

# EFFECTS OF BOTTOM DEPTH AND ARTIFICIAL SAND NOURISHMENTS ON OVERTOPPING

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Worldwide beaches and dunes are under coastal erosion due to sediments deficit and climate change effects, leading to the shoreline retreat and loss of territory. The reports about events of coastal overtopping and flooding are being more frequent in last few years. In fact, overtopping can occur during extreme events, such as storms, or more recurrently, due to sea level rise or coastal erosion. When the wave runup exceeds the maximum height of a coastal structure, whether natural (dune) or a coastal defence work, overtopping will flood the adjacent areas. This work aimed to evaluate the behaviour of the beach profile and its effects on overtopping of dunes and coastal structures. In front of longitudinal rocky revetments, due to the waves reflective effect, a deepening trend of the cross-shore bottom profiles is observed, requiring structures reinforced foundations and/or increased crest levels. These cross-shore sediments dynamic associated with the scarcity of sediments (areas protected by coastal works usually present a sediment deficit and erosion problems), will increase the depth, which will consequently allow higher waves breaking nearshore, also increasing overtopping. This behaviour was tested in a flume, for two different beach profiles, with a coastal structure. Then, discussing eventual mitigation measures, different scenarios of artificial nourishments were tested in a numerical model, CS-Model, for a cross-shore profile with a dune being overtopped. Options included reinforcing the dune in different locations and with different deposited volumes. The objective was to evaluate the impact of different scenarios of artificial sand nourishments, in order to mitigate coastal overtopping, in generic wave climate and geometric profile conditions, representative of the northwest Portuguese coast. The obtained results show that there is a deepening trend of the bottom in front of coastal structures and the best way of artificially nourish beach profiles can be discussed using numerical models, helping in future maintenance of coastal structures and design of nourishment projects.

*Keywords: Physical modelling; Numerical modelling; CS-Model; Dunes; Coastal structures*

## INTRODUCTION

Coastal erosion results from the removal of sediment from beaches and dunes, leading to the shoreline retreat and consequent loss of territory. Reports of coastal overtopping and flooding due to coastal erosion processes are common. Overtopping can occur sporadically, during extreme events, such as storms, or more recurrently, due to sea level rise or coastal erosion. Overtopping occurs when the wave runup exceeds the maximum height of a coastal structure, whether natural (dune) or a coastal defence work (e.g. rocky revetment). Due to the reflective effect of longitudinal coastal structures, a deepening trend of the cross-shore bottom profiles is observed, requiring structures reinforced foundations and/or increased crest levels (Figure 1).



**Figure 1. Reinforced coastal revetments: left) works deepening the foundation of a longitudinal revetment at Vagueira, Portugal; right) increased crest level of a longitudinal revetment at Esmoriz, Portugal.**

This work aimed to evaluate the behaviour of the beach profile and its effects on overtopping of dunes and coastal structures. The reflection of incident waves on structures causes reflexes (which depend on the slope, roughness and permeability of the surface), that promotes sediment transport to greater depths. Therefore, in one initial phase, physical tests in a flume were conducted, in the presence of a coastal structure. Later, numerical modelling was applied to test nourishments influence on the

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number of overtopping events. The objective was to evaluate the impact of different scenarios of artificial sand nourishments (volumes and cross-shore location), in order to mitigate coastal overtopping, in generic wave climate and geometric profile conditions, representative of the northwest Portuguese coast.

### METHODOLOGY AND MODELLED SCENARIOS

The cross-shore sediments dynamic in front of a longshore rocky revetment, associated with the scarcity of sediments (areas protected by coastal works usually present a sediment deficit and erosion problems), will increase the bottom depth, which will consequently allow higher waves breaking nearshore, also increasing overtopping. This behaviour was tested in a flume, for two different beach profiles, with a coastal structure. Then, discussing eventual mitigation measures, different scenarios of artificial nourishments were tested in a numerical model, CS-Model (Larson *et al.*, 2016), for a cross-shore profile with a dune being overtopped. Options included reinforcing the dune, feeding the beach berm, deposit sand along the entire active profile or, reinforcing a submerged bar, a barrier that dissipates wave energy. Therefore, the study's methodology consisted of two main phases, one considering flume tests and the other, considering numerical simulations.

