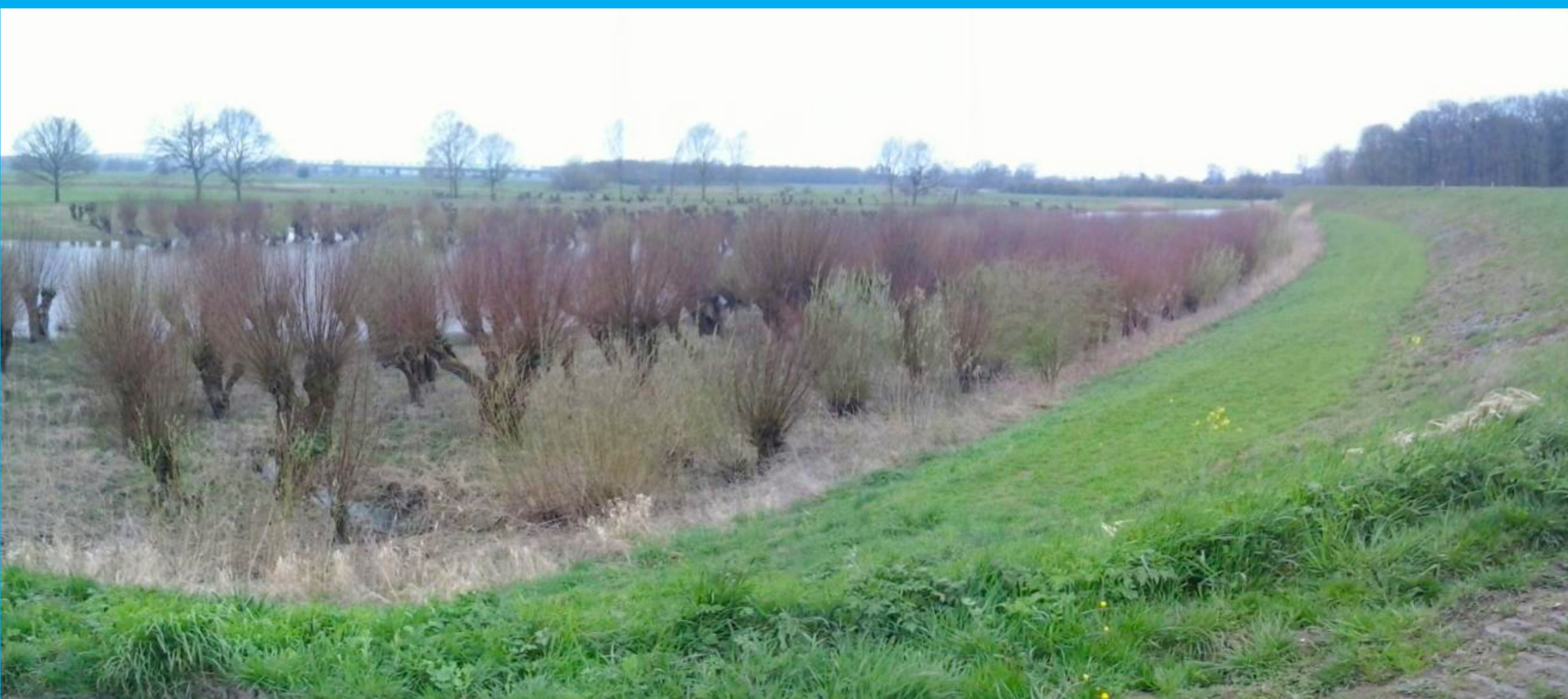
Reliability of willows for wave load reduction on river dikes

Design and maintenance principles for willow vegetation based on the quantified natural and knowledge uncertainties

M.M. Stam



TU Delft

HKV LIJN IN WATER

Waterschap Rivierenland

Reliability of willows for wave load reduction on river dikes

Design and maintenance principles for willow vegetation based on the quantified natural and knowledge uncertainties

by

M.M. Stam

to obtain the degree of Master of Science
at the Delft University of Technology,
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Student number:	4160606	
Thesis committee:	Prof. dr. ir. S.N. Jonkman,	TU Delft
	Ir. V. Vuik,	HKV Consultants & TU Delft
	Prof. dr. ir. S. van Vuuren,	TU Delft
	Prof. dr. ir. B. Hofland,	TU Delft
	Ir. M. Olieman,	Waterboard Rivierenland & TU Delft

Summary

Flood defenses are important to keep large parts of the Netherlands dry. These primary flood defences are every twelve years assessed on safety during the Dutch national safety assessment. In 2017, the new safety standards (WBI2017) were introduced. These stricter standards caused that in total 251 km of the primary flood defences was rejected on height, which includes the failure mechanisms wave overtopping and overflow. Traditionally, dike strengthening is required. However, the new Delta Plan gives also special attention to the implementation of innovative nature-based solutions, for example the integration of shallow foreshores without or with vegetation in the safety assessment. These foreshores can reduce the incoming wave load by dissipating energy through wave breaking, bottom friction and vegetation attenuation. (Vegetated) foreshores are also present in front of some river dikes, called floodplains. Probably, 5 to 15 procent of the foreshores in the current reinforcement program (HWBP) is not or conservatively considered in the safety assessment, which entails unnecessary costs (circa 0.5 - 1 billion euros). In a quickscan of the riverine area several locations are indicated which meet the requirements as promising locations for wave reduction by vegetation. However, despite a renewed focus on building with nature, implementation of nature-based flood protections is hindered by a knowledge gap in the effects of variable vegetation on wave energy dissipation. The state and functioning of vegetation during design conditions is uncertain. This uncertainty is the most important reason for dike managers to hamper the implementation of a nature-based flood protection. The main objective of this thesis is to determine the reliability of willow vegetation as wave load reduction for river dikes.

In order to assess the variability of vegetation on the wave damping, a field test and simulation models are used. The measurement set-up of Deltares consists of a plot of 7 x 7 meters with young willow branches and pressure transducers perpendicular to the river, which measure the (by ships produced) waves in the river Noord. Based on the field measurements, a model is developed and applied to determine the drag coefficient of willow branches. This model is an one-dimensional SWASH model which contains the bathymetry and the willow vegetation, characterised by a density, branch diameter and drag coefficient for three height ranges. These parameters provide the obtained wave attenuation by vegetation. The diameter and density were measured in the field. Therefore, the drag coefficient can be determined by calibrating the outcomes of the numerical model with the field measurements.

From the field measurements by Deltares, it can be concluded that willow branches reduce incoming waves with a height higher than 0.20 meter with approximately 4 % per meter willow vegetation width. The wave attenuation depends mainly on the water depth and shape of the willows. The stiff stem of old willows damps waves less than high dense, more flexible branches above the stem, and the wave damping decreases with increasing water depth mainly when branches submerge. The field measurements are used to calibrate the drag coefficient. The 25th and 75th-percent value of the calibrated drag coefficient were calculated on -1 and 5, a large range. A negative value may not be possible, because this means an increase of the wave height by the willow vegetation. This large range in calibrated values and the existence of negative values are caused by the measurement set-up. The plot with willows was too small for accurate measurements and the crates, in which the willow branches were planted, caused distortion of the waves due to the sudden bottom elevation. Because of this, the first sensor at the edge of the crate (at the river side) has probably encouter measurement errors. Third, the angle of the incoming ship waves caused an underestimation of the calculated wave damping capacity of willows. The set-up should be improved to give proper results and conclusions

about the drag coefficient of willows. The drag coefficient remains therefore uncertain and gets a large standard deviation in the second part of the research.

In this second part, a study is carried out to the uncertainties of implementing wave damping willow vegetation. A one dimensional wave model based on the wave energy balance, is created for a dike section at the Heesseltsche Uiterwaarden, alongside the river Waal. Waterboard Rivierenland suggest this floodplain as opportunity for planting wave damping willow vegetation to compensate the required heightening of the dike.
In the wave model, various input parameters are required to calculate the wave damping: boundary conditions, dike-foreshore parameters and the vegetation parameters. These parameters have all certain standard deviations or variations. First, the effect of these standard deviations on the wave damping is determined, and so the overtopping discharge and required crest level. Second, a thorough analysis is made to exogenous threats which affect the vegetation parameters. For willows this could be diseases, insects, ice, animals, drought, flood, fire and storm. The effects of these threats on the vegetation parameters are estimated by the knowledge and expertise of willow experts and a literature study.
It is concluded that from all input parameters with standard deviations, the variations of the vegetation parameters has the largest effect on the obtained wave overtopping. The wave reduction depends mostly on the vegetation height and water depth, which was also concluded by the field measurements. Second important vegetation parameter is the density of the branches or the drag coefficient, if the drag for willows can be lower than 0.4. The most relevant influential threats with a high risk and significant consequence are storms, floodings and droughts.
These effects of the standard deviations of input parameters, exogenous threats and annual maintenance on the overtopping discharge (and required crest level) are used for a recommendation about the design and maintenance strategy of willow vegetation as solution. The willow vegetation should ensure enough wave damping during the total lifespan of the reinforcement to comply the safety assessment. Therefore it is recommended to extend the width of the willow vegetation with a buffer zone in which all the vegetation uncertainties can be accommodated. The width of the vegetation plot is therefore the main parameter that should be assessed during inspection. Note that the uncertainties and probabilities of the exogenous threats are assumed. Further research is required to validate these assumed values.

To conclude, willows can be used as wave damping vegetation at floodplains along rivers. The branches of willows will reduce the incoming waves significantly if they are not submerged. The height of the willows is therefore the most important vegetation factor and should be assessed during inspections just like the required vegetation width to ensure the wave damping capacity during the total lifespan of the dike reinforcement. The reliability of willows for wave load reduction on river dikes is sufficient if the maintainer apply the design and maintenance principles as recommended.

Preface

This thesis completes the master Hydraulic Engineering at Delft University of Technology. Research for this thesis was supported by HKV-consultants, Waterboard Rivierenland and the Hydraulic Engineering section at Delft University of Technology. The research is part of the research programme BE SAFE, which is financed by the Netherlands Organisation for Scientific Research (NWO).

The work for this thesis has been carried out at the HKV offices both in Delft and Lelystad. It was great to work at these locations, because of the really pleasant ambience. It was always fun in Delft during the lunch, table tennis sessions and vrijdagmiddagborrels, but also in the working rooms. I would like to thank all colleages for sharing their knowledge and stories, and the discussions about my thesis subject.

I would like to thank my entire thesis committee for their guidance and feedback during this research despite I was a bit absent. First of all, I want to thank my daily supervisor, Vincent Vuik, especially for keeping me motivated. When after five months of working my bag (including all back-ups on the two laptops and hard disk) was stolen, your enthusiasm about small parts of my work after this event was needed to kept me going. You have really pushed me in the right direction. Bas Jonkman, thanks for your knowledge about doing a good research with clear boundaries and a smaller research-area. This has helped me to focus. Saskia van Vuren, thanks for your critical view and comments about the structure of my report and research. Bas Hofland, thanks for your enthusiasm and critical view. You was sincerely interested in the subject of the research, which motivated me too. Marike, special thanks to you. You helped me to made the outcomes of the research applicable and practical.

Furthermore, I would like to thank my close family and friends for supporting me during this research.

"If I will do it again, I would do everything else." I think many students say this about their graduation research. However, despite of the setbacks and bad communication with the committee, I'm looking back on a year in which I have learned a lot and what I will always remember. Willow vegetation before a river dike as wave load reduction, in one word: beautiful.

Martine Stam
Delft, April 2018

Figure 1: Wave damping vegetation in the river Merwede (photo by William Stam)

Contents

1 Introduction

1.1. Background

Every twelve years, the safety of dikes in the Netherlands is investigated in a nationwide assessment. This safety assessment is performed according to the 'Wettelijk Beoordelingsinstrumentrium' (Jongejan, 2017), which is set by the Delta program. The dikes are assessed on their ability to meet the safety standards during storm conditions. This means that a dike needs to remain high water levels and wave overtopping, be resistant against wave attack and remain stable and impermeable. The definition of failure for flood defences is *the loss of the water-retaining function* and occurs when the load acting on the dike exceeds the strength of the dike.

In 2014, the Delta Committee presented the new Delta Plan with stricter safety standards. The assessment switched from semi probabilistic to fully probabilistic. Therefore the standards are expressed in terms of the probability of flooding of a dike system, from once every 300 years up to once every 100.000 years. The probability depends on the acceptable risk, which is based on both economic considerations and a statutory minimum level of protection for each individual in the Netherlands. The definition of flood risk in context of flood risk management is:

Flood risk is the probability of a flood event multiplied by the consequences (Jonkman et al., 2008)

The reliability of a flood defence is assessed considering various possible failure mechanisms. That means all known (or imaginable) ways a levee or flood defence structure could fail to fulfill its safety standard are considered. Figure 1.1 shows the most commonly encountered failure mechanisms for river dikes in the Netherlands. The acceptable failure probability needs to be distributed over these mechanisms.

In figure 1.1, there is also a distance given in km. These are the stretches of dikes in the riverine area that have been assessed, but do not meet the new safety standard requirements. For these dikes the probability of failure is higher then the defined acceptable risk. The owner is responsible for meeting the requirements and should take measures, like constructing an stability bank or heightening of the dike. These measures can be noted in the Dutch Flood Protection Program (HWBP) (Hoogwaterbeschermingsprogramma, 2018). This program (2018) contains 923 km of flood defences that do not meet the standards, a major reinforcement task.

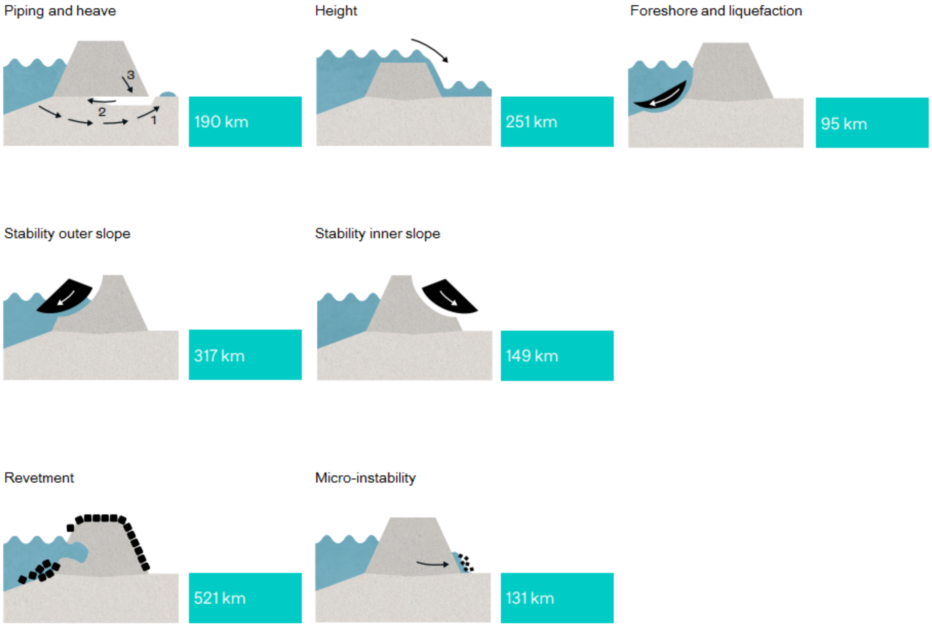


Figure 1.1: 923 km of flood defences do not meet the standards due to these failure mechanisms. A defense can also not meet the standards due to a combination of mechanisms (Excluding the projects from the general filter (Top 13)). (Hoogwaterbeschermingsprogramma, 2018)

Failure mechanisms overflow and wave overtopping (in figure 1.1 mentioned as 'height') play a major role with regard to the flood defence in the riverine area. Traditionally, the rejected dike parts are strengthened to fulfill the safety standards. However, the new Delta Plan gives also special attention to the implementation of nature-based and innovative solutions (Deltacommissie, 2008), like reduction of the wave load instead of a reinforcement. One of these innovative solutions is the integration of shallow foreshores in the safety assessment as found in the Wadden Sea (Wijnstra, 2015).

Shallow foreshores can reduce the incoming wave load by dissipating energy through wave breaking and bottom friction. Vegetation on these foreshores will induce even more dissipation. At various locations in the Netherlands, for example along the coastal defenses in the Delta and the Wadden Sea these foreshores with vegetation are present (Vuik et al., 2016).
These foreshores can also be created artificial, as a measure for load reduction. This is done in a large-scale pilot study located on the Houtrib Dike between the cities of Enkhuizen and Lelystad in the Netherlands. A 450-meter-long foreshore test section was constructed in the summer of 2014 and will be monitored for four years. Monitoring includes water levels as well as wave strength measurements, and the observed effects of vegetation. A topographic survey will be conducted several times per year. With this research an answer will be given to the question of how a secure, stable and cost-efficient sandy foreshore can be designed for use in lake systems (Steetzel et al., 2018).

Foreshores are also present in front of some river dikes, called floodplains. Probably, 5 to 15 procent of the foreshores in the current reinforcement program is not or conservatively considered in the safety assessment. The HWBP-alliance make unnecessary costs (circa 0.5 - 1 billion euros) by taking this wave damping foreshores not into account (Roode, 2016). Therefore, waterboards of the Netherlands have established the Project Foreshores (POV Voorlanden). The strategic goal of the Project Foreshores is to incorporate foreshores with a positive contribution on the floodrisk, in the safety assessment of the primary flood defenses from 2019 onward. This contribution is positive when there is energy dissipation at the floodplain during design conditions. Energy dissipation due to bottom

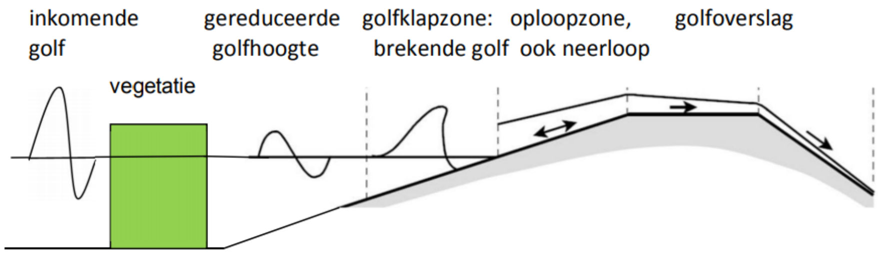


Figure 1.2: Wave attenuation obtained by vegetation (translation of the terms above the figure: incoming wave - vegetation - reduced wave height - breaking wave - wave set-up - wave overtopping) (Verheij and Sprengers, 2012)

friction and wave breaking will be small in the river area due to the large water depth during design conditions. However, there could be wave attenuation by vegetation.

Vegetation can have a positive or negative contribution to the flood risk. During high water, water flows over the floodplains and vegetation impede the flow of water if it stands in the flow path. As a result, the water level rises and the risk of flooding increases (Rijkswaterstaat, 2013). The negative effects of vegetation are checked in the program 'Stroomlijn' of Rijkswaterstaat, which covers the rivers Rhine and Meuse. The intention of this program is to remove vegetation at specific locations on floodplains where the current is fastest during high water.
At other locations vegetation can achieve reduction of the wave height. With a quickscan by Deltares (Verheij and Sprengers, 2012), floodplains in the riverine area are checked on having a positive contribution. The quickscan gave an overview of locations in the river area where a significant wave height may occur higher than 0.5 meter and where wave attenuation of the current vegetation can have a beneficial effect on the required crest level of the dike relative to the situation without vegetation. In total eleven floodplains with vegetation along the rivers Waal, Ijssel and Lek had a positive contribution.
Waterboard Rivierenland is currently preparing the reinforcement of some rejected dike sections along the Waal. The flood defense is rejected on height, stability and piping. In this research, a dike section is highlighted which is rejected on height. Waterboard Rivierenland want to investigate a number of innovative options to limit or avoid the heightening of dike sections at the dike track Tiel-Waardenburg (WaterschapRivierenland, 2017), among which "wave reducing vegetation on foreshores".

Wave attenuation by vegetation depend partly on the (vegetation) parameters: diameter of the branches, number of branches per square meter and the drag coefficient. These parameters multiplied give the vegetation factor, which is used in energy dissipation formulas. In fact this vegetation factor contains a lot of uncertainties. The diameter and the density of the branches can be measured, but varies through the years and seasons. Second, wave attenuation does not only depend on these vegetation properties, but also on hydraulic characteristics such as the wave height, the water depth (?) and ambient currents (Hu et al., 2014). The drag coefficient is being influenced by these hydraulic and biological factors and therefore also highly variable. Last, the vegetation parameters varies by nature continuously in time, but can also be affected by maintenance and by exogenous threats like diseases, ice, drought and storm. These threats and pruning of willows give a decrease of the wave damping capacity. However, the flood defense including the vegetated foreshore should always have to comply the safety standards if the vegetated foreshore is included in the assessment. Therefore, the probability of occurrence of these threats and the effect on the wave reducing capacity should be included in the design of the willow vegetation and the assessment of the river dike.

1.2. Problem description

Foreshores are present in front of some river dikes, so called floodplains. Probably, 5 to 15 procent of the foreshores in the current reinforcement program are not or conservatively considered in the safety assessment leading to unnecessary costs up to 1 billion euros, for governments and waterboards that need to implement measures to meet safety requirements (Roode, 2016). This main reason is that the effects of vegetation on wave energy disappation are unsure. In a quickscan of the riverine area several locations are indicated which meet the requirements as promising locations for wave reduction by vegetation. However, despite a renewed focus on building with nature, implementation of more nature-based flood protections is hindered by a knowledge gap in the effects of vegetation on wave energy dissipation. The state and functioning of vegetation during design conditions is uncertain. This uncertainty is the most important reason for dike managers to hamper the implementation of a nature-based flood protection.
In order to come up with a design criterion for river dikes with willow vegetated floodplains it is important to understand: the drag coefficient of willows during storm conditions, the effects of variations in vegetation parameters and dike-, foreshore- and model parameters might have on the wave attenuation capacity and the effects exogenous threats like diseases, drought and storms have on this wave attenuation capacity. Quantification of these uncertainties, which is important for safety assessment and design of a plot with willow vegetation, is not available in literature.

1.3. Research objective and questions

The research objective is to determine the reliability of willows for wave load reduction on river dikes, by quantifying the effects of the variations in (vegetation) parameters on the required crest level and required width of the plot with wave damping willows.
An analysis to the reliability of willows is required for a proper design and maintenance plan for the wave damping willow vegetation, and a smart method to assess the osier plantation on safety.

In order to achieve the goal of this thesis, following sub-questions should be answered:

- How much wave attenuation has been measured in a plot with willows?
- What is the drag coefficient of the willow vegetation, needed to reproduce (in the numerical wave model) the measured wave attenuation in the field?
- What is the effect of the standard deviations of the wave model parameters on the wave overtopping and required crest level?
- Which exogenous threats can affect the wave attenuation by willow vegetation?
- What is the effect of the variations in vegetation parameters, caused by the threats, on the required plot width or required crest level of river dikes?
- How should a wave damping vegetation plot with willows be designed and assessed?

1.4. Research methodology and outline

In this section the approach for the research is presented in two parts, with in total six steps. These steps are linked directly to the six research questions.
Part one contains a study about the wave damping capacity of willows. Wave measurement analysis is the first step of the approach corresponding to the first research question.
To determine the wave reduction by willows, wave measurements from Deltares are used. The measuring set was located in the river Noord near Dordrecht. The set consists of a number of pressure transducers located at the bottom perpendicular to the river, which register continuously the water

pressure above the sensor. The reduction capacity of the vegetation should be determined, mainly for ship waves. Previously, the mean water level varying in time by the tide is determined and the data is detrended. The wave height and period of waves travelling to the dike are determined for each sensor so the wave characteristics for each sensor can be compared and conclusions about wave attenuation by willows can be made. All waves are individually analysed by using the zero-crossing technique.

Second, the wave measurements over the plot with willows, are reproduced in the wave model SWASH (Simulating WAves till SHore, (Zijlema et al., 2011)). The drag coefficient C_D (-) of willows, can be determined by calibrating this wave model with the measurements. The determined coefficient is checked with theoretic values, which are used in literature.

In the second part, a study is made to the uncertainties of implementing wave damping willows. A wave model based on the wave energy balance (Vuik et al., 2018a), is created for a dike section at the Heesseltsche uiterwaarden, alongside the river Waal. The Heesseltsche uiterwaarden is suggested by Waterboard Rivierenland as opportunity for planting wave damping vegetation to compensate the required heightening of the river dike.

In the wave model, various input parameters are needed to calculate the wave damping. The effect of the value-variations of the input parameters on the wave damping capacity, is determined by a sensitivity analysis. In the sensitivity analysis, the uncertainty in the output of a mathematical model is apportioned to different sources of uncertainty in its inputs. This gives an increased understanding of the relationships between input and output parameters in the model. Especially for design conditions, parameters like the drag coefficient shows big variations in value.

Further, a thorough analysis of relevant exogenous threats which have effect on the amount of wave damping is made, often inherent uncertainties. Inherent uncertainties are uncertainties with a natural character. For willows this could be diseases, uprooting, frost, ice drift, animal feeding, drought, flood and stem breakage as well as difference of vegetation strength throughout the seasons and years.

The effect of these threats and maintenance on the vegetation parameters, is estimated by the knowledge and expertise of (foreshore) maintainers, willow experts and a literature study. With the estimated parameter values for each threat, new wave damping and overtopping calculations can be made. The reduced wave height is needed to determine the effect on the required crest level, wherefore the maximum wave overtopping is not reached.

The sensitivity of the input values and exogenous threats on the overtopping discharge and required crest level are discussed, and conclusions are made about the reliability of implementing wave damping willow vegetation. Recommendations has been devised about the design and maintenance of willow vegetation, which ensure for the total lifespan of the reinforcement enough wave damping to comply the safety assessment.

2

Theory of wave attenuation

This chapter describes the theory necessary for understanding the features of the modelled waves, the output from the model and the interactions between waves and vegetation. In this study we will use the non-linear wave theory for ship-waves that are used for determining the wave attenuation by willows. The most important characteristics of a wave are the wave period and the wave height. The definition of the wave period T, is defined as the time between two downward zero-crossings. The wave height H is defined as the crest height minus the trough between these zero-crossings. Different processes that affects the wave height at the foreshore will be discussed. The mechanisms are all included in the wave energy balance either as a mechanism what adds energy and increase the wave height or a mechanism what decrease the wave height.
To understand the differences between non-linear and linear waves, first the characteristics of linear waves are explained.

2.1. Linear surface gravity waves

Surface gravity waves occur at free surface. Gravity is the restoring force. The waves propagate along x-axis at the surface with a sinusoidal form (Kundu and Cohen, 2008)

$$\eta = a\sin(kx - \omega t)$$

Where
η surface elevation (m)
a amplitude (m)
k wavenumber which is a function of wavelength $k = \frac{2\pi}{\lambda}$ (rad/m)
ω wave frequency (rad/s)
t time (s)

The wave frequency is connected to the wavenumber by the dispersion relation for surface gravity waves (Kundu and Cohen, 2008), namely

$$\omega = \sqrt{gk\tanh(kd)}$$

Where d is the average water depth in meters and g the gravitational acceleration (m/s^2).

