Wave attenuation by vegetation applied on dike design

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ABSTRACT

Wave attenuation by vegetation on the foreland can reduce hydraulic loads on dikes. Literature study showed the reliability issues within several methods. The currently most popular method is based largely on an empirical constant, called the bulk drag coefficient. Several datasets were analyzed to find a relation for this coefficient. With the use of this data a quantitative method and tool was developed for computations of this effect. The impact of the vegetation on the design crest height and dike cover was significant. However, current methods for the computation of this effect are still to unreliable for application in practice.

Keywords

Building with Nature, Wave attenuation, Eco-engineering

INTRODUCTION

Currently there is a lot of attention for the application of ecosystems in coastal engineering (Wolters, 2014). One subject in this field is the ability of vegetation to attenuate waves (Bouma, 2014). Predictability of attenuation for wooden vegetation, such as mangroves, is quite accurate and reliable (Mazda, 2006). However, flexible vegetation is proven to be more complex and poses challenges in modelling. Although most researchers agree on the existence of an attenuating effect of low flexible vegetation there is still no consensus on the method of quantifying this effect (Anderson, 2011). However, integrating this phenomenon in dike design could lead to massive cost savings.

This leads to the main research question of this thesis which is: What is the effect of wave attenuation by low flexible vegetation on dike design?

A few restrictions were made while stating the pre-conditions for the research. Firstly only low and flexible vegetation which is standing in the water column is considered. Secondly only application on sea dikes is discussed. Thirdly only the effect of attenuation by vegetation is considered. Finally no experiments can be executed due to time constraints.

LITERATURE STUDY

To quantify the effect of wave attenuation by vegetation an extensive literature study was executed.

Energy dissipation models

With a model based on the dissipation of energy, the changing hydraulic conditions over a foreland can be computed. Especially the significant wave height (H_S) is important because this is the major parameter which influences the needed crest height and dike cover (Pullen et. al., 2007). Energy dissipation is also caused by wave breaking or bottom friction, but only the effect of vegetation will be considered in this research (van Rijn, 2011).

Energy dissipation by vegetation can be expressed in several ways (Bouma et al., 2005). It is possible to measure the direct force on vegetation in an experiment (Bouma et al., 2014). It is also a possibility to express the dissipating effect of vegetation by using a bottom friction coefficient. However, this method neglects the fact that the vegetation is standing in the water column and is therefore insufficient (Suzuki et al., 2012). The most popular method was completed in 2004 by Méndez and Losada. It uses vegetation and hydraulic parameters to express the wave dissipation by vegetation (Méndez and Losada, 2004). This method is also used in several modules for digital application.

Méndez and Losada

Despite the fact that many parameters are included in this model there is still a knowledge gap in this method. Unknown effects are hidden in the interaction between vegetation and hydraulic parameters. These are represented by a bulk drag coefficient (C_D) which can only be determined using an experimental approach (Méndez and Losada, 2004). Besides this the non-wave currents are not taken into account (Hu et al., 2014).
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When all parameters are known the wave attenuation by vegetation can be computed over the length of a foreland of a dike. According to Méndez and Losada it is highly advisable to use a numerical model for computing the attenuation. This is mainly because vegetation and hydraulics are not independent. This makes the computation of wave attenuation an implicit numerical process which needs numerical computation.

Vegetation parameters

The physical characteristics of vegetation are very important for the wave attenuation (Anderson, 2011). The included parameters in this method are:

- Height of the vegetation (h_{veg})
- Diameter/width of the vegetation (b_v)
- Density of the vegetation (N)
- Length of the vegetated bed (L_{bed})

Vegetation is no constant factor. This implies that the parameters from the enumeration above vary over time and place. When considering application in dike design the variation of these parameters is very important, because a minimal safety should be guaranteed (Moller et. al., 2014). Research was conducted on the link between spatial distribution of vegetation and wave attenuation (Suzuki et. al., 2012). However, besides some specific data on species, too little data is available to include this variation in this work.

Hydraulic parameters
The hydraulic conditions are important when considering the vegetation parameters as well as the dike design (Pullen et. al., 2007; Anderson et. al., 2011). The following parameters are used as conditions in this thesis:

- Water depth (h)
- (Significant) wave height (H_{m0}, H_s, H_{rms})
- Wave period (T_p, $T_{m-1,0}$)

H_s is considered equal to H_{m0} and both can be transformed to H_{rms} using the characteristics of the Rayleigh distribution (van Rijn, 2011). When estimating attenuation by vegetation the peak period (T_p) is used (Méndez and Losada, 2004). However, when considering the dike design the specrtral wave period ($T_{m-1,0}$) is often used (Pullen et. al., 2007).

Dimensionless quantities
To achieve results on the bases of the vegetation parameters and hydraulic conditions several dimensionless quantities are used in the process of computing wave attenuation (Méndez and Losada, 2004; van Rijn, 2011). The most relevant ones are:

- Relative vegetation height (α)
- Reynolds number for vegetation (Re_v)
- Keulegan Carpenter number (KC)
- Characteristic velocity on vegetation (u_c)

The first three parameters are easy to compute but this is not the case for the characteristic velocity. During the literature study it became clear that several authors use different formulas.. It is necessary to take this variation into account while comparisons between experiments are made (Moller et. al., 2014; Anderson, 2011).