#### Flume Tests

The flume tests were carried out in a 10m long channel, with a cross section of 0.4x0.5m<sup>2</sup> and a manual wave generator. A 1/40 model scale structure was installed in the channel and two beach profile scenarios were considered (Figure 2). A narrow-emerged beach and a wider submerged beach were tested during 6 minutes, under 3 different water levels (10cm, 13cm and 15cm), for one wave height of 10cm (4m at the prototype) and 2 different wave periods (1.5 and 3 seconds). The 6 minutes time of tests was considered enough to get the profiles developing to an equilibrium shape, that is similar at the end of both beach profiles, when under the same water level and wave conditions.



Figure 2. Beach profiles tested: top) 15cm initial emerged berm level; bottom) 10cm initial submerged berm level (adopted from Pires, 2024).

The slope of the structure was 2/3 (V/H), with concrete blocks as a resistant layer and rip rap in the intermediate layers. The beach in front of the structure was characterized by a median sediment grain size ( $d_{50}$ ) of 0.36mm. As referred, to study the morphological behaviour of the beach, two similar profiles were created, changing the berm heights and widths, but considering the same amount of sand. Both were built with around 18 000cm<sup>3</sup> of sand, where the first profile, with a 20cm berm width at a height of 15cm, simulates an emerged beach profile, and the second an immersed beach (berm width of 30cm, at a height of 10cm). On the back of the coastal structure was installed a reservoir, in order to collect and quantify the overtopped water. See Pires (2024) for a detailed description of the flume tests performed.

#### CS-Model numerical simulations

To simulate the cross-shore profile behaviour of a beach, the numerical model CS-Model (Larson *et al.*, 2016) was applied, as it is able to reproduce transversal sediment transport processes, also allowing to quantify the occurrence of overtopping events. Using a small number of parameters representative of

the profile, and the definition of the wave climate, water level and wind action (not considered in the performed tests), the model simulates the processes of dune erosion, wind sediment transport and exchanges between the bar and the beach berm (Larson *et al.*, 2016; Palalane *et al.*, 2016; Marinho *et al.*, 2018; Hallin *et al.*, 2019). The time instants in which overtopping occurs were identified throughout the simulation.

The CS-Model (Larson *et al.*, 2016), employs a set of formulas to compute sediment exchanges within the beach profile. In this study, the considered processes included wave impact on the dune system ( $q_D$ ) and bar-berm sediment exchange ( $q_B$ ). The wind-blown sand transport ( $q_{WS}$ ) was not evaluated, being considered null. As illustrated in Figure 3, the model describes profile evolution through morphological parameters such as dune toes position ( $Y_L$  and  $Y_S$ ), shoreline position ( $Y_G$ ), berm crest position ( $Y_B$ ), dune height ( $S$ ), berm height ( $D_B$ ), bar volume ( $V_B$ ), depth of closure ( $D_C$ ), dune face slopes ( $\beta_L$  and  $\beta_S$ ) and berm slope ( $\beta_F$ ). The cross-shore model assumes the mass conservation within the profile.

According to Larson *et al.* (2013), the CS-Model simulates bar evolution based on the concepts of equilibrium bar volume presented by Larson & Kraus (1989), and deviations from this equilibrium. At each time step, the model calculates the equilibrium bar volume and the evolution of the bar is dictated by the relationship between the actual bar volume and the equilibrium volume. If the bar volume is higher than the equilibrium volume, the sediments are transported from the bar to the berm. Conversely, the sediments are transported from the berm to the bar (Larson *et al.*, 2013). The equilibrium bar volume is a function of the dimensionless fall speed, a dimensionless coefficient, and wave parameters, including deep-water wavelength, the deep-water wave height and wave period (Ferreira *et al.*, 2024a; 2024b).

Dune erosion caused by wave impact is calculated according to the wave impact model developed by Larson *et al.* (2004). If overwash does not occur, the model assumes a relationship between the cross-shore transport rate from the dune face to the berm, and the wave runup height, the surge and tide level, the dune toe elevation, the swash period and an empirical transport coefficient (Ferreira *et al.*, 2024a; 2024b).