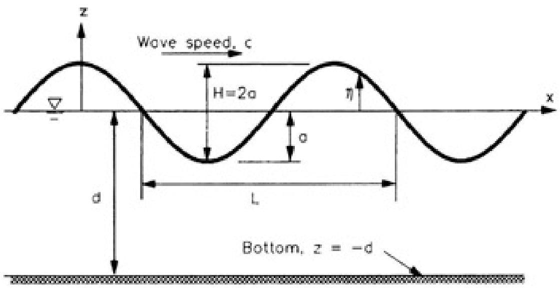


Figure 2.1: Wave nomenclature with sea surface at z = 0

2.1.1. Orbital velocity and Reynolds number

For linear surface gravity waves the maximum velocity, here in the direction of wave propagation (x), is defined in Kundu and Cohen (2008) as

$$u_{max}(z) = a\omega \frac{\cosh(k(z+d))}{sinh(kd)}$$

and decreases rapidly with the depth. At the bottom ($z = -d$) the orbital velocity will be equal to:

$$u_{max,bot} = \frac{a\omega}{\sinh(kd)}$$

For shallow waters the equation can be simplified to:

$$u_{max,bot} \approx \frac{a\omega}{kd}$$

The horizontal orbital velocity is in this study used to determine the Reynoldsnumber of a wave group. The Reynolds number is correlated to flow patterns in different fluid flow situations. At high Reynolds numbers flow tends to be dominated by turbulent flow which differ in speed and direction, such as during storms. At low numbers the flow is laminar.

To determine the Reynolds number for waves, the orbital velocity $u_{max,bot}(m/s)$, diameter of the branches $b_v(m)$ and viscosity of the water $v(m^2/s)$ are necessary:

$$Re_w = \frac{b_v * u_{max,bot}}{v}$$

This formula is used to determine the drag coefficient for storm conditions in chapter 3.5.3.

2.1.2. Water pressure

The water pressure contains two parts: hydrostatic pressure, caused by gravity, and dynamic pressure, caused by waves. The subsurface pressure at any water depth can be determined according to the formulation of Schiereck (Schiereck, 2003):

$$P = -\rho g z + \rho g a \frac{\cosh(k(h+z))}{\cosh(kh)} \sin(\theta)$$

The first part of this equation represents the hydrostatic pressure, the second part represents the pressure caused by waves. Further readings about this water pressure in the following chapter 3.4.1.

2.2. Non-linear ship waves

Boats moving across the surface of water produce a wave pattern. Ship wave patterns are similar to the combination of two Kelvin wave systems generated by two pressure points, with one near the bow and the other near the stern. The pattern consists of transverse waves which are perpendicular to the direction of movement, and diverging waves of which the connecting line of the highest points make an angle of 19° 28' with the direction of moment of the ship (Pethiyagoda et al., 2014). However, the propagation direction of the diverging waves on this line makes theoretically an angle of 35° 16' with the direction of movement of the ship. This is the angle in which the waves are travelling to the side of the river.

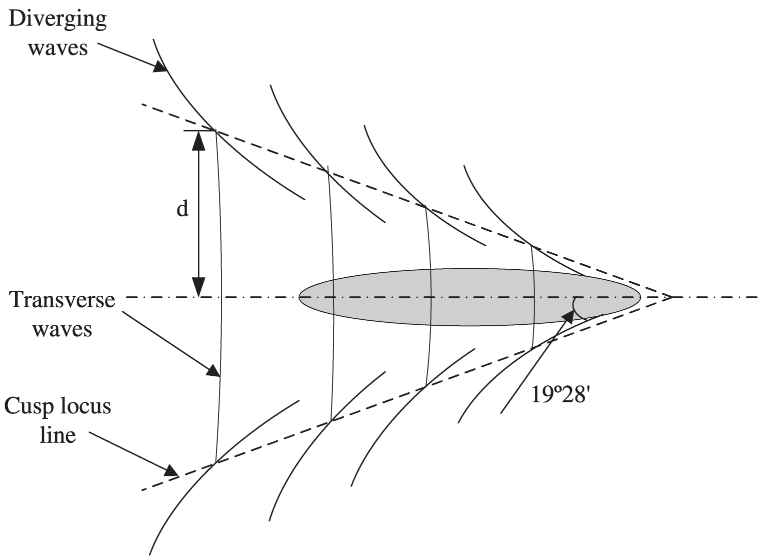


Figure 2.2: The Kelvin ship wave pattern in deep water. The included half-angle 19° 28' of the waves is called the Kelvin angle and is affected by the water depth (Pethiyagoda et al., 2014)

In linear wave theory, the wave amplitude is assumed to be sufficiently small in compare to the water depth. For these waves contributions of terms of second order and higher (the nonlinear terms) in the wave amplitude can be ignored (Whitham, 2011). In this case, it is sufficient to consider only one Fourier component at a time. For waves with a larger amplitude, the linear approximation breaks down and nonlinear effects must be taken into account.
In this study, ship waves are used for determining the wave attenuation by willows. These ship waves are steep and short, which results in nonlinear waves. Nonlinear waves are described by nonlinear equations and therefore the superpostition principle does not generally apply as mentioned in the Korteweg-de Vries equation (Linares and Ponce, 2015). This means that nonlinear wave equations are more difficult to analyze mathematically and that no general analytical method for their solution exists. Thus, unfortunately, each particular wave equation has to be treated individually. Linear theory predicts exponential growth of unstable waves, but nonlinear effects cause saturation and limit the wave amplitude at a finite level.

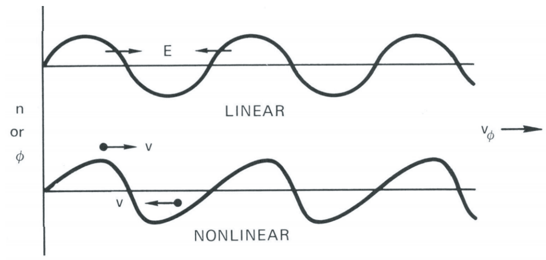


Figure 2.3: A large amplitude ion acoustic wave steepens so that the leading edge has a steeper slope than the trailing edge (unknown, 2012)

The hydrostatic pressure assumption can be made in case of propagation of long waves, such as large-scale ocean circulations, tides and storm surges. This assumption does not hold in case of propagation of short waves, flows over a steep bottom, unstable stratified flows, and other small-scale applications where vertical acceleration is dominant. So in the wave model, the non-hydrostatic function is used.

2.3. Theory energy dissipation

Wave attenuation originates from the dissipation of wave energy. In a steady situation the incoming and outgoing wave energy of an element Δx, normal to the shore, is equal. This leads to an energy balance:

$$\frac{\partial F}{\partial x} = \frac{\partial}{\partial x}[E * c_g] = 0$$

$$\frac{\delta c_g}{\delta x} E = 0$$

Where the propagation of the wave group is denoted with c_g and the wave energy (J/m^2)is expressed by:

$$E = \frac{1}{8}\rho_w g a^2$$

where ρ_w is the density, g the acceleration due to gravity and a the amplitude (Kundu and Cohen, 2008).

Waves propagating from deep water to a river dike, can lose energy when a foreshore with vegetation is present. This dissipation of energy is caused by different mechanisms: depth-induced wave breaking ()$S_{ds,b}$), bottom friction ($S_{ds,f}$), whitecapping ($S_{ds,w}$) and vegetation ($S_{ds,v}$). These mechanisms are all energy 'sinks' and provided in the energy balance a negative source term. Input of energy is conducted by the wind (S_{in}), which give the following one-dimensional wave energy balance:

$$\frac{\partial}{\partial x}[E * c_g] = S_{in} - S_{ds,b} - S_{ds,f} - S_{ds,w} - S_{ds,v}$$

Dissipation due to wave breaking, bottom friction and vegetation will be dominant on vegetated foreshores.

2.3.1. Depth-induced wave breaking

Depth-induced wave breaking is the first and most important process that leads to wave energy reduction on shallow foreshores in front of the river dike ((Janssen and Battjes, 2007); (van Loon-Steensma and Vellinga, 2013); (Vuik et al., 2016)). This process is a function of wave height, water depth and the

bed slope towards the river dike.
Wave breaking is caused by exceeding the maximum steepness of a wave. The maximum possible wave height depends primarily on the water depth. Generally wave breaking is expressed with the following formula, which is only valid in shallow water conditions[1].

$$H_b = h * \gamma$$

Where
H_b wave height of the breaking wave (m)
h waterdepth (m)
γ breaker parameter

For shallow water, the wave height of the breaking wave is lower than for deep water, so high waves will break during travelling to swallow water. The value of breaker parameter γ can be calculated with the following formulas:
Battjes and Stive (Battjes and Stive, 1985)

$$\gamma = 0.5 + 0.4\tanh(33H_0/L_0)$$

Ruessink et al. (Ruessink et al., 2003)

$$\gamma = 0.29 + 0.67kh$$

The ratio H_0/L_0 is mentioned as the deep water wave steepness. The steepness of an incoming wave increased when it enters shallow water.
When the wave exceeds the maximum steepness, the wave will break and loss energy.

2.3.2. Bottom friction

Second, wave energy can be dissipated by bottom friction on shallow foreshores. Due to the wave-induced motion of water pa rticles a turbulent layer is created at the bottom. Between the turbulent layer and the orbital motion of the water particles due to the waves transfer of energy ta kes place. Incoming waves decreased by the transfer of energy to the turbulent layer. The amount of this energy dissipation depends on the particle velocity at the bottom u_{bottom} and the shear stress τ_{bottom}. The shear stress at the bottom can be determined by:

$$\tau_{bottom} = \rho_w C_{bfr} u_{bottom}^2$$

Where C_{bfr} is the bottom friction coefficient that depends on the characteristics of the bottom profile, such as material and ripples and the wave conditions. Madsen (Madsen et al., 1989) derived a bottom friction formulation based on the eddy-viscosity concept:

$$C_{brf} = \frac{f_w}{\sqrt{2}}\langle U^2\rangle^{1/2}$$

where f_w is a non-dimensional friction factor. In the SWASH or SWAN model, the following formulation, based on the work of Jonsson (Jonsson, 1967), for f_w is used (Padilla-Hernández and Monbaliu, 2001):

$$for \frac{a_b}{K_N} < 1.57 f_w = 0.3$$

$$for \frac{a_b}{K_N} > 1.57 m_f + log_{10}[\frac{a_b}{k_N}]$$

where $m_f = -0.08$, a_b is a representative near-bottom excursion amplitude and K_N is the bottom roughness length.

[1] Shallow water condition: characteristic horizontal length scale is much larger than the characteristic vertical length scale of a wave ($kH << 1$ or $d/L << 1$)

2.3.3. Dissipation due to vegetation

The amount of energy dissipated by the interaction with the vegetation is based on the assumption that all energy of the mean flow is converted to turbulent energy due to the plant drag. The vegetation effect is due to the drag force on a fixed body in an oscillatory flow which can be determined using the well-known Morison equation. The Morison equation (Morison et al., 1950) can be used to quantify the total force on a cylinder in oscillatory flow. The total force is divided into the drag force and inertia force:

$$F = F_D + F_I = \frac{1}{2}\rho C_D d h_v U_w |U_w| + \frac{1}{4}\rho C_M \pi h_v d^2 \frac{\partial U_w}{\partial t}$$

Where
F total force
F_D drag force
F_I inertia force
ρ density of the fluid
d diameter of cylinder
h_v length of the stem immersed in the water
U_w characteristic velocity in oscillatory flow
C_D drag coefficient
C_M inertia coefficient
In this formula, the vegetation parameter V_f is shown:

$$V_f = C_D * b_v * N$$

. This vegetation parameter was described as a measure for the wave attenuation by vegetation. However, wave attenuation does not only depend on vegetation properties like vegetation height, stem diameter and spacing, but also on hydraulic characteristics such as the wave height, the water depth (**?**) and ambient currents (Hu et al., 2014). This variation is mainly integrated in the value of the drag coefficient, see section 2.4.

2.4. Drag coefficient

The drag coefficient C_D represents the drag that is caused by pressure differences and skin friction, but also processes like plant swaying. The coefficient is being influenced by hydraulic and biological factors. A biological factor, is the group-effect bulk-drag. For a higher density the drag coefficient can decrease to 60 % of the original value (Suzuki and Arikawa, 2011).

The drag coefficient of a smooth, rigid cylinder has a value of approximately 1.0 (-) for subcritical flow, but for vegetation bulk drag coefficients there is no single formulation or value available. For flexible vegetation it is complicated, because the drag coefficient is not constant due bending of the branches. Formulations for the resistance coefficient of vegetation, based on physical tests vary considerably in the literature (Vuik et al., 2016). However, in various formulas for determining the wave damping, a constant value is used for the drag coefficient for flexible or rigid vegetation. The coefficient for flexible vegetation without side-branches is higher than 1 and for rigid vegetation it is smaller than 1 (Galema, 2009). These are often invalid for the hydraulic characteristics of storm conditions, because the physical tests are done under other circumstances.

Author formula	Given C_D	Vegetation type
Tsujimoto et al. (1991)	3.14	Flexible
Rowinski et al. (2002)	1.22 - 1.35	Flexible
Poggi et al. (2004)	0.69 - 1.02	Rigid
Murphy et al. (2007)	0.66 - 1	Rigid
Stone and Shen (2002)	0.98 - 1.11	Rigid

Table 2.1: Values for the drag coefficient as given by different studies (Galema, 2009)

An estimation of the drag of vegetation during design conditions for different densities and flexibilities, required for a safety assessment, is difficult. The drag coefficient should be determined for a certain vegetation type including characteristics in a laboratory test.

3

Numerical model of wave measurements in willow vegetation

Willow branches reduce the wave height of incoming waves significantly as measured during a field test. The quantity of the wave damping capacity depends on the shape of the willow and the submergence. The wave damping is highest for dense, flexible willow branches when they are not totally submerged. The drag coefficient of willows is determined by calibrating a numerical SWASH model with the field measurements. However, the calibrated value of the drag coefficent and the calculated wave damping capacity of willows are despite of various defects of the measurement set-up uncertain, so conclusions about the drag coefficient and real wave damping capacity of willows cannot be made. The set-up should be improved with some mentioned recommendations to give better results and conclusions.

Wave attenuation by (willow) vegetation is basically determined with theoretical values for the drag coefficient. These values for the drag coefficient are rarely calibrated. In the summer of 2015, Deltares has placed a measurement set in the river Noord to determine the drag coefficient for one and three year old willows. However, there was no budget left to compute the wave damping capacity and drag coefficient of willows. In this research the measurements are elaborated.
Based on the measurement set-up, a numerical wave model is developed and applied to get an estimation of the drag coefficient C_D of willows. By calibration of the wave model with the field measurements, the C_D can be determined. The determined drag coefficient of willows can be used in future wave damping calculations.

3.1. Field site and data

The measurement set-up is located in the tidal river Noord near Dordrecht, close to the Ridderhaven (see figure 3.1). At the location of the set-up, the river has a width of 200 meters. The river Noord is an important connection to Rotterdam for inland navigation. Therefore, there are a lot of waves in the river produced by ships. These ship waves are used to determine the wave attenuation by the willows.

Technical drawings of the measurement set-up are shown on page 17. To conduct a minimum of undesirable conditions in the research, the willows are placed in bigbags and crates on a flat bottom created with rubbles. The slope from the river bottom to the measuring setup has a gradient of 1:4 and is equal at each side. The young and old willows are placed in a plot size of 7 x 7 meters, next to eachother. In each willow vegetation plot, five air-vented pressure transducers with data loggers are deployed on a line through the middle of the plot, perpendicular to the river. In the plot with young willows the pressure transducers are situated in horizontal direction at 0, 1.5, 3, 4 and 5.5 meters from the start of the vegetation at the riverside, and attached on the crates. In the plot with old willows, the transducers are attached to the five trunks close to the ground level in the bigbag at 0.45, 1.95, 3.45, 4.95 and 6.45 meters from the riverside. Data collection occurred during June 25-30, 2015. To isolate the effectiveness of the measurements, the transducers transmitted only the water pressure from 7 AM to 7 PM (the period in which ships pass by). A data acquisition system was configured to record signals from the instruments at a sampling interval of four hertz.

The vegetation parameters, density and diameter of the branches, were measured at various heights by hand in the field, see 3.1. In the numerical model, these vegetation parameters are inserted to determine the drag coefficient.

height (m)	b_v **(m)**	N
< 0.7	0.15	1
0.7 - 1.8	0.0098	46
1.8 - 4.0	0.0080	80

(a) Old willows

height (m)	b_v **(m)**	N
< 0.6	0.0084	190
0.6 - 1.2	0.0065	190
1.2 - 1.5	0.0038	190

(b) Young willows

Table 3.1: The diameter b_v and density N per m^2 per section of height for the old and young willows

3.2. Approach

Several steps have to be executed to determine the drag coefficient of willows. First, the wave measurements in the field should be analysed to obtain more knowledge about the behavior of willows concerning wave reduction. Second, this behavior should also be visible in the numerical model. Finally, the model needs to be calibrate using the field measurements, to determine the only unknown vegetation parameter C_D in the model.

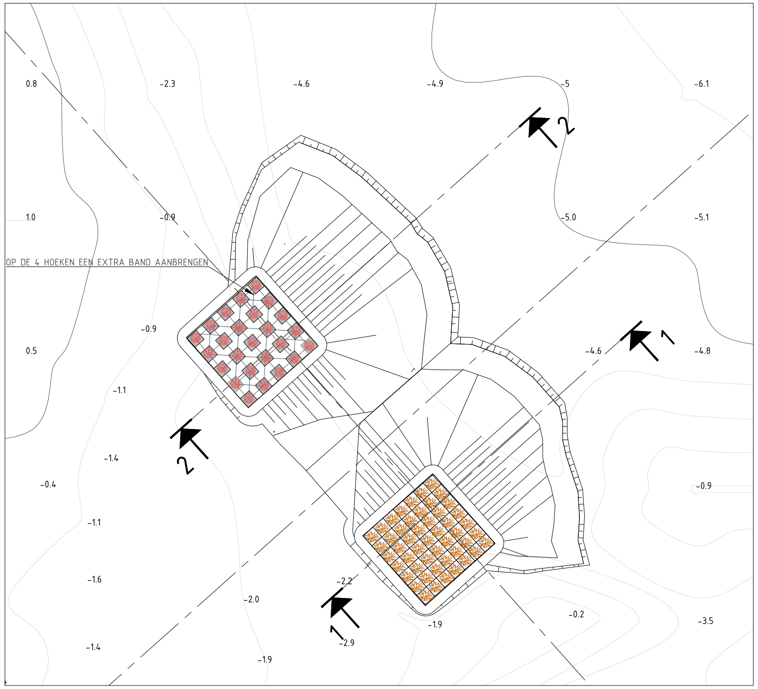
3.2.1. Analysis wave measurements

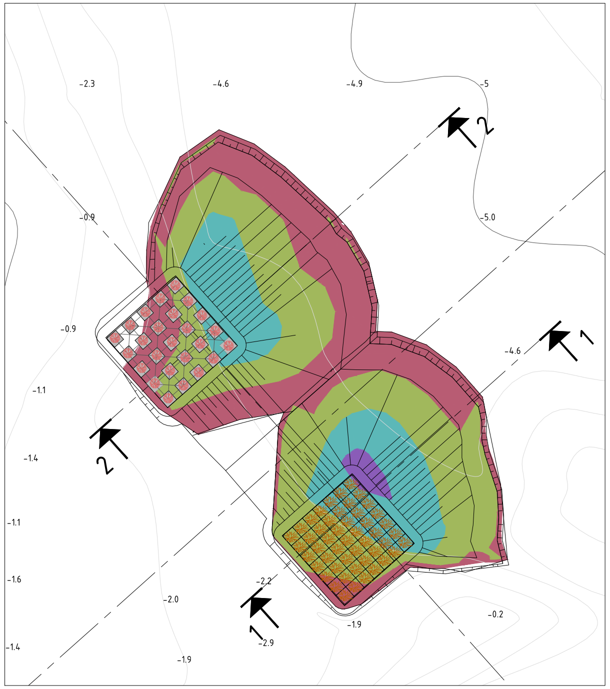
Waves are extracted from the corrected water level time series by using zero-down crossing. The averaged mean water level needed to convert the measured pressure to a water level elevation, is determined by using the 'trend' function. This trend function is applied on each burst, a part of seven minutes of the pressure measurements. The wave reduction of a single wave can be determined as follows:

$$damping = \frac{H_{sensor(i+1)} - H_{sensor(i)}}{H_{sensor(i)}} \cdot 100$$

The extracted waves are divided into four classes of wave height. For all these classes the wave damping for every seperate wave is determined:

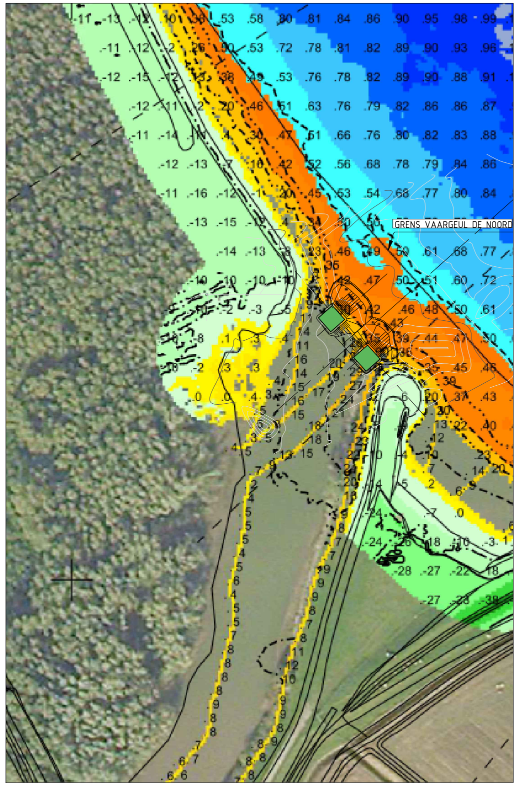
- over the whole vegetation plot, damping of the wave height in meters $(H_{outgoing} - H_{incoming})$ per meter;
- over the whole vegetation plot, percentage damping at the end of the plot in comparison with the incoming wave height per meter;
- in between the pressure transducers, damping of the wave height in meters $(H_{sensor(i+1)} - H_{sensor(i)})$ per meter;

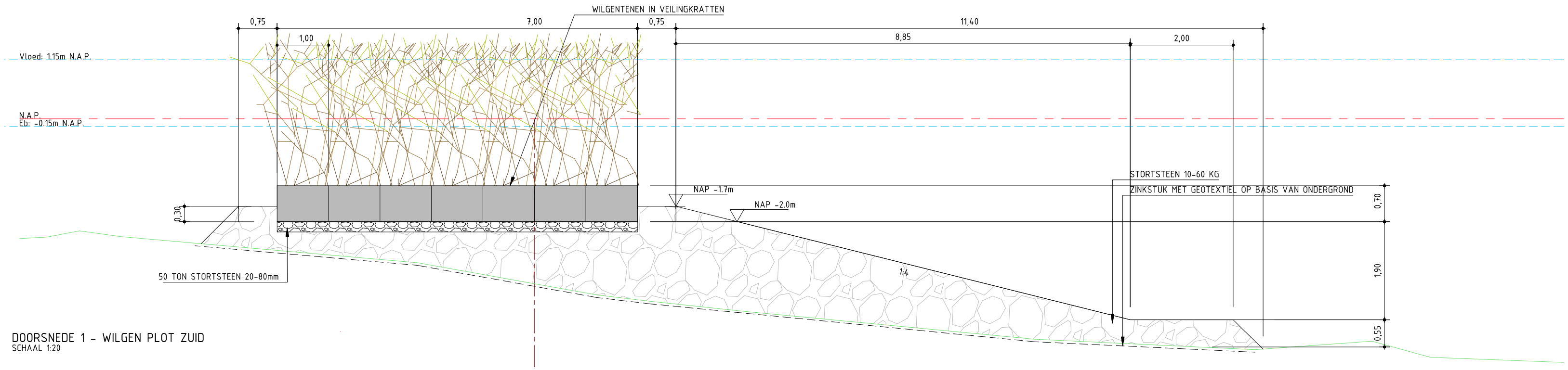




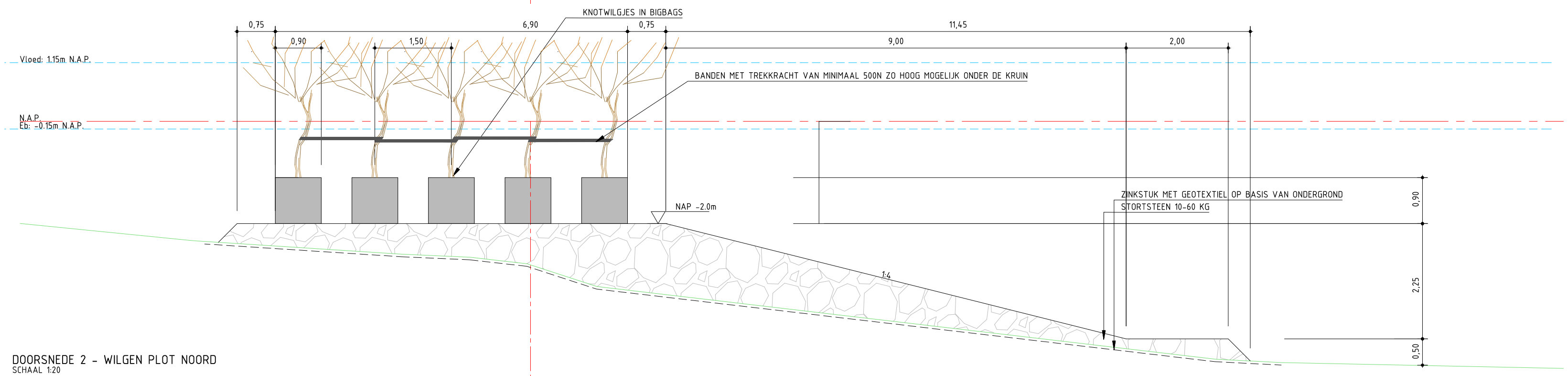
AANVULLEN - STORTSTEEN		
	0,0	0,5
	0,5	1,0
	1,0	1,5
	1,5	2,0

HOEVEELHEDEN - STORTSTEEN	
ZUID	207 m³
NOORD	187 m³
TOTAAL	394 m³





DOORSNEDE 1 - WILGEN PLOT ZUID
SCHAAL 1:20



DOORSNEDE 2 - WILGEN PLOT NOORD
SCHAAL 1:20

Gemeente Dordrecht
BWN Stadswerven Dordrecht

Hoeveelheden Stortsteen

Witteveen+Bos
Postbus 233
7400 AE Deventer
Telefoon 0570 69 79 11
Telefax 0570 69 73 44

Getekend	S. Slot
Gecontroleerd	J. De Jong
Goedgekeurd	J. De Jong
Datum	12-05-2015
Schaal	Var.
Formaat	A1

Wijzigingen
G
F
E
D
C
B
A

Figure 3.1: Top view of the research location in the Noord in between Dordrecht and Rotterdam (Google Maps, 2017)

- in between the pressure transducers, percentage damping at sensor$(i+1)$ in comparison with the wave height at sensor(i) per meter

The determined reduction in percentage per meter vegetation (e.g. willows) is the most relevant one, because this factor can be used in other scenarios with more or less meters of vegetation in front of the river dike.

