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Longitudinal revetments to mitigate overtopping and flooding: Effectiveness, costs and benefits

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ABSTRACT

Several anthropogenic actions have been weakening sediment supplies to coastal areas, reducing the amount of sediments available on beaches and leading to a general and recurrent retreat of the shoreline position. As a consequence, different coastal defense interventions, oftentimes longitudinal revetments, have been established over the past decades in areas with high erosion rates. However, the lack of monitoring of these coastal defense structures combined with the high exposure of the urban areas to erosion, have led to an increased frequency of damage events in several locations, damaging infrastructures, commercial establishments and housing. This study purposes to assess the effectiveness, costs and benefits of different types of longitudinal revetments that aim to protect urban waterfronts from erosion and overtopping. A statistical analysis was developed and applied in order to assess the overtopping frequency of longitudinal revetments, depending on the seabed depth at the toe of the structure and on the structure's freeboard. Given that wave climate and beach profile are intrinsically associated with overtopping frequency over time, causes for the deepening of the beach profile were identified and various formulations were analyzed in order to estimate the maximum scour depth, to anticipate the frequency of damage events and to assess the severity of overtopping and flooding events. The effectiveness of different interventions to reduce wave overtopping at longitudinal revetments was assessed, including crest elevation, artificial beach profile nourishment and construction of an intermediate berm. A cost-benefit analysis was performed to assess the economic viability of these interventions, based on their additional investment, operation and maintenance costs and corresponding avoided flood damage costs over time. Results for the case of Furadouro beach (Portugal) show that reinforcement of longitudinal revetments is usually economically viable in the mid-term, especially when an increase in overtopping frequency is anticipated. The avoided costs associated with the negative impacts of overtopping tend to break-even with the interventions' costs within a period of around 10 years.

1. Introduction

Worldwide a growing trend in coastal erosion is observed, representing a conflict between shoreline evolution, erosion mitigation measures and land use. One of the most applied mitigation measures are longitudinal revetments that allow to fix the shoreline position as well as protect people and assets in urban waterfronts. However, longitudinal revetments imply considerable costs related to their maintenance that are often underestimated at the time of construction. Due to their lack of monitoring and maintenance over time, frequent damages to the structure and the surrounding areas are observed. In fact, if the foreshore continues to erode the ruble mound revetment may collapse, resulting in a less effective defense structure. Repairs may be necessary to provide continued backshore protection at the design standard. Thus, revetment design must anticipate ongoing erosion that may result in toe scour or overtopping and may cause partial structural failure (CIRIA, 2007).

It is difficult to assess all the direct and indirect effects (positive and negative) of longitudinal revetments. Vasco-Costa et al. (1996)

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referred that the new challenges for the coastal engineering would be the search for technical solutions that may minimize the negative aspects of the installation of coastal revetments and the quantification of cost-benefits associated to this action. Non-spatially explicit coastal protection cost-benefit analyses were performed by Darwin and Tol (2001), Bosello et al. (2007) and Costa et al. (2009). Roebeling et al. (2011) developed and applied a spatially-explicit approach that allowed for the cost-benefit assessment of coastal protection investments options at the local scale. Hudson et al. (2015) refer that construction costs for coastal protection works are highly variable due to the varied nature of works required, site conditions, and the costs, availability and source of materials used.

Therefore the main goal of this study is to contribute to the optimization of the decision process, based on the type, effectiveness, costs and benefits of longitudinal revetments to protect urban waterfronts from erosion and overtopping. To this end, a statistical analysis was developed and applied to determine the structures' overtopping frequency, depending on their geometrical characteristics and the wave climate. It was also considered that the beach profile in front of the structure tends to deepen over time, due to scour related to the reflective effect of the structure and the continuous deficit of sediments in an erosive coast. The deepening of the seabed in front of the longitudinal revetment increases the overtopping frequency over time, due to the higher waves that are able to directly attack the structure. To reduce the frequency of overtopping at longitudinal revetments, three types of interventions were analyzed: crest elevation; artificial beach profile nourishment; and construction of an intermediate berm. A cost-benefit analysis was performed to assess the economic viability of these interventions, based on the additional investment, operation and maintenance costs and the corresponding avoided flood damage costs of these interventions over time. The presented work considers the Furadouro case study on the Portuguese Northwest coast, where several erosion problems and different mitigation measures have been adopted in the past.

