Temporal Evolution of Wave Overtopping of a Hybrid Dune-Dike Structure Under Extreme Storm Conditions

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Abstract. Hybrid dune-dike structures are innovative developments creating coastal defense systems which are more conveniently integrated with the natural environment. In this study, a numerical study was conducted to investigate the temporal evolution of wave overtopping, with the changing profile of the dune under extreme storm conditions with a constant water level, of two types of hybrid dune-dike structures in Katwijk (dike-in-dune type) and Raversijde (dune-in-front-of-dike type). XBeach 1DH was used to firstly calculate bed profiles for different time steps during a 10-h storm duration using the Surfbeat mode and then, in a second step, mean wave overtopping rates were modelled for each calculated bed profile using the Non-hydrostatic mode. According to the simulation results, most of the dune erosion occurs during the first two hours of the storm, and then continues at a slower rate as the sand deposits in front of the dune. Once the hybrid structure is eroding (so for t > 0), the significant wave height at the dike toe and the mean overtopping discharge increase in time for both Katwijk and Raversijde, although it quickly reaches a plateau for Raversijde. The first simulations with the original non-eroded profiles deviate from this trend. The reason for this deviation needs to be further investigated.

Keywords: Wave Overtopping · Hybrid Structures · XBeach · Dike · Dune

1 Introduction

Climate change induced rising sea levels, growth in trade and economy, and population increase in coastal regions have put pressure on coastal regions (Almarshed et al., 2020). To ensure the safety of these coastal regions and to minimize and/or prevent life and property loss, hard and soft coastal defence, mainly dikes and dunes, have been constructed. These traditional coastal defense structures protect against storm surges and floods. However, with the increasing impact of climate change, there is a need to adapt these structures to more extreme storm scenarios in the future. A way forward is the combination of these two types of coastal defenses. This development enables to create dune-dike nature-based hybrid defense systems which are more conveniently integrated with the natural environment.

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A few hybrid structure demonstrators have been identified (e.g. Katwijk in the Netherlands, or Raversijde in Belgium), and in the last decades, several experimental and numerical studies have been conducted on these types of structures. Van Geer et al. (2009) and Boers et al. (2011) conducted physical model tests to investigate dune erosion and scour at the toe of a hybrid structure. Figlus et al. (2015) carried out movable bed tests to study the effect of different type core-enhancements in dune structure on the profile change. Kobayashi and Kim (2017) compared the effectiveness of four different combinations of rock seawall and dune on the foreshore on sand overwash and wave overtopping. As examples of numerical studies, van Geer et al. (2012) and van Thiel de Vries (2012) studied dune erosion near seawalls and above revetments, respectively, using the XBeach numerical tool and Muller et al. (2018) examined hydro- and morphodynamical effects on the Galveston Seawall by adding a sand cover using the same numerical model. Irish et al. (2013), Smallegan et al. (2016) and Walling et al. (2016) carried out studies on the impacts of Hurricane Sandy on hybrid structures by comparing dune systems without any hard structure effect on the field where was affected by the hurricane. However, because these studies did not consider the time evolution of the overtopping discharge during dune erosion scenarios, existing knowledge is still insufficient to fully describe their overtopping performance under hydrodynamic loadings and extreme storm conditions.

In this study, a numerical study is carried out to investigate the temporal evolution of wave overtopping of two representative dune-dike hybrid structures, Katwijk (Netherlands) and Raversijde (Belgium), under extreme storm conditions. This work is conducted as a part of the DuneFront project, focusing on design and engineering aspects of hybrid systems, apart from other research done in the DuneFront.

