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Soltau, Felix; Arns, Arne; Ulm, Marius; Jensen, Jürgen

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Classifying Wave Attenuation by Vegetation Using a Decision Tree Model

F. Soltau, A. Arns, M. Ulm & J. Jensen
Research Institute for Water and Environment, Siegen, Germany

Abstract: Environmental compatibility of coastal protection plays an important role in today's development and realization of new projects as well as in redesigning existing protection measures. In coastal protection strategies, natural structures like foreshore vegetation fields could be included as supportive element against wave forces and at the same time contributing to ecosystem quality and health. In this study, we present the development of a decision tree model to estimate wave attenuation by vegetation on the dike foreland. Our model is based on data from different published field measurements and laboratory experiments. In addition, a Smoothed Particle Hydrodynamics (SPH) model is used to extend our dataset beyond the observed parameter range. Overall, we can see a good agreement between observed wave attenuation rates and the predictions of our decision tree model. The model is supposed to be a robust tool for practical applications in coastal protection strategies, returning ranges of the attenuation capability as induced by vegetation fields.

Keywords: coastal protection, wave attenuation, wave damping, foreshore vegetation, decision tree model, nature based solutions, ecosystem services, smoothed particle hydrodynamics

1 Introduction

The world's coastlines are threatened by extreme coastal events, which can have devastating societal impacts (see e.g. Muis et al., 2016). To prevent coastal cities from flooding, coastal protection measures have to withstand extreme sea levels at specific return periods such as the 100 or 200-year return water level (see e.g. Arns et al., 2013), usually also taking waves (e.g. the wave run-up) into account. Wind induced waves are the main driver of erosion processes at dikes, which – if not properly accounted for – can cause a failure of existing protection measures (Kortenhaus et al., 2002; Kobayashi & Weitzner, 2015). To provide high safety standards along coasts, coastal engineers, managers, and planners need to robustly estimate i) the load on coastal defenses, ii) ensure a certain level of resistance against i), and estimate iii) potential impacts associated with i).

Modern coastal defense strategies usually include a safety margin, also allowing for loads, which are higher than anticipated in the design process. However, ongoing sea level rise (SLR) will also cause changes in the hydrodynamic load such as increasing extreme sea levels (Arns et al., 2015; Vousdoukas et al., 2018) and waves (e.g. Melet et al., 2018). In order to maintain a sufficient degree of safety at the inhabited coastlines, it is necessary to mitigate the consequences of SLR, e.g. by adjusting the existing protection heights or by reducing the load on the defense structure. In traditional engineering, coastal protection largely focuses on technical solutions (e.g. sea walls, dikes) but ecosystem services such as salt marsh induced wave attenuation or shore stabilization have contributed to costal protection ever since (see e.g. Fig. 1). In recent days, however, ecological compatibility has become an important factor in coastal defense design and the key challenge is to preserve the main function of the defense structure with an appearance adjusted to the landscape. This is why an increasing number of scientists and practitioners focus on this emerging field (see e.g. Bouma et al., 2005; Augustin et al., 2009; Möller et al., 2014) aiming at ecofriendly ways of designing coastal defenses. This overall approach is usually referred to as *Engineering* or *Working with Nature*, *Building with Nature,* or *Nature based Solutions (NBS),* hereafter jointly addressed as NBS.

Specifically, there have been several studies trying to value the role of vegetated foreshores for coastal hazard mitigation and climate change adaptation (see Shepard et al., 2011; Temmerman et al., 2013) as well as on wave attenuation by vegetation in particular (see e.g. Knutson et al., 1982; Bouma et al., 2005; Augustin et al., 2009; Möller et al., 2014). In summary, these studies highlight the cost-effectiveness and ecologically sound contribution of NBS to coastal protection. As supportive element, analyses based on field studies and laboratory experiments are considered but mostly focusing on one or two different types of vegetation and a narrow range of wave parameters. Although providing scientifically highly relevant insights, a comprehensive approach useful for practical (engineering) applications is still missing.