3.2.2. Modelling approach

The measurements of wave propagation over the willow plots have been reproduced with the wave model SWASH because of the non-hydrostatic character of the ship waves, see chapter 2.2. The bottom (friction), the characteristics of the incoming waves (input) and vegetation parameters determine the total dissipation of the energy, i.e. the wave reduction. The bottom can be conducted from the technical drawings. The vegetation parameters were measured in the field. For the input, the water level measurements produced by the sensor at the river side are used. The measurements have been done in a single horizontal line so an one-dimensional model can be used.

3.2.3. Model calibration and validation

The model in SWASH should imitate the real determined wave damping. In other words, the output points in the model should give circa the same water level elevations as measured in the field. Expected is that the willows will prove the main energy dissipation mechanism which cause the wave reduction. The drag coefficient C_D is the main and only calibration parameter in the SWASH model. As mentioned in chapter 3 the drag coefficient of a smooth, rigid cylinder for subcritical flow has a value of 1. In literature values for the drag coefficient varies between 0.2 and 3 for various flow circumstances and vegetation characteristics (Yusof et al., 2017).
It should be logical if these values were used in the calibration. However, it was quickly visible that for calibration the drag coefficient should be larger than 3. Therefore a range from $C_D = 1$ to $C_D = 8$ is used.

3.3. Limitations

To avoid a big data calculation a selection of timeserie bursts (seven minutes of water level data) is made to determine the wave reduction by willows. This selection consist of bursts within waves with a height of more than 0.15 meter and a water depth of at least 0.80 meters above the bigbags or crates. This last criterion will reduce the transformation of waves by shoaling, refraction and wave breaking due to the elevation of the bottom by the crates or bigbags, making the transformation of waves by only vegetation become more clear. Waves with a large wave height provides more accurate measurements and wave damping calculations. Second, the drag coefficient needs to be determined for design conditions, which are used during a dike assessment. Design conditions are approximately storm conditions, so high waves.

At the research location the incoming waves are measured at the top of the bigbag or crate at the river side. The measurements of this measuring point are also used as inlet for the model. The other four sensors were also located at the same height as this first measuring point so the bottom is in one case assumed to be flat. However because of the suddenly elevation (by the crates and bigbags) waves can be deformed which could make other dissipation mechanisms more important. This has impact on the wave damping only by the willows. Therefore a second case is made including the elevation by crates and bigbags as bottom. The results of this second case are added in the appendices 8 and discussed in the discussion.

Willows applied as wave damping vegetation on floodplains will largely be submerged during design conditions. Wave damping is therefore obtained by the (highest) willow branches. However, this was not the case in the field measurement setup with old willows, where waves travel mostly along the stems and only with high water through the first 0.5 meter of the crown. Wave damping obtained in the plot with old willows is therefore unreliable. However, there are a number of other reasons, which are mentioned below.

The measurements in the plot with old willows show a large variation of wave attenuation between the pressure transducers, see chapter 8. First, the wave steepens due to the 90 cm higher bottom of bigbags. This results in a higher wave height at sensor three, than at sensor two.

Second, the high bigbags reflect waves and cause a lot of bottom friction. The bigbags are placed close to eachother, but are not connected, so there is space in between. Therefore the water depth can varies with 90 centimeters, which is 50 to 100% of the assumed water depth (above the bigbags). Variations in water depth influence also the wave height. Assumed is that a large part of the energy dissipation is caused by the bigbags in which the willows are planted.

In the plot with old willows, the transducers were fixed at the riverside of the stem. When a wave travels to the plot, the stems will cause wave reflection and some run-up. This wave run-up is also measured due to the location of the pressure transducer. Behind the stem a shadow area will be created due to diffraction [1]. The sensors are located in a straight line on the stems, perpendicular to the river and close to eachother. Possibly sensors will be in the shadow area of the previous stem and experience distorted and disturbed waves. In the plot with young willow branches, diffraction is negligible due to the small diameters of the branches.

Branches of willows provide in comparison with the stem 80% of the total wave damping, see 8 [2]. In conclusion, by applying willows as wave damping vegetation, the branches are really important. Therefore, only the measurements of the young willow branches are worked out.

In short the limitations:

- Only bursts with averaged water level higher than 0.80 meter and wave heights larger than 0.15 meter
- The bottom is assumed to be flat
- Only the measurements of the pressure transducers in the plot with young willows are worked out

[1] Diffraction is the bending of wave crests around obstacles and openings.

[2] The vegetation factor, which is equivalent to the wave damping, of the crown is four times larger than the vegetation factor of the stem for an assumed drag coefficient of 1

Figure 3.2: Photos of the measurement set of Deltares in the river Noord

3.4. Field measurements

As mentioned in the approach, a field measurement campaign has been carried out, in which wave reduction by a plot of willows has been measured during some days in June, 2015. The limitations provides a selection of bursts, which are used to obtain a data set that has been used for the calibration of the numerical model. A selection remains of circa 100 bursts with in each burst multiple high waves.

3.4.1. Configuration of wave measurements

The measured water pressure (mPa) contains hydrostatic and dynamic pressure, what should be converted to water depth. The hydrostatic pressure provides information about the still water level, while the dynamic wave pressure depends on the surface waves (Vuik et al., 2016). The hydrostatic pressure is formulated by:

$$\frac{\partial p}{\partial z} = \rho_w * g$$

where
∂p Measured water pressure (Pa)
∂z Height of surface elevation t ime series from bottom (m)
ρ_w Density of water (kg/m^3)
g Acceleration of gravity (m/s^2)

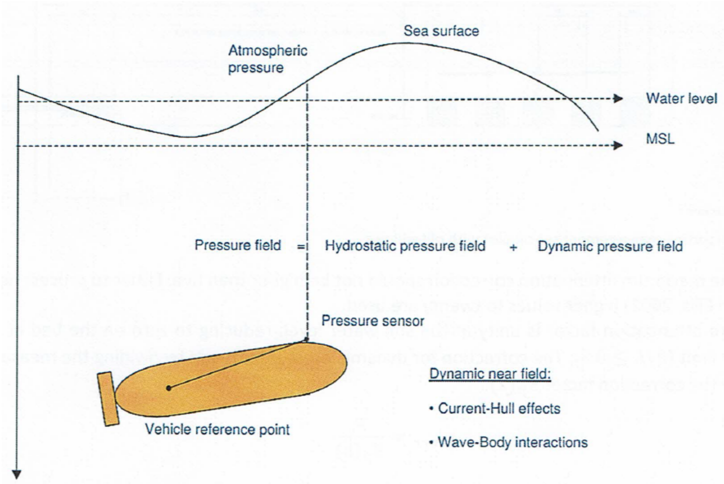


Figure 3.3: Submerged pressure measurements (Navlab.net)

Either this formula takes depth attenuation of the dynamic pressure not into account (Zijlema and Stelling, 2008). At any depth $(-z)$ under a wave crest, the pressure is a maximum and comprises the static pressure, $-\rho_w gz$ plus the dynamic pressure, $\rho_w g(\frac{H}{2})K_p(z)$

$$p = -\rho gz + \rho g\eta K_p(z)$$

The wave height can be calculated from the pressure variation by calculating the correction factor $K_p(z)$ and substracting the hydrostatic pressure (mean value of recorded pressure). This requires the solution of the wave dispersion equation for the wavelength in the particular depth, knowing the wave period. The river surface time-series are corrected for depth attenuation of pressure in the frequency from 0.05 to 0.33 Herz. For calculating the wave height the static pressure is removed by calculating and removing the trend. As a result, only the waves will be visible. The correction factor of the spectrum for pressure is determined [3]:

$$K_p(z) = \frac{\cosh k(d+z)}{\cosh(kd)}$$

K_p Correction factor of the spectrum for pressure (-)
k Wave number (-)
z Height of pressure transducer from the river bed (m)
d Mean water depth (m)

In this research set-up the pressure transducer is located at the crate or bigbag, the 'bottom'. This is shown in the technical drawing of the measurement set-up on page .... Therefore, z is equal to d, so the equation can be reduced to:

$$p = -\rho gz + \rho g\eta \frac{1}{\cosh(kd)}$$

$$K_p(z) = \frac{1}{\cosh(kd)}$$

[3] This approach does not work when there is a current in the direction of the waves, due to Doppler shift.

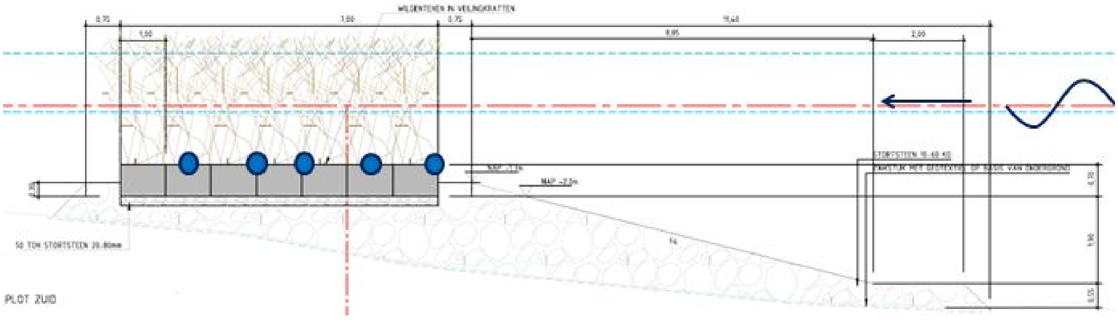


Figure 3.4: Crossection measurement set-up plot with young willows in including the locations of the pressure transducers

Normally the maximum attenuation correction should not be higher than five. However to process ship waves (Ellis et al., 2002), higher values to twenty are used.

The pressure attenuation factor is unity at the still water level, reducing to zero on the bed at the deep-water limit ($d/L \geq 0.5$). The correction for dynamic pressure is made by dividing the measured pressure by the correction factor $K_p(z)$.

$$p_{corr} = \frac{p}{K_p(z)}$$

After all, the surface elevation due to the waves can be determined:

$$\eta = \frac{p_{corr}}{\rho g}$$

This surface elevation, and so the wave height is analyzed for all the pressure transducers in the vegetation plots to determine the attenuation caused by the vegetation.

3.4.2. Wave characteristics

The selected water level measurements are elaborated in Matlab focussing on wave reduction and wave characteristics. Following figures and tables shown the results of the measurements and calculations. The results are shown in boxplots. The central mark in red indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the '+' symbol (Mathworks).
Figure 3.5 shows the water level measures of the two outer pressure transducers of the plot of seven minutes (one burst). The measured pressures are converted to wave height, with the amplitude in meters.

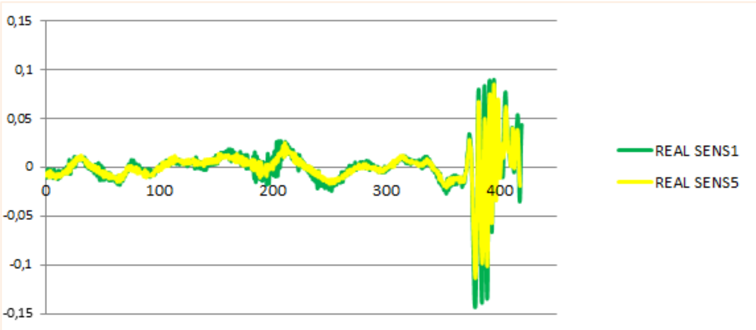


Figure 3.5: Wave amplitude in meter measured with sensor 1 (close at the riverside) and sensor 5 (located at 5.5 meter) of one burst of 420 seconds

Reduction of the wave amplitude between sensor 1 and 5 is clearly visible. This reduction in wave heigth of approximately 5 cm is caused by a stretch of 5.5 meters of willows. Attenuation is visible over the total burst-length. However, the wave damping is larger for higher waves and smaller for small waves. In the next section, this observation is explicitly vizualised.

Relation between wave damping and incoming wave height

The analyzed waves from the water level time series shows a clear wave damping over the vegetation plot. The class with the highest waves shows the largest wave attenuation with the slightest variation. This variation is for the biggest part caused by the number of waves in the waveheight classes. The class with the lowest waves consist of 519 waves while the class with the highest waves consist of 36 waves.

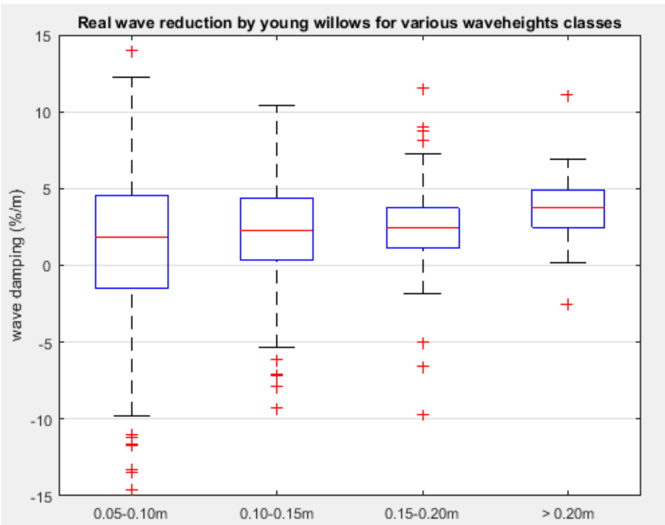


Figure 3.6: Wave attenuation between sensor 1 and 5 in %/m for incoming waves divided in various classes of waveheights

Relation between wave damping and location in the plot

In between sensor 3 and 4 and sensor 4 and 5 the wave attenuation is bigger than the attenuation at the riverside of the plot. The variation of the calculated attenuation between sensor 3 and 4 is also remarkably large. Possible cause of this variation is discussed in the discussion 3.6.

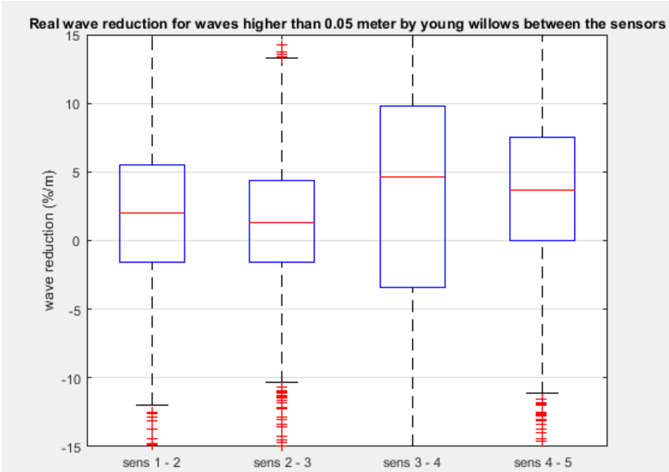


Figure 3.7: Wave attenuation in %/m for waves in the areas between the five sensors

Reduction of the significant waveheight, the highest one-third of the incoming waves, is illustrate in figure 3.8 (black line). The reduction in height is slightly parabolic. At the end of the plot, the angle of the line is steeper downwards what corresponds with the rigthmost boxplots with a higher reduction value, in figure 3.7.

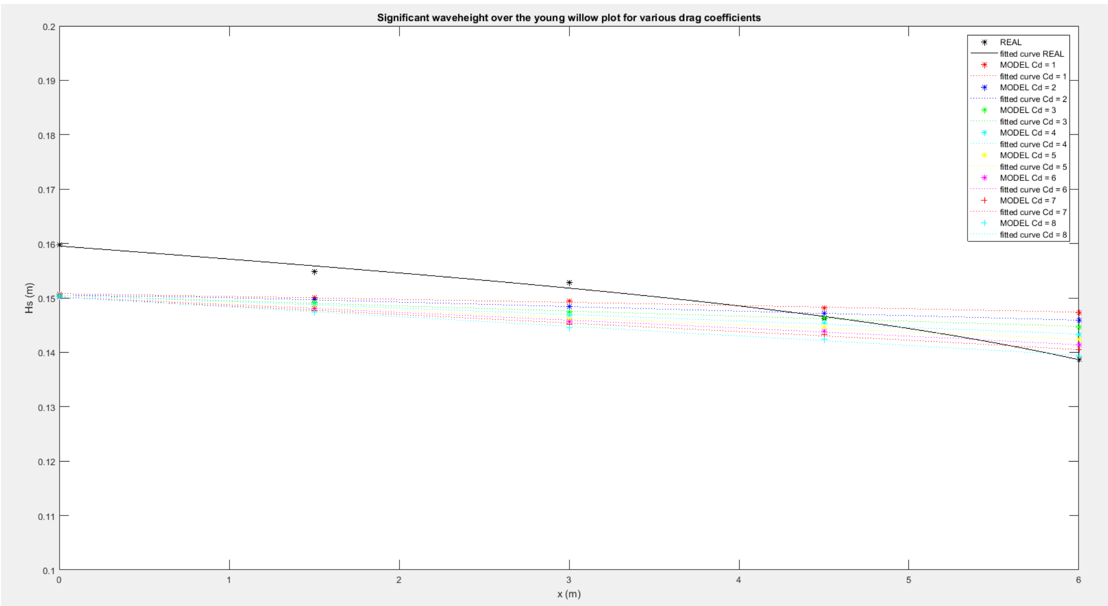


Figure 3.8: Reduction of the significant waveheight over the plot with young willows in horizontal direction, determined at the locations of the pressure transducers

Relation between wave damping and water level

To analyze the relation between the wave attenuation and water level, the average wave attenuation of waves larger than 0.05 meter, for the bursts with different water levels are compared. The bursts are divided into four classes of water depth.

Water depth (m)	Wave reduction (%/m)	Number of bursts
0.8 - 1.0	3.28	14
1.0 - 1.2	2.58	11
1.2 - 1.4	1.80	27
> 1.4	1.41	14

Table 3.2: The average wave reduction of waves with a wave height larger than 0.05 m, which are in the bursts with a water depth which fits in one of the four depth classes

Table 3.2 shows a clear difference in wave reduction between the four water depth classes. For a water level of 0.8 meters above the crates the reduction was twice as large as the reduction of the bursts with a water level higher than 1.4 meters.
The gained knowledge about the wave reduction and characteristics are discussed in the discussion 3.6.

3.5. Numerical wave model

The measurements of wave propagation over the willow plots are reproduced with the wave model program SWASH. This program is used, because of the non-hydrostatic character of the ship waves that should be modelled.
First, the settings and in- and output parameters of the numerical SWASH model are explained. Second, the model is calibrated by varying the drag coefficient. In section 3.5.3 the calibrated drag coefficient is evaluated and discussed in the section afterwards.

3.5.1. Settings model

The measurements have been done in a single horizontal line, so the model is set on the one-dimensional mode. All other settings are discussed in the following paragraphs.

Inlet and outlet boundary

The water level measurements of the pressure transducer at the edge of the crates are not affected by vegetation. These measurements which contain all the incoming waves are used at the inlet wavemaker boundary in the model. In the SWASH model the area of interest should be at least five times the wave length away from the input point of the model. The wave length is approximate by

$$L \approx 1.5T_p^2 \approx 1.5 * 3^2 \approx 14 meter$$

so the vegetation plot is in the model located at a distance of hundred meters.
The outlet boundary is defined as a boundary without any reflections. These non-reflective boundary is created by a sponge layer, which absorbs all the wave-energy. The spongelayer should be three to five times the wave length. Therefore, the spongelayer in the model is set to fifty meters.

Model grid

For the calibration of the SWASH model, a part of the bathymetry of the field site was included in the model. One wave length should contain 50 to 100 grid points, so the grid size has been set to five centimeters. This size is even small enough for the smallest waves. For bottom friction a constant Manning roughness length scale is used with $n = 0.015 s/m^{1/3}$.

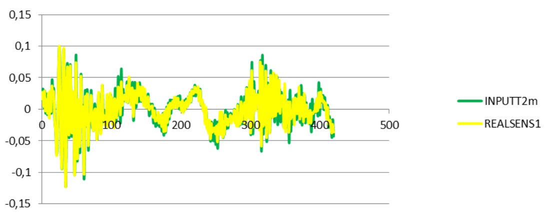
Vegetation

The characteristics of the vegetation required for the SWASH model are measured at the research location. The young willow branches have an averaged diameter of 8.4 millimetres to a height of 60 centimetres from the crate, 6.5 millimetres from 60 to 120 centimetres high and 3.8 millimetres from 120 to 150 centimetres. The crates were filled with approximately 190 branches. This density does imitate the density of willow branches in a realistic osier plantation. The measured density at an old osier plantation near Rhoon was between 129 and 430 branches per square meter (de Vries and Dekker, 2009).

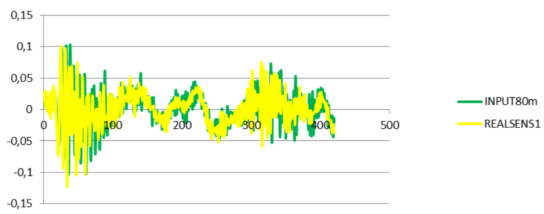
Calibration input timeserie

Due to the distance in the model from the input point to the first pressure transducer at the riverside of the plot with willows, the waves in the input timeserie are already distorted by probably bottom friction, reflection of the sudden bottom elevation and other numerical modeling aspects, see figure 3.9. However, the goal is to imitate the reality. The modelled water level at sensor 1 in the SWASH model must match with the actually measured water level at sensor 1.

To improve the imitation of the model with the real time serie, the input timeserie (burst) is cut into smaller parts. The drag coefficient is only calibrated on the serie of ship waves in the burst with a wave height larger than 0.10 meter. However, despite of the smaller time series, the modelled waves remain distorted. Therefore the input timeserie is scaled for better similarities in the model.



(a) 2 meters



(b) 80 meters

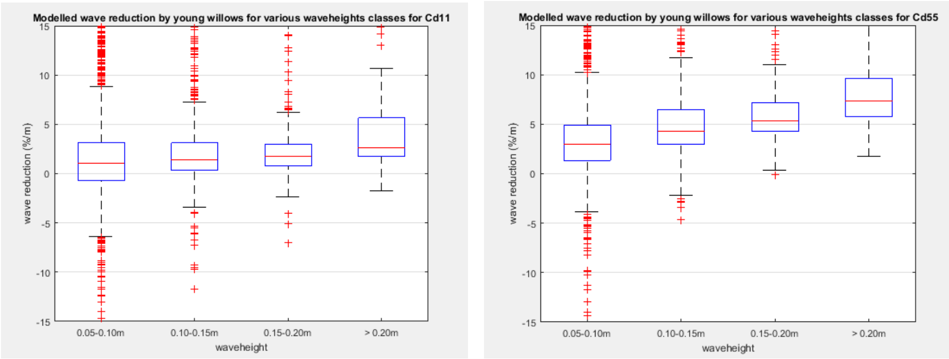
Figure 3.9: The modelled water level variations of one burst at the input point (yellow) and at 2 and 80 meters (green) from the input point without any disruptions

3.5.2. Model calibration

In this section the results of the SWASH model and the calibration steps are demonstrated. First, the sensitivity of the drag coefficient on the wave reduction for various wave height classes are illustrated. Second, the value of the drag coefficient is varied, wherefore the wave reduction is determined and compared with the real measured wave reduction. The drag coefficient is calibrated with this comparison.

Sensitivity drag coefficient

In theory a drag coefficient of 1 is normal for stiff beams which is comparable with a stem of a willow. For the young willows this could be a lower value, because the branches are flexible. However, with calculations of the wave reduction it seemed that a drag coefficient of 1 does not give the wave reduction that is obtained by the actual plot with young willows. So the sensitivity of the drag coefficient is theorytically determined by analyzing the wave reduction boxplots for $C_D = 1$ and $C_D = 5$.

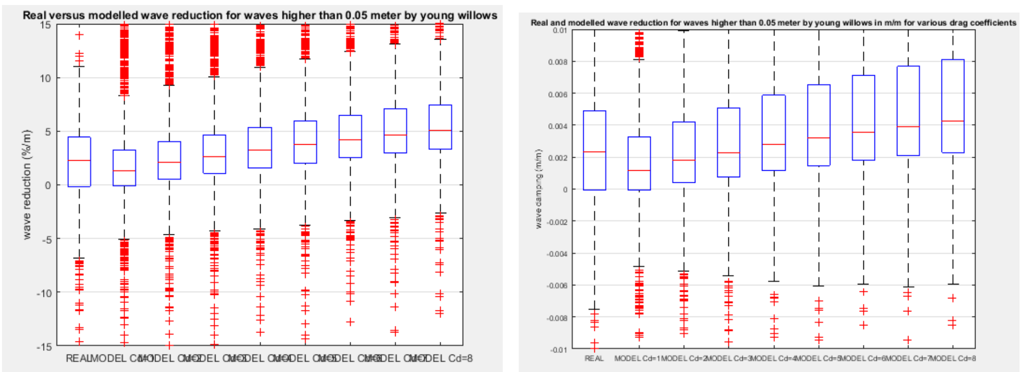


(a) $C_D = 1$ (b) $C_D = 5$

Figure 3.10: Wave reduction for $C_d = 1$ and $C_d = 5$ for various wave height classes in %/m for model with a flat bottom

Calibration drag coefficient

The drag coefficient for young willows is calibrated for the model with and without elevation of the bottom. The coefficient is calibrated on the actual measured wave damping. First, boxplots are showed for the actual measured reduction and the reduction of the model with a drag coefficient varied from 1 to 8. Second, the drag coefficient is determined by plotting the actual mean wave reduction and the modelled mean wave reduction. The intersection point gives the drag coefficient. The boxplots give a bigger variation in wave reduction than the boxplots for the bottom including elevation. The reduction values are also higher in this model. For a drag coefficient $C_d = 2-3$ the reduction is almost the same as the actual measured value.



(a) Wave reduction in %/m (b) Wave reduction in m/m

Figure 3.11: Actual wave reduction in the plot with young willow branches versus the modelled wave reduction for various drag coefficients for waves with a wave height higher than 0.10 meter

Intersection point of the line with the real mean wave reduction and the interpolation-line of the modelled mean wave reduction results in drag coefficient of $C_d = 1.3$. The 75%-upperbound of the modelled wave reduction will result in a value of 4.9. However, the 25%-lowerbound will be negative. This outcome will be discussed in the chapter 3.6.