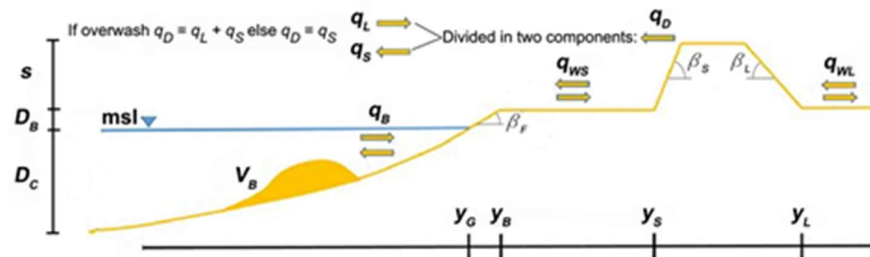


Figure 3. Scheme of the beach profile used by CS-Model: morphological parameters and sediment transport components (based on Larson *et al.*, 2016).

To apply the numerical model, a one-year wave climate was used (Figure 4), considering records every 3 hours, referring to measurements taken on the Leixões buoy (Coelho *et al.*, 2023). This adopted wave climate is representative of the Portuguese west coast, essentially exposed to waves coming from the northwest, with an average height between 2 and 3 meters and average period between 8 and 12 seconds (Coelho *et al.*, 2015).

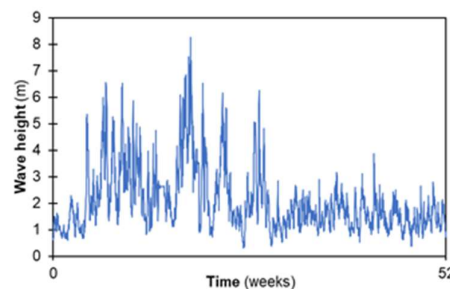
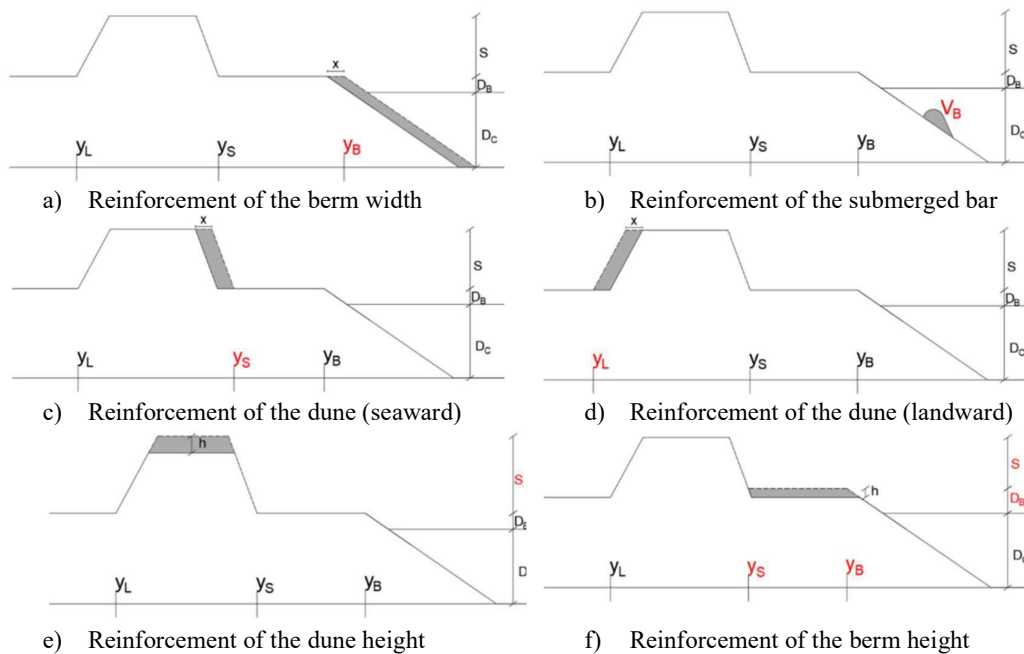


Figure 4. Significant wave height during the 52 weeks of the simulation (Coelho *et al.*, 2023).

