problems (Coelho *et al*., 2009; CEHIDRO, 2010; Cruz *et al.*, 2015). The coastal defence works built in urban areas located at north of Ovar also lead to changes in sediment dynamics, spreading the sedimentary deficit problems to the south, due not only to the retention of sediments by the groins, but also to the reduction of beaches erodibility associated to the artificial state of the coastline due to longitudinal revetments (Coelho *et al.*, 2015).

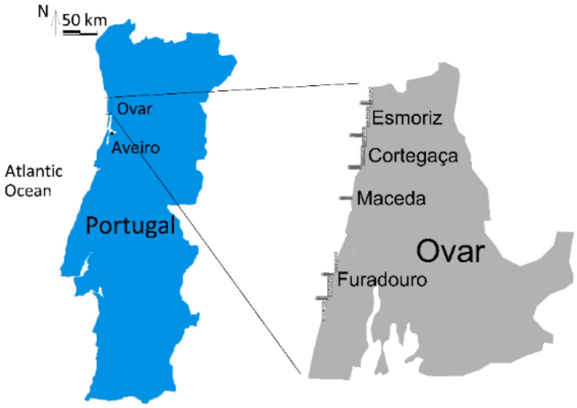
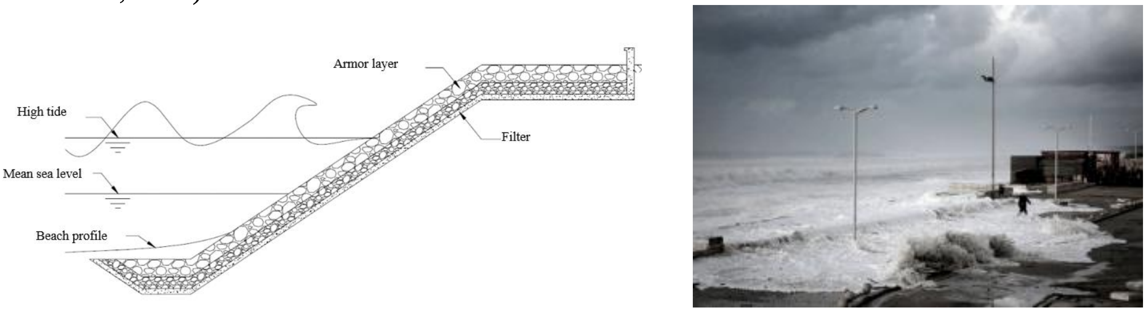


Figure 3: Study area location - Furadouro, at the Ovar Municipality (Cruz *et al.*, 2015).

Along the Ovar Municipality coast, Furadouro is the most densely populated area. The southern limit of the urban waterfront is protected by a longitudinal rocky revetment as schematized in Figure 4a. Due to the current exposure of Furadouro urban waterfront to wave actions during storms, the occurrence of damage events such as overtopping, flooding of public roads and facilities and damage to infrastructures along the coast are frequent (Figure 4b). Furadouro beach has also the highest number of damage events in Ovar municipality, keeping a clear upward trend in the number of occurred events in recent decades (Coelho *et al.*, 2016)



a) b)

Figure 4: Furadouro coastal defence: a) Scheme of the longitudinal rocky revetment and b) occurrence of overtopping events [**Error! Reference source not found.**].

Since mid-2017, this type of occurrence is being registered by the Portuguese Environmental Agency (APA) in record sheets with flooding extension and the observed damages data, within the scope of a monitoring program. Figure 5 represents an example of these sheets and the location and type of the 44 events registered between 2018 and 2020 at Furadouro beach. To reproduce these events by formulas, the 2018-2020 wave climate was considered in the developed analysis. The used information corresponds to hindcast data from the reconstituted series obtained through the WAVEWATCH III^{TM} spectral model, whose results have been validated (Dodet *et al.*, 2010). Considering the mean sea level (+2.0m CD) and the wave propagation phenomena of refraction and shoaling, the run-up estimates were evaluated for 2018 to 2020, every 3 hours, as shown in Figure 6. For the calculations, the rocky revetment slope was defined as 30º, the crown level was considered equal to +5.8m (CD) and overtopping was assumed if the run-up exceeded the wall level (+6.7m CD), corresponding to the black line in the Figure 6. The red dots represent the 44 events registered between 2018 and 2020 at Furadouro beach (according to Portuguese Environmental Agency data sheets).

