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Assessing safety of nature-based flood defenses: Dealing with extremes and uncertainties

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ABSTRACT

Vegetated foreshores adjacent to engineered structures (so-called hybrid flood defenses), are considered to have high potential in reducing flood risk, even in the face of sea level rise and increasing storminess. However, foreshores such as salt marshes and mangrove forests are generally characterized by relatively strong temporal and spatial variations in geometry and vegetation characteristics (e.g., stem height and density), which causes uncertainties with regards to their protective value under extreme storm conditions. Currently, no method is available to assess the failure probability of a hybrid flood defense, taking into account the aforementioned uncertainties. This paper presents a method to determine the failure probability of a hybrid flood defense, integrating models and stochastic parameters that describe dike failure and wave propagation over a vegetated foreshore. Two dike failure mechanisms are considered: failure due to (i) wave overtopping and (ii) wave impact on revetments. Results show that vegetated foreshores cause a reduction in failure probability for both mechanisms. This effect is more pronounced for wave impact on revetments than for wave overtopping, since revetment failure occurs at relatively low water levels. The relevance of different uncertainties depends on the protection level and associated dike height and strength. For relatively low dikes (i.e., low protection levels), vegetation remains stable in design conditions, and plays an important role in reducing wave loads. In case of higher protection levels, hence for more robust dikes, vegetation is less important than foreshore geometry, because of expected stem breakage of the vegetation under these more extreme conditions. The integrated analysis of uncertainties in hydraulic loads, dike geometry and foreshore characteristics in this paper enables the comparison between nature-based flood defenses and traditionally engineered solutions, and allows coastal engineers to design hybrid flood defenses worldwide.

1. Introduction

Climate change, land subsidence and population growth in coastal areas lead to an increase in flood hazards and in its consequent economic damage and loss of life (Mendelsohn et al., 2011). Frequency and destructiveness of floods will steadily increase if sustainable flood risk reducing measures are not adequately implemented. Flood risk can be reduced by various interventions, ranging from construction and maintenance of dikes and dams to mitigation measures such as flood warning systems (Carsell et al., 2004) and evacuation strategies (Kolen and Helsloot, 2014). In a systems approach, multiple lines of defense are perpetuated, integrating structural and non-structural flood protection with coastal restoration (Lopez, 2009). Within this context, efforts are being made to make greater use of nature-based approaches to flood risk reduction (Spalding et al., 2014; Bridges et al., 2015). Coastal ecosystems, such as salt marshes, mangrove forests and reefs, can contribute to flood risk reduction by surge attenuation (Wamsley et al., 2010), wave energy dissipation and erosion reduction (Gedan et al., 2011). On the long term, they can raise their bottom surface because of their sediment trapping capacity, thereby counterbalancing the effect of sea level rise

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(Mckee et al., 2007). However, these ecosystems are under threat worldwide because of sediment starvation (Adam, 2002; Willemsen et al., 2016), land reclamation (Zhao et al., 2004), deforestation (Bradshaw et al., 2007) and eutrophication (Deegan et al., 2012). This has resulted in a global loss rate of 1–3% of total area per year (Duarte et al., 2013). This trend necessitates conservation, sustainable management and restoration of coastal ecosystems to preserve, or even enhance their role in flood risk reduction. Coastal ecosystems can work stand-alone, but can also be incorporated into hybrid solutions, where ecosystems are utilized as vegetated foreshores along engineered structures. Depth-induced wave breaking, bottom friction and wave attenuation by vegetation lead to a reduction in wave energy over the foreshore, which reduces the required strength and dimensions of structural interventions (Vuik et al., 2016). Hybrid solutions are especially suited for low-lying and flat delta areas, since ecosystems can efficiently reduce wave energy, but are not able to keep out the surge completely.

Although vegetated foreshores are present along many coastlines, their role for coastal protection is rarely incorporated into flood protection strategies, and most examples of successful implementation concern small-scale pilot projects (Spalding et al., 2014). One of the causes is a lack of methods for testing hybrid solutions according to engineering standards for safety, often expressed by means of the probability of failure (Van Wesenbeeck et al., 2014). With state-of-the-art statistical and probabilistic techniques, it is possible to determine a failure probability and an optimal design of a traditional dike, considering the stochastic behavior of both load and strength (e.g. Vrijling (2001); Voortman (2003); Steenbergen et al. (2004)), with applications in for example the Netherlands (Jonkman et al., 2008), the UK (Buijs et al., 2004) and China (Zhang and Xu, 2011). Some studies have applied probabilistic methods to sandy shorelines, to describe coastal cliff recession (Hall et al., 2002) and dune erosion (Den Heijer et al., 2012; Vuik et al., 2017). Uncertainties are even more relevant for more complex flood defense systems like hybrid solutions, which combine ecological and engineering features. However, no methods are available to assess the failure probability of hybrid systems and to incorporate effects of relevant uncertainties, such as spatial and temporal variations in vegetation characteristics, wave attenuation by flexible vegetation, and stability of vegetation under extreme wave forcing. Consequently, it is difficult to assess effects of vegetated foreshores on safety.