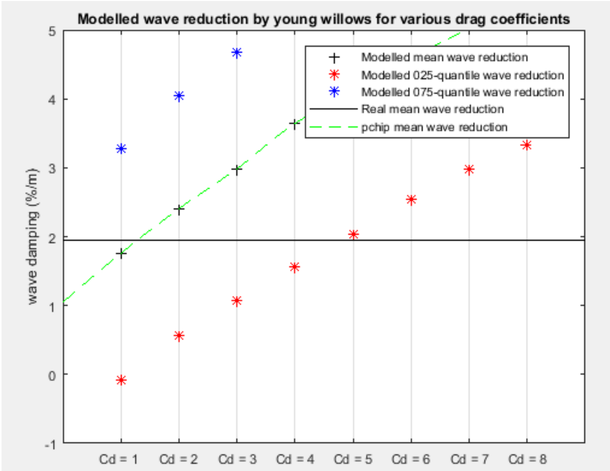


Figure 3.12: Modelled wave reduction (mean, 25-quantile and 75-quantile) in %/m for various drag coefficients for waves with a wave height higher than 0.10 meter, and the actual measured mean wave reduction obtained by willow branches

3.5.3. Evaluation calibrated drag coefficient

The drag coefficient C_D is calibrated for each burst. The best correspondence between the measurement data and outcomes of the SWASH model, for various drag values, was obtained. To determine the drag coefficient of vegetation during storm conditions also the Reynolds number of each burst is calculated. Extended explanation about the Reynolds number can be found in chapter 2.1.1. A river dike is designed on storm conditions, also named as design conditions. A higher Reynolds number is equivalent to a turbulent waterflow, which occur during storm. By plotting the calibrated drag coefficient and Reynolds number for all bursts an extrapolation can be made to determine the drag coefficient of the willows for design conditions. The drag coefficient is calibrated for all pieces of the selected bursts with waves with a wave height larger than 0.10 meter. Figure 3.13 illustrates the outcomes. The spread of the markers in the scatterplot is relatively large. The calibrated coefficient will be in between -1 and 4.

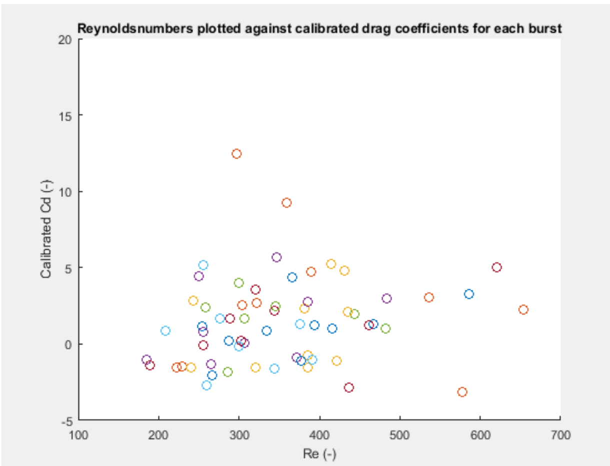


Figure 3.13: Reynolds numbers plotted against calibrated drag coefficients for each piece of burst which includes waves with a higher wave height than 0.10 meter

For high Reynolds numbers the C_D-value is approximately $C_D = 3$. The spread is less and the average calibrated drag coefficient is closer to 1, than for lower Reynold numbers. However, this value is relatively high in comparison with drag coefficients for vegetation which are determined in relatively new researches with high Reynold numbers (Yusof et al., 2017).

3.6. Discussion

This chapter presents a combination of field measurements and numerical modelling of wave attenuation by vegetation. The numerical SWASH model has been applied to determine the drag coefficient of willows. First, the measurement set-up is discussed. Second, the numerical wave model and the result, the calibrated drag coefficient values, are discussed. Attention is payed to the applicability of the results and demands to improve the research.

3.6.1. Field measurements

The field measurements of wave attenuation by willow vegetation are probably the first measurements doing through willows. However, it was appeared from calculations that various parts of the set up can result in reduction of the wave height due to dissipation of energy instead of just the willows.
The plot with willows is partly well designed. For instance, a gentle slope with stones is made from the deep river till the toe of the vegetation plot. This will decrease energy dissipation due to bottom friction or shoaling. However, the setup contains a sudden increase of the bottom height by the crates and bigbags with willows. A vertical wall provides reflection, and the decreased water depth can cause wave breaking. Last phenomenon is discussed in section 3.6.1.

The size of the measuring plot (7 x 7 meters) is also small in comparison with willow vegetation along river dikes or what should be planted by waterboards especially for wave damping. A larger size of the measuring plot and more pressure transducers should be better to avoid or reduce errors in the measurements. In table 3.3 the variation in wave reduction for various water levels is plotted for young and old willows. The not continous variations in wave damping by the old willows will conduct errors in wave damping calculations, so are not used to work out.

water depth (m)	wave reduction young willows (%/m)	wave reduction old willows (%/m)
0.8 - 1.0	3.28	1.71
1.0 - 1.2	2.58	2.41
1.2 - 1.4	1.80	1.99
> 1.4	1.41	2.13

Table 3.3: The average wave reduction of the bursts for a certain water depth for old and young willows

Deformation of ship waves

In chapter 2 various processes that affects the wave height at the foreshore are discussed. In the following paragraphs the effect of these processes are checked for the measurement setup with willows.

Refraction of ship waves

Refraction provides a change in direction of the incoming waves. This depends on the water depth and can be calculated by Snell's Law (Shirley, 1951):

$$\sin\alpha_1 = \frac{L_1}{x} and \sin\alpha_2 = \frac{L_2}{x}$$

$$\sin\alpha_2 = \sin\alpha_1 \frac{L_2}{L_1} = \sin\alpha_1 \frac{C_2}{C_1}$$

Ship waves are coming with an angle from the waterway to the vegetation plots, see chapter 2.2 The diverging waves make an angle of $35°16'$ to the direction of movement of the ship, so also an angle of approximately 35° with the river side. However, the waves will change in direction by refraction. At the measuring setup the river bottom goes from approximately -5.0 NAP to -1.5 NAP in 12 meter horizontal. The wave angle of diverging waves is 35°, than the wave speed C_1 is $1.56T = 1.56 \times 3 =$

$4.7m/s$ and L_0 is $1.56T^2 = 14.0m$.

d	$\frac{d}{L_0}$	$\frac{c}{c_0}$	c (m/s)
5	0.36	0.97	4.6
1	0.11	0.74	3.5

$$\sin\alpha_2 = \sin 35 \times \frac{3.5}{4.6} = 0.26$$

$$\alpha_2 = \arcsin 0.44 = 0.45rad = 25.9^\circ$$

Due to the decrease of depth the wave angle is decreased to 26° relative to the river side. In figure 3.14, this scenario is vizualised. If waves parallel to the river side enters the vegetation plot, the waves are measured by the sensors at 0, 1.5, 3, 4 and 5.5 meter (for the plot with young willows). However, if the incoming waves has an angle of 26° the travelling distance between the sensors is smaller:

$$x_{angle} = x_{perpendicular} \times \cos(\beta)$$

Where
β wave angle (in °)
x_{angle} distance between the sensors for incoming wave with angle (in m)
$x_{perpendicular}$ distance between the sensors perpendicular to the river side (in m)

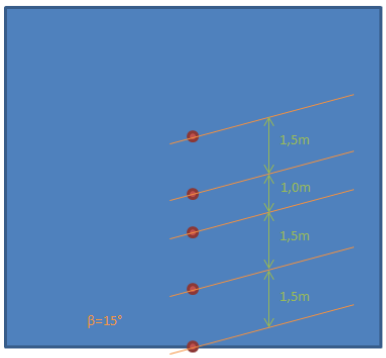


Figure 3.14: Topview of the plot with willows and pressure transducers including incoming wave with an angle of 26 degrees relative to the river side

The wave reduction (in %/m) is calculated with the distances between the sensors perpendicular to the river side. So a larger distance than actually the case with . Because of this the wave reduction in %/m is underestimated. For a wave angle of 26° the underestimation is 8.5%.

Shoaling and wave breaking

Shoaling is the deformation of waves travelling to the shore and starts when the water depth becomes less than about half the wavelength. Due to the reduction of water depth the wave propagation velocity will reduce and the waves will become steeper. Wave breaking is correlated with this deformation due to shoaling. This depends on the characteristics of the deep water wave and the water depth at the side of the river.

$$H_b = h * \gamma$$

Where
H_b wave height of the breaking wave (m)
h water depth (m)
γ breaker parameter
The value of breaker parameter γ can be calculated with the following formulas:
Battjes and Stive (Battjes and Stive, 1985)

$$\gamma = 0.5 + 0.4\tanh(33H_0/L_0)$$

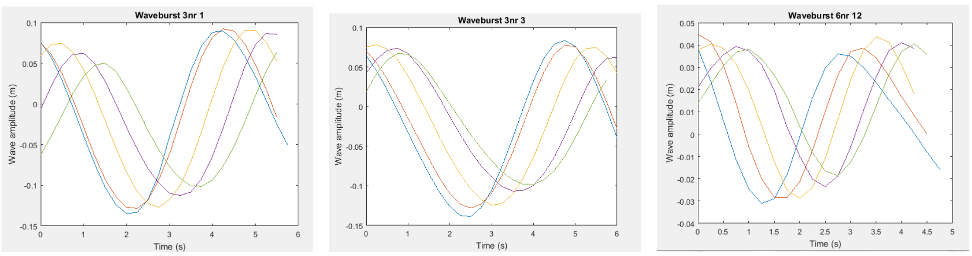
The ratio H_0/L_0 is mentioned as the deep water wave steepness. The L_0 is in section 3.5.1 set on 14 meters and $H_0 \approx 0.10m$, so:

$$\gamma = 0.5 + 0.4\tanh(33 \times 0.10/14) = 0.59$$

$$H_b = h * 0.59$$

This means that with a water depth of 0.8 meter, waves break if they have a wave height of approximately 0.45 meter. This wave height is measured only once during the test, so a conclusion could be that waves will not break due to the elevation of the bottom.
However, the reliability and accuracy are low of this calculation. It is difficult to approximate the deep water parameters correct, because the first sensor was already located at the top of the first crate or big bag. At that location deformation of the wave is already be started. Therefore, it is assumed that there could be wave breaking.

Figure 3.15 demonstrates the deformation of waves over the plot of willow vegetation. Wave reduction is clearly visible in the two individual wave from burst 3. The incoming wave deforms from a steep wave to a wave with a smoother slope of the front and tail. However, the reduction of the wave from burst 6 is smaller. This is probably caused by the small wave height.



(a) First wave higher than 0.05 m in burst 3

(b) Wave number 3 higher than 0.05 m in burst 3

(c) Wave number 12 higher than 0.05 m in burst 6

Figure 3.15: Three individual ship waves which propagate through the willow vegetation plotted for the five sensors at 0 (blue), 1.5 (red), 3 (yellow), 4 (purple) and 5.5 (green) meters from the river side of the plot with the wave amplitude in meters

The wave reduction in horizontal direction over the plot is shown in figure 3.8. The significant wave height decrease in only six meters from 0.160 meters to 0.138 meters. The damping per meter width increases farther away from the entry of the plot at the riverside, which was also visible in figure 3.7. This is an opposite effect of what is mentioned in literature and formulas, thus remarkable. The first meters of the plot at the river side should reduce the largest part of the wave height.
Cause of the opposite effect, could be the sensor at the riverside (x = 0), which probably measured too low waves due to discontinuities obtained by the abrupt elevation. The incoming wave angle of the shipwaves will just decrease the opposite effect, because perpendicular incoming waves will be

reduced much more, due to the longer travel path through the willows, which acts in just a lower significant wave height. Therefore, this measured effect has relations with the measurement set-up.

Bottom friction

The dissipation mechanism bottom friction is of no importance, because the measured waves are too short to be dependent on small bottom obstacles. The plot with willows causes also higher water levels. Travelling waves should be move between the willows which cause a narrowing and so the waterlevel set up. This is visible in table 3.4. Due to this phenomenon, friction is just less important.

Water depth (m)	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5
Young willows	0.511	0.621	0.652	0.616	0.670

Table 3.4: Average measured waterdepth in meter above the five sensors in the plot with willow branches, for the selection of bursts

Maximum measured wave height versus design conditions

For the plot with willows, the wave reduction was larger for higher incoming waves. High waves experience more resistance of the vegetation than low waves. However, the height of the waves during the measuring periods were not as high as expected during storms. Design conditions for dikes are based on such a storms. So with this experiment, no good representation is obtained how waves attenuates during storm conditions.

3.6.2. Discussion numerical wave model

To compute the drag coefficient of willows, an one-dimensional SWASH model of the field test was applied. The vegetation parameters diameter bv and density N were measured in the field, so the only unknown parameter was the drag coefficient. The influence of other energy dissipation mechanisms than the vegetation mechanism, in the model is checked. Further are the outcomes of the drag coefficient calculated for all the selected bursts evaluated.

Effects variation drag coefficient

Obviously, there is a bigger wave damping in the model by higher drag values. In figure 3.16 the significant wave height of the sensors in the actual situation and model (for various drag coefficients) are plotted. The plot with willows started at $x = 0$, the asterisks gives the significant waveheight at the sensor locations.

In the model the significant wave height at sensor 1 is lower than the calculated height in the actual situation. The ship waves in the water level serie used as input are probably already reduced in the distance from the inputpoint to the vegetation plot in the SWASH-model by friction. A parabola is not visible, only straight lines with a short steep line downwards in the beginning. The biggest reduction in significant waveheight is in the model between sensor 1 and 2, while in the actual situation this was at the end of the plot. The line fitted for $C_d = 3$ has almost the same wave reduction over the plot than for the actual situation.

Flat bottom versus elevated bottom

In the calibration of the drag coefficient there was also a significant difference between the model with flat or elevated bottom. Wave attenuation was reproduced with a value of C_D between 1.2 for the flat bottom and 4.3 for the bottom with elevation (figures 8.14 and 3.12), given the method applied to schematize the vegetation with three layers for on average a turbulence value of $Re = 350(-)$. In comparison, in a study about wave damping by willows in the Noordwaard, values between 0.7 and 1.0 are used (de Vries and Dekker, 2009).

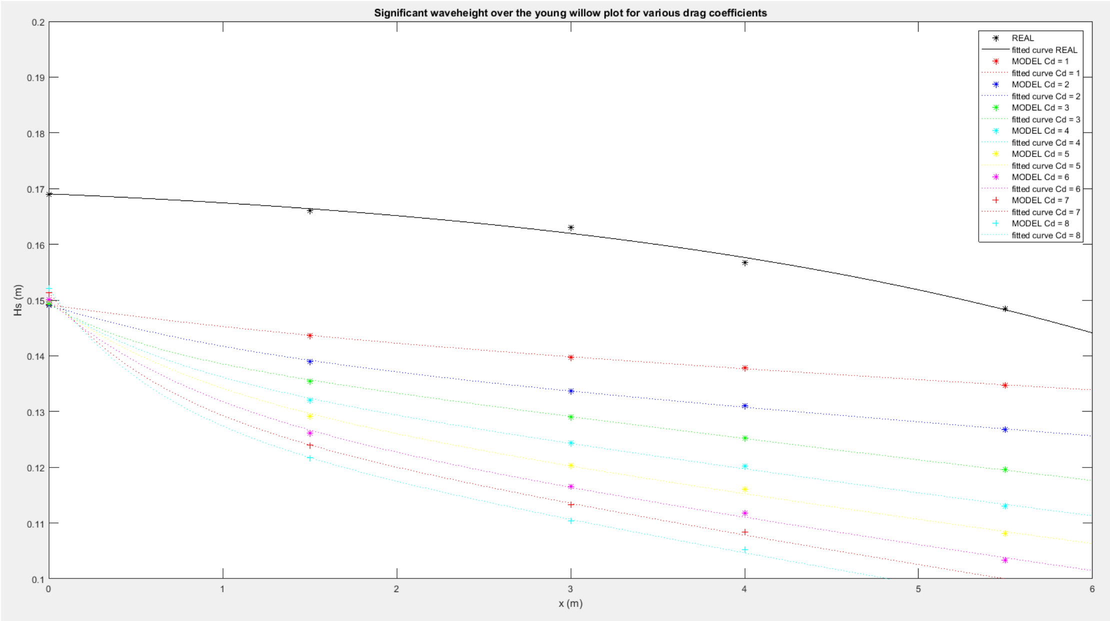


Figure 3.16: Reduction of the significant waveheight in the model with flat bottom over the plot with young willows in horizontal direction, determined at the locations of the pressure transducers

The difference in outcomes between the two models with other bathymetry means that in the SWASH model, the bathymetry had a large influence. Due to the elevation of the bottom, there is a higher significant wave height over the plot and less reduction by vegetation, than for the flat bottom.

Energy dissipation by other systems

Energy dissipation systems which can effect the wave height besides the vegetation are already be discussed in chapter 3.6.1 for the measurement set-up. However, in this section the SWASH model is checked on these systemes. First, the real obtained wave reduction between sensors 2 - 5 and sensors 3 - 5 are used to calibrate again the drag coefficient. The coefficient is compared with the calculated reduction over the total plot.

The calibrated drag coefficient for the total plot was $C_d = 1.2$. The calibrated value for the model between sensor 2 and 5 ($C_D = 4.3$) and sensor 3 and 5 ($C_D = 3.6$) is higher than the calibrated coefficient for the total plot.

These variations in the coefficient are considerable. It is therefore concluded that the model and the field measurements includes to many uncertainties for determining a proper value for the drag coefficent. In the model wave breaking is assessed by varying the breaker parameters. Variation in parameter value had no effect on the results, so wave breaking do not occur for these circumstances in the wave model.

3.6.3. Summary discussion points

In short, the discussion points of the field measurements:

- Plot with willows is too small for accurate measurements
- Possibly underestimation of the calculated wave reduction due to the angle of incoming ship waves
- Possibly wave breaking due to the vertical elevation of the crates
- Steepening of the incoming waves due to the vertical elevation of the crates, therefore increase in wave height instead of a decrease

• The branches causes a water level elevation over the plot with willows
• Bottom friction is assumed to be negligible

And the discussion points of the numerical model:
• Significant wave height at sensor 1 lower than the actual significant wave height at the same sensor
• No wave breaking in the model, because the bottom is assumed to be flat
• Increase of the wave height between sensor 2 and 3 without a clear cause

3.7. Conclusions

The wave damping by young (branches) willows were obtained by field measurements. In table 3.5 the variation in wave reduction for various water levels is plotted for young willows.

water depth (m)	wave reduction young willows (%/m)
0.8 - 1.0	3.28
1.0 - 1.2	2.58
1.2 - 1.4	1.80
> 1.4	1.41

Table 3.5: The average wave reduction of the bursts for a certain water depth for old and young willows

The plot with young willows reduced the incoming waveheight with on average 2.68% per meter width. Wave height reducing effects are highest for the highest waves. Waves in the class 0.05-0.10 meter damp on average 2.2%/m, while the reduction for waves higher than 0.20 meter is twice as much. All results are summerized in table 3.6.

Wave height (m)	Mean wave damping (%/m)	25th-percentile (%/m)	75th-percentile(%/m)
0.05 - 0.10	2.2	-1.5	4.8
0.10 - 0.15	2.4	0.5	4.7
0.15 - 0.20	2.5	1.3	3.9
> 0.20	4.1	2.5	5.0

Table 3.6: The obtained average wave damping and the 25th and 75th-percentile deviations for various wave heights

The relation between water level and wave attenuation depends totally on the shape of the willows. The stiff stem of the old willows damps the waves less than the high dense, more flexible, branches above the stem. For the young willows, the wave attenuation decreased with increasing water level. With a water level higher than the vegetation heigth of 1.5 meters, the water flows over the young willows and waves will be less reduced in height. Submerged vegetation cause less dissipation of energy.

The drag coefficient is calibrated based on the calculated wave reduction values from the field test. The coefficient received a large range of calibrated values. The 25th and 75th-percent value of the calibrated drag coefficient were calculated on -1 and 5. A negative value may not be possible, because this means an increase of the wave height by the willow vegetation instead of a decrease. These negative drag values are caused by the extrapolation of bursts wherefore the wave was not damped, but increased over the plot. The large range in calibrated values and the existence of negative values are caused by the measurement set-up.
The plot with willows was too small for accurate measurements and the crates, in which the willow branches were planted, caused distortion of the waves due to the sudden bottom elevation. Because of this, the first sensor at the edge of the crate (at the riverside) has probably encouter measurement errors. Third, the angle of the incoming ship waves caused an incorrect calculated value of the wave

damping capacity of willows. The drag coefficient was calibrated on this value and therefore uncertain. And most important, the ship waves were small, which causes a lot of disturbance and a bad comparison with design conditions wherefore the wave damping vegetation should be assessed if it is applied by waterboards. To conclude, the measurements produced by the set-up of Deltares in the river Noord can not be reproduced by the SWASH model so no conclusions can be drawn about the drag coefficient of willows.

As discussed, the measurement set-up causes various inconveniences. The set-up should be improved to come up with better results and conclusions. In chapter 7 recommendations are described for a new field test.

Further research can be done to the drag coefficient during design conditions. A decrease in C_D with increasing Re as described in the literature was not be recognized in the results. Another research can be done to the flexibility of the willow branches relative to the wave height. Larger waves makes the willow less stiff, wherefore the drag reduce and so the wave damping capacity. Probably the calibrated drag coefficient for only the high waves in the measurements should be lower than for the small waves.

4

Sensitivity analysis for the dike-vegetation system

In safety assessments, the failure probability of the river dike is assessed by using design criteria in a wave model. In this wave model a lot of input parameters, like boundary conditions and dike characteristics with their own standard deviations are used to determine for example the wave overtopping. By application of willow vegetation at floodplains as wave load reduction, this vegetation should also be inserted in the safety assessment including the variations of the vegetation parameters (density, diameter of the branches, height and drag coefficient). It is concluded, that the variations of the vegetation parameters has largest effect on the wave overtopping and so the required crest elevation to meets the safety standards. Most important is the height of the willows, which should be higher than the water depth for wave damping and the density. The variations in the value of the drag coefficient of willows should be carried out to come up with more accurate wave damping calculations.

4.1. Introduction

Vegetation on the floodplain in front of a river dike can be affected by threats such as storm, diseases, ice, drought and flood. As a result, the wave damping capacity of the vegetation can decrease. To know more about the effects of these scenarios, the effect of the standard deviations of the input parameters of the wave model are investigated. The effect of these variations on the wave damping, resulting wave overtopping and required crest level will give a better understanding of the importance of maintaining the wave damping vegetation.

4.2. Approach

A wave model is made to determine the sensitivity of the input parameters which are used to assess river dikes. The used wave model is based on the wave energy balance (see chapter 2.3). The SWASH model was mainly suitable for the non-hydrostatic ship waves. The wave energy balance can be used for larger dimensions and input parameters during design conditions, so wind waves. To use a realistic river dike, Waterboard Rivierenland has come up with a location. A simple one-dimensional wave model is made of a river dike section nearby Heesselt at the dike project Tiel-Waardenburg. This section is rejected on the failure mechanism 'crest level'. The failure mechanisms overflow and wave overtopping have a calculated probability of 1/4600 year (Vergouwe, 2014), while the failure probability of this river dike should be less than 1/10000 (Pleijter et al., 2017). However, this permissible failure probability is distributed over all failure mechanisms. A combination of all these probabilities will not exceed the maximum permissble failure probability of the flood defense. For the failure mechanism height, the part of the distribution is 24%, which results in a failure probability requirement of 1/41.666.

First, the case location is described. The sensitivity analysis is conducted by a wave model with a dike profile, after execution of the dike project Tiel-Waardenburg. This new dike will have another steepness of the outer slope, which affects the wave overtopping discharge and required crest level. The river dike system of the base case is based on this new dike profile. Finally, the onedimensional wave model with all input parameters and the base case are discussed.

4.2.1. Case location

The cross section of the river dike including foreshore is nearby the village Heesselt along the river Waal. The dike is fully covered with grass, and has an outer slope of 1:2. Waterboard Rivierenland considers to apply wave damping vegetation at this floodplain (de Heesseltsche Uiterwaarden) to reduce or preferably, avoid heightening of the dike. Figure 4.1 shows the required dike heightening to meet the critical wave overtopping discharge of 5 l/s/m in the project Tiel-Waardenburg. The selected part of the river dike around the Heesseltsche Uiterwaarden starts at dikesection TG120 and ends at TG140. The current crest level, with the current slope, should actually be heightened between the 0.23 and 0.72 meter (Bos, 2017) to meet the requirements for the design year of 2075.
As mentioned in the quickscan (Verheij and Sprengers, 2012), there are high waves at this location [1], due to the long fetch. As a result, the required crest level of the dike is high sensitive on wave height. The crest level could be lowered a lot, when the wave height should be reduced to zero.

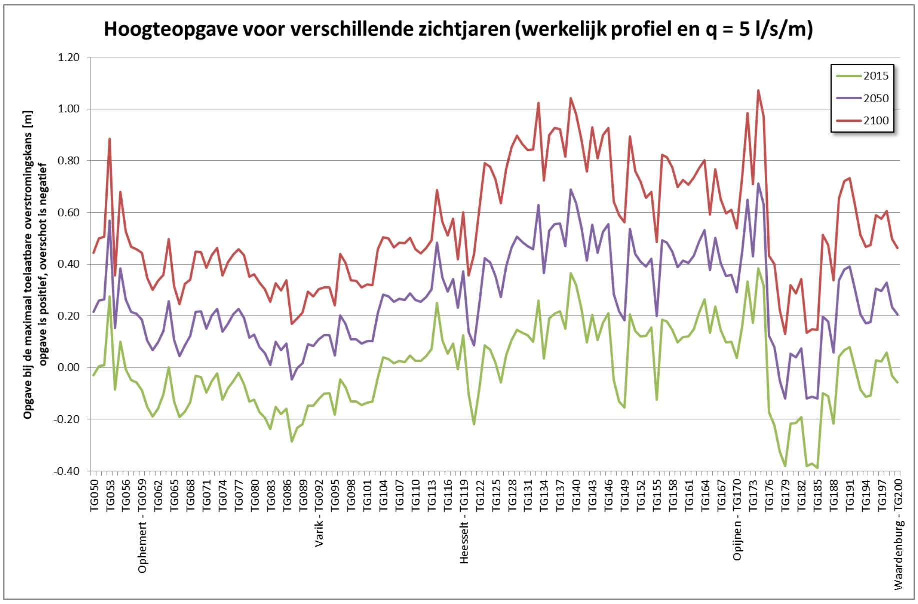


Figure 4.1: Task (difference between the current crest level and the required crest level) for the current dike profile and an overtopping discharge of 5l/s/m for various years (Pleijter et al., 2017)

[1] The wave height is determined using the old standards (1:1250)

Wave damping vegetation is not particularly present at this floodplain. Because of this, Waterboard Rivierenland will plant a wide strip of vegetation in front of the river dike just outside the main stream of the river. This strip with vegetation will be probably willows [2], comparable with the willows at Fort Steurgat (Venema et al., 2014). Figure 4.2, shows the first idea of Waterboard Rivierenland for the Heesseltsche Uiterwaarden.