Dynamic behavior

As earlier stated there is an interaction between the vegetation characteristics and the hydraulic conditions. This is very significant for the numerical process.

Bulk drag coefficient (C_D)
The bulk drag coefficient is a constant which represents the unknown effects of the interaction between the vegetation and the hydraulic conditions. One of these effects is the swaying of the vegetation under the influence of hydraulic loads. The bulk drag coefficient is often used for calibration of the method of Méndez and Losada to the results of an experiment. The calibrated value is then only valid for the unique experimental conditions. Often after the experiment is finished an empirical formula for the bulk drag coefficient is introduced which is dependent on a dimensionless number (Dalrymple et. al., 1984; Méndez and Losada (2004); Suzuki et. al., 2012).

However, during literature research it was discovered that there is still a considerable amount of setbacks regarding the application of the bulk drag coefficient. The drag coefficient is a value which contains several effects for specific vegetation types. When expressing several effects in one empirical formula, which is slightly dependent on dimensionless quantities, the influence of several parameters are ignored. This way of calibration is very rough and does not fully describe the problem (Hu et. al., 2014). Also the need for an expensive large scale experiment is no proper base for an effective application of this method in practice. Despite this, in further computations the bulk drag coefficient and the Méndez and Losada are adjusted for the application in dike design. It is the most common method and has the most data available. By using the many experimental data more can be discovered on the relevance and stability of this method.

Other dynamic effects
Vegetation also has impact on sedimentation. It increases the process and therefore creates bed elevation. This can also create higher attenuation of waves due to breaking (van Rijn, 2011). Besides that it can assure that the water depth does not change due to sea level rise (Bouma et. al., 2014). Due to the long time span of these effects they are not included in this work.

During storm surges extreme hydraulic conditions will have an effect on the vegetation. Due to the impact of waves, currents or water depths vegetation can bend, break or it can even be completely removed. During a large scale experiment on salt marsh vegetation one third of the biomass was removed by a simulated storm surge (Moller et. al., 2014). These effects have a considerable impact on the wave attenuation and especially on the applicability of the phenomenon in dike design. Moller et. al. (2014) was the only full scale experiment in which these effects were properly measured. Therefore a lack of data is present and this effect cannot be included in this thesis.

METHODS

In this section the methodology which is developed and which will be used for the case study will be explained.

Summary of recent studies
Ten studies (all based on experiments and the method of Méndez and Losada) were used for this research. All the data and all the results were gathered, filtered and adjusted to make them comparable. This was necessary to get an indication on the variation between studies but also to approximate the bulk drag coefficient in the case study.

Energy dissipation model
The method of Méndez and Losada is used for the case study in this research. This method is based on a first order differential equation for energy dissipation.

$$\frac{\delta E c_g}{\delta x} = \langle \epsilon_v \rangle$$

The energy dissipation is caused by a drag and a lift force on the vegetation (Suzuki et. al., 2012). However, due to the high KC numbers that occur the drag force is dominant and the lift force negligible (Dalrymple et. al., 1984). When integrating the drag force over the height of the vegetation the energy dissipation factor ($\langle \epsilon_v \rangle$) can be computed.

Afterwards the differential equation can be solved and rewritten to a wave height transformation expression:

$$H_{rms} = \frac{H_{rms,x=0}}{1 + \beta x}$$

$$\beta = \frac{1}{3\sqrt{\pi}} C_D b_v N k \frac{\sinh^3(k\alpha h) + 3\sinh(k\alpha h)}{(\sinh(2kh) + 2kh)\sinh(kh)} H_{rms,x=0}$$

Approximation of the bulk drag coefficient
No own experiments will be executed for the case study and therefore an approximation of the bulk drag coefficient is needed. This was tried using three methods.

Conservative value
First it was tried to find a value for the bulk drag coefficient that will always be present in the vegetation field. One cannot take the smallest available value for each vegetation because only a few experiments where conducted on vegetation in storm surge conditions. Therefore the possibility that the smallest value found for one species is not actually the lowest boundary. The most conservative value that can be used is the value which was determined for *Zostera Noltii* (small sea grass) by Paul and Amos (2011). This is very flexible seagrass and therefore a proper conservative estimation for all stronger vegetation.

Extrapolation of empirical formulas
As earlier stated most recent studies propose a formula for the bulk drag coefficient in their experimental setup. Too use these formulas their range need to be extrapolated to dike design (storm surge) conditions. Due to the fact that these formulas are empirical a prediction interval should be applied on the extrapolation to assure a range of reliability.

Correlation of variables with the bulk drag coefficient (C_D)
With the summary of recent studies available it was tried to find a correlation between the drag coefficient and other relevant parameters (for instance biomass per m^2 or relative vegetation height). However, due to the sheer variation in possible included effects in the drag coefficient a correlation was not found.