2 Research Methodology

In the scope of this study, two representative types of dune-dike hybrid structures are considered: the dike-in-dune system of Katwijk, the Netherlands and the dune-in-front-of-a-dike system of Raversijde, Belgium. These are studied using the XBeach numerical model (Roelvink et al., 2009) in 1D in both Surfbeat and Non-hydrostatic modes to investigate the temporal evolution of mean overtopping discharges of the hybrid structures under extreme conditions with a fixed design water level to better understand overtopping performance of these hybrid structures under hydrodynamic loadings and extreme storm conditions. In Table 1, the considered offshore boundary conditions and grain size values are presented for both cases. In the present study, constant extreme water levels are considered as a first step rather than more realistic time-varying water levels. 1000 and 10000 years return periods are considered according to the safety assessment and/or design methodologies of Belgium and the Netherlands to determine the offshore boundary conditions for Raversijde and Katwijk, respectively (see Wouters and Boer (2014) for Katwijk and Vuik et al. (2020) for Raversijde). In the simulations (for both Surfbeat and Non-hydrostatic modes), a constant grid size as 0.5 m in x-direction is applied for both cases.

This study consists of two main steps. As the first step, XBeach is used in morphodynamic Surfbeat mode to examine the profile evolution of the hybrid structure under extreme storm conditions with a fixed design water level. For these simulations, a 10-h

Table 1. Considered offshore boundary conditions and grain size values

Case	Water level (m)	SLR (m)	Return Period (Years)	H_{m0} (m)	T_p (s)	Grain size (μm)
Katwijk	5.20 (+ NAP)	1	10 000	7.99	13.90	211
Raversijde	4.72 (+ TAW)	1	1 000	5.13	11.22	370

storm duration is considered for both dune-dike hybrid structures. From this first set of simulations, bed profiles are gathered every 30 min for the first 2 h and every 2 h for the last 8 h, representative of different stages of the storm. In these simulations, the high water level including sea level rise, high tide and surge levels are considered for the constant water level for both cases.

As the second step, XBeach simulations are conducted in Non-Hydrostatic mode using the bed profiles gathered in the first step. These hydrodynamic simulations are conducted for 2 h to obtain reliable statistics for mean overtopping discharge over the dike structures. The mean overtopping discharge 'q' is calculated for each simulation on the dike crest where the dike crest starts at the seaward side (x = 618 m for Katwijk and x = 593 m for Raversijde).

3 Results and Discussion

In Fig. 1, the predicted evolution of the profile is presented for Katwijk (Fig. 1a) and Raversijde (Fig. 1b). The majority of the erosion around the dike crests occurs during the first 2 h of the storm. The crest level of the dike in Katwijk (dike-in-dune) is fully shown up after the first two hours of the storm. Similarly, the top part of the dune in front of the hard structure is eroded in Raversijde (dune-in-front-of-dike) after 2 h.

In Fig. 2, the time-evolution of mean overtopping discharges (Fig. 2a) and the time-evolution of the significant wave height that includes both sea-swell and infragravity waves from the spectral analysis (H_{m0}) at the toe of the dike structures (Fig. 2b) from XBeach 1D in Non-hydrostatic mode are presented. For Katwijk, except for the first time step (non-eroded profile), an increasing trend is observed in the mean overtopping discharge as a function of time in the simulations. For Raversijde, a decrease is seen for the first 30 min of the storm and then there is slight increase in mean overtopping discharge values. After the first 1.5 h, mean overtopping discharge values start to fluctuate around 30 l/m/s.

The time-evolution of significant wave height from the spectral analysis (H_{m0}) at the toe of the dike structures for the Katwijk and Raversijde cases are presented in Fig. 2b. Both cases show an increasing trend in terms of significant wave height at the toe of the dike structures through the extreme storm case with the effect of erosion. For $t > 0$, i.e. for all profiles except the initial one, the increase in mean overtopping discharge for Katwijk coincides with the increase in significant wave height at the toe of the dike. For Raversijde, except the initial profile case, same increasing pattern for the mean overtopping discharge is observed up to $t = 4$ h. After the fourth hour, the mean overtopping discharges fluctuate around 30 l/m/s despite the increasing significant wave