The geometric characteristics of the adopted profile for the reference scenario were: depth of closure ( $D_C$ ) of 12.4m; beach berm slope ( $\beta_F$ ) of 7 degrees, with a berm height ( $D_B$ ) of 2.6m and a berm width of 100m; 6m dune height ( $S$ ), with face slopes of 14 and 18 degrees, respectively the seaward side ( $\beta_S$ ) and the landward side ( $\beta_L$ ); initial volume of the submerged bar equal to  $100\text{m}^3/\text{m}$  ( $V_B$ ). At the end of a year of simulation, the profile with the characteristics mentioned record 197 overtopping events. In an initial phase of the simulation, there was no overtopping. However, during the most energetic wave climate, overtopping begins to occur, also contributing for dune erosion. With the dune eroded, even during the period of less wave energy, occasional overtopping occurs.

Considering that the adopted cross-shore profile presents a behaviour that can be reinforced in order to reduce the frequency of overtopping, several intervention scenarios were defined considering artificial nourishments with volumes up to  $600\text{m}^3/\text{m}$  and different locations for the deposited sediments: reinforcement of the berm width; reinforcement of the submerged bar volume; reinforcement of the dune, depositing the sediments on the seaward or on the landward slopes; reinforcement of the dune height; and reinforcement at the berm height (Figure 5). See Zinca (2023) for a detailed description of the numerical model scenarios definition and modelled assumptions.



**Figure 5. Artificial nourishment intervention scenarios. In red are identified the parameters changed in the numerical simulations, depending on the tested nourishment volumes (adopted from Zinca, 2023).**

## RESULTS

After collecting the results of the tests carried out, different aspects related to the morphology of the beach profile were evaluated, namely the final shape of the profile and the amount of water overtopped, in each laboratory test. Considering the numerical simulations, the number of overtopping events was quantified for all the intervention scenarios, depositing sand volumes ranging from 0 to  $600\text{m}^3/\text{m}$ .

### Flume tests

In the flume tests evaluation, each scenario was analysed, allowing to compare and discuss the effects of different water levels, wave periods and the two initial beach profiles. During all the tests, changes in the profile characteristics were observed, narrowing the beach berm and lowering the berm crest level along time. Both emerged and submerged beach profiles have common aspects in the morphological evolution throughout the test (bars formation, transport of sand for lower levels, etc.) but, depending on the test, these events occur in different locations of the profile (Figure 6).

In the emerged profile, the water surface level is below the level of the beach berm and therefore, the waves run up along the sand profile and only then, run onto the structure. In the wave reflux process, the sand is transported to lower elevations, creating submerged bars. The location of these bars depends on the water surface level, but occurs practically in the same locations, for both wave periods. However,

as can be seen in Figures 6a and 6b, despite the location being similar, the bars have a different shape when the wave period differs. This fact may be due to the reflux effect of the waves, which interfere with the following waves, which has greater impact for the wave period of 1.5s, since the waves have a greater frequency, moving more sand, creating bars with greater volume, when compared to the bars generated with the 3s wave period. Another aspect that stands out from the analysis is that the wave runup on the beach slope is lowering the beach profile next to the structure. The refluxes dissipate the energy of the coming waves, causing a lower capacity of the backflow to move sand close to the structure. This aspect is quite visible in Figures 6a and 6b, in the tests with water levels at 10cm and 13cm. While in the scenarios of water level of 15cm, for the wave period  $T=3s$  one can observe a greater depth than in the test with a period of 1.5s. As the frequency of waves is smaller, the reflux caused by waves of 3s period can move a greater amount of sand in the vicinity of the structure until the next wave come, making the bottom level decrease more significantly nearby the structure.

In the submerged beach profile (Figures 6c and 6d), the 1.5 seconds wave period scenarios generated several submerged bars, when the water level was 13cm and 15cm, also lowering the profile next to the structure. For the 10cm water level, the sand extends along the slope of the structure, despite registering a general deepening of the berm. The multiple submerged bars can be due to the existence of a layer of water over the berm, interfering with the high frequency (low period) waves reflux. For the wave period  $T=3s$ , the profiles present a more regular shape, with just one submerged bar, at surface levels of 10cm and 13cm. The three different water level scenarios show the lowering of the submerged berm crest and an increase in the elevation of the beach profile next to the toe of the coastal structure. With  $T=3s$  there are fewer wave refluxes and the wave moves the sand from the horizontal berm to locations closer to the structure. In turn, the reflux of these waves transports the sand from the crest of the berm to deeper levels, forming submerged bars. In the 15cm water level scenario, the submerged bar is not formed, maybe due to the higher water column, which reduces the wave reflux effects in the sand transport to deeper areas.