Fig. 1. Dike foreland vegetation on Hiddensee Island, Germany (Soltau, 2018).

Here, we present a first of its kind approach that assimilates different published datasets of field campaigns in order to estimate the wave attenuation by vegetation for various kinds of scenarios. In addition, we use numerical model data, which has been calculated using a Smoothed Particle Hydrodynamics (SPH) model. The SPH model allows an extension of the limited range of existing observations towards yet unobserved conditions, including a variety of wave and vegetation parameters required to investigate the influences of single parameters on the attenuation rate. Our approach is based on a decision tree model and provides three attenuation classes: low (< 33%), medium (≥ 33 and < 66%), and high attenuation (≥ 66%). The overall aim of this study is to develop a robust tool for estimating wave attenuation by vegetation suitable for practical applications in coastal protection strategies.

2 Data basis

Over the last decade, an increasing number of NBS studies has been published but we were mainly interested in studies dealing with vegetation induced wave attenuation. We focused on published field campaigns and laboratory experiments on interactions between wave and vegetation. According to our data mining task, the predictors of the classification tree are water depth, slope, wave height at different locations, and vegetation characteristics. Wave height information is needed in front of and inside or behind the vegetation field. The vegetation parameters are the following: height of vegetation, stem diameter, number of stems per unit area, and vegetation field length. Tab. 1 lists all parameters we assimilated during the literature study.

Our dataset for the decision tree model currently consists of 80 observations sampled from five different studies as follows: The natural vegetation species are smooth cordgrass (Knutson et al., 1982) and common cordgrass (Bouma et al., 2005) as well as artificial plastic sticks which were used in the laboratory studies of Bouma et al. (2005), Schürenkamp (personal communication, 2018) and Augustin et al. (2009), and artificial cylinders in the numerical model (Soltau, 2018). All parameters vary within broad ranges as highlighted in Tab. 1.

Tab. 1. List of data set parameters and ranges of observed values.

Parameter	Symbol	Minimum	Mean	Maximum	Standard deviation
Vegetation height in [m]	h_{Veg}	0.100	1.056	4.717	1.401
Number of stems per area in [m^{-2}]	N_{Stem}	0.16	282.13	2400.00	452.80
Stem diameter in [m]	D_{Stem}	0.003	0.068	0.300	0.121
Wave height in [m]	H_{x0}	0.028	0.215	0.623	0.188
Water depth in [m]	d_{x0}	0.12	1.05	4.00	1.10
Vegetation field length in [m]	L_{VegFld}	2.0	8.8	50.0	8.2
Slope [m/m]	-	0.000	0.026	0.136	0.041
Wave height attenuation in [%]	-	4.1	41.2	100.0	29.6

Other important parameters such as the wave period or the wavelength are often missing in the literature, especially when the waves are measured in the field; in contrast, they are usually available from controlled laboratory experiments. To make use of the entire attenuation dataset, we decided to not consider the wave period or wavelength and that is why the model is currently set up without taking these values into account. However, in order to specify the vegetation more precisely, future steps aim at including both wave period and wavelength but also further biomechanical characteristics such as the plant flexibility (e.g. using the bending stiffness).

3 Methodology

A numerical model is used to extend our dataset to unobserved or unpublished parameters describing the interaction of wave and vegetation. The software used for the computations is DualSPHysics, a three dimensional Smoothed Particle Hydrodynamics (SPH) based code. The advantage of using SPH to simulate wave attenuation by vegetation is the implementation of three dimensional vegetation objects inside the model domain as shown in Fig. 2. As a next step, the numerical model will be validated against data from laboratory experiments provided by Schürenkamp (personal communication, 2018) and later on used to a) extend our dataset and b) investigate the general response of changes in individual parameters on wave attenuation.