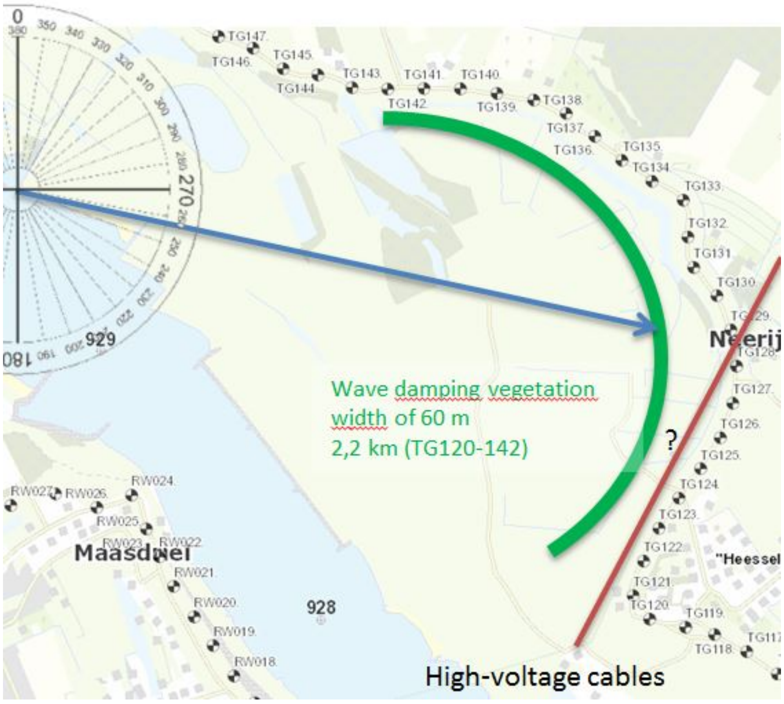


Figure 4.2: Topview foreshore Heeseltsche Uiterwaarden with in green potential wave damping vegetation and in red the high voltage cables and pylons (WSRL, 2018)

The vegetation cannot be planted close to the dike (from TG120 to TG130) due to power pylons. At dike section TG129, the powerlines crosses the dike. Heightening of the crest level at this section should be avoided because of these lines. The base case model is based on the cross section of TG129 including the floodplain (in the wave direction according to the design point), after execution of the dike project. The dike gets a more gentle slope of 1:3 or 1:2.5, which reduces wave overtopping as shown in figure 4.3.

The wave damping willows are located 60 meters away from the toe of the dike. The plot with willows has a width of 60 meters. In the next sections, the wave model and the input parameters of the base case are discussed.

[2] Following the Natura 2000 (en Voedselkwaliteit, 2006) this location ('Rijntakken - Uiterwaarden Waal') should be characterized by 'zachthout ooibos' like willows.

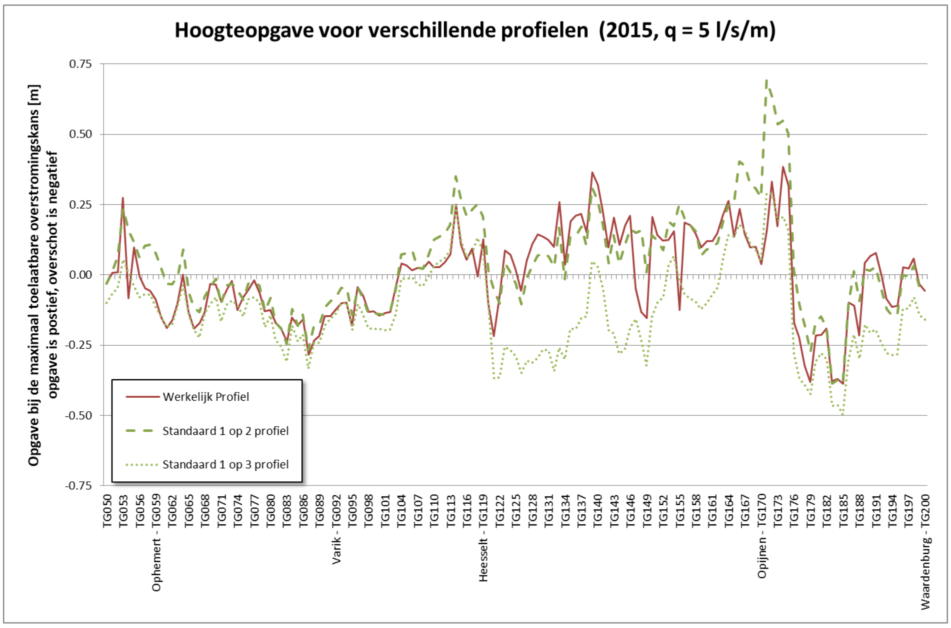


Figure 4.3: Task (difference between the current crest level and the required crest level) for various dike profiles and an overtopping discharge of 5 l/s/m for the year 2015 (Pleijter et al., 2017)

4.2.2. River dike system: base case

The representative combined dike-foreshore system of the base case is schematized in figure 4.4. The combined characteristics of the dike, foreshore and vegetation determine the strength and wave damping capacity of the system (Vuik et al., 2018b).

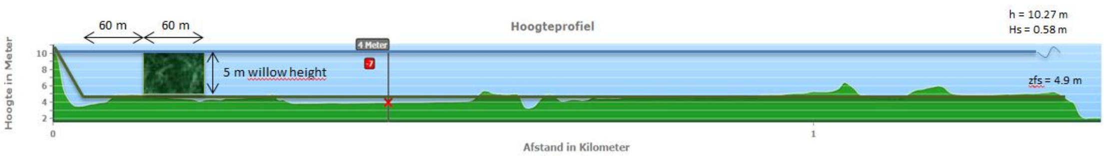


Figure 4.4: Cross section of the dike and foreshore of section TG129 including heights in meters above NAP and distance in kilometers. The green line is the simplified dike-foreshore model used for the sensitivity calculations (AHN2 Profile, 2018).

Hydrodynamic boundary conditions depend on the wind speed U_{10} (m/s) and are represented by a water level h (m NAP), significant wave height H_{s0} (m) and a characteristics wave period, such as the peak period T_p (s) or the spectral mean wave period $T_{m-1,0}$ (s) or the representive wave period T_{rep}. The foreshore is characterized by a certain bottom height z_{fs} (m NAP). The vegetation is described by a set of variables, which together with vegetation model parameter C_D determine the wave attenuating capacity of the vegetation in the model.

Failure of the dike is considered by the mechanism wave overtopping, which occurs when the actual wave overtopping discharge q (l/s/m) exceeds a critical value q_c that depends on the erosion resistance of the crest and inner slope of the dike. Waterboard Rivierenland takes as critical discharge a value of 5 l/s/m.

Failure is described by means of a limit state function (LSF), which is defined as the difference between strength (R) and load (S): $Z = R - S$. Both load and strength are considered as stochastic variables.

Failure occurs when $Z < 0$. For overtopping, the function will be: $Z_{ov} = q_c - q$ (Vuik et al., 2018b). The wave model is applied to compute this point of failure.

4.2.3. Wave model

The wave model is a one-dimensional model based on the wave energy balance (chapter 2.3). The model is primarily meant for computations over distances less than 1 or 2 km (Vuik et al., 2018b). Propagation of waves over the foreshore to the river dike can be affected by vegetation but also by the other dissipation mechanisms (chapter 2). For some mechanisms, various formulas can be used.

To determine the sensitivity of the various formulas, a base case is used with the following settings. For vegetation, the dissipation formula of Mendez and Losada (Mendez and Losada, 2004) is implemented in the wave energy balance. The formula of Battjes and Janssen (1979) with the breaker parameter γ described by Battjes and Stive (Battjes and Stive, 1985) is used for determining the depth-induced wave breaking. Bottom friction is represented by a roughness height k_N (m), following Madsen et al. (1989) 2.3.2.

The processes wind input (due to (Snyder et al., 1981)) and whitecapping (due to (Komen et al., 1984)) can be added to the set of equations, to avoid an overestimation of the wave height reduction for this relatively long foreshore. However, the parameters for the boundary conditions coming from Hydra NL, are already calculated for an output point at approximately 50 meter distance from the toe of the riverdike. The wave height will be overestimated if these boundary conditions are set at a distance before the river dike and wind input is added. Therefore wind-induced wave grow and whitecapping are not implemented in the base case. In section 4.4 the effects of wave grow and whitecapping are determined for a case study of Waterboard Rivierenland.

The wave model needs some input parameters to determine the reduction of waveheight by the various dissipation mechanisms over the foreshore during failure of the dike. These parameters are used for designing and assessment of the riverdike and are formulated in a design point. For dike design by Waterboard Rivierenland in the project Tiel-Waardenburg, the following assumptions are made (WSRL, 2017): an overtopping discharge of 5 l/m/s, a water level with an exceedance frequency of 1/10.000 per year (for wave overtopping 1/41.667 per year) and a lifespan of the river dike to 2075 upon which the design boundary conditions are made. The design point consists of a certain combination of variables which occurs failure, and is defined as the point on the failure limit with the highest probability of occurence.

The water level and bathymetry of the foreshore are important in the model, because the water depth above the foreshore has influence on the amount of dissipation. However, at the Heesseltsche Uiterwaarden, the foreshore bathymetry has a small contribution in the wave dissipation, because of the high water depth on the foreshore. The waves are described by the significant wave height H_s and the spectral wave period $T_{m-1,0}$ at the boundary of the model.
To determine the wave damping by vegetation for various scenarios, vegetation is implemented in the model. Dissipation of energy by vegetation is determined by Mendez and Losada (2004).

4.2.4. Base case parameters

The sensitivity analysis is based on a base case. The dike profile of the base case is shown in figure 4.4. The current crest level is located at 10.92 meter NAP (Bos, 2017). For the new requirements as mentioned in the previous section, the crest level should be heightened to 11.24 meter including 0.2 meter for soil subsidence, in total an heightening of 0.32 meter (for an outer slope of 1:3). This required elevation of the crest level will be avoid by application of wave damping vegetation. Grass can influence the run-up process for significant wave heights H_s less than 0.75 m. For waves higher than 0.75 m, the roughness of the slope with grass is not taken into account. For lower waves, lower influence factors γ_f are recommended by TAW (Verheij et al., 1997). This is due to the relatively greater hydraulic roughness of the grass surface for thin wave run-up depths. However, this is mainly the case for gentle slopes. The wave height can be reduced in that case by (Van der Meer et al., 2016):

$$\gamma_f = 1.15 * H_{m0}^{0.5}$$

In the formulas that calculate the overtopping discharge, there are parameters with various probability distributions adopted from EurOtop (Van der Meer et al., 2016). These parameters C1, C2 and C3 for breaking waves ($\xi_{m-1,0} < 5$), non-breaking waves ($5 < \xi_{m-1,0} > 7$) and very shallow foreshores ($\zeta_{m-1,0} > 7$) have a certain standard deviation, which is used in uncertainty analysis.

The foreshore has a length of 1.3 km from the riverbed to the toe of dike section TG129. The foreshore is schematized as an horizontal plane without variations in height. The average elevation of the foreshore is set to 4.9 m + NAP determined from the AHN-viewer (2018).

The four vegetation parameters density, diameter, height and drag coefficient, are input for the wave model, see chapter 2.3.3. In the onedimensional wave model, there cannot be varied in parameter values over height sections, instead of in the SWASH model. As a result, only the branches of the willows are used for input, because the height of the stems is low, so we assume that waves only travel through these branches. In chapter 3.5, it was also clear that the wave height is mostly reduced by the branches. The diameters of the branches and stems, and the density of all the branches are measured in the research set-up of Deltares at various heights. However, this set-up was not based on the natural growth of willows. For the willow project at Fort Steurgat, more extensive measurements at natural willow plots have been done by Deltares (Venema et al., 2014). In table 4.5 the measured and assumed characteristics of willows at the Rhoonse grienden.

The drag coefficient C_D is a highly uncertain factor. Deltares used for the willows at Fort Steurgat a resistance coefficient between 0.6 and 1, after doing a literature study (Venema et al., 2014). Because of the onedimensional model a drag coefficient of 0.8 is chosen for the base case.

Griend	D (mm)			N/stoof			N / m²			C_D	V_f		
	H	L	Gem	H	L	Gem	H	L	Gem		H	L	Gem
Takken 1 jr	13	**9**	11	100	**30**	60	430	**129**	258	0,7	3,9	0,8	2,0
1 – 3 jaar	15	11	13	100	30	60	430	129	258	0,8	5,2	1,1	2,7
Takken >3 jr	16	14	15	100	30	60	430	129	258	0,8	5,5	1,4	3,1
Stoven	300	**100**	200					**4,3**		1	1,3	0,4	0,9

Figure 4.5: Characteristics of willows measured in the field (Rhoonse grienden) D =diameter, N/stoof = number of branches per stem, N/m^2 = number of branches per square meter, C_D = drag coëfficient and V_f = vegetation factor. Per character a high (H), low (L) and average (gem) assumption is made. (Venema et al., 2014)

At the boundary, the input parameters water level, wind speed, significant wave height and wave period are read from the design point values as used in the dike assessment (from the modelling program Hydra-NL, used by HKV consultants). The required crest level (HBN) is determined for the required failure probability for each dike cross section. The maximum allowable probability of occurence of a particular failure mechanism is corrected with a certain factor ω. For wave overtopping this is $\omega = 0.24$. This results in a probability of exceedance for wave overtopping of 1/10000 * 0.24/1 = 1/41.667 year [3]. The water level, wave height, wave period and wind speed for a probability of 1/41.667 and a design year of 2075 are read from the design point of dike section TG129 in Hydra NL. In the base case, wind growth and whitecapping are not implemented as mentioned in the previous section.

[3] 1 is the length effect of wave overtopping. This is equal to N=1, in accordance with the OI2014 version 4.

Variable	Symbol	Units	Parameter base case	Source
Dike characteristics				
Dike crest level	z_c	m + NAP	10.92 /10.44 *	Hydra-NL
Dike slope angle	α_d	deg	1:3	(Bos, 2017)
Reduction factor slope roughness	γ_f	-	$1.15 * H_{m0}^{0.5}$	(Van der Meer et al., 2016)
Wave load model				
Parameters wave overtopping	$C_1\, a-b$	-	2.7 & 0.023	(Van der Meer et al., 2016)
Parameters wave overtopping	$C_2\, a-b$	-	1.5 & 0.09	(Van der Meer et al., 2016)
Parameter wave overtopping	C_3	-	-0.79	(Van der Meer et al., 2016)
Foreshore bathymetry				
Foreshore bed level	z_{fs}	m + NAP	4.90	AHN2-viewer
Vegetation properties				
Height	h_v	m	5	(Venema et al., 2014)
Diameter	b_v	m	0.013	(Venema et al., 2014)
Density	N_v	branches/m^2	258	(Venema et al., 2014)
Vegetation width	W_v	m	60	-
Vegetation model				
Drag coefficient	C_D	-	0.8	(Venema et al., 2014)
Boundary conditions				
Wind speed	U_{10}	m/s	12.26	Hydra-NL
Water level	h	m + NAP	10.34	Hydra-NL
Significant wave height	H_s	m	0.58	Hydra-NL
Mean wave period	$T_{m-1,0}$	s	2.59	Hydra-NL
Wave direction	β_w	deg	5**	Hydra-NL

Table 4.1: Overview of input variables inluding symbol, unit, parameter value of the base case and the source *) The actual crest level is 10.92 m NAP, for the base case with vegetation the crest level is lowered to 10.44 m NAP **) Wave direction is 247.5° and right angle to the orientation of the dike is 242.5°, so relative 5°.

The dike and boundary parameters are checked in the wave model by taking the vegetation not into account. The wave overtopping for only these parameters gives a discharge of 5 l/s/m, which corresponds to the critical discharge. Due to the high water level on the foreshore, depth-induced wave breaking and bottom friction plays no role. Variation in formula or parameter value results in the same wave height as without these mechanisms. Dissipation by whitecapping is in this case also no issue, because the wave height is too small as compared to the wavelength for steepness-induced wave-breaking. The dissipation mechanism 'vegetation' is therefore in this case the only dissipation mechanism, which is further analyzed in 4.3.3.

For the sensitivity analysis, a 60 meter wide plot with willows is implemented in the model, which reduces the incoming wave height to 0.19 meter, see figure 4.6. To give a better view on the impact of the value variations, the crest of the modelled dike is lowered to 10.44 m NAP, the point of failure, so $q = q_c$. In the following sections, an analysis is made of the sensitivity of the dike system characteristics, the input parameters at the boundary and most important, the vegetation parameters.

4.3. Uncertainty analysis

In the uncertainty analysis, the response of the wave overtopping discharge and required crest level is tested to different choices concerning important system characteristics, the input parameters. All input parameters have a certain standard deviation relative to the base case value. Hydraulic and dike parameters, which are used for the dike assessment (during design conditions) have deviations which are described in literature. Variations in the vegetation parameters are measured by Deltares in the

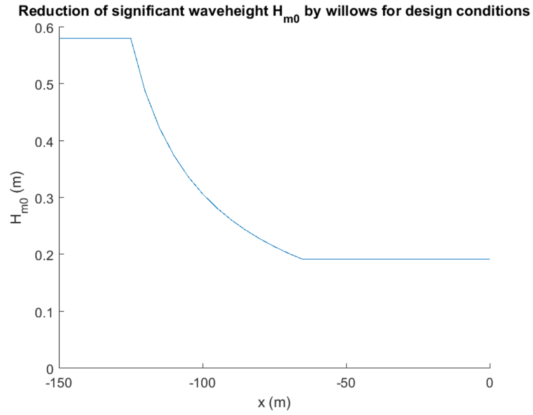


Figure 4.6: Wave reduction in the base case from x=-150 m to the toe of the dike at x=0 with a willow plot of 60 meters situated between x=-120 and x=-60 m and the input parameters as mentioned in the table above. Wind growth and white capping are not taken into account

Rhoonse grienden (see figure 4.5). The deterministic value of the standard deviation is substracted and added up by the value of the base case. The effect of these deviations on the wave overtopping and required crest level are calculated and compared with the base case situation.
The crest of the modelled dike is lowered to the point of failure for the base case parameters. As a result, variations results in less than 5 l/s/m wave overtopping or more, so failure.
The wave overtopping is determined with the, by the energy balance calculated wave height at the toe of the dike, using the EurOtop (Van der Meer et al., 2016) coefficients in a probabilistic analysis. In the next figures, the parameter sensitivity is shown on a logaritmic scale, based on the exponential wave overtopping function. The system characteristics are divided into three types of parameters. First, the model parameters like dike and foreshore geometry and the foreshore models are analyzed. Second, the boundary conditions like water level, wave characteristics and wind. Last, the vegetation properties, which is for this research the most important type. Variations in parameter value are applied on the base case system characteristics listed in table 4.1.

In literature (Pleijter et al., 2017) a wave overtopping discharge of 50 l/s/m can be seen as wave overflow. This discharge will affect the inner grass slope of the river dike. A dike with a moderate quality grass cover and clay layer, could fail after 7 hours with q = 50 l/s/m (Hoffmans et al., 2009). For 100 l/s/m, failure can happen already after 3 hours. The following sections give background information about the possible variations (standard deviations) of the parameters and the effect of these variations on the wave overtopping discharge and required crest level in comparison with the base case model, wherefore the wave overtopping discharge is already critical: 5 l/s/m.

4.3.1. Relevance dike and foreshore parameters

Uncertainties in the dike characteristics are for example spatial variations and measurement errors. For the crest height a standard deviation of 0.1 m is taken into account and for the slope angle a deviation of 5%, 1/60. These variations are based on characteristic spatial variations in dike geometry measured in the Netherlands, and correspond with the choices made in the VNK2 project, in which the failure probabilities of all Dutch primary flood defenses were determined (Vuik et al., 2018b).

In the base case, the roughness formula of grass which depends on the incoming wave height is used (Van der Meer et al., 2016). For waves higher than 0.75 m, the roughness of the slope with grass will be 1 equal to a block or asphalt revetment. The effect of this difference in roughness is analyzed.

The foreshore has a length of 1.3 km from the riverbed to the toe of dike section TG129. The foreshore is schematized as a horizontal plane without variations in height. The elevation of the foreshore is set to 4.9 m + NAP. This value is based on the airborn laser altimetry measurements done for the ANH-2 project of the Netherlands. A standard deviation of 0.04 m in the vertical direction is obtained by these measurements (Sande et al., 2010). However, as showed in the cross section of the foreshore there is a lot of variation in the height. As a result, a deviation of 0.2 meter is applied to the foreshore elevation, to account for spatial and temporal variations.

In the base case, the Iribarren number $\xi_{m-1,0} = \frac{tan\alpha_d}{\sqrt{H/L_0}} = 2.42$ is between 2 and 5, so waves do not break. As a result, $C_2 a$ is varied in model with 1.5 + - 0.15 (-) and $C_2 b$ with 0.09 + - 0.0135 (-), following the standard deviation as mentioned in EurOtop (Van der Meer et al., 2016).

Variable	Symbol	Units	Base case	Standard deviation	Source
Dike characteristics					
Dike crest level	z_c	m + NAP	10.42	0.10	(Vuik et al., 2018b)
Dike slope angle	α_d	deg	1/3	1/60	(Vuik et al., 2018b)
Factor slope roughness	γ_f	-	1	$1.15 * H_{m0}^{0.5}$ *	(Pullen et al., 2007)
n Wave load model					
Parameters wave overtopping	$C_2 a - b$	-	1.5 & 0.09	0.15 & 0.0135	(Van der Meer et al., 2016)
Foreshore bathymetry					
Foreshore bed level	z_{fs}	m + NAP	4.90	0.20	-

Table 4.2: Overview of input variables dike and foreshore base case and deviations. *) Following the EurOtop manual for roughness grass on a gentle slope (when $H_{m0} < 0.75m$)

Results

Effects of the parameter variations on the wave overtopping are shown in figure 4.7. The base case with the average parameter values as mentioned in table 4.1 is the vertical line at 5 l/s/m. Minimum and maximum values of these parameters result in a lower or higher overtopping discharge. The effects of the parameter variations are compared with the situation without wave damping vegetation, which results in an overtopping discharge of 92.2 l/s/m.
The slope angle is not shown in the figure, because the variation in slope angle has no effect on the overtopping discharge. The angle has effect when there is a transition in breaker type. In the base case, this is only achieved by a slope of 1:1.5.
Variations in probabilistic overtopping parameter C_2 has a negligible effect on the required increase of crest level. This overtopping parameter could be C_1 if reduction of the period (to 1.8 sec) was obtained in the model by the vegetation.

The elevation of the foreshore and slope roughness have the largest effect. In the base case, the effect of roughness was $\gamma_f = 1.15 * H_{m0}^{0.5} = 0.51$ which reduces the wave overtopping significant. For a revetment without roughness, like a stone revetment or for waves with a wave height higher than 0.75 meter, the crest level should be elevated with 6 cm. The foreshore elevation has also a significant effect, which is caused by the combination: water level on the foreshore $h - z_b$ and height of the willows h_v. Maximum wave damping is reached when the branches of the willows are not submerged.
For a floodplain level of 4.7 meter, the overtopping discharge will increase to more than 13 l/s/m, which means failure. However, the effect of an exceedance of 6 l/s/m on the critical overtopping discharge is small. The crest level should be heightened with 6.1 cm to meet the requirement of a maximum overtopping of 5 l/s/m, equal to the effect of the roughness.

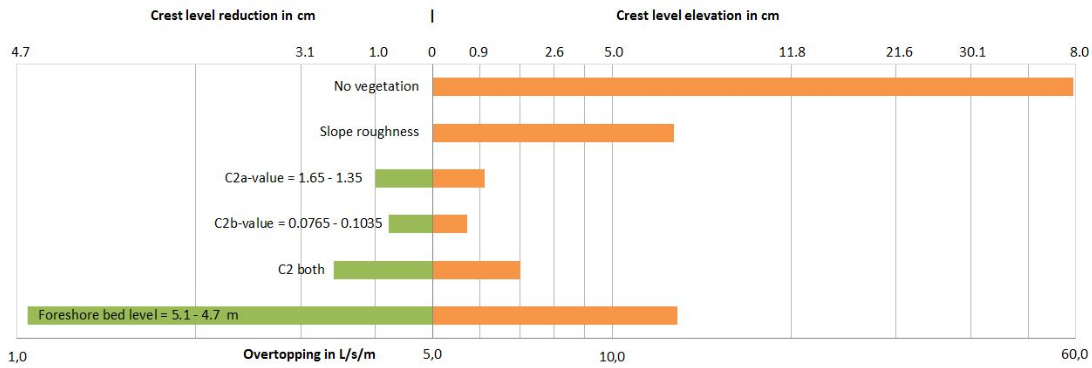


Figure 4.7: Dike and foreshore parameter sensitivity on the wave overtopping discharge and required crest level heightening (or reduction) to meet the critical discharge, in compare to the base case with a wave overtopping of 5 l/s/m

4.3.2. Relevance boundary parameters

The boundary parameters wave height and wave period depend on water level, wind direction and wind speed. In the project Tiel-Waardenburg, the formula of Brettschneider was used to determine the wave height and period in the design point (Hydra NL).
The water level has a model uncertainty of 0.15 m for the river Waal as mentioned in the assessment tools (Chbab and Groeneweg, 2017) and used in the Hydra NL calculations for the project Tiel-Waardenburg (Pleijter et al., 2017). The significant wave height and wave period have an uncertainty of allowance of 0.15 m and 0.07 s as prescribed (Chbab and Groeneweg, 2017) in the assessment tool OI2014 version 4. However, in the Hydra NL calculations for the project Tiel-Waardenburg uncertainties are included by integration according to the method in WBI 2017. This starting point differs from the advice in the OI2014 version 4, but is in line with the calculation method as mentioned in literature (Deltares, 2017). The statistical and model uncertainties are taken from the WBI2017 databases physics. Deviations of 0.27 m for the wave height and 0.13 s for the period are used (Pleijter et al., 2017). These stricter deviations are also used in this sensitivity analysis.
The wind speed is in the design point part of the wave height and wave period. In the base case model, wind input is not activated, so variations will not affect the wave overtopping and required crest level. However, in section 4.4 the variation in windspeed should be investigated. The 5% and 95% confidence intervals of the wind have a deviation of on average 3 m/s with the average wind speed with an exceedance probability of 1/41667 (Caires, 2009). This deviation is chosen to determine the sensitivity of the uncertainty of the modelled wind speed.
The wave direction depends on the wind direction which strongly influences the probability of occurence of a high wind speed and so coherent high water levels and waves. The wave direction in the design point is the direction which gives in combination with the wind speed the highest probability of occurence. The model uncertainty for the wave direction is neglected in the assessment tools report about hydraulic loads (Chbab and Groeneweg, 2017). However, at dike section TG129 the river dike is not straight but orientated between on average 337 and 347 degrees [4], so $0 < \beta_w < 10$.

[4] Measured from the *legger* dike project Tiel-Waardenburg (WSRL,2016)

Variable	Symbol	Units	Base case	Standard deviation	Source
Boundary conditions					
Wind speed	U_{10}	m/s	12.26	3.0	(Caires, 2009)
Water level	h	m + NAP	10.34	0.10	(Chbab and Groeneweg, 2017)
Significant wave height	H_s	m	0.58	0.27	(Pleijter et al., 2017)
Mean wave period	$T_{m-1,0}$	s	2.59	0.13	(Pleijter et al., 2017)
Wave direction	β_w	deg	5**	5	-

Table 4.3: Overview of input variables base case and deviations at boundary. **) 5 degree relative to the orientation of the river dike.