apa agência portuguesa do ambiente

MONITORIZAÇÃO COSTEIRA

Ocorrência nº 455

Módulo de Reporte de Ocorrências no Litoral

ARH: ARH do Centro
Distrito: AVEIRO
Concelho: OVAR
Freguesia: OVAR
Praia: Praia do Furadouro
Longitude: -8.67800401694405
Latitude: 40.8702627401453

Data da Ocorrência: 2018-11-19 11:15
Data do Registo Local: 2018-11-19 11:15

Técnico: Paulo Manuel Correia da Silva
Email: paulo.silva@cm-ovar.pt
Entidade: Câmara Municipal de Ovar

Observações: Arrastamento de 2 blocos de enrocamento para a marginal na ordem dos 3 metros, na sequência dos galgamentos costeiros no dia 17.11.2018.

c. Dano em obra/estrutura de proteção costeira
b. Danos em infra-estruturas
v. Outras

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Figure 5: Example of APA record sheet with data on occurred events (left) and their respetive location (right) at Furadouro beach. The coloured dots represent different consequences: orange - shoreline retreat; yellow - overtopping; green - damages in infrastructures; pink - damages in coastal defence structures.

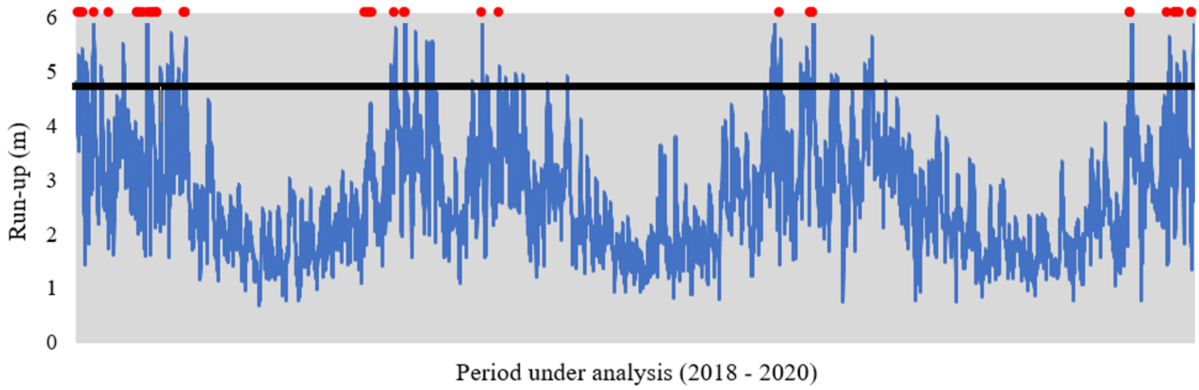

Figure 6: Wave run-up estimates between 2018 and 2020 (black line – overtopping limit; red dots – events registered by APA).

The results show a good convergence between the overtopping prediction (blue curve in Figure 6, calculated according to equation 1) and the real events registered (red dots in the same figure corresponding to overtopped waves). For the waves that result in overtopping, equations 2 and 3 were applied to estimate the flooding volumes. If several consecutive waves result in overtopping, only one event was considered, and the overtopped volume of each wave was added. Table 1 represents the obtained results and the relationship between the real data and observed consequences. The difficulty of adjusting formulas to the site-specific characteristics of the places where overtopping events occur may explain the discrepancies between flooding volumes and observed flood extension/damage.

Table 1: Data cross-checking: expected overtopping discharg (q) and actual flood extension and consequences.