Considering the previous, in this paper a short review on longitudinal revetments and intervention scenarios is presented. The methods adopted to develop the study are described, considering the estimation of overtopping frequency, beach profile deepening trends and cost-benefit analysis of different reinforcement scenarios. Next, a brief description of the case study and corresponding adopted data are presented. In turn, results on overtopping frequencies and cost-benefit analysis for each scenario are presented. Finally, results are discussed and major conclusions are drawn.

2. Longitudinal revetments

Longitudinal revetments are artificial coastal defense structures built along the face of a dune system or a beach slope. It consists of rock fill, concrete blocks or geosynthetics and are primarily intended to protect the coast from erosion (Burcharth and Hughes, 2011a), leading to a reduction and dissipation of the wave energy through the direct impact of the waves on the blocks and the space between the blocks (Coelho, 2005). Such structures also provide the reflection of waves whose reflux promotes sediment transport offshore and, in addition to longitudinal sediment deficit, reduces the amount of sediments in front of the revetment and results in the deepening of the beach profile. This phenomenon is associated with the erodibility of the structure's toe. The increased seabed depths near the structure can change the arrangement of the blocks and the foundation, inducing instability in the posterior elements and affecting the overall performance of the longitudinal revetment in the affected areas (Burcharth and Hughes, 2011a). In these situations, it is common to reinforce the structures over time.

Alternative solutions to reinforce the structure and to reduce the overtopping frequency can assume different intervention approaches: increasing the crest level of the revetment (Fig. 1a); decreasing the seabed depth near the structure toe by artificially nourishing the beach profile with sediments (Fig. 1b); or building an intermediate berm in the slope of the structure (Fig. 1c). Each approach is associated with different levels of effectiveness and benefit-cost ratios, depending on the geometric characteristics of the longitudinal revetment and on the degree of exposure to the wave climate (CIRIA, 2007; Burcharth and Hughes, 2011b).

The increase of the structure's crest level causes a higher freeboard gap (ΔH). The maximum run-up will not reach the top of the structure so often and thus, the frequency of overtopping is reduced.

Artificial nourishments aim to increase the beach seabed level in front of coastal defenses, also providing sediments to beaches located downdrift due to littoral drift over time. By performing the artificial nourishment in front of the longitudinal revetment, the depth d is reduced (ΔH is constant). The periodicity of the artificial nourishment depends on the initial state of the beach profile and on the ratio between the maximum erodible depth and sand height introduced in front of the longitudinal revetment.

The main function of intermediate berms on longitudinal revetment slopes is to break the waves before they reach the structure, dissipating energy, reducing the run-up and thereby, mitigating overtopping. According to Waal and van der Meer (1992), the effect of the berm is considered by a reduction coefficient (γ_p) applied to the maximum wave run-up ($R_{\max}$). The berm efficiency depends on its width (B_p) and on its relative position to the mean seawater level, MSL (d_p), allowing a maximum reduction of 40% of the wave run-up ($\gamma_p = 0.6$).

3. Methods

Statistical analysis of overtopping frequency and beach profile evolution over time are required to perform the cost-benefit evaluation of the different intervention scenarios. This section describes the methods adopted in this study to effectively achieve a cost-benefit analysis.

3.1. Overtopping assessment

With the objective of identifying overtopping events by comparing the incident wave height at a longitudinal revetment and the maximum wave run-up, an exhaustive evaluation of incident wave heights was performed considering the Northwest Portuguese maritime wave climate. To this end, two wave propagation phenomena were considered (shoaling and refraction) in a simplified manner. Calculations were made for different depths (d; up to 10 m), assuming that maritime waves present a sinusoidal linear behavior, considering a regular bathymetry and applying the Snell's law (see Cruz, 2015).

According to Eurotop (2007), wave run-up ($R_{2\%}$) is referred to as the vertical height measured from the mean seawater level (MSL) that is exceeded by 2% of the incident waves. This dimension depends on the wave steepness, the level of the water surface, the bathymetry and the porosity, roughness and permeability of the resistant layer of the coastal defense structure. There are several empirical formulations to estimate wave run-up, considering different fields of application and types of waves (see Teixeira, 2014). Based on characteristics of the existing coastal structures along the Portuguese Northwest coast and on the relations between the different levels of wave run-up stipulated by Grune and Wang (2000), Teixeira (2014) established the relationship between the different levels of wave run-up and the maximum wave run-up ($R_{\max}$):