Results

As mentioned in the previous section, the ratio vegetation height versus water depth at the forehore, have the largest effect on the wave overtopping discharge. The water level, which has a deviation of 0.10 meters in height, results in a maximum overtopping discharge of 30 l/s/m. For comparison, this effect is equivalent to a crest level elevation of 21.6 cm to fulfill the assumptions of Waterboard Rivierenland.
The effect of the parameters wave period $T_{m-1,0}$ and direction β_w relative to the orientation of the river dike, are negligible since waves do not break (C2-regime)
The significant wave height has a larger effect on the overtopping discharge, when the height is lower than the base case value. Higher incoming wave heights are reduced more in height by the vegetation, than small waves. As a result, the earlier high waves are damped a lot and gives a wave overtopping which is just more than the critical discharge. This effect was also visible in chapter 3. To conclude, the effect of the standard deviations of the significant wave height on the required crest level are negligible, when vegetation (like in the base case) is present.

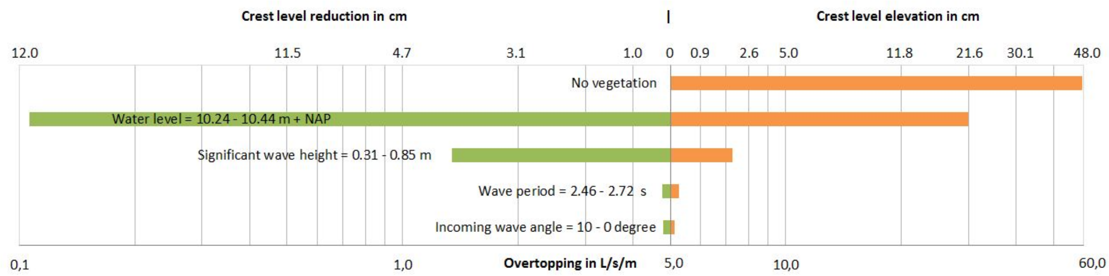


Figure 4.8: Boundary parameter sensitivity on the wave overtopping discharge and required crest level heightening (or reduction) to meet the critical discharge, in compare to the base case with a wave overtopping of 5 l/s/m

4.3.3. Relevance vegetation parameters

Willows are fast growing plants. In the first year a willow grows to a height of 3 meters, in the second year to 5 meters and after that to a maximum height of 6 meters (Venema et al., 2014). The wavedamping willows will be pruned on average, once in the two years just after the storm season. For the new storm season, the willows will already have grown to a height of approximately 3 meters. So, in this sensitivity analysis a minimum height of the willows of 3 meters is held and a maximum of 6 meters.
The diameter of the branches b_v and density per square meter N can varies a lot over the strip with willows. Further in the one dimensional wave model, there can not be varied in parameter values over height sections instead of in the SWASH model. As a result, the variation in the diameter and density is large, which causes an uncertainty in wave damping. In table 4.5 the uncertainties of all vegetation parameters are based on the field measurements of Deltares (Venema et al., 2014).

The big spread in width of the plot is implemented to determine clearly the sensitivity of this factor. At various foreshores there is probably ten meters left for planting of wave damping willows. While at other foreshores, a hundred meter wide strip of willows could be possible, for example at Heesselt.

The drag coefficient is still a factor with a large variation in value as described in literature. As mentioned in chapter 3.5 the drag coefficient value will be going to 1 for high Reynold numbers, so during design conditions [5]. However, the drag coefficient is also influenced by the type of flow (subcritical or super critical), vegetation density and the relative submergence depth (Liu and Zeng, 2016). Liu (2016) analyzed experiments about the drag coefficient of rigid vegetation, of various investigators. For different circumstances, the drag value of the vegetation was ranged between 0.5 and 2.0. Flexible vegetation, like couch grass (growing on salt marches at the wadden sea), have a drag coefficient around 0.2 (Vuik et al., 2018a). Willow branches are, mainly at the end which breaks the water surface, also really flexible. So, the effect of the drag coefficient is determined for $0.2 < C_D < 2.0$.
This variation is large, because Deltares used for the willows at Fort Steurgat a resistance coefficient between 0.6 and 1. In the results, also the effect of this smaller variation is shown.
The importance of knowing the real drag coefficient value of willows for design conditions, appears from the sensitivity analysis. In part one of this research, a proper drag coefficient for willows was not found. In the recommendations a new set up is described to determine the drag coefficient.

Variable	Symbol	Units	Parameter base case	Min value	Max value
Vegetation properties					
Stem height	h_v	m	5	3	6
Stem diameter	b_v	mm	0.013	0.009	0.016
Stem density	N_v	stems/m^2	258	129	430
Vegetation width	W_v	m	60	30	90
Vegetation model					
Drag coefficient	C_D	-	0.8	0.2	2.0

Table 4.4: Overview of vegetation parameters base case and deviations based on the field measurements of Deltares in the Rhoonse grienden (Venema et al., 2014) and the drag coefficient for design conditions as mentioned in (Liu and Zeng, 2016)

Results

The three vegetation parameters b_v, N_v and C_D have, for an equal variation, the same effect on the wave reduction. This is due to the linear vegetation factor equation, as mentioned in chapter 2.3.3. For the assumed minimum and maximum values, the effect on the overtopping discharge of the drag coefficient (values which were used by Deltares) and the diameter of the branches is almost the same. The vegetation density N_v has a very big natural variation. For a vegetation density half of the original, the overtopping discharge will increase to 22 l/s/m. While, if the width of the plot with willows has been halved, the discharge will be 20 l/s/m.
In figure 4.9 the parameter with the highest sensitivity is h_v. If the willows have an height of 3 meters, the overtopping discharge is almost equal to the discharge without any vegetation. The willows are fully submerged due to the water level of 5.44 m on top of the foreshore.
The drag coefficient with the extreme variation has a really big spread in overtopping discharge. This indicates the importance of obtaining more knowledge about the drag resistance of, especially willows during design conditions.

[5] Following Schlichting et al. (Schlichting et al., 1955) a $C_D = 1 for 800 < Re < 8000$ and $C_D = 1.2 for 8000 < Re < 10^5$

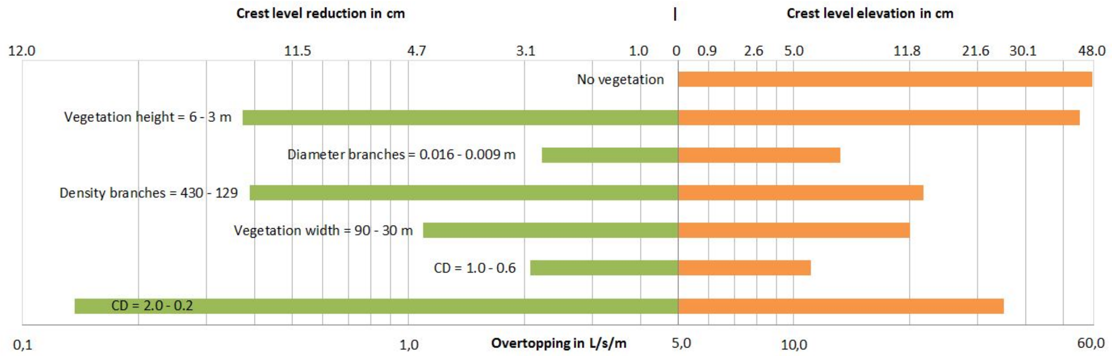


Figure 4.9: Vegetation parameter sensitivity on the wave overtopping discharge and required crest level heightening (or reduction) to meet the critical discharge, in compare to the base case with a wave overtopping of 5 l/s/m

4.4. Variation in location of wave damping vegetation

At the case location, high voltage pylons are located at the riverside of the dike on the foreshore. From dike pole TG120, at the bend near Heesselt, to pole TG129, vegetation cannot be planted close to the dike due to these pylons. An analysis is made to determine the effect of the location of the strip with wave damping vegetation if wind input is turned on in the wave model. For the analysis, 60 meters wide zone wave damping vegetation is set at 60, 100 and 200 meters distance from the toe of the dike. A modelled wave with a height of 0.20 meter [6] is used to determine the sensitivity of the wave on the windspeed. Growth of this wave in between the toe and vegetation can be expected due to the wind. The wind speed, as mentioned in the design point (1/41667 year) was U_{10} = 12.26 m/s, with a standard deviation of 3 m/s.

In table 4.5 the wave overtopping discharge is shown for the three distances with average, minimal and maximum wind speed, when the wind input is turned on (without wind input the wave overtopping discharge was 5 l/s/m).

	Influence of windspeed	- - - - - - -	- - - - - >
Influence of distance		Overtopping (l/s/m)	
Distance (m)	Minimum	Average	Maximum
60	5.3	5.6	5.9
100	5.5	6.0	6.5
200	6.2	7.2	8.4

Table 4.5: The wave growth in meter for the minimal, average and maximal windspeed and the wave height at the toe and overtopping discharge for the maximal wind speed for a distance between the vegetation and dike of 60, 100 and 200 meters, with all other parameters set as in the base case.

The wave growth for the three distances is less, also for the maximal wind speed. The increase in wave overtopping discharge is negligible. For a distance of 200 meters, the crest level should be heightened with 2.7 cm for the maximum wind speed.

[6] Based on the wave height of the base case at the end (60 m) of the plot with willows. The wave height is reduced from 0.58 to 0.20 m.

4.5. Conclusions

In figure 4.10, the sensitivity of all the parameters are shown for the assumed variations. The combination of the variables; water depth (on the foreshore) and height of the willows, has the most impact on the wave damping capacity and therefore, on the overtopping discharge. The wave damping capacity of submerged branches decrease fast. Therefore, the height of the willows should be maintained.
However, this height is highly variable due to natural uncertainties. Maintenance and scenarios like fire, storm or diseases can result in a lower willow height. These scenarios and their consequences are described in the chapter 5.
Second important parameter is the drag coefficient with his extreme variation. This highlights the importance of research to drag coefficients of vegetation.
The vegetation parameters width W_v and density of the branches N/m^2, have almost the same effect on the overtopping discharge as the water depth and crest level variations. Conclusion, the vegetation parameters including the drag coefficient, and the water and crest level are the most important factors in the wave model.
The other standard deviations of the parameters have a relative small effect on the required crest level, they are not sensitive. For new calculations (applying wave damping vegetation), these parameters can set to an average value. The high sensitive parameters get an extra high value (for example a 95 or 90%-value) to take the uncertainties into account.

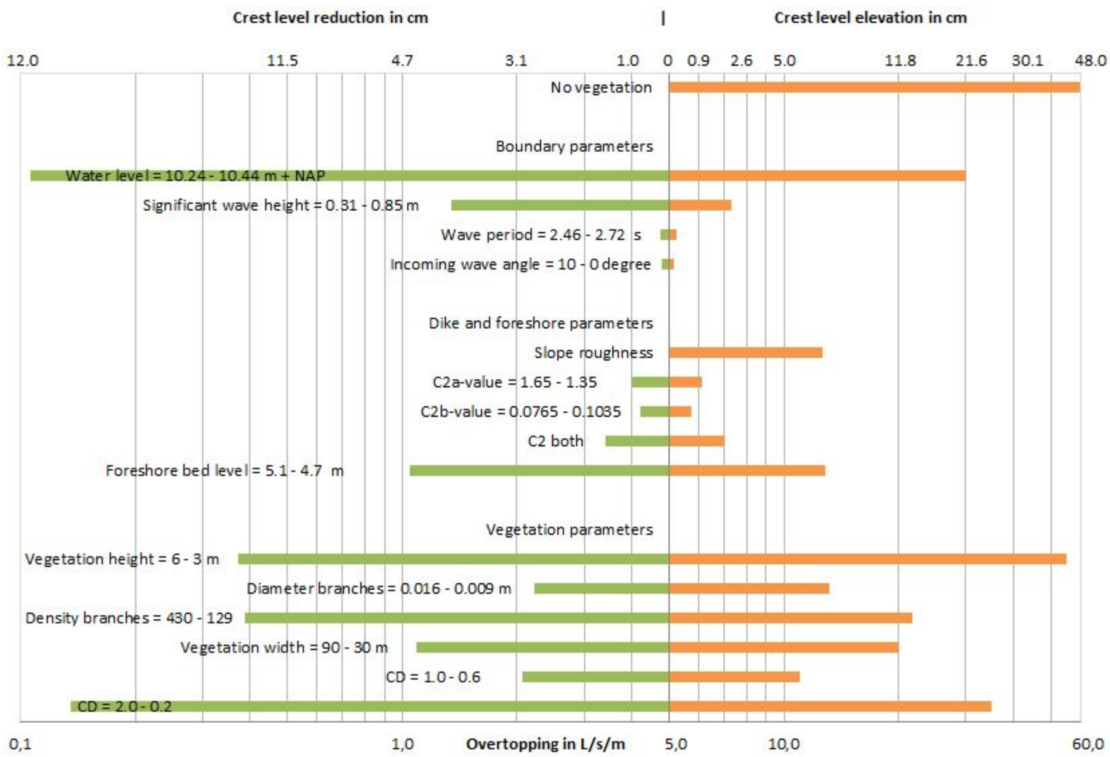


Figure 4.10: Sensitivity of all parameters on the wave overtopping discharge and required crest level heightening (or reduction) to meet the critical discharge, in compare to the base case with a wave overtopping of 5 l/s/m

The effect of the location of the wave damping vegetation on the wave overtopping, and so the required crest level, is not significant in this case. The location of the willows can be chosen on basis of other arguments like landscape design. The effect on the crest level is more than 5 cm, for a distance between the willow vegetation and toe of the dike of 500 meters. To conclude, the wind grow effect with a wind speed around the 12 m/s is not significant for a distance less than 500 meters.

5

Effects exogenous threats of willow vegetation

The vegetation parameters of willows can vary due to the natural spatial variations as mentioned in the previous chapter, but can also varied due to exogenous threats, like diseases, storm, ice, drought, fire, flood, beavers and insects. Effects of the threats on the vegetation parameters and the probabilities of occurence are assumed based on literature and interviews with willow experts. The three exogenous threats with the highest risk and significant consequence are storms, floods and droughts. To take the effects of these threats into account in the design, the crest level should be elevated with 7 cm or the width of the vegetation plot should be widened with a buffer zone of 30 meters.

5.1. Introduction

Different types of uncertainties can be discerned following Van Gelder (Gelder, 2000). In chapter 4 the sensitivity of the knowledge uncertainties, like statistical and model uncertainties, are determined. However, there are also inherent (or natural) uncertainties, which are related to the variability of nature. The sensitivity of the vegetation parameters is already examined for natural statistical uncertainties determined by the field measurements, but not for (extreme) scenarios. For example, vegetation on the foreshore of a riverdike can be affected by scenarios like breakage of branches, diseases, ice drift, drought and frost. As a result of these scenarios, the wave damping likely to decrease. Nontheless, the flood defense including vegetated foreshore should always meets the safety requirements, when the vegetation (with wave damping capacity) is included in the assessment. So the probability of occurrence of these scenarios and the effect of the scenarios on the wave reducing capacity should be included in the wave model.

First, suitable willow types for wave damping are described and a preference for a specific type is made. In the following sections, scenarios are described and their consequences on the wave damping capacity and on the required crest level are calculated. Finally, control measures to reduce the consequences of scenarios are given.

5.2. Willow characteristics

An osier bed, a willow forest on a marshy ground, is created by inserting willow branches in the ground (stekken). These willow branches should have a diameter of between 5 to 8 centimeters and an average length of two meters. The branch/trunk without side branches is put in the ground at a depth of 0.5 - 1 meter. The typical Dutch pollard willows grow really fast. After one year, there exists already a new willow with an approximate height of three meters

There are various types of willows ("Salix"). In total there are 300, but within the Netherlands there are only twelve species can be found, of which the salix types; Caprea, Fragilis, Purpurea, Alba, Triandra and Viminalis are most common in the river areas. In table 5.1 the pros and cons of the various willow types are shown and a score is given with regards to the application of this type of willow as wave damping vegetation, based on interviews and literature.

Type	Pros	Cons	Score
Caprea	Max 10m high	Sensitive for watermark disease, Pruning in high water season (early flowering)	–
Fragilis	Max 20m high	Fragile, very easily depleting branches, high demands on soil moisture	-
Purpurea	Resistant to frost	Only 2-6m high, requires moist humus rich soil	-
Alba	Grow fast, to 25m high, deep roots	Sensitive for diseases *Erwinia salicis*	+
Triandra	Tree to 10m high, 3x more dense than Alba and Viminalis	Sensitive to frost, really flexible	+ +
Viminalis	Resistant to frost, strong	Max 6m high, low density, sensitive for diseases	-+

Table 5.1: Six types of willows which are common in the river areas with their pros and cons and a total score concerning the application of the type as wave damping vegetation. Characteristics are collected in the Rassenlijst Bomen (bomen Raad voor plantenrassen, 2018) and Interviews with Den Hartog and Bontekoe

The *Salix Alba* and *Salix Triandra* have the highest score, hence are best applicable for wave damping on the Heesseltsche Uiterwaarden. These types of willows are also used in the Noordwaard. The *Salix fragilis* is also a type of willow which often stands in osier plantations. However, this type has fragile branches and as application for wave damping, branches must not break. In the following chapters, it is assumed that the types Alba and/or Triandra are used at the case location.

5.3. Exogenous threats

Possible threats which can affect the wave damping capacity of willows, are described in the following sections. Figure 5.1 presents a summary of these threats. The consequences and probabilities for willow vegetation at the Heesseltsche Uiterwaarden are estimated for the upcoming 50 years, which is the design period for the dike reinforcement Tiel-Waardenburg, based on literature and interviews with willow experts.

5.3.1. Bacterial and fungal diseases

Many Salix types are sensitive for the Erwinia salicis bacteria s' attacks, the cause of the so called *watermark disease*. Whereas the *Salix Alba* is most sensitive for this disease. The disease occurs on branches of five years and older and causes a blockage in the wood vessels, through which leaves wilting. Branches wither from the outside to the inside, both in the top and middle of the crown. The process of this disease is slow. Risk is that dead branches, break out. Finally, the willow will die in a few years. However, a damaged tree can be preserved by being cut, because the disease do not affect young shoots.
Bacteria can easily spread due to the rain or wind, therefore it is recommended for infected areas not to plant new Salix types for the time being. Cuttings are disease-free up to two years old (beterebomen.nl Burobol and Nostra, 2015).

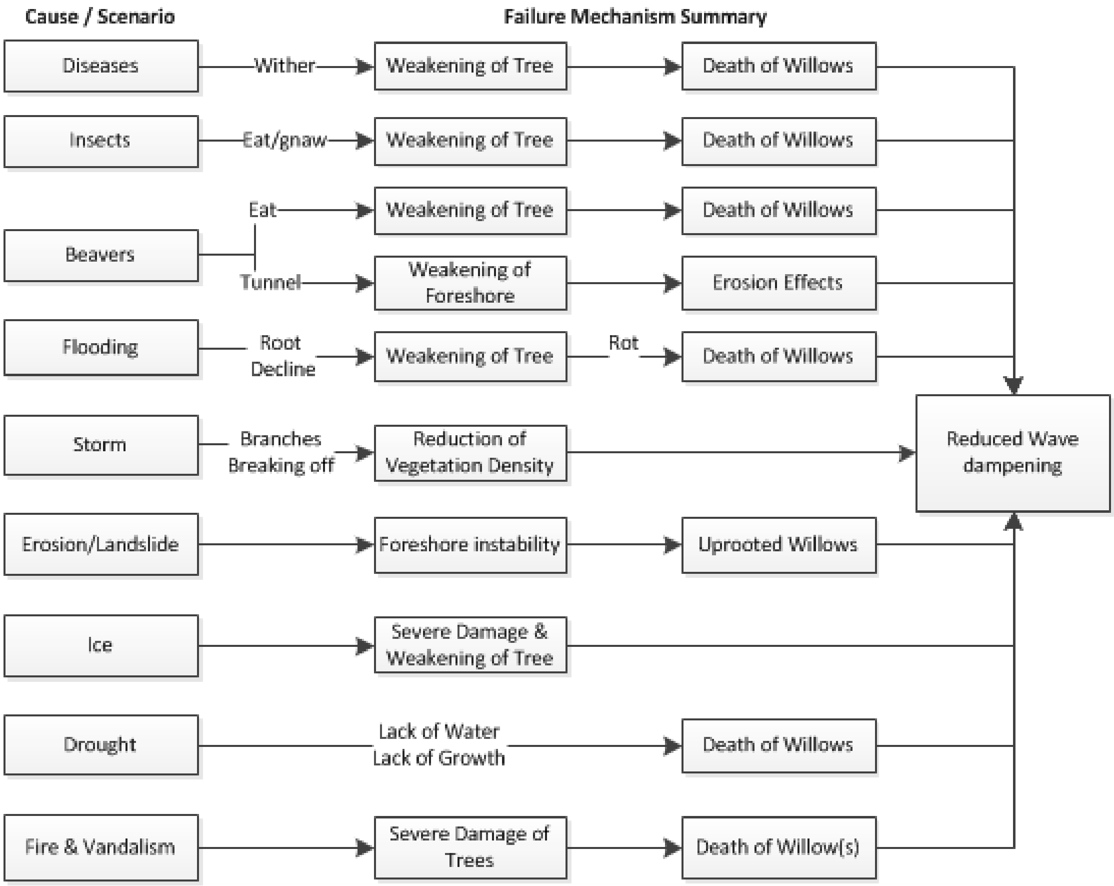


Figure 5.1: Overview of the exogenous threats including the consequences on the wave damping capacity of willows

The most important fungal disease is the *black cancer*, which can occur massively in places where the density of young willows is high, like in osier plantations (de Populier, 2018). In an early stage of the disease, whilst still in the leaves, it can easily been removed. Whenever the disease is transferred to the branches (mostly after two years), there is no good workin treatment and infected trees will die after a few years. All infected trees should be removed after the high water period and be replaced, so the disease cannot spread (mainly during spring and autumn). The black cancer can give a lot of damage to the osier bed, but it can be prevented with enough visible inspections. Phenomenons of the black cancer are black spots show on the leaves that also curl up a bit, later these black spots arise on the wood as well (Kol, 2018).

Almost continuously willows are plagued by all kinds of diseases and fungi (Interview Den Hartog, see chapter 8). However, they are all accustomed to those attacks and do not care much about it. Therefore it is estimated that only 10% of the willow vegetation will be fragile due to these diseases and cannot act as wave damping vegetation. These willows should be renewed.
Diseases happends continuously during the total life-time of willows. However, approximately diseases make a willow fragile (or give too much damage) after just two years without taking measures (Interview Den Hartog). Therefore, the probability of this exogenous threat is set on 1/2 year.

5.3.2. Insects pests

Various insects can affect the trunk or branches in such a way that it will break down due to wind forces, which seriously affects the wave damping. The *Goat Moth (Cossus Cossus, Wilgen Houtrups)* makes approximately 5 mm large holes in the bark and a tunnel system in the stem searching for places with cambium. The Goat Moth hibernate three to four times in the tree, whereafter the pupation in May takes place in a solid cocoon. In one to three years the willow is pierced completely and should be cut before the earlier mentioned pupation takes place (de Populier, 2018).
Second, the larvae of the *populieren boktor (Saperda populnea)* causes tunnels and swellings in the wood. As a result, branches and twigs can break easily reducing wave dampening capabilities. The boktor has a life cycle of three years and will hibernate twice in the stem. The insect can be recognized in the osier plantation by the round holes in the leaves with a diameter of 2 centimeters.
Branch lices cause weakening of the branches. In osier plantations a lice infestation of the *Pterocomma salicis (wilgentakluis)* in the spring and summer results in a lot of damage and the *Tuberolachnus salignus (dromedarisluis)* in the autumn and winter.

Insects plagued willows also continuously, because of the very important food source. However, the Goat Moth, the boktor and lices will damage the willow significantly after just three years. Therefore the probability will be once in three years.
The spread of insects in the osier plantation, and thus the damage, will be smaller than diseases. It is estimated that insects will damage just 5% of the willows in the osier plantation.

5.3.3. Beavers and other animals

In the Heesseltsche Uiterwaarden beavers and their tracks have been spotted (Waarnemingen.nl, b). A beaver population requires approximately five square kilometres for a single colonie (Waarnemingen.nl, a). Thus at the case location, there will probably live two families on short-term. However, it is expected that in the upcoming 50 years (design year) the beaver population in the river area will grow. Mainly during high water, beavers will move to the plot with willows, which should be served as refuge.
In the growing season (April till October) beavers eat grasses, herbs and water plants. During winter, beavers switch to roots, shrubs and bark from soft wood trees like willows. One family of beavers can annually harvest 900 kg of trees per year (Waarnemingen.nl, a), effectively damaging approximately 100 willows, which is 0.5% of the osier plantation. These willows cannot be used as wave damping vegetation and should be replaced by new willows. The total damage in the plot on short-term with two families is small, but in the future, with probably six families, the damage will increase considerably (Interview M. Olieman).
Side branches of fallen trees are being dragged through dug channels to their hole and will be used as winter supplies. Beavers dig channels to stay in the water, for safety. With digging, roots of the willows can be damaged. Further, beavers dig holes in the banks, whose entrances are usally just above the water level (Marijn van den Dool, 2015). During inspection it is important to pay attention to these entrances and digged channels.

Animals like rabbits, deers and hares are observate various times at the surrounding floodplains (Waarnemingen.nl, b) (Zaltbommel, Hurwenen and Opijnen). Still not at the Heesseltsche Uiterwaarden. These animals can damage the willows a lot during the winter. The bark of the willow is a popular food source for animals like insects, deers and bacteria. A willow will die without a bark, so it is important to observate all animals this area.

The consequences are estimated based on insights for the future, thus six beaver families (Interview M. Olieman). These will harvest 3% of the osier plantation every year. It is expected that also other animals will move to the Heesseltsche Uiterwaarden. Therefore the consequences will be larger, approximately 4% per year.

Figure 5.2: Deer during the winter season on floodplain the Avelingen (photo by Wim van der Pijl)

5.3.4. Flooding

Literature (Baughman, 2010) (Ebben) shows that the Salix Alba and Triandra are tolerant for a flooding of 10 days during the growing season, thus short-term floodings. Trees are most susceptible to flood damage in late spring (May and June), just after the first flush of growth. Most damage is caused due to the displacement of air in the soil by water, leading to root decline, major long-term damage or eventually death. Injury increases when a higher percentage of the crown is submerged by water, which is the case during high water. It is assumed that a quarter of all the willows will have a growth stop or die in the next year.
Flooding is usually no problem when it happens in late winter or early spring, when the willows are not actively growing and water recedes before growth begins (depending on the soil drainage). Most willow species can withstand in that period one to four months of flooding.