The two first techniques will be used in the case study. When extrapolation is used a prediction interval is applied with a lower boundary characteristic value. The only precondition will be that this lower boundary value cannot be lower than the most conservative value. This is deemed physically unrealistic.

Vegetation tool
To make a quick indication of the attenuation of waves by vegetation a programmed script was developed for this research. It runs the methods above but the script is interactive and can be used by everybody.

Dike design
The impact of this phenomenon on dike design will be determined using the crest height and the time the dike cover can resist wave attack. Two scenarios will be evaluated: one with vegetation and one with no vegetation included. These scenarios will be compared. For the impact on the crest height the European Overtopping Manual will be used (Pullen et al., 2007). When estimating the resistance of the cover against a wave attack standard diagrams for grass covers are used (Weijers, 2015).

CASE STUDY
The developed method for estimating the wave attenuation by vegetation was put to the test on a section in Friesland, the Netherlands (coordinates: 53.343141, 5.794492). The reference vegetation for this case study is approximately the same vegetation as used in the experiment of Moller et. al. (2014). The formula of Moller will therefore be extrapolated for approximation of the bulk drag coefficient.

RESULTS
The case study proves that the bulk drag coefficient (C_D) can significantly vary over the foreland during numerical computation (figure 1).
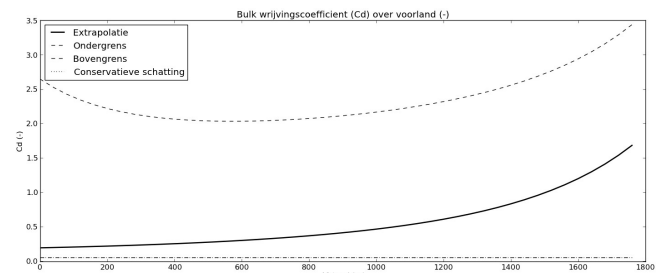

Figure 1 Variation of the bulk drag coefficient over length considered

The use of a continuously updated drag coefficient during the numerical computation results in the following wave attenuation results for the section considered (figure 2).
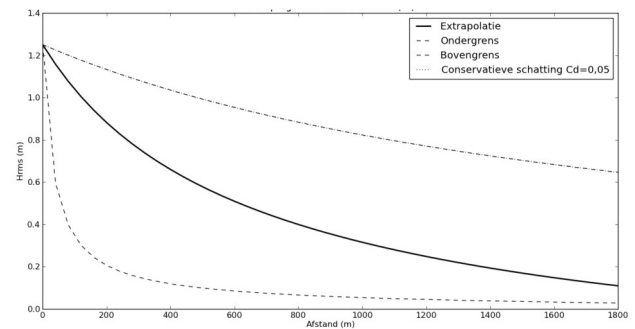

Figure 2 Wave attenuation example for case study dike

Both the upper and lower reliability bounds are presented in the figures using dotted lines. For dike design the upper bound of the wave height will be relevant, because this is the least beneficial scenario. In this case this upper boundary is equal to the bulk drag coefficient based on the conservative value.

The case study resulted in the following impacts on the design with respect to a scenario without a vegetated foreland taken into account.

- The design crest height reduces by 1.02 m.

- The standard dike cover is the only cover needed and no more reinforcements are necessary contradictory to the first scenario.

Besides the results of the case study itself the process in developing this analysis gave results as well. More insight is gathered on the current methodology and differences between studies. Finally an interactive script was developed for a quick scan on the potential effect of wave attenuation by vegetation.

CONCLUSIONS

When reviewing the results it is clear that in the case study the upper boundary (which is most relevant for dike design) is equal to the wave attenuation with a conservative CD. However, it became clear that the method of Mendez and Losada is far from ready for application in practice. Despite an indication can be made there is hardly any data available considering the variation of vegetation parameters, breaking and removal of biomass and the estimation of the drag coefficient. Besides that a full scale experiment is needed every time it is applied and this is no base for an easy application.

RECOMENDATIONS

The current method for determining the wave attenuation by vegetation can be used for an indication but is far from ready for application. There are three main recommendations for improving the Méndez and Losada method:

- More experiments under storm surge conditions to create relevant datasets for dike design.

- More long term measurements for quantifying the variation of vegetation parameters.

- Deciding on clear and proper agreements for determining parameters and dimensionless quantities.

Instead of improving the current method it is also an option to radically change the computation method used for this effect. Two clear recommendations can be formulated:

- Parameterize the unknown effects in C_D and eliminate the empirical relation as much as possible.

- Simplify the model with a design table for different vegetation by conducting large scale experiments under storm surge conditions.

ROLE OF THE STUDENT

The whole thesis and every research step was developed and written by the student and was supervised by both Deltares and the TU Delft. The topic was developed by himself after getting in contact with B. van Wesenbeeck at Deltares. Most of the meetings were discussions on the topic and all the conclusions and recommendations were formulated by the student.

ACKNOWLEDGEMENTS

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