The aim of this paper is to assess the failure probability of nature-based flood defenses, more specifically, for a configuration with a dike accompanied by a vegetated foreshore. A probabilistic model framework is developed, in which uncertainties in hydraulic loads, characteristics and functioning of the vegetated foreshore, and strength of the dike are taken into account. The two most prevalent wave-driven failure mechanisms are considered: (i) erosion of the crest and inner slope of the dike due to wave overtopping, and (ii) erosion of the revetment or grass cover on the outer slope due to impact of breaking waves. Different foreshore configurations are defined, inspired by dikes and salt marshes bordering the Dutch Wadden Sea. This paper shows how these foreshore configurations affect the failure probability of the flood defense, and to what extent different variables and processes influence this failure probability.

2. Methods

2.1. System description

In hybrid solutions, ecosystems are utilized as vegetated foreshores along engineered structures. The combined dike-foreshore system is schematized, as shown in Fig. 1. Parameters will be introduced throughout the methods section, and are summarized in Appendix A. The combined characteristics of the dike, foreshore and vegetation determine the strength of the system. Hydrodynamic boundary conditions depend on the wind speed U_{10} (m/s) and are represented by a still water level ζ (m MSL), significant wave height H_{m0} (m) and a characteristics wave period, such as the peak period T_p (s) or the spectral mean wave period

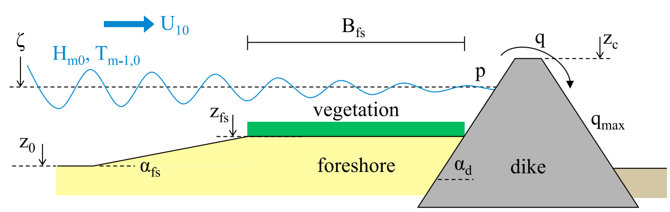

Fig. 1. Schematic representation of a dike-foreshore system, with a stretched vertical scale. System characteristics and computed quantities are shown in black, boundary conditions in blue, and model parameters in red. Parameters will be introduced throughout the methods section, and are summarized in Appendix A. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

$T_{m-1,0}$ (s). The foreshore is characterized by a flat part of B_{fs} meter wide and an elevation z_{fs} (m MSL), which is naturally close to high water spring, because of sediment deposition by the tide (Allen, 2000; Borsje et al., 2017). Offshore from the marsh edge, the profile slopes under an angle α_{fs} to the bed level z_0 (m MSL) of the tidal flats. The marsh vegetation is described by a set of physical characteristics and model parameters, which together determine the wave attenuating capacity and stability against stem breakage. This will be discussed in section 2.2.

Two different failure mechanisms of the dike are considered. Firstly, failure due to wave overtopping over the dike with crest level z_c (m MSL) and slope angle α_d, which occurs when the wave overtopping discharge q (l/s per m width) exceeds a maximum tolerable value q_{max} that depends on the erosion resistance of the crest and inner slope of the dike (section 2.3). Secondly, failure due to wave impacts p (N/m^2) on the outer slope, which leads to damage of the cover and subsequent erosion of the underlying dike core material if the storm duration exceeds a threshold value. For this second failure mechanism, covers with grass (section 2.4) and asphalt (section 2.5) are considered.

A model framework (Fig. 2) is applied to compute the failure probability of a dike, including the effect of a vegetated foreshore. Local water levels and wave characteristics are generated by wind and tide. Wind speed, water level and offshore wave conditions are applied as boundary conditions. Without foreshore, a flat bottom at z_0 is considered. Presence of the vegetated foreshore affects the wave conditions, impact, run-up and, in extreme cases, overtopping over the dike. The framework consists of modules to account for foreshore effects (section 2.2), wave overtopping (section 2.3) or wave impact (sections 2.4 and 2.5).

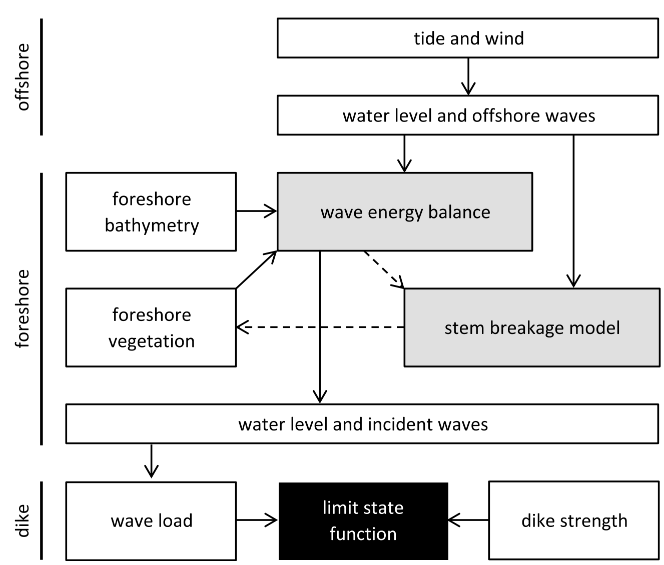

Fig. 2. Model framework to compute a probability of failure. A limit state function Z is defined, and given by the difference between strength and load. The definitions of dike strength and wave load differ per failure mechanism.