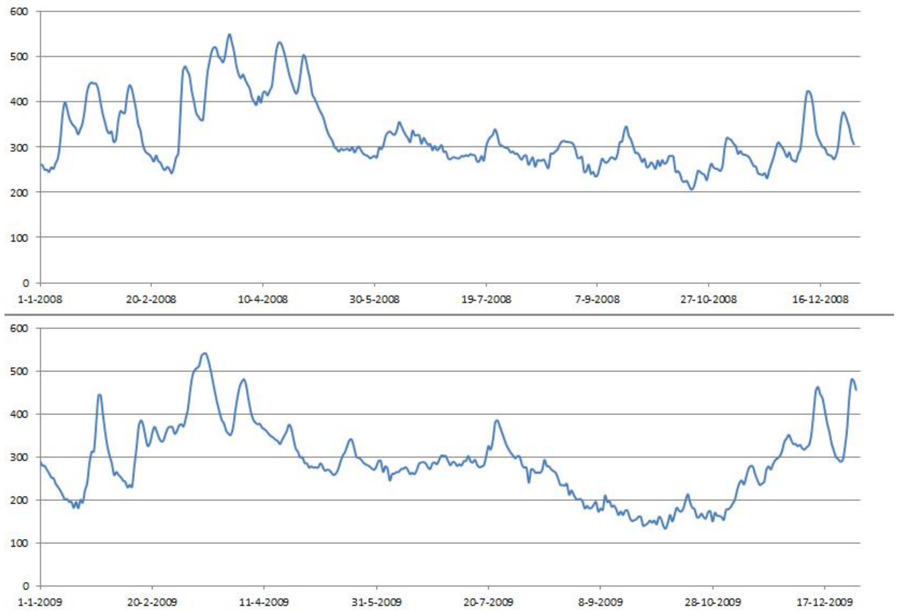


Figure 5.3: Water level Waal 2008 and 2009 (Rijkswaterstaat, 2018)

For wave damping willows only floodings from March to June are important. In this period willows are susceptible to injuries if the flooding period is more than ten days. A water level timeserie (1993 - 2017) is checked of a measurement set at Zaltbommel, close to the case location (Rijkswaterstaat, 2018). The foreshore is flooded when the water level in the river reach a level of 4.9 meters above NAP. From 1993 till 2017, this occurred 52 times, from which 14 times in January - February, 19 times in March - April, 5 times in May - June, 5 times in November and 9 times in December. The duration of the flooding in May or June was in 1 of the 24 years longer then 10 days, so a probability of 1/24 years but conservatively 1/20 years.

5.3.5. Storm

During storms branches can break and stems can break or be uprooted (Vuik et al., 2018a). Following the classic windtable of Beaufort, for a windspeed of 17.2-20.7 m/s (Beaufort 7) twigs breaks, 20.8-24.4 m/s (Beaufort 8) branches will break and for higher windspeeds trees will break or be uprooted. Trees, regardless of their diameter, height, or elastic properties, don't tend to break until wind speeds reach about 42 m/s (Virot et al., 2016). However, this applies only for willows that not have been weakened by diseases, insects or wrong maintenance.
A storm will mainly damage the first meters of willows at the riverside of the osier bed, because southwest is the wind direction with the highest probability of occurence. It is assumed that during storm, the outer twigs and branches of the willows will break, on average one of the twenty. Also the height of the willows reduce with on average 10 centimeters.

To determine the probability of occurence, wind statistics have been requested and viewed of the KNMI station at Herwijnen, 18 kilometer from Heesselt. In seventeen years, since the start of the measurement station, there had been 22 days with a maximum hourly mean windspeed above the 17.2 m/s and 4 days above the 20.8 m/s [KNMI, 2018]. The most extreme windspeeds occur in January to March, further in order November, December, October and April. When looking to the maximum wind gust every day, Beaufort 9(!) has been registered on 26 days, Beaufort 8 during 197 days and Beaufort 7 for 459 days. By taking these registered days as probability of occurence for this threat it would be once every 9 years.

5.3.6. Erosion and land slide

During storm conditions, waves and currents can erode the foreshore. Water will flow over the foreshore and the soil will get saturated. A land slide of the foreshore into the river can occur due to the rise in groundwater table or liquefaction of the soil. However, land slide is only a problem for wave damping, when willows are displaced or being uprooted because they were placed at the edge of the floodplain. The Heesseltsche Uiterwaarden is a large area and the distance from the river to the dike is approximately a kilometer. The wave damping vegetation will be planted close to the river dike. For the case location, this scenario is not relevant.
Erosion of the edge of the floodplain at the riverside is also not relevant for this case. However, with high water the flow paths over the floodplain can also provide erosion if there is a high flow speed. At the case location, the storage capacity is large due to the big area of the floodplain, so the flow velocity will significantly decrease. It is assumed that erosion will be negligible.

5.3.7. Ice

In periods of prolonged freezing and longer periods of high water, ice arise on the floodplain and in the osier plantation. Solid ice will start to appear 4 to 6 days after after the first drift ice. The solid ice grows in an upstream direction at a speed of about 20 km per day (Engberts, 2015).
The probability of occurence of this threat is small, because the conditions needed for river ice rarely occur. In the twentieth century only a total of 10 winters of solid ice on the Waal, Nederrijn or Lek have been recorded, the last time in 1987. (Engberts, 2015). Secondly, only during high water the

willows can damaged by ice or whenever the river ice breaks up and starts to crawl to the floodplains. However, at this case location the willows are too far from the river.

Besides real river ice there can also arise ice on flooded floodplains. The water depth and flow speed at a floodplain are small in compare to the circumstances in the river, thus water freezes more quickly. Water between the willows become a large ice mass. Due to temperature rise, the ice plate goes down including the frozen branches, which breaks from the stew. The willows are severely damaged and the only control measure is mowing. It is estimated that the density of willows decrease with 5%, which means that one of twenty branches will break.

Figure 5.4: Ice between the willows at floodplain the Avelingen (photo by Ewoud Klop)

The last ten winters, the floodplain was flooded 15 times (Rijkswaterstaat, 2018). On average, once in 2 years, 7 cm of ice will form and remain in 9 days, given stagnant water with a depth of 2 meters (Klimaatdata en advies, 2007).
However, at the floodplain the depth will be approximately 3 meters (the height of the summer dike) or more and this ice will be affected by wind and currents. As a result, the probability of occurence will be less, approximately once per six years.
Nowadays, less drainage of cooling water is allowed which makes the water colder. The long-term expectation is that the probability of ice in rivers and at floodplains increases.

Frost is no issue, because willows have a good resistance to frost. A Salix Alba and Triandra have a winter hardiness classification of 4, which means that they could withstand temperatures of -28.9 to -34.4 $^{\circ}C$ (den Berk Boomkwekerijen).

5.3.8. Drought

Rapidly declining water levels in river banks during the growth period can result in limited availability of water. Approximately, a low water level (below 1 m + NAP) for three weeks in April - July, occurred once every 25 years in the Waal (Rijkswaterstaat, 2018).

The research of van Splunder (Splunder et al., 1996) examines the difference in drought resistance among Salix Alba, Salix Triandra, Salix Viminalis and Populus nigra, four species dominating the Rhine river banks. In a greenhouse experiment, mortality and growth responses of seedlings where studied under well-watered and dry conditions for three weeks. Drought-induced mortality was 37.5% for the Salix Triandra, for the Alba it was zero. So for a osier plantation with these two types, the maximum mortality should be around 20%. After approximately one year the roots of the willows are deep enough to get enough ground water. If the willows are planted on an elevation this could require more time. Drought is therefore only important in the first year(s) of the planted willows.

5.3.9. Fire and Vandalism

Fire can occur naturally, but can also be lit by humans. The Heesseltsche Uiterwaarden is a recreational area, with paths and beaches along the river Waal. In summer, people smoke, makes fires on the beaches and go barbecuing. A fire in the willow vegetation could occur, but the probability is hard to estimate. The probability of a natural fire on the Veluwe is 4% every year (NIFV, 2012), so once in 25 years. It is assumed that on the swampy soil at the floodplains, fire including serious damage happends only once every 50 years.

Fire can happen throughout the year, however the damage should be heavier in dry periods usually from July to September (KNMI). Fire will make the willow branches really fragile. If a fire would happen, the fire goes fast due to the high density of willows. The total damage will depend on the response time of the fire department. In fact, it is a forest fire, but with the difference that willows stand in a swampy soil. A fire in a osier plantation is difficult to extinguish (Brandweer, 2013). The speed of expansion is approximately 8 meter per minute which means for a response and quenching time of total 45 minutes, a damaged area of 360 m^2 (Stalenhoef-Willemsen, 2009), less than 1% of the osier plantation. However, at small scale the damage is significant. It is estimated that at a fire path from the river side to the dike (whereover waves travel to the dike and which is also the case in this one-dimensional model), 30% of the mostly long willow branches will be unusable for wave damping.

Kids can make huts in the osier plantation. These huts will probably be made of willow branches. The willows get damaged, but is limited to a small-scale meaning so it has no relevant impact on the wave damping capacity.

5.4. Overview exogenous threats

Table 5.2 presents an overview of all the described threats. At the Heesseltsche Uiterwaarden, stability of the foreshore will not be considered as scenario for the damping capacity, because willows will be not uprooted or disappear by land slide or erosion due to the large surface area. Similarly the scenarios of vandalism and frost are excluded due to their occurance and consequences. The probability of occurence and consequences of the scenarios are assumed based on the literature study as mentioned in chapter 5.3 and the interviews with willow experts 8.

Exogenous threat	Probability of occurrence	Consequences
Diseases	once a year	10% of the willows are unusable
Insects	1/3 year	5% of the willows is unusable
Beavers	once a year	600 willows is +-3% of the willow plot is unusable
Flooding*	1/20 year	25% of all the willows are unusable
Storm	1/9 year	the outer twigs and branches break
Ice	1/6 year	the small twigs and branches break
Drought**	1/25 year	20% of the young (1-2 year) willows are unusable
Fire	1/50 year	30% of the willow branches are unusable on a fire path

Table 5.2: Overview of the scenarios including their assumed probability of occurence and consequences based on expert information and literature. *Flooding longer than 10 days in May to August **Only in the first two years after planting for a drought of at least 3 weeks for a osier plantation with 50% Alba and 50% Triandra

A relevant scenario, is a scenario which has a significant risk and affects the required crest level by at least a few centimeters. Risk can be described as the probability of occurence times the consequences. For the osier plantation, it is the risk that the wave damping capacity is less than required damping for safety. A significant risk can be achieved by either a large probability and small consequence or by a small probability and large consequence. In the following section, the consequences of the scenarios are quantified to wave overtopping, required crest level and the required vegetation width.

5.5. Consequences of the exogenous threats

In this section, the effect of the threats on the wave overtopping and required crest height are calculated for the modelled dike at the Heesseltsche Uiterwaarden. The same method as for the sensitivity analysis is used, see chapter 4 for more details. Calculations to the effects of the scenarios are made with the energy balance formulas. Wave damping vegetation cannot fail completely, like other dike failure mechanisms. It is only possible for vegetation to become less effective, resulting in a lower dampening and a higher overtopping discharge. As a result of this reduced dampening, the dike system can fail due to the exceedance of the critical overtopping.
To determine the effect of the threats on wave overtopping and crest level, the vegetation parameters are modified and used in the model. For all scenarios, the consequenses on the vegetation parameters are estimated based on literature and interviews as described in the previous section.

Exogenous threat	Consequence vegetation parameters
Diseases	10% reduction in density N
Insects	5% reduction in density N
Beavers	3% reduction in density N
Flooding	25% reduction in density N
Storm	5% reduction in density N, 0.1 m reduction of vegetation height h_v
Ice	5% reduction in density N
Drought*	20% reduction in density N
Fire	30% reduction in density N

Table 5.3: Overview of the exogenous threats with their consequences on the vegetation parameters
*This scenarario only applies for 1-2 year old willows for a drought of at least 3 weeks

5.5.1. Computational results exogenous threats

Starting point of the calculations and parameter values is the base case for the case location as mentioned in chapter 4. In the new wave calculations, the consequences on the vegetation parameters are included. It is assumed, that the effects of the threats are equally spread over the osier plantation (for this one-dimensional model thus equally spread over one line from the river to the dike), because the energy balance only accepts a single value for each parameter and unlike SWASH is not spatially embedded. For example for diseases, the willow parameters are averaged for: 90% base case values and 10% nothing a.k.a. zero density.
In table 5.4, the effect of the threats is showed on the wave overtopping discharge, required crest level elevation and willow vegetation width to meet the critical discharge of 5 l/s/m.

Exogenous threat	Probability of occurrence	Overtopping discharge (l/s/m)	Crest elevation (cm)	Required buffer zone (m)
Diseases	once a year	6.8	1.0	7
Insects	1/3 year	5.8	0.8	5
Beavers	once a year	5.5	0.5	2
Flooding	1/20 year	10.7	6.7	21
Storm	1/9 year	9.3	5.6	16
Ice	1/6 year	5.8	0.8	5
Drought	1/25 year	9.2	5.6	16
Fire	1/50 year	12.4	8.2	27

Table 5.4: Effect of the exogenous threats on the wave overtopping discharge, required crest elevation in centimeter or required increase of the vegetation width in meters (buffer zone) to kept the wave overtopping at a maximum of 5 l/s/m.

For the scenarios flood, storm and drought the crest level should be elevated by approximately 6 cm, which is a significant increase in elevation for river dikes. Alternatively the vegetation width can be increased to meet the requirements, this results in values of 16 - 21 meters.
As mentioned earlier, the risk of all scenarios depends on the probability of occurence. The relevance of the threats is determined by combining these two parameters, see figure 5.5.

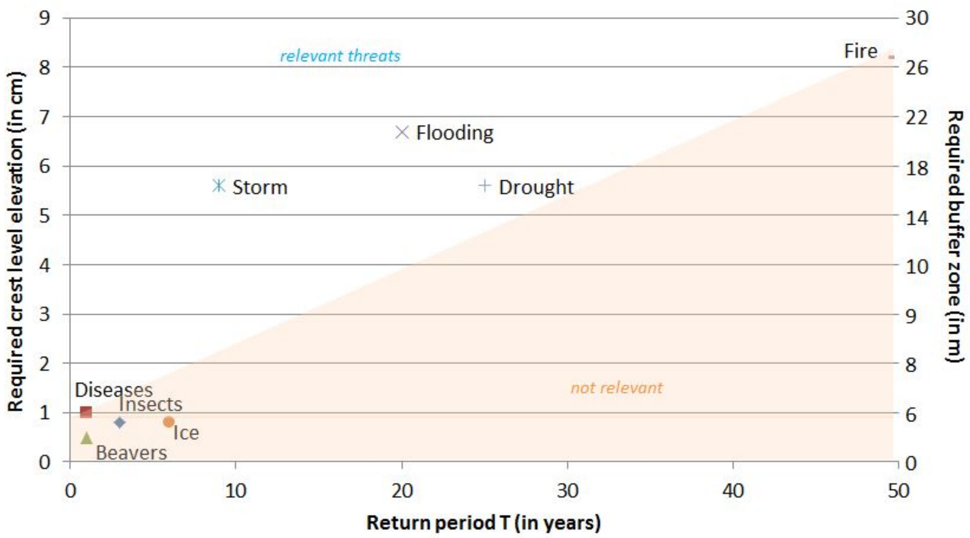


Figure 5.5: The exogenous threats with their return period and the consequence on the required crest level elevation in compare to the crest level in the base case, wherefore the relevant threats are located in the white area above the orange triangle.

The three exogenous threats with the largest consequences are fire, drought, storm and flooding. These threats can damage a large part of the plot with willows given certain conditions. The damage of drought depends on the used type of willow on the foreshore. The Salix Triandra is really sensitive, but the Salix Alba could withstand this drought. Second, this threat will only affect young willows. So it is mainly important when the osier plantation is completely planted for wave damping. Drought is also important when just individual willows or small parts of the plantation should be renewed due to other scenarios like fire. Willows around will draw too much water.
The consequences of the threats storm and drought are equal to eachother. However, the probability of occurence of a storm is higher than a drought. The risk of a storm is therefore 2.5 times more than for a drought.
Fire causes large consequences, but the threat has a low probability. In comparison with the risk of a flooding in the growing period, the risk is still twice less.
The relevance of the exogenous threats depends on the risk [1] and on the required crest level elevation, the consequence. A required crest level elevation less than approximately 3 cm is irrelevant in a dike strenghtening program. Therefore, the threats: diseases, insects and beavers are despite of their high risk undervalued and designated as irrelevant.
To conclude, the three exogenous threats storm, floodings and drought are most relevant, followed by the threats diseases, beavers and other animals, insects, fire and ice.

The effect of the exogenous threats can be reduced by control or temporary measures. Most important is prevention of large impacts by scenarios by performing regular inspections of the wave damping willows. Consequences can be significantly reduced if the management is attentive. The

[1] Probability of occurence, which is 1/return period, multiplied with the consequences a.k.a. the required crest level elevation

wave damping willows should always reduce the waves enough to meet the safety requirements. This is why regular checks and a good management and maintenance plan are vital for safety. However, visual inspection does not guarantee 100 percent certainty about the wave damping conditions of the willows.
Second important measure is replantation of willows. Replantation is required if willows are about to die, or whenever the total achieved wave damping does not meet the requirements. Willows at the riverside should be replaced first, because they contribute most of the wave height reduction within the osier plantation. It is preferable to plant new willows in the winter season, from November to the beginning of March. Other control measures focused on the specific exogenous threats can be read in the appendix chapter 8.

Temporary measures that can be considered are measures which increases the crest level of the dike causing a decrease of the wave overtopping discharge. Emergency temporary measures like sand bags, Dutchdam or the Block-IT (van Damme et al., 2016) can resist a water level of approximately one meter. This is enough to withstand the calculated scenario effects in respect to the required increase of elevation on the crest. Fast wave breaking measures are not possible at this location, because of the large water depth on the floodplain.

5.6. Discussion

The average effect of the exogenous threats on the vegetation parameters has been determined based on literature and interviews with willow experts. However, it remains an estimation, thus the actual risk and consequences of a threat could be less or more. It is recommended to do specific research to the effects of the various threats on the vegetation parameters (of willows).
The assumed effects of the threats on the vegetation parameters and so on the required crest level and vegetation width are considerable, thus should be taken into account when willows will be applied as wave damping vegetation. In chapter 6, all uncertainties and the calculated effect of these, are used to design a wave damping osier plantation.

Another assumption which has effect on the crest level and width is the assumed equal spread of the vegetation parameters over the total osier plantation. For storm, fire, insects and diseases this might not be the case. The damaged willows can be located within a small area in the osier plantation causing a weak spot. At this location, the wave damping can be highly decreased, whilst the other part of the plot acts normally. This assumption results in an underestimation of the consequences.

Final assumption is that the affects of the threats are not be reduced before the following high water season. Probably, affected, diseased or (almost) dead willows can already be replaced by new young willows if this is observed during a visual inspection. These small young willows gives already more wave damping than for the assumed willows without any damping. Therefore, the calculations are conservative, probably over-estimated.

6

Design and maintenance principles for willow vegetation

The design and maintenance principles for wave damping willow vegetation depends on the uncertainties of the vegetation on the wave damping. These variations in the wave damping should be included in the design, because the required wave damping should be ensured during the total lifetime of the reinforcement. To maintain the osier plantation it is the best as the willows are pruned once every two year in strokes. The wave damping of the pruned willows will be negligible for a large water depth, which is mainly the cause for design criteria in the river area. Therefore, the width of the vegetation plot should be doubled if crest elevation is no option, to produce enough wave damping. The vegetation plot should be assessed on the vegetation width and the height of the not-pruned willows during regular inspections in March and October.

6.1. Introduction

Waterboard Rivierenland want to use (new planted) vegetation on the floodplain to reduce incoming waves, causing a lower required crest level. At the case location, the required crest level elevation of 0.32 meter needs to be avoid. The vegetation will act as a part of the flood defence, so the effectiveness of vegetation needs to be retained and assessed. In a dike assessment, design conditions are calculated and used to check if the dike meets the safety requirements. Design conditions are usually similar to extreme storm conditions with a certain probability of occurrence, which depends on the dike section. The vegetation must have a certain wave damping capacity during this design storm with high water and waves. The high water season for the river Waal starts in December and ends in May, which can be linked to the discharge hydrograph in figure 6.1.

In chapters 4 and 5, the sensitivity of vegetational wave damping capacity is determined for possible variations in model-, boundary- and vegetation parameters. It was concluded, that the obtained wave damping mostly relies on the vegetation parameters. Variations in these parameters can occur due to:

- exogenous threats, as mentioned in chapter 5;
- development, growth of vegetation over the years;
- maintenance, by the waterboard or an external party.

It is important to know which vegetation parameters have a large impact on the wave damping

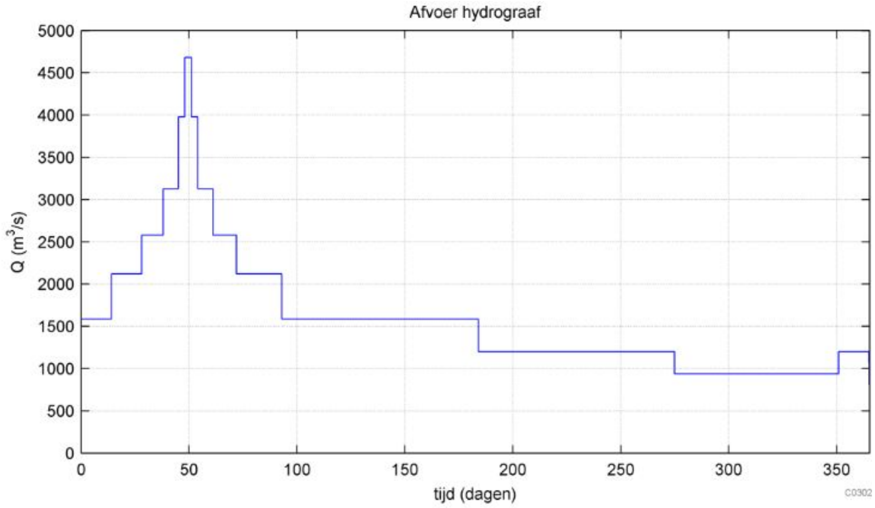


Figure 6.1: Hydrograph of the discharge in m^3/s in the Waal during the year (in days) (Le, 2010)

capacity in order to design a reliable wave damping vegetation plot. These parameters have to be managed and controlled. Another suggestion to ensure the safety requirement is to plant additional willows, to create a buffer for potential reduction effects on damping parameters, as mentioned in the above nummeration.
In the following sections, the previous chapters are summarized and used to make recommendations for a wave damping vegetation plot. First, the effects of the relevant exogenous threats of chapter 5 are described. These effects depend on the varied vegetation parameters. The natural uncertainty of the vegetation parameters and the drag coefficient are described in section 6.3.
The values of the vegetation parameters depend mainly on the willow development; natural grown and development by pruning. Knowledge about this is required for a future design, see sections 6.4 and 6.5.

6.2. Relevant exogenous threats

Most relevant exogenous threats for reduction in wave damping parameters are storms, floods and droughts, see figure 5.5. For each of these threats, the important elements are summerized in a paragraph.
During storms the damage due to heavy winds have a direct effect on the wave damping, especially if this storm occurs prior to high water. The outer twigs and branches of the willows will break, which cause a reduction of the vegetation density and vegetation height. Mainly for willows at the riverside and wind side of the osier plantation. It is impossible to immediately restore the vegetation density and height an corresponding wave damping capacity. As a result, temporary measures will have to be taken, unless this uncertainty has already been accounted for in the vegetation plot width (implemented in the earlier mentioned buffer zone).
Long-lasting floods during the growing period have a big effect on willows. In literature, a long-lasting flood is defined as a flooding of more than ten days, but willow experts claim up to one month for the Salix Triandra. Damage of the willows due to a long-lasting flooding of the plantation is visible at the leaves within a month. However, willows are strong swamp trees, able to recover even after such a flooding. In the sensitivity analysis, a conservative scenario [1] is taken into account. The damaged

[1] 25% of the willows is damaged and should be renewed after 10 days of flooding in the growing season

willows will have a lower strength in the following storm season but will still reduce the waves more than in a scenario without the wave damping capacity of these willows (turned off). This conservative scenario was used to assume the effect of the scenarios. If the flooding occurs early in the growing period and inspections conclude that the damage is substantial, new willows can be planted and grow for five months till the start of the high water season. The effect of the scenario on the wave overtopping will be smaller than estimated.
Drought is a threat for willows if the drought, a low (ground) water level, remains for three weeks. The damage of drought depends on the age and on the used type of willow on the foreshore. The Salix Triandra is really sensitive, but the Salix Alba could withstand drought due to the deep roots. Drought will only affect young willows to two years. So it is mainly important when the osier plantation is completely planted for wave damping. The water level in the Waal should be monitored to avoid heavy damage. Watering is the only control measure to avoid that 35% of the Salix Alba died in the osier plantation. It is assumed that the osier plantation is just half the Triandra-type. Therefore, the effect on the required crest level or vegetation width is underestimated when a larger part is planted with the Salix Triandra.
Fire will reduce the vegetation density like storms, but only in the affected area. The consequences on the wave damping largely depend on the location and size of this affected area. The risk of this scenario is low, mostly due to the low probability of occurrence. However, the consequences can be large so it has to be taken into account.
Diseases weaken the vegetation from the inside and can affect large groups of trees within a plot. The effects of diseases can be reduced by performing regular checks of the osier plantation and by applying quick control measures whenever a disease affects the plantation. In most cases the affected willows should be cut. If a disease is noticed early, the affected willows can be replaced between January and April and can grow seven to nine months before the next high water season starts. In that time, the willow will have already reached a height of 2.5 - 3 meters, enough to function as wave damping vegetation.

Summarized, due to the scenarios of diseases, insects, drought, flooding and fire, willows get damaged. The damage causes weakening of the willow and an increase of their failure probability (for example of stem breakage). Damaged willows can fail during design conditions, so there wave damping contribution is not taken into account in the effect calculations. If it is too late in the year (summer or autumn), the willow cannot be replaced before the high water season, but just after.

6.3. Vegetation parameters to manage

Chapter 4 concludes that the obtained wave damping mostly depends on the water depth $d_{fs} = h - z_{fs}$ at the floodplain in combination with the vegetation height h_v. Height of the vegetation is highly manageable by maintenance. For example, willows should be cut preferably just after the high water season so that branches can still grow a few meters tall before the next high water season starts. The vegetation density N/m^2 is the third important vegetation parameter, which also highly depends on the maintenance strategy. The vegetation density is affected by all exogenous threats. Using a good pruning strategy, the number of branches per stem can be quickly increased. This is very useful for newly planted willow plots and individual replaced willows.

