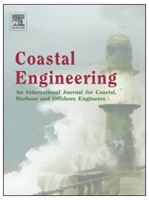
Coastal Engineering 116 (2016) 42–56

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng



Nature-based flood protection: The efficiency of vegetated foreshores for reducing wave loads on coastal dikes

V. Vuik [a,b,*], S.N. Jonkman [a], B.W. Borsje [c,d], T. Suzuki [e,a]

[a] Delft University of Technology, Civil Engineering and Geosciences, P.O. Box 5048, 2600 GA Delft, The Netherlands
[b] HKV Consultants, P.O. Box 2120, 8203 AC Lelystad, The Netherlands
[c] University of Twente, Water Engineering and Management, P.O. Box 217, 7500 AE Enschede, The Netherlands
[d] Deltares, P.O. Box 177, 2600 MH Delft, The Netherlands
[e] Flanders Hydraulics Research, Berchemlei 115, 2000 Antwerpen, Belgium

ARTICLE INFO

Article history:
Received 21 July 2015
Received in revised form 24 May 2016
Accepted 4 June 2016
Available online xxxx

Keywords:
Vegetation
Wave dissipation
Salt marsh
Coastal protection
Building with nature
Wave overtopping
Foreshore

ABSTRACT

This paper analyses the effect of vegetation on wave damping under severe storm conditions, based on a combination of field measurements and numerical modelling. The field measurements of wave attenuation by vegetation were performed on two salt marshes with two representative but contrasting coastal wetland vegetation types: cordgrass (*Spartina anglica*) and grassweed (*Scirpus maritimus*). The former is found in salty environments, whereas the latter is found in brackish environments. The measurements have added to the range with the highest water depths and wave heights presented in the literature so far. A numerical wave model (SWAN) has been calibrated and validated using the new field data. It appeared that the model was well capable of reproducing the observed decay in wave height over the salt marsh. The model has been applied to compute the reduction of the incident wave height on a dike for various realistic foreshore configurations and hydraulic loading conditions. Additionally, the efficiency of vegetated foreshores in reducing wave loads on the dike has been investigated, where wave loads were quantified using a computed wave run-up height and wave overtopping discharge. The outcomes show that vegetated foreshores reduce wave loads on coastal dikes significantly, also for the large inundation depths that occur during storms and with the vegetation being in winter state. The effect of the foreshore on the wave loads varies with wave height to water depth ratio on the foreshore. The presence of vegetation on the foreshore extends the range of water depths for which a foreshore can be applied for effective reduction of wave loads, and prevents intense wave breaking on the foreshore to occur. This research demonstrates that vegetated foreshores can be considered as a promising supplement to conventional engineering methods for dike reinforcement.

1. Introduction

Integration of ecosystems in coastal protection schemes is increasingly mentioned as a valuable supplement to conventional engineering methods (Jones et al., 2012; Temmerman et al., 2013; Van Wesenbeeck et al., 2014). Coastal ecosystems like sand dunes can fulfil the same function as man-made flood defences, such as dikes and dams. Other ecosystem types, such as salt marshes (e.g. King and Lester, 1995; Möller et al., 1999; Möller and Spencer, 2002; Möller, 2006; Arkema et al., 2013), intertidal flats and mangrove forests (e.g. Mazda et al., 2006; Quartel et al., 2007; Horstman et al., 2014) can potentially be used as foreshore protection to reduce the impact of storm surges and wind waves on the flood defences (Borsje et al., 2011; Gedan et al., 2010; Sutton-Grier et al., 2015). This paper focuses on the latter ecosystem types: vegetated foreshores in front of coastal dikes (Fig. 1), since this system has only received limited attention in the literature, despite of the potential of this type of ecosystems to directly affect the flood risk in the area behind the flood defence.

A vegetated foreshore consists of a sediment body, covered with vegetation, in front of a dike. Surface waves, propagating from deep water towards a coastal dike, can significantly lose energy when a vegetated foreshore is present, due to depth-induced wave breaking, bottom friction and wave attenuation by vegetation. Wave run-up on the outer slope of coastal dikes is governed by the incident wave height and wave period. When the wave run-up exceeds the crest height of the dike, wave overtopping over the dike occurs. This might ultimately lead to erosion of the inner slope and breaching of the dike. Both wave run-up and wave overtopping discharge directly depend on the

---

* Corresponding author at: Delft University of Technology, Civil Engineering and Geosciences, P.O. Box 5048, 2600 GA Delft, The Netherlands.
E-mail address: V.Vuik@tudelft.nl (V. Vuik).

http://dx.doi.org/10.1016/j.coastaleng.2016.06.001

Westkapelle, sandy foreshore, North Sea
Foreshore elevation 4.0 m+NAP, slope 1:40
Dike height 12.6 m+NAP, slope 1:6
Design conditions: h = 4.9 m+NAP, H_{m0} = 4.6 m, $T_{m-1,0}$ = 9 s