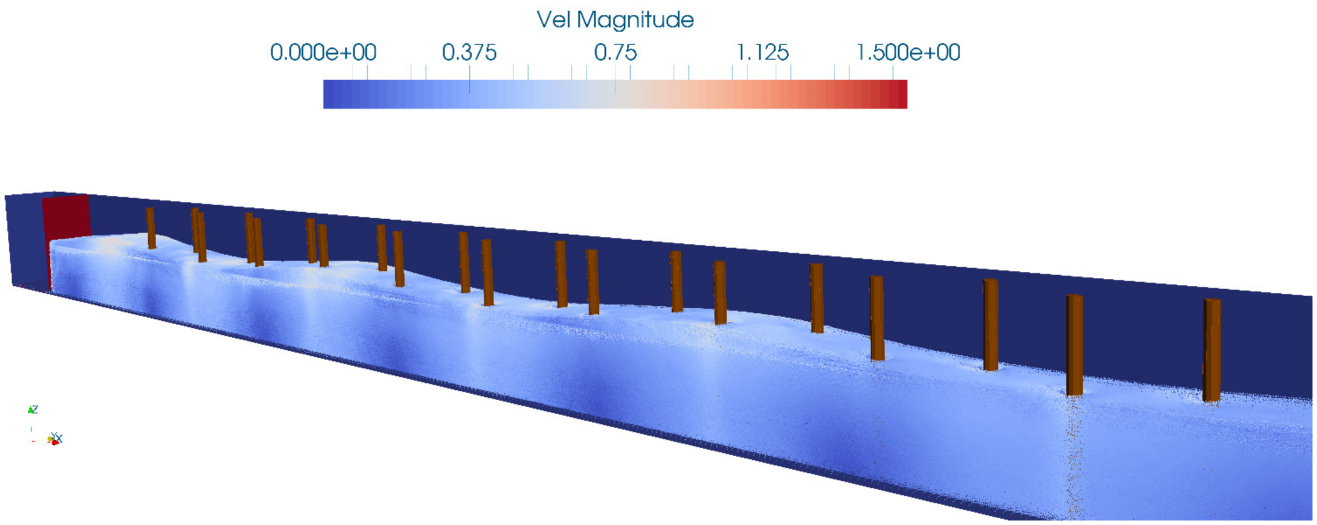

Fig. 2. SPH model used to simulate wave attenuation by vegetation (based on the SPH code of DualSPHysics).

Our newly compiled dataset (including the SPH data) shows a large spread in the individual parameters, because of the different spatial scales of field measurements and laboratory experiments. However, our dataset also includes similar attenuation rates at a number of individual observations. Aiming at a decision tree with as few splitting nodes as possible, this would cause problems as the tree would be branched too deeply. Therefore, it is necessary to preprocess the data. Here, we decided to transform some of the absolute parameters from different spatial scales into relative quantities. These quantities are the relative vegetation height (i.e. the vegetation height divided by the water depth in front of the vegetation field), the relative wave height (i.e. the wave height in front of the vegetation field divided by the water depth at the same location), and the vegetated area per square meter or vegetation density (calculated by multiplying the area of one single plant with the number of plants per square meter). The vegetation field length and the slope remain as absolute values. The equations used to derive relative quantities and the associated range of relative parameters are given in Tab. 2.

Tab. 2. Equations and ranges of relative parameters used for the decision tree.

Parameter	Equation	Min value	Max value
Relative vegetation height	h_{Veg} / d_{x0}	0.443	1.630
Relative wave height	H_{x0} / d_{x0}	0.063	0.667
Vegetation density	$\pi/4 \cdot D_{Stem}^2 \cdot N_{Stem}$	0.001	0.047

When growing the classification tree, the algorithm computes the weighted impurity of a potential node and estimates the probability of an observation being in that node. The impurity is given by calculating the Gini index of that node. As a first step, the first predictor is sorted in ascending order while every value of this predictor is a potential split point. Then the algorithm finds the best way to split that node by maximizing the impurity gain for every single value (Coppersmith et al., 1999). This computation is repeated for each of the currently five predictors until the value with the largest impurity of all values from all predictors is found. This process is repeated again for every potential splitting node. The algorithm terminates, if the number of observations at any splitting node falls below a certain value. This value is chosen to be 5% of the size of the data set.