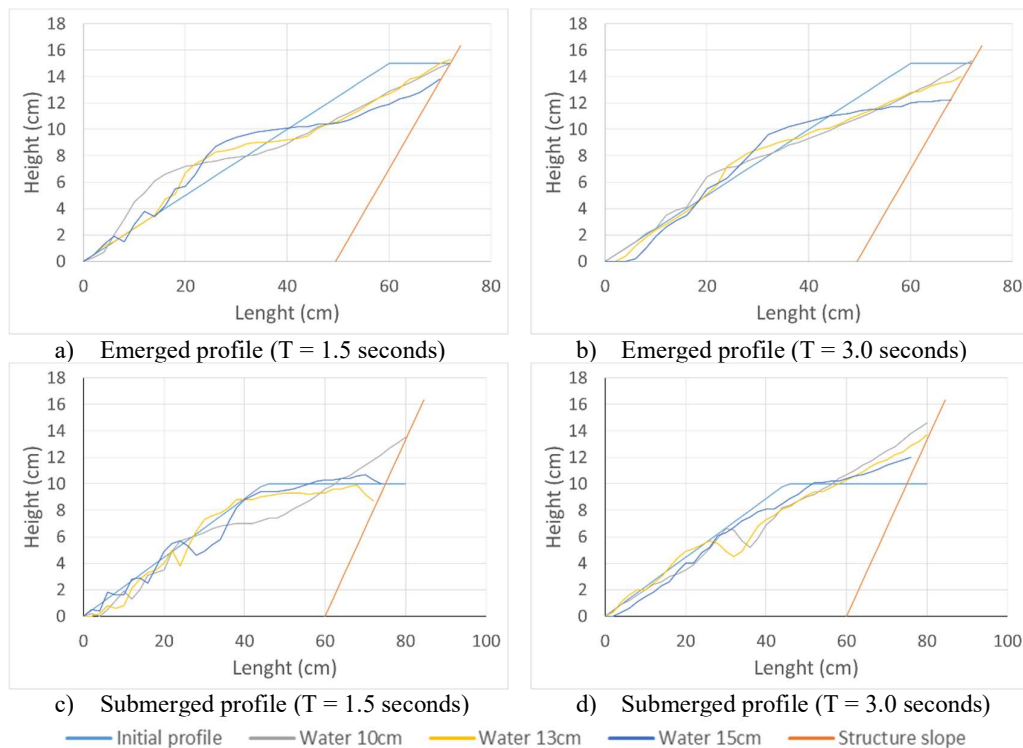
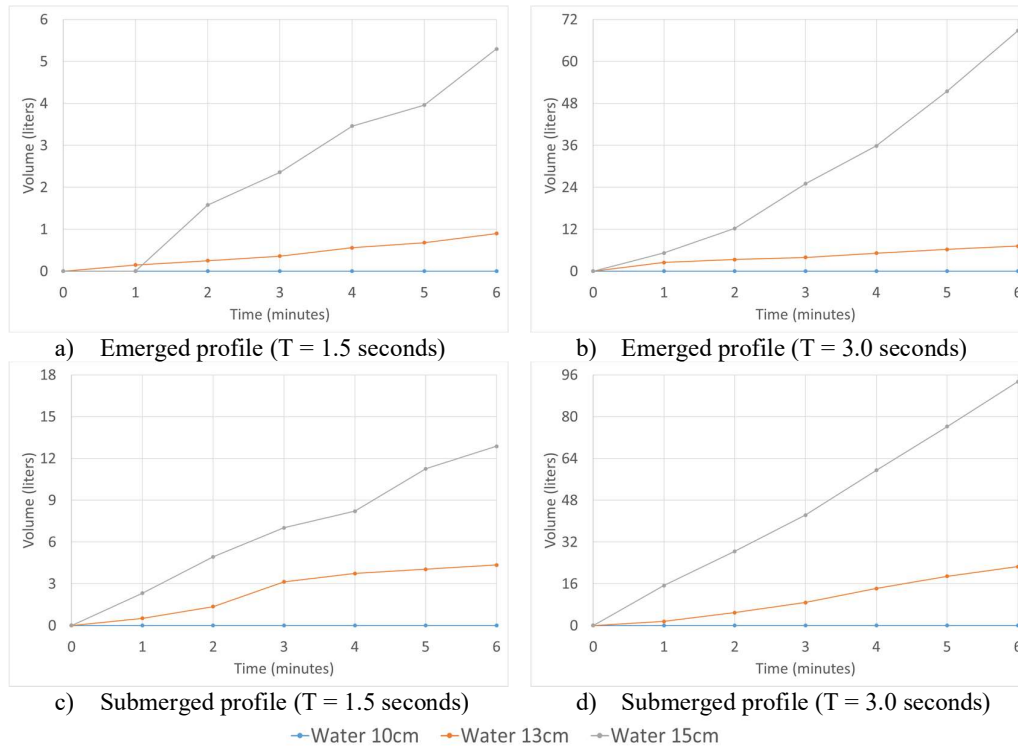