Date	**q (x10^3 m^3/m)**	**Real data - flood extension (m)**	**Date**	**q (x10^3 m^3/m)**	**Real data - flood extension (m)**	**Date**	**q (x10^3 m^3/m)**	**Real data - flood extension (m)**
01/01/2018	4.21	25	09/10/2018	-	20	12/12/2019	11.65	-
04/01/2018	8.91	15	13/10/2018	-	- *	15/12/2019	18.19	-
06/01/2018	8.47	25 to 30	04/11/2018	4.56	-	20/12/2019	99.67	25 *
10/01/2018	13.85	-	07/11/2018	20.16	15	22/12/2019	99.67	27
17/01/2018	70.11	20	17/11/2018	37.49	1 to 30 *	23/12/2019	99.67	15 to 30 *
25/01/2018	6.76	-	28/11/2018	11.53	-	08/01/2020	4.35	-
01/02/2018	14.11	5	09/12/2018	6.70	-	14/01/2020	3.46	-
01/03/2018	-	40	13/12/2018	28.15	-	10/02/2020	15.73	-
03/03/2018	-	30	23/01/2019	4.35	-	15/02/2020	5.30	-
05/03/2018	-	15	01/02/2019	91.66	10 *	17/02/2020	20.18	-
11/03/2018	69.02	20	06/02/2019	3.03	-	01/03/2020	1.01	-
15/03/2018	-	15	18/02/2019	5.93	20 *	26/10/2020	2.78	-
16/03/2018	-	15	25/02/2019	1.19	-	29/10/2020	41.09	20 to 35 *
24/03/2018	9.04	-	06/03/2019	4.34	-	04/12/2020	66.18	20
30/03/2018	10.68	25	13/03/2019	5.84	-	12/12/2020	4.12	30
31/03/2018	10.68	20	06/04/2019	1.51	-	13/12/2020	4.28	30
04/04/2018	15.69	20	25/04/2019	4.91	-	14/12/2020	4.28	50 *
09/04/2018	1.14	-	10/11/2019	4.42	-	15/12/2020	4.28	30 *
10/04/2018	4.87	-	12/11/2019	70.61	-	16/12/2020	4.28	20 *
16/04/2018	2.88	6 to 40 *	20/11/2019	10.18	20 to 25 *	18/12/2020	11.47	-
17/04/2018	11.65	45 *	09/12/2019	4.98	-	28/12/2020	65.71	5 to 25 *

* Damages observed in the rocky revetment structure or in the surrounding infrastructures.

5. CONCLUSIONS

The high costs related with coastal erosion mitigation structures require improved knowledge on their performance, being important to search for optimal solutions.

The XD-Coast model was developed to facilitate pre-design processes However, first version of the XD-Coast model does not allow to forecast structures overtopping and these events directly affect the populations causing flooding, losses, and damages. In addition, they can cause very high maintenance costs. COAST software, which encompasses XD-Coast and LTC models allows to perform cost-benefits analysis. Thus, this work aimed to improve the numerical modelling capability to reproduce the overtopping and flooding phenomena. This modelling potential will make possible to evaluate the relationship between the structure design cost and the consequent costs due to overtopping and flooding damages, leading to optimized solutions. LTC carries for the XD-Coast the propagated wave climate considering the local bathymetry of the structure site. Considering the structure characteristics and the wave climate from LTC numerical model, on XD-Coast the wave run-up and the average overtopping discharge per unit length of structure can be estimated and the parameters related to overtopping phenomena can be defined. Changing these parameters, it is possible to evaluate the consequences of the overtopping events on total costs of the structure. With cost-benefit module it is possible to assess the monetary consequences of overtopping events, considering the structure cross-section defined. These new features allow sensitivity analysis to be carried out that lead to an optimized rocky revetment solution in terms of costs.

To better understand if overtopping and flooding formulas adequately reproduce real situations, a case study on the Portuguese coast (Ovar) was also analysed. Overtopping and flooding discharges estimates were compared with data recorded by APA, the entity responsible for coastal management in Portugal.

The ability to adequately reproduce overtopping and flooding impacts by formulations can represent a step forward to define a relationship between events and related costs. Considering this, the performed work will allow to discuss the design of rocky revetments (slope and crown level) and their construction costs, with the benefits of reducing the overtopping and flooding consequences and impacts.

The integrated coastal zone management needs these tools and studies to ensure sustainable coastal zones, mitigating erosion and climate change effects with optimized solutions that allows better performances at lower costs.