The final decision tree lets the user find a way along the branches and across the splitting nodes to the leaves. Depending on the input values, the user ends up at different leaves of the tree. The leaves at the end of the branches provide an estimation of the wave height attenuation according to the input values. The final estimation is separated into three different classes: low (< 33%), medium (≥ 33% and < 66%), and high (≥ 66%) attenuation.

4 Results and discussion

Here, a decision tree (see Fig. 3) is developed using the algorithm described above. The tree consists of 25 nodes while 13 of them are leaves showing the estimated attenuation class. The tree is able to predict 78 out of the 80 known attenuation classes correctly. For instance, there is one parameter configuration of Knutson et al. (1982) given in Tab. 3, showing the observation in the first row and the decisions using the tree in the second row. The medium attenuation class fits the observed value of 53%. Two of the predictions of attenuation classes, however, mismatch with the observations, which is potentially due to currently used algorithm preferences, that need further improvement.

Tab. 3. Example of using the decision tree with an observation by Knutson et al. (1982).

Parameter	Vegetation density	Vegetation field length	Relative wave height	Slope	Relative Vegetation Height	Attenuation
Observation	0.0025	8.69	0.18	0.043	0.6	0.53
Decision tree prediction	< 0.008	< 9.8	< 0.365	< 0.055	(1) ≥ 0.55 (2) < 0.795	medium

The decision tree in Fig.3 was developed as supportive tool for practical applications, aiming at a first estimation of wave height attenuation by a vegetation field. This is why a rather coarse distinction into three classes of attenuation has been chosen. Currently, there are seven parameters describing the wave and vegetation characteristics as predictors in the model. However, parameters such as the wave period or the wavelength are still missing, which are known to be important to describe the process of wave attenuation (Anderson et al., 2011). Specifically, the wavelength is usually needed to distinguish between deep water, shallow water, and intermediate water waves. Therefore, in case of submerged vegetation, the wavelength will most likely be a factor influencing the intensity of interaction between waves and vegetation. Another parameter that needs to be integrated in the prediction of vegetation induced attenuation is the flexibility of plants. The importance is demonstrated by Bouma et al. (2005), highlighting a high variability of attenuation rates due to different flexibilities. To further improve the classification tree, an expansion of the existing dataset is required, considering all above-mentioned parameters.