Figure 6. Final shape of the beach profiles, for different water level scenarios (Pires, 2024).

In general, for the emerged beach profiles, the greater deepening of the bottom is for the 15cm water level scenario. For the scenarios of 10cm and 13cm, the waves runup on the beach slope, losing energy and not mobilizing as much sand in the reflux processes. As in the emerged profile scenarios, the maximum bottom variations in the submerged profile scenarios tend to stabilize over time. The scenario where a greater deepening is observed is for 10cm water level. In this case, as in the emerged profile, the

elevation of the beach berm coincides with the water level, facilitating the mobilization of sand. For scenarios with other water levels (13cm and 15cm), as the profile is submerged, the waves do not impact directly on the beach profile and while attacking the structure, they mobilize less sand to be transported through the runup and reflux of the waves.

Considering the overtopped volumes along the laboratory tests, with the exception of the 10cm water level scenarios, overtopping was recorded, for both beach profiles and wave periods (Figure 7).



**Figure 7. Cumulative overtopped volumes along time, for different water level scenarios (Pires, 2024).**

The overtopping records present larger values for the 3s wave period, in both beach profiles. The difference in behavior between scenarios with different wave periods is mainly due to the wave reflux effects, already mentioned. It is highlighted the difference in the order of magnitude of the results, since, for example, in the scenarios with 15cm water level, the accumulated overtopping volumes at the end of each test are around 5.3 liters (T=1.5s, emerged), 13 liters (T=1.5s, submerged), 69 liters (T=3.0s, emerged) and 93 liters (T=3.0s, submerged). This result shows that the wave period is more important than the bottom depth of the initial profile, in the obtained results.

The overtopped flows for the two profiles presented different types of growth along the tested scenarios. For the emerged profile, the overtopped water volumes accumulated throughout the tests presented an exponential growth while the submerged profile presented a more linear growth, which indicates that the emerged profile, while deepening the bottom, was worsening the overtopping situation throughout the time. This is more evident in the 3 seconds wave period scenario, for the 15cm water level (Figure 7b). The obtained results highlight the need for intervention measures to mitigate overtopping trends, and thus, nourishments were tested numerically, applying the CS-Model.

#### CS-Model numerical simulations

To apply the numerical model, a one-year wave climate was considered, with records every 3 hours. The initial beach profile presented 197 overtopping waves, allowing to test the impacts of the reinforcement locations with different sand volumes (Figure 8). It is verified that artificial nourishments always lead to a reduction in the number of overtopping events, but there are significant differences in the performance and volumes needed, depending on the sand deposition location.

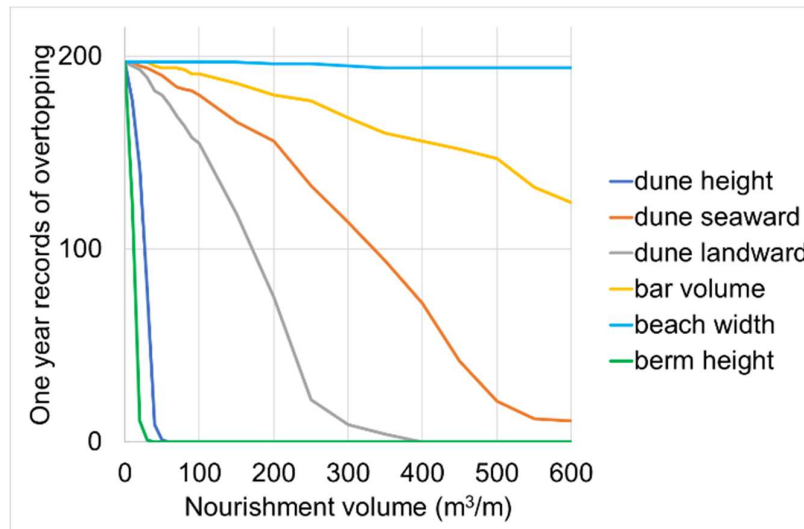


Figure 8. Number of overtopping events, considering reinforcement volumes and locations (Coelho *et al.*, 2023).