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AUTHOR’S CONTRIBUTION

ML developed and wrote the first draft of the manuscript and was responsible for the improvements in the numerical models. CBC supervised and coordinated the work and developed the case study content. RNP developed the theoretical content about overtopping and flooding phenomena. AFJ performed the calculation required for the study case. All authors edited and approved the manuscript.

REFERENCES

Alves, F., Roebeling, P., Pinto, P. and Batista, P. (2009). Valuing ecosystem service losses from coastal erosion using a benefits transfer approach: A case study for the central Portuguese coast. Jour. Coast. Research, SI56, 1169-1173.

Breil, M., Catenacci, M. and Travisi1, C. (2007). Impatti del cambiamento climatico sulle zone costiere: Quantificazione economica di impatti e di misure di adattamento - sintesi di risultati e indicazioni metodologiche per la ricerca futura. Palermo, Italy. Report prepared for the APAT Workshop: 27–28.

Burchart and Hughes (2011); “Fundamentals of Design”; Coastal Engineering Manual, Part VI, Chapter 5, U.S. Army Corps of Engineers, Washington, D.C.

CEHIDRO; (2010); Exigência do elemento prévio número 1 da DIA do projecto de reconfiguração da barra do Porto de Aveiro, Administração do Porto de Aveiro.

Coelho, C. (2005). Riscos de Exposição de Frentes Urbanas para Diferentes Intervenções de Defesa Costeira (in Portuguese). Ph.D. Thesis.

Coelho, C., Veloso Gomes, F. and Silva, R. (2007). Shoreline Coastal Evolution Model: Two Portuguese Case Studies. Proceedings of the 30th International Conference on Coastal Engineering, pp. 3430-3441.

Coelho, C.; Conceição, T.; Ribeiro, B. (2009). Coastal erosion due to anthropogenic impacts on sediment transport in Douro river, Portugal, Proceedings of coastal dynamics, impacts of human activities on dynamic coastal processes; ISNB: 978-981-4282-46-8.

Coelho, C., M. Lima, and F. Veloso-Gomes (2013); Relationship Between Cross-Shore Active Profile and One-Line Shoreline Evolution Models Performance. Journal of Coastal Research: p. 2107-2112.

Coelho, C.; Pereira, C.; Costa, S.; Lima, M. (2015); A erosão costeira, as tempestades e as intervenções de defesa costeira no litoral do concelho de Ovar, Portugal, Ressacas do Mar/Temporais e Gestão Costeira (2015). 448 p. ISBN 978-85-7924-440-7 (in Portuguese).

Coelho, C., Cruz, T. and Roebeling, P. (2016). Longitudinal revetments to mitigate overtopping and flooding: Effectiveness, costs and benefits. Ocean and Coastal Management 134: 93-102.

Cruz, T. (2015). Análise Custo-Benefício de Obras Longitudinais Aderentes. Master thesis, University of Aveiro, Portugal, 140 p.

DGT (2021); Áreas das freguesias, municípios, distritos e ilhas da carta administrativa oficial de Portugal, Instituto Geográfico Português; Portugal; (last access in 04/ 2021) URL: https://www.dgterritorio.gov.pt/cartografia/cartografia-tematica/caop.

Dodet, G., Bertin, X. & Taborda, R. (2010). Wave climate variability in the North-East Atlantic Ocean over the last six decades. Ocean Modelling, 31 (3-4), 120-131.

EEA (2006). The Changing Faces of Europe's Coastal Areas. Copenhagen, Denmark. EEA - European Environment Agency: p. 107.

INE; (2012); Censos 2011: Quadros de apuramento por freguesia, URL: http://www.ine.pt/investigadores/Quadros/Q101.zip (last access in April 2021).

Lima, M. (2011). Programação de Métodos de Pré-Dimensionamento de Obras Costeiras. Master Thesis, Aveiro University, 131p.

Lima, M., Coelho, C., and Cachim, P. (2013).“Programming Methods for Pre-Design of Coastal Structures”, V International Conference on Computational Methods in Marine Engineering, Marine 2013, 12 p.

Lima, M. and C. Coelho (2017). LTC shoreline evolution model: Assumptions, evolution, validation and application. Journal of Integrated Coastal Zone Management. 17(1): p. 5-17.