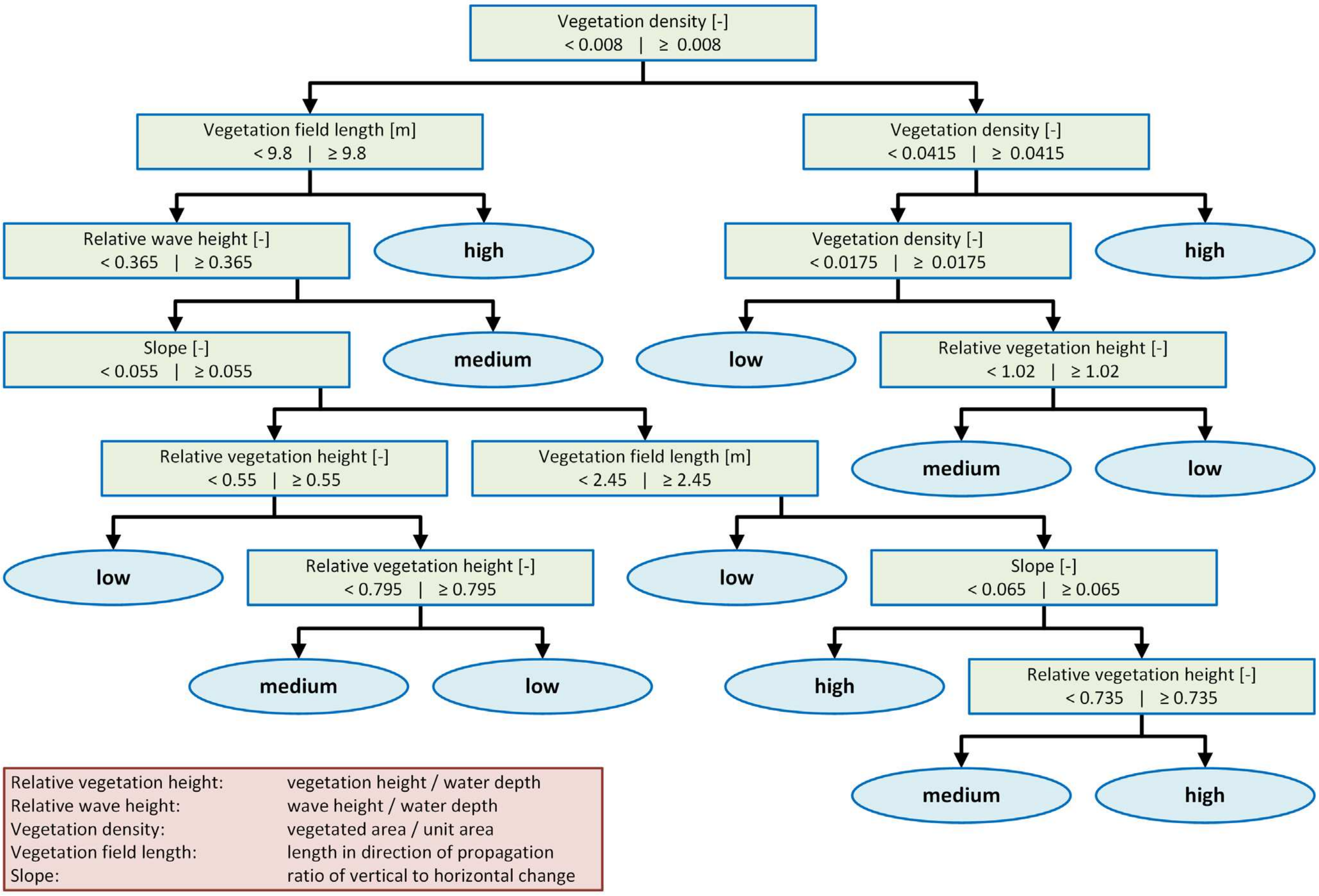

Fig. 3. Decision tree with 25 nodes and 13 leaves, trained by 80 observations.

5 Conclusion and Outlook

Waves are the main dynamic load on coastal defenses, which – due to their high erosive power – strongly affect the durability. Climate change induced intensifications of extreme sea levels and waves will further increase this load, and mitigation and/or adaptation are needed to maintain the protective function of coastal defenses. At the same time, there is a growing demand for ecologically valuable solutions and the need to create holistic coastal protection strategies taking both technical as well as Nature Based Solutions into account without reducing current safety standards. Therefore, traditional approaches to calculate required design heights need to incorporate the benefits provided by natural systems. Here, we present a newly developed method aiming at a semi-empirical solution to quantify the wave attenuation by vegetation. For the first time, several different campaigns are combined and a generalized attenuation estimate including a variety of different plant species is provided. We use a decision tree as a tool to estimate wave height attenuation by vegetation. The decision tree requires wave and vegetation parameters as input and returns attenuation estimates subdivided into three different attenuation classes. The current tree has been set up using 80 observations, containing seven different predictors, and the resulting attenuation. Next, the data set will be extended and additional parameters will be included to improve the accuracy of attenuation estimates.

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