Hellegat, salt marsh, Western Scheldt
Marsh elevation 3.0 m+NAP, width 200 m, slope 1:40
Dike height 9.5 m+NAP, slope 1:4
Design conditions: h = 6.0 m+NAP, H_{m0} = 1.9 m, $T_{m-1,0}$ = 5 s

Groningen, salt marsh, Wadden Sea
Marsh elevation 2.0 m+NAP, width 800 m, slope 1:750
Dike height 9.1 m+NAP, slope 1:4
Design conditions: h = 5.3 m+NAP, H_{m0} = 1.8 m, $T_{m-1,0}$ = 5 s

Texel, salt marsh Schorren, Wadden Sea
Marsh elevation 1.8 m+NAP, width 400 m, slope 1:250
Dike height 6.9 m+NAP, slope 1:3
Design conditions: h = 4.4 m+NAP, H_{m0} = 1.4 m, $T_{m-1,0}$ = 5 s

Fig. 1. Examples of foreshores in the Netherlands and their characteristics: sandy foreshore near Westkapelle sea defence, bordering the North Sea (upper left), natural salt marsh Hellegatpolder in the Western Scheldt (upper right), man-made salt marsh along the Wadden Sea dikes of Groningen province (lower left), salt marsh Schorren at the Wadden Sea side of the barrier island Texel, with marsh edge protection (lower right). Source: https://beeldbank.rws.nl, Rijkswaterstaat. The numbers in this figure will be explained and used in Section 4.

incoming wave height, which means that the presence of a vegetated foreshore influences the likelihood of dike breaching due to wave overtopping.

The first process that leads to wave energy reduction on vegetated foreshores is depth-induced wave breaking (Battjes and Janssen, 1978; Duncan, 1983) on the shallow foreshore in front of the dike. The maximum possible wave height depends primarily on the water depth. The ratio between both is the dimensionless breaker parameter. Several studies explain how the breaker parameter can vary due to differences in offshore wave steepness (e.g. Battjes and Stive, 1985; Nairn, 1990), bottom slope (e.g. Nelson, 1994) or wave length (Ruessink et al., 2003). For a (nearly) horizontal bottom, the height of individual waves in a naturally occurring random wave train is at maximum 55% of the water depth (Massel, 1996; Nelson, 1994). On steep slopes, higher values can be found.

Additionally, wave energy can be dissipated by bottom friction on shallow foreshores with a surface covered with for instance vegetation, shells or sand ripples. Padilla-Hernández and Monbaliu (2001) have compared the capability of different bottom friction formulations in reproducing wave measurements in shallow water conditions, and argue that formulations for dissipation by bottom friction, like the models by Madsen et al. (1988) or Weber (1989), which explicitly take physical parameters for bottom roughness into account, should be preferred in wave modelling in shallow water areas.

And third, surface waves propagating through vegetation fields lose energy when they perform work on vegetation stems, branches and leaves (Dalrymple et al., 1984). This results in a decrease in wave height. Understanding wave attenuation by vegetation is crucial for determining the efficiency of vegetated foreshores in reducing wave loads on coastal dikes. Therefore, as part of this research, an inventory has been made of available studies that give insight in wave attenuation by vegetation (Fig. 2). Most of these studies are based on field or laboratory

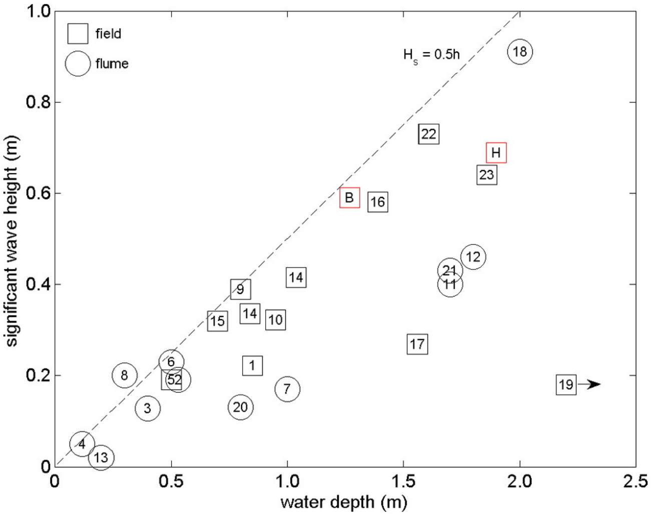


Fig. 2. Maximum water depth and significant wave height, as reported for experiments with wave attenuation by vegetation. For regular waves, the plot position is determined by a computed equivalent significant wave height, using $H_s = 1.41H$. The dotted line roughly indicates depth-limitation due to breaking. Studies included: see Table 1. The letters H and B belong to the field measurements described in the current paper at the salt marshes Hellegat and Bath, respectively (Section 2).