When the goal is to reduce the frequency of overtopping, the best nourishment reinforcement technique is to raise the berm, followed by raising the dune. Both deposit sites completely eliminate the number of overtopping, using relatively low sand volumes. When considering larger volumes of sediment for deposit, strengthening the dune on the landward side is also effective in eliminate overtopping, while strengthening the dune on the seaward side reduces overtopping almost to zero. In this last scenario, some overtopping still occurs, since the reinforcement reduces the width of the berm, not allowing the full runoff of the wave along the berm, which leads to more frequent wave attacks to the dune. For the tested range of volumes, reinforcing the submerged bar does not reduce the number of overtopping by 50%. Finally, reinforcing the width of the berm is not very effective in reducing overtopping, as a large volume of sediments is needed to increase significantly the width of the berm.

The developed analysis aimed to evaluate the effectiveness of artificial nourishments in reducing the number of overtopping, but the results also show that the interventions allow for an increase of the beach area, which can lead to greater recreational use, and can also make the dune profile more robust, for greater resilience in facing the coastal erosion problems.

## DISCUSSION

Nourishment can be an effective method for short-term storm protection by reducing flooding, wave attack and erosion. However, the ability of nourishment to mitigate the effects of storms and sea level rise and improve coastal resilience over decadal time scales is not well understood (Passeri *et al.*, 2021). Passeri *et al.* (2021) have assessed the effectiveness of beach and dune nourishments on barrier island morphological resilience over a 30-year period, accounting for storms and a moderate scenario of sea level rise. Their results show that at the end of the 30 years, nourishment contributes to maintaining island volumes by increasing barrier height and width, compared with a no-action scenario. During storms where the collision regime was dominant, higher volumes of sand were lost from the wider beach in the nourishment scenario than in the no-action scenario. During stronger storms, nourishment reduced dune overtopping compared with the no-action scenario, allowing the island to maintain height and width. Additionally, nourishment was particularly effective in reducing breaching during back-to-back storms occurring in the same year. The results described by Passeri *et al.* (2021) are completely aligned with the ones obtained in the present research.

Van Doorslaer *et al.* (2009) presented a study discussing solutions to mitigate overtopping at the Belgian coastal regions. They have referred that if a 1000 thousand years return period storm would appear in 2009, the safety of one third of the Belgian coastal zone would be insufficient. The authors state that a beach nourishment is an option to increase the safety against these severe storms, but is not always possible close to harbours, may be expensive due to necessary monitoring and restoration during its lifetime. Therefore, they have also discussed another safety measure, like heightening of the dikes, which is often restricted because of its inconveniences, like the reduction of the visual attraction of the open sea. Therefore, Van Doorslaer *et al.* (2009) highlighted that a sound practical solution is needed

within the spatial restrictions and dealing with the architectural desire of a touristic area. In accordance with the work of Van Doorslaer *et al.* (2009), the present work has shown that the trends to the future are not optimistic, but nourishments can be a way to mitigate the problem. However, authors are aware of the specific conditions tested and extrapolations for other specific conditions may present different results.

Van Steeg *et al.* (2020), carried out controlled tests in a channel with a model of a structure with a smooth concrete embankment with a slope of 1:3. In those tests, the bottom level was varied, increasing the level of the free water surface and the crest level of the structures, but maintaining the distance between them. They also varied the waves steepness and height. The results obtained demonstrate that increasing the distance between the bottom level and the crest level influences the overtopped flows, which is in accordance with the results now obtained in the flume tests. In the same direction of the laboratory tests developed in the present work, Ridder *et al.* (2024) also developed laboratory tests and refer that the short-wave steepness, relative crest height and the low-frequency wave height are the most important parameters when predicting the mean overtopping discharge in shallow water. In the present work, the test scenarios with the 3 seconds wave period always showed higher overtopping volumes, when compared to the 1.5 seconds wave period scenarios.