Lima, M. (2018). Ferramenta Numérica de Análise do Impacto de Intervenções de Defesa Costeira na Evolução da Linha de Costa: custos e benefícios. PhD Thesis. University of Aveiro.

Lima, M., Coelho, C. (2019a). “Improvement of an Existing Shoreline Evolution Numerical Model”; Proceedings of the MARINE 2019 - Computational Methods in Marine Engineering VIII, 502-513.

Lima, M.; Coelho, C. (2019b). Assessing Costs and Benefits of Coastal Structures to Mitigate Erosion. In Proceedings of the Coastal Structures, 30 Sept.–2 Oct. 2019; pp. 864–874.

Lima, M.; Coelho, C.; Veloso-Gomes, F.; Roebeling, P. (2020), An integrated physical and cost-benefit approach to assess groins as a coastal erosion mitigation strategy. Coastal Engineering, 156, 103614.

Martínez, M. L., Intralawan, A., Vázquez, G., Pérez-Maqueo, O., Sutton, P. and Landgrave, R. (2007). The coasts of our world: Ecological, economic and social importance. Ecological Economics 63(2-3): 254-272.

Nicholls, R. J. (2002). Rising sea levels: Potential impacts and responses. Global Environmental Change. R. E. Hester and R. Harrison, The Royal Soc. of Chem.17: 83-108.

Nicholls, R. J. and Tol, R. S. J. (2006). Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century. 364(1841): 1073-1095.

Pedersen, J., Burcharth, H. (1992); "Wave Forces on Crown Walls"; Proceedings of the 23rd International Coastal Engineering Conference, American Society of Civil Engineers, Vol.2.

Pedersen, J., (1996). "Experimental Study of Wave Forces and Wave Overtopping on Breakwater Crown Walls"; Series paper 12, Hydraulics & Coastal Engineering Laboratory, Department of Civil Engineering, Aalborg University, Denmark.

Pullen, T.; Allsop, N.; Bruce, T.; Kortenhaus, A.; Schüttrumpt, H.; van der Meer, J.; (2007); EurOtop Wave Overtopping of Sea Defences and Related Strutctures: Assessment Manual; Expertise Netwerk Waterkeren, Netherlands, 193 p.

Robinson, S. A. (2017). Climate change adaptation trends in small island developing states. Mitigation and Adaptation Strategies for Global Change 22(4): 669-691.

Roebeling, P. C., Coelho, C. D. and Reis, E. M. (2011). Coastal erosion and coastal defense interventions: A cost-benefit analysis. Journal of Coastal Research, SI64, 1415-1419.

Roebeling, P., d'Elia, E., Coelho, C. and Alves, T. (2018). Efficiency in the design of coastal erosion adaptation strategies: An environmental-economic modelling approach. Ocean and Coastal Management 160: 175-184.

Silva, A.; Taborda, R.; Lira, C.; Andrade, C.; Silveira, T.; Freitas, M.; (2013); "Determinação e Cartografia da Perigosidade Associada à Erosão de Praias e ao Galgamento Oceânico"; Entregável 1.3.2.a, Consultoria para a Criação e Implementação de um Sistema de Monitorização do Litoral abrangido pela área de Jurisdição da Administração Regional Hidrográfica do Tejo, FCUL, Lisboa.

Teixeira, N.; (2014); "Estudo do limite de espraiamento das ondas"; tese de mestrado, Departamento de Engenharia Civil da Universidade de Aveiro, Aveiro, 186 p.

van der Meer, J., Allsop, N., Bruce, T., De Rouck, J., Kortenhaus, A., Pullen, T., Schüttrumpf, H., Troch, P. and Zanuttigh, B. (2016). EurOtop "Manual on wave overtopping of sea defences and related structures. An overtopping manual largely based on European research, but for worldwide application.

Veloso-Gomes, F. (2010); Contributos para a revisão do plano de ordenamento da orla costeira na região centro, Quintas Jornadas de Hidráulica, Recursos Hídricos e Ambiente; FEUP; ISNB: 978-989-95557-4-7 (in Portuguese).

Zerbe, R. O. and Dively, D. D. (1994). Benefit-Cost Analysis in Theory and Practice. Harper Collins College Publishers, New York, USA, 557p.