Another important parameter is the drag coefficient, which is a model parameter. This parameter has a large range of possible values going from 0.2 to 2, thus highly uncertain. The variation in value mainly depends on flow characteristics (laminar, turbulent, flow speed) and some vegetation characteristics (stiff or flexible) , see chapter 4. These characteristics will be different at each location where wave damping vegetation is applied. However, the drag coefficient has a certain value and depends only slightly on the vegetation branch diameter b_v. This diameter depends on the age of (the branches of) the willow. Older, larger diameter, branches will increase the wave damping and the drag whereas younger branches will have a lower damping and drag. In order to prevent diseases from affecting the plot it is better to cut the branches every two year. As a result, the variation in diameter over time is small, and the variation in drag will be even smaller and more predictable. To conclude, the drag coefficient is a value which depends on many characteristics and circumstances and cannot be influenced by a management plan. It is therefore recommended to do more research into the resistance coefficient of willows for various circumstances, such as during storm, a higher density of the osier plantation, after cutting the branches and for different ages of willows. Design for a full scale test is described in the recommendations, chapter 7.

6.4. Willow development

6.4.1. Natural development

As mentioned in chapter 5, an osier plantation is created by inserting willow branches in the ground. This should be preferably done between January and April, when the ground water level is high. It is also possible to plant willows in other months, but only if the groundwater level is kept artificially high, which takes a lot of energy and is not recommended.

In general, willows grow during the summer period (July and August) at an average of 2 cm/day. Totalling up to 2.5 meters height in the first and second year. The willow grows in one year from a branch/stem of 1 meter into a tree of 3 - 3.5 meters, and in the second year into a tree of 5 - 5.5 meters. Within the third year the willow grows up to a height of 6 - 7 meters, but more important, there is the thickening of the stoves and branches (Venema et al., 2014). This thickening of branches and stems also happens in the following years. As a result, the space between the stems and branches becomes smaller. If these spaces become too small, branches get too little sunlight and will die (Interview Den Hartog). Due to the high density the drag will reduce, causing a lower wave damping factor (Liu and Zeng, 2016). Cutting of willows is probably required in order to preserve the required wave damping capacity.

The Salix Triandra tends to tipple over quickly at the beginning. Therefore it starts to grow in width instead of height. The natural growth in width in the first and second year is more than 1.5 times the height. The branches are very flexible. Branches which touch the ground germinate immediately, causes a dense willow osier plantation shaped like a mangrove. This happens mainly without pruning. If the Triandra is being pruned, an osier plantation is formed but with a three times higher branch-density than the Salix Alba of Salix Viminalis types would have.

6.4.2. Development by pruning

Willow development strongly depends on the used prune policy. The height and number of the branches per stem are the most important vegetation factors for the wave damping capacity of the willows. In general, cutting of the willow should be done after the leafs fall and when the sap flow has stopped, preferably during the winter period, no later than March or April. If branches are removed during the growing season, the oxygen production in the leaves will disappear, and the stem of the willow will die off.

The Salix Triandra should be pruned mid-summer. The willow reacts with a double amount of branches after each pruning season until the maximum density is achieved. The loss of height is compensated with long new branches, appearing in an extremely short time. During the growing season after pruning, the branches of the Triandra can grow with three meters. A disadvantage of its pruning time is the short growth period between the pruning and high water (Interview willow expert Den Hartog). The wave damping of only the stem during the design water depth is negligible.

If a willow is used for wave damping, it is recommended to cut the stem as close to the ground as possible, because the branches grow up from the stem will result in the required density. Branches take care of the largest part of wave damping, as mentioned in chapters 3.5 and 4. Another advantage of this low cutting is that the willows probably can be pruned by machines. This is applied for the wave damping willows at Fort Steurgat. The stems of the willows are planted close to eachother in straight lines and strokes. It is plausible that the waterboard prefers a more natural [2] look of the osier plantation at the Heesseltsche Uiterwaarden. It should be checked if the effects of the parameter standard deviations on the required vegetation width and crest level are the same by the application of more natural willows with probably other vegetation parameters.

Figure 6.2: Pruned willows in the Avelingen along the river Merwede near Hardinxveld (photo by Wim van der Pijl)

Following standards, willows are being pruned once every 2-4 years. In order to reduce the probability of diseases, it is better to prune more frequently, once every 2 years. A higher frequency of cutting, for example twice a year, stimulates the growth of branches and will increase the vegetation density, but can weaken the willow.

For wave damping willows pruning could start in the second year, to reach the required density faster. During the first year, the willows are still too weak because of the formation of roots. In the table below, the general development of an osier plantation is shown for consecutive mowing rounds ((Venema et al., 2014) and interview).

Mowing round	Process	Number of branches/stem N	Branch diameter b_v (m)
0	Root system formation	0 - 12	0.011
1	Increase of branches	10 - 15	0.013
2	Increase of branches	15 - 25	0.015
3	Increase of branches	25 - 30	0.017
4	Increase in diameter	> 30	0.019
17	Maximal lifespan willows	> 30	0.034

Table 6.1: Overview of the development of the osier plantation in density and branch diameter for the lowest estimation (see figure 4.5), given a pruning frequency of once every 2 years (Venema et al., 2014)

After 2-3 years the willows are most likely strong and high enough to provide some wave damping (Interview willow expert Den Hartog), but as shown in the table the willows will have the required

[2]A 'classic' willow which is always pruned at a height of approximately 1 meter above groundlevel, and has a thick stem. In accordance with the preferences of the waterboard and external parties

density of 258 branches per square meter (base case), so more than 30 branches per stem with 4 stems on a square meter after mowing round 3 - 4. Therefore the required wave damping is reached after 6 - 8 years (Venema et al., 2014). An option to get a full crown in a shorter amount of time is to "thin" the willow. In this process, one third of the twigs should be cut off at about 70 centimetres of the stem. These twigs will then grow faster (VTWonen).

Willows can be pruned maximal 17 times, depending on the density of the stems in the osier plantation and the pruning frequency. The diameter of the stems and branches increases, causes a too small area in between. These old willows should be removed in phases and replaced by young willows.

6.5. Design and maintenance plan

Main goal of the design and maintenance plan is to create an osier plantation, which always meets the required wave damping to fulfill the safety standards. The wave damping vegetation on the floodplain has to be assessed and maintained. The next steps will lead to a recommendation for a well designed plot with wave damping vegetation. In this case, focused on willows.

6.5.1. Maintenance plan

A maintenance and management plan is made to keep the osier plantation intact, free of diseases and other damages. This maintenance is required throughout the the whole year.

To minimize the damage of willows due to the various possible scenarios in the osier plantation a number of recommendations are made:

- the use of various types of willows, preferably Salix Alba, Triandra and Viminalis;
- the possibility of watering new planted willows and during heavy droughts;
- protection against animals during winter ;
- regular visual inspection in October and April and additional inspection during extreme circumstances;
- direct treating of wounds.

The effects of diseases are migitated as the diseases might not be transferred between different willow types. Therefore, it is better to apply various types of willows, so there will be always some willows to preserve the wave damping capacity.

Drought can be countered if there is a possibility to provide watering for the young willows at the start of the osier plantation, or for individually replaced willows. This means any effects of this scenario can easily be overcome with this investment.

According to the interview with willow expert Den Hartog (2018) it is important to pay attention to larger animals, like deers, hares and rabbits. In strong winters, the bark of willows could be the only source of food for all animals. Without a bark even willows will die. To prevent this, a fence can be placed around the plantation preventing larger animals access to the plot. Another option is to plant more willows than actually required, therefore a certain percentage of the willows can be damaged and eventually die due to these animals whilst preserving the wave damping feature of the plot.

Inspection will avoid a lot of damage if direct action is taken for example by control or temporary measures. The immediate treating of wounds due to diseases, storms and animals can prevent further damage to the willow and might allow the tree to naturally recover and maintain its wave damping function.

Pruning should be done once every two years. To increase the branches density faster, it could be better to start with a pruning frequency of once a year until the required density has been reached. Other option to increase the density faster is to 'thin' the branches (see previous section). Reduction of the effects of pruning on the wave damping capacity is achieved by:

- Pruning in April, at the second last month of the high water season;

- Phased pruning of the total plot;
- High pruning frequency to prevent and decrease damage by diseases;

By pruning in April, the willows have still 5-6 months to grow before the new high water season starts in October. During the growth season of four months, the branches grow 2cm per day, which means approximately three meters before October (Venema et al., 2014).

In order to maintain some parts with thick branches spread over the plot, the plot is pruned in phases. The resulting wave damping should be equally spread over the dike length, therefore strips are created in longitudinal direction, parallel to the river dike. The plot is divided in an even number of strips, whose width can be chosen by the plot manager. Certain strips are pruned in the even years, other strips in the odd years. Advantage of a strip is the ease of pruning. For machinable pruning, paths between the strips are required. Another option (to create a more natural look) is to prune by hand or to prune in alternating squares, such as a chessboard pattern. In order to stimulate the density, the willows are pruned close to the ground, just above the 'ogen' where the willow can make fast new branches stimulating an increase of density (Venema et al., 2014).

The wave damping is reduced from 0.40 m to 0.29 m (wave overtopping discharge of 20.0 l/s/m) if 30 meters of the plot with a width of 60 meters is pruned [3] The wave damping obtained by the pruned willows at the case location is negligible (mostly caused by the low vegetation height)when the minimum vegetation parameters are used in the calculation (see table 4.4). To achieve the same reduction as for the basecase, the plot width with half pruned willows and half two year old willows, should be increased to 120 meters instead of 60 meters. Thus a buffer zone of sixty meters.

During the initial phase, the new osier plantation will not meet the required wave damping. It will take about three years before the willows can act as a reliable wave damping measure and probably six years if the required density is strict and high. However, according to agreements of the government, the flood defense should agree the safety requirements within a certain period. So, the start of the realisation of the osier plantation depends on these agreements.

Regular inspections of the osier plantation should be done in March and September, in and before the high water season. In March, the willows do not have leaves, so damage probably caused by storms in the winter is clearly visible. Willows with damage need to be marked and reinspected in the beginning of the growth season. At that time, the severity of the damage can be assessed. During the inspections, the vegetation parameters should be checked. If the vegetation parameters do not meet the required values, temporal measures should be taken, see chapter 8. Additional inspections after or during extreme weather, like floods, ice, drought or storms are even more important.

6.5.2. Design and assessment wave damping vegetation

Dikes are assessed on the water-retaining function and can be rejected if the flood probability is larger than the safety standard of, in this case, once every 10000 years. Therefore the failure probability of various failure mechanisms are determined. At the case location, the dike cannot be heightened due to the crossing power lines. Therefore the main failure mechanism is wave overtopping. The overtopping discharge is for the new standards larger than the critical discharge, which causes damage and finally failure of the river dike.

The assessment and the design of the dike are obtained by probabilistic calculations. Probabilistic design needs a definition of failure, which is expressed in a limit state function:

$$z = R - S$$

where R is the resistance term and S the stress term. Failure is defined as a negative z-value. In probabilistic sense it is a failure in this case, if flooding occurs. In the probabilistic fault tree of a river dike,

[3] Second half of the plot had the base case vegetation (> 2 year) parameter values and the first half closest to the river, the minimum (1 year) values as noticed in table 4.4

wave overtopping is a non-structural failure mechanism which also leads to instability of the landward slope causing failure (PONZIANI and BACHMANN, 2016)

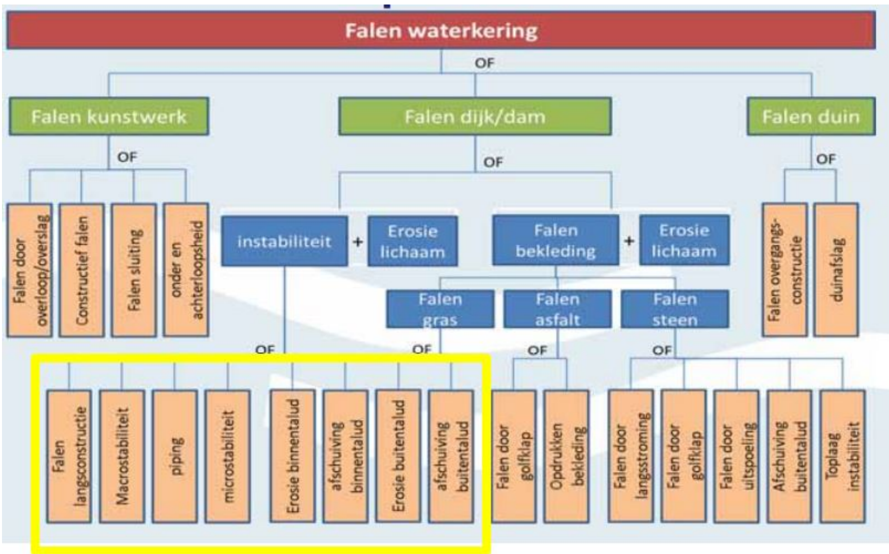


Figure 6.3: Fault tree including all assessment paths according to WBI2017

Vegetation on the floodplain reduces the wave height, which has an impact on the wave overtopping discharge. In figure 6.4 the relationship between the load, incoming waves and a certain high water level, and the failure mechanisms are shown (Naulin et al., 2011).

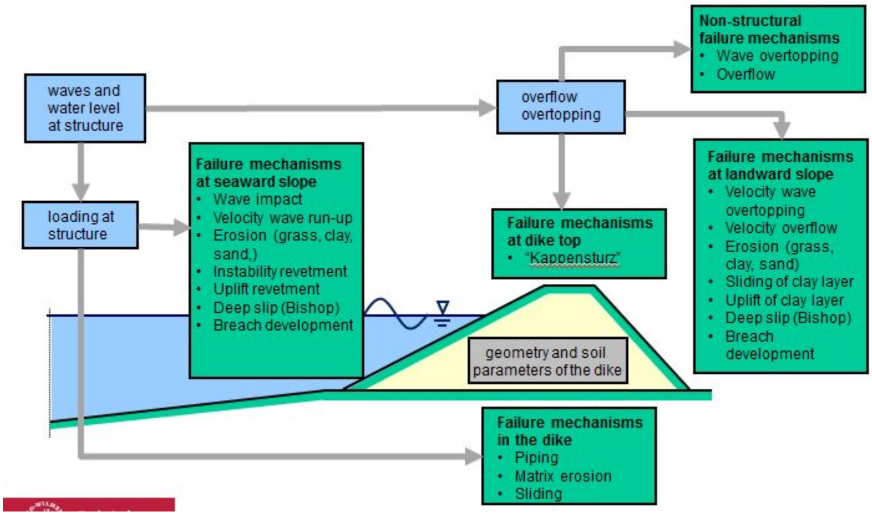


Figure 6.4: Failure mechanisms of a dike conducted by the loading; wave height and water level (Naulin et al.,2011)

Vegetation fail mostly not completely. Only the wave damping capacity is reduced, for example due to the effects of a storm. Therefore limit state functions cannot be used to determine if vegetation fails or not. Previously mentioned threats and maintenance strategies cause a reduction of the vege-

tation parameters, and thus a reduction of the wave damping capacity. The wave damping vegetation ’fails’ when waves are not reduced enough and the resulting wave overtopping will be higher than the critical value causing failure of the flood defence. This lack of damping is the difference between the actual incoming wave height after passing the vegetation, and the design wave height (in combination with the water level of the design point) which is linked to the crest level of the dike.
The crest level of a dike is designed on a certain wave height, therefore the vegetation should always reduce the incoming waves to this wave height or lower. The willows in the plot should meet the assumed averaged vegetation parameters to obtain this reduction.
For the design, certain willows are chosen with their own biological characteristics. These characteristics are used in the wave model for the design. The wave model SWAN is a proper program to determine the obtained wave damping by the vegetation for wind-generated surface gravity waves. Further, the effects of the variations in vegetation parameters on the wave overtopping are determined just as in the wave energy balance. Advantage of SWAN, is that the floodplain can be modelled in 2D wherefore also currents can be included, which will affect the wave damping.

Based on the outcomes of the uncertainties in the wave model, a design is made for a plot with the assumed willow vegetation characteristics. The uncertainty is included in the crest level or width of the vegetatation plot. This is the design.
In a later stage, the willow vegetation should be assessed on safety. The vegetation characteristics of the willows should meet the used parameters as in the design. First, the crest level or width is assessed, in which the uncertainties are collected. Second, the height of the willows is checked if it meets the assumed characteristics, because this is the most important parameter. Third, the density of the willow branches is measured. During regular inspections, these vegetation parameters can be checked. Therefore, the wave damping vegetation can always be assessed. If the parameters do not meet the required values, additional temporary measures should be taken.

6.5.3. Design reliable wave damping osier plantation

The design of the osier plantation depends on the variations of the vegetation parameters due to the development, pruning and the exogenous threats. Starting point is a reliable plot with wave damping vegetation. The definition of *reliable* is in this case; a plot with vegetation which always meets the required wave damping, whereby the dike will approved on the safety standards.
To take the uncertainties due to the exogenous threats and maintenance into account, the width of the plot will increased with a certain margin, a buffer zone. This buffer zone was already determined for the scenarios in table 5.4 and in section 6.5.1 for pruning.
The threats which requires the largest buffer zone were fire, floods, drought and storm. For these, the maximal buffer zone was around 30 meters, so a total width of 90 meter. The effects of the scenario drought and fire can be minimalized or canceled by watering, so flood and storm are the scenarios with the highest consequences. For pruning, the width of the plot should be increased to 120 meters. So a buffer zone of 60 meters.
The largest required buffer zone is implemented in the design. In this case the required buffer zone for pruning, which means a width design of the plot of 120 meter.
This vegetation width of 120 meter applies only when the not-pruned willows (so half of the plot) have a density of 258 stems/m^2, a diameter of 0.013 m and a height of 5 m in November (before the high water season). These parameters should be maintained and checked during inspections.

To summerize the recommendations for a design of a vegetation plot for wave damping:
• Use various types of willows, to reduce diseases
• Phased pruning of the plot by making strokes
• Pruning frequency of once every two years
• Mowing at the ground has as advantages that it can be done machinal and there is there is already a

high density of branches close to the ground

- Regular inspection in (March) and before (September) the high water season, vegetation parameter check and treating of wounds
- Extra inspections during and after extreme circumstances, like high water, drought or storms
- In winter protection against animals, if they damage the willows
- Possibility of watering for new planted willows
- Calculate the effects of exogenous threats and the pruning strategy on the required vegetation width to retain the required wave damping for the assumed vegetation parameters, and use this buffer zone in the design

7

Conclusions & Recommendations

7.1. Conclusions

This thesis provides insight in the wave damping capacity of willows and the uncertainties of this natural-based flood defence, which consists of a river dike accompanied with a vegetated floodplain. The wave damping capacity of willow branches has been determined using field measurements in the river Noord, by Deltares. The set-up with willow branches cause a reduction of the wave height due to the dissipation mechanisms bottom friction and wave attenuation by vegetation. For incoming waves with a wave height of 0.15 m, the reduction of the height over the plot was 4.5% per meter width, which was twice the wave reduction of waves with a height of 0.05 m.
The relation between the water depth and wave attenuation completely depends on the shape of the willows. The stiff stem of old willows damp the waves less than the high dense, more flexible, branches above the stem. For a water depth larger than the vegetation height, the wave damping reduce significantly.

A one-dimensional SWASH model based on the measurement set-up was developed to calibrate the drag coefficient of the willows from the field measurements. The drag coefficient is a measure of resistance which is used to determine wave reduction by vegetation. However, due to mistakes in the measurement set-up, the drag coefficient cannot be determined by calibration of the model with the field measurements. In chapter 7.2, a recommendation for a new measurement set-up to determine the drag coefficient of willows is provided.

A wave model based on the energy balance with a dike-floodplain system was developed to determine which parameter uncertainties are most influential in an assessment, and to compute the required crest level or the required width of the wave damping vegetation to fulfill the safety standards. These uncertainties comprise the standard deviations of the dike system parameters (e.g. dike slope and height of foreshore), vegetation parameters (e.g. spatial and natural variations) and model parameters (e.g. the drag coefficient).The model has the characteristics and design conditions for a dike section near Heesselt, but including an osier plantation with a width of sixty meters on the floodplain (the Heesseltsche Uiterwaarden).
It is concluded, that the largest impact on the required crest level is obtained by the variations of the vegetation parameters. The most important parameters are the water depth and vegetation height, as combination. The wave damping reduces quickly when willow branches were completely submerged. Second important vegetation parameter was the density of the branches. However, the drag coefficient C_D had even a larger effect on the required crest level for an extreme chosen variation of 0.2 - 2 (-). This variation is possible, and depends highly on flow (flow speed, turbulence) and vegeta-

tion characteristics (flexibility and density branches). Since the drag coefficient of willows cannot be determined by the field measurements, this remains a large knowledge gap.
Besides the standard deviations (based on natural and spatial variations) also exogenous threats affect the vegetation parameters, and will influence the wave damping capacity and required crest level. The most relevant influential threats with a high risk and significant consequence are storms, floodings and droughts.

The uncertainties in wave damping should be included in the design of the wave damping vegetation plot to provide a reliable plot with willow vegetation which ensure the required wave damping (to meet the safety standards) during the total lifespan of a dike strengthening. The effects can be include in the required crest level or required vegetation width, a buffer zone. The most relevant threats need for the base case a buffer zone of 30 meters or a crest level elevation of 7 cm, to meet the critical overtopping discharge.
Maintenance has also a big impact on the wave damping capacity. Pruning will be done every two years in strips, first year one half, second year the other half.By pruning the density, height, drag coefficient and diameter of the branches will decrease. The wave damping by the pruned willows is negligible. Therefore, the width of the vegetation plot should be doubled, to produce enough wave damping. Another option is to elevate the crest level with 17 cm (valid for the base case).

To conclude, a willow is a good type of vegetation to reduce the wave height on river floodplains. Most important characteristic is the resistance of willows against flooding and the appearance of willows in river areas. To design a plot with wave damping vegetation, the effects of all uncertainties (at a specific case location) like exogenous threats, standard deviations in parameters and a pruning plan have to be assessed. A buffer zone should be implemented in the design of the wave damping willow vegetation to ensure the required wave damping. The manager must assess the total vegetation width, and height and density of the not-pruned willows during the regular inspections.

7.2. Recommendations

Based on this research, recommendations will be given for research improvements, further research and for applying wave damping vegetation by waterboards.

7.2.1. Recommendations for research improvements

Field measurement set-up and a 2D SWASH model

The field measurement set-up was made to determine the actual wave damping through young willows (only branches) and three-year old willows with a stem and branches with leaves. The incoming (ship) waves were low and propagate probably under an angle through the small plot. Due to the angle, the travel distance between the sensors is smaller, wherefore the calculated wave damping is underestimated. This underestimation is not included in the wave damping calculations, also to determine the drag coefficient. To improve the set-up, incoming waves should be refracted and the size of the plot should be increased to reduce errors.
Pressure transducers should be better devided in the plot with willows, with multiple lines. Therefore, a 2D SWASH model can be made to determine the drag coefficient. The water level should also be measured before waves enters the plot with willows, to reduce errors in the model.
Second, on the bottom there is a sudden increase due to crates and bigbags. A vertical wall provides reflection and steepening of incoming waves, so should be avoid. The program SWASH can also not model vertical walls, only steep slopes. Therefore the set-up should be adjusted.
The old willows were located too high above the mean water level, so waves were not damped by the branches but by the stems. This is not the case, when willows are used on floodplains for wave damping. Willows as wave damping vegetation should reduce the waves with branches. To improve the set-up the bottom with the old willows should be lowered.

SWAN instead of the wave energy balance model

The effect of the standard deviations of the wave model parameters on the required crest level is determined in an one-dimensional wave energy balance model, made in Matlab [Vuik, 2017]. Disadvantage of the energy balance model in comparison with SWASH or SWAN, is that the vegetation parameters cannot be varied in height and space. The parameters are averaged for the plot with vegetation, while the waves for example only flows through the small diameter branches, with a lower drag coefficient.
Second disadvantage of this model is the wave period, which remains the same. Actually, the vegetation will makes the period shorter, which affect the wave overtopping in a positive way. Further, the Iribarren number can change the used wave overtopping parameter C. For a shorter period (1.8 sec instead of incoming wave period of 2.59 sec), the wave becomes steeper, wherefore the C_2 switcht to C_1. The wave will break on the slope and the wave overtopping discharge will decrease. In SWASH or SWAN, this should be modelled.
Boundary conditions are used from the design point in Hydra-NL which is actually located approximately 50 meters before the toe of the dike. In the model these values are used as input at a distance of 150 meters from the toe, before the vegetation plot. Wind grow is set off in the model. Therefore, the windgrowth is actually forgotten the last 50 meters from the design point to the toe of the dike, causing an underestimation of the wave overtopping discharge.
All disadvantages of the energy balance model as mentioned above, can be solved by using the program SWAN. The problem should be 2D-modelled wherefore spatial differences can be solved. Vegetation in SWAN can also be modelled in various height sections and the wave period will differs due to the wave damping vegetation.

Quantification of the effects by exogenous threats

The effect of the exogenous threats on the vegetation parameters is assumed, based on literature and interviews with willow experts. These assumptions should have to test more accurate, and particularly

for various willow types.
Because of the use of the one-dimensional energy balance model, the effect of the threats on the vegetation parameters is averaged over the total vegetation plot (the total line). However, this is not the case for fire or local diseases. The damaged willows can be located at a small area in the osier plantation, which cause a weak spot. The effect of the variation in location of the damaged willows on the wave overtopping, should be investigated by using a 2D or 3D modelling program.

7.2.2. Recommendations for further research

Measurement set-up to determine the drag coefficient of willows

More research should be conducted to the drag coefficient of vegetation. In this case, the drag coefficient of willows as wave damping vegetation on river floodplains.
Recommended, is to do a full-scale test based on the circumstances with high water on floodplains. These circumstances like the characteristics of waves and currents on floodplains, should be monitored or modelled with a 2D or 3D river model and applied in the field test. This full-scale test can for example be done in a wave flume like the Delta Flume. Here, the circumstances can easily be varied and controlled very well.
A vegetation width of at least twenty meters is required with preferably multiple lines of pressure sensors through and before the vegetation plot.
The variations of the vegetation parameters have the most impact on the wave damping. The drag coefficient depends besides hydraulic characteristics also on the vegetation properties. Therefore, the wave damping and so the drag coefficient, should be determined for various willow types and characteristics. Mainly the submergence of a willow has an incredible effect on the wave damping capacity. It is recommended to do tests with various water depths, especially more detailed tests for water depths close to the height of the willows. Recommended is to determine the drag coefficient for various hydraulic circumstances and vegetation parameters with a 1D or 2D wave model by calibrating the model with the field test results.

Effect of the wave damping vegetation on the failure mechanism: wave impact

In this research, only the failure mechanism wave overtopping is taken into account. Another failure mechanism is wave impact on the outer slope. In this case, the river dike is covered with grass. Erosion due to high waves can be an issue in the river areas, especially at some dike sections belong the Waal. Further research to the effect of wave damping willows on this failure mechanism can be useful.

Assessment of wave damping vegetation

The probability of the exogenous threats and the effect on the vegetation parameters should be determined more accurate to include the wave damping vegetation in the dike assessment. The dike is assessed based on hydraulic characteristics with a certain probability of occurence. Inspections will always be needed to assess the vegetation parameters. Vegetation is more variable than for example the dike-body or underground.
The probabilities of scenarios and consequences on the wave damping vegetation are assumed based on experts and literature. Recommended is to do more research to these consequences and probabilities for example by conducting more interviews or doing