Numerical modelling of sediments reinforcement depends on beach profile characteristics and the choice of the cross-shore location for sediment deposit must consider the specific factors of each location. Considering the CS Model results, nourishments represent a way to reduce overtopping events. For the adopted profile, it was concluded that reinforcing the height of the beach berm is the most effective location to deposit the sand. Additional tests with more energetic wave conditions, increased sea water levels, or decreased beach berm widths also have shown that nourishments to increase beach berm heights continue to be effective in overtopping reduction. According to Coelho *et al.* (2020; 2023; 2024), it was also found that the location of the artificial nourishments with better performance depends on the objective for which they are carried out (reduction of overtopping, reinforcement of the profile, recreational use of the beach berm). These main numerical results are aligned with other published studies focused on investigate nourishments efficacy, including laboratory and monitoring studies. For example, Atkinson and Baldock (2020) conducted laboratory tests to evaluate the efficacy of nourishments in mitigating erosion induced caused by sea level rise. The tests considered different cross-shore locations for sediments deposition. According to the authors, the efficacy of nourishments depends on how cross-shore profiles recession is measured. They found that, in terms of mean recession, the highest efficacy was observed when all the nourishment volume was placed within the active profile. Regarding shoreline retreat mitigation, nourishments placed on the upper beach are most effective, as they prevent additional recession caused by wave overtopping.

Brand *et al.* (2022), based on their analysis of the Dutch experience with sand nourishments, also notice that the choice of nourishment design depends on the methodology, the local conditions and the purpose of the nourishment. Based on all the previous, it is considered that numerical modelling can assist decision-makers in defining the best approach to perform nourishment interventions. One of the main difficulties in numerical modelling for coastal management purposes is related to time scales required for analysis, which often involve medium to long-term time periods (years), as well as the computational effort needed to conduct such studies (Larson *et al.*, 2005). In this study, the CS-Model was select to conduct the numerical analyses. The application of the CS-Model to real-world case studies has demonstrated its ability to simulate cross-shore beach profile evolution over medium to long-term scales, overcoming some limitations of numerical modelling for large-scale beach profiles evolution (Palalane *et al.*, 2016; Hallin *et al.*, 2019; Elko *et al.*, 2021). Furthermore, recent numerical studies have shown the model capacity to be combined with longshore sediment transport models, enabling the inclusion of longshore transport gradients in numerical simulations (Ferreira *et al.*, 2024a). These gradients play a crucial role in distributing nourishments alongshore and are essential for assessing the performance and longevity of nourishment projects. Additionally, Hallin *et al.* (2019) highlighted the importance of incorporating longshore gradients into cross-shore numerical modelling of beach profiles evolution through CS-Model.

## CONCLUSION

The obtained results show that there is a deepening trend of the bottom in front of coastal structures and the best way of artificially nourish beach profiles can be discussed using numerical models, helping in future maintenance of coastal structures and design of nourishment projects.

The emerged profile, showing part of the beach profile above the water level, have lower number of waves reaching the structure and in turn, less overtopping than in the submerged profile. During

laboratory tests, sand moved to deeper areas and simultaneously there was an increase in amount of water overtopping. In the emerged profile, while deepening the bottom, the waves break closer to the structure, which resulted in an increase of overtopping. In the submerged profile, the existence of water in front of the structure, allowed greater overtopping since the beginning of the tests. These results showed the trend observed in several coastal areas worldwide, which are presenting increased overtopping problems, demanding for mitigation interventions.

With the help of the CS-Model, a baseline scenario was defined as starting condition to compare the performance of nourishment interventions, looking for the most effective in reducing overtopping events. The CS-Model is capable of temporally simulate the exchange of sediments along the cross-shore profile and its response, with a small number of parameters representative of the profile and with a fast processing time. In the simulated conditions, the best intervention technique was to reinforce the height of the beach berm, as this completely nullifies the number of overtopping using relatively low nourishment volumes, in comparison to the remaining options. The obtained results need to be evaluated carefully, as simulations were performed for a specific cross-shore profile and conditions, and did not account for the need to repeat nourishments in time, as no longshore sediment transport gradients were considered. The presented approach shows that physical and numerical modelling can help designing future coastal interventions to mitigate the increasing overtopping trends observed worldwide.

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