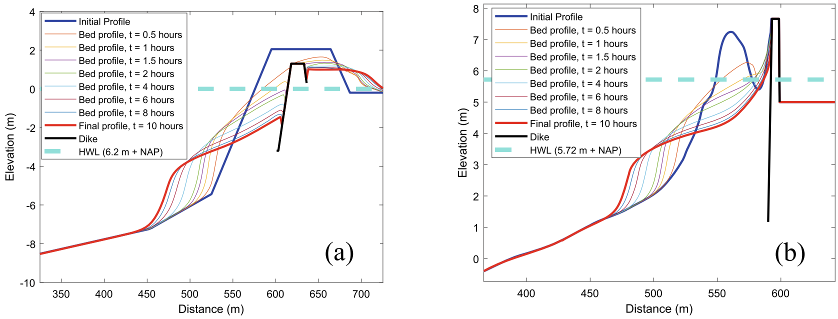

Fig. 1. Calculated evolution of the bed profile of the (a) Katwijk and (b) Raversijde hybrid structures under 10 h extreme storm conditions with constant water level.

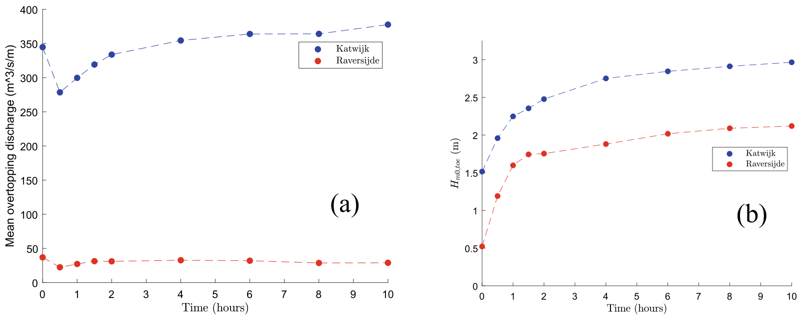

Fig. 2. Predicted evolution of (a) mean overtopping discharges and (b) significant wave height at the toe ($H_{m0,toe}$) as a function of time for Katwijk (dike-in-dune, in blue) and Raversijde (dune-in-front-of-dike, in red)

height at the toe of the dike. For this case, berm formation on the foreshore of the hybrid structure because of dune erosion might be causing secondary breaking and may prevent an increase in mean overtopping discharges despite of increasing significant wave height at the toe of the dike structure.

Overall, the maximum mean overtopping discharges are observed for the initial bed profile (not eroded) for Raversijde and for the final profile (eroded) for Katwijk according to the simulations. Observing relatively high values for the initial profiles (not-eroded scenario) can be identified as a counterintuitive result and needs to be further investigated. It should be noted that, in general, erosion and overtopping values are overestimated in our study because the extreme water level and wave conditions are kept constant for 10 h. In a realistic case, varying water level and storm build-up should be considered. Moreover, because the XBeach simulations were performed in 1D mode, it is expected that infragravity waves are overestimated. This is likely to lead to an overestimation of the dune erosion when compared to a more realistic case. These aspects will be investigated in a follow-up study.

4 Conclusions

A numerical study was carried out to improve the understanding of the temporal evolution of wave overtopping for two representative dune-dike hybrid structures; the dike-in-dune system of Katwijk in the Netherlands and the dune-in-front-of-a-dike system Raversijde in Belgium. XBeach simulations were conducted for both demonstrators in two main steps. In the first step, bed profiles in every 30 min in the first 2 h of the storm and in every 2 h for the rest of the storm were gathered, representative of different stages of the storm with 10 h duration in XBeach 1D on Surfbeat mode. In the second step, XBeach simulations in Non-hydrostatic (i.e. phase resolving) mode were conducted with 2-h duration on the bed profiles gathered in the first step to estimate mean overtopping discharges at different stages of dune evolution.

According to the results, it is observed that erosion for the top levels of dune structure is maximal in first two hours of the storm and that, except for the initial profiles, mean overtopping discharge values tend to increase with the effect of erosion (for Katwijk) or at least, fluctuate around a constant value after a certain time (for Raversijde). These results should be confirmed with additional simulations. For better understanding on this topic, further studies with XBeach 2D and physical model tests are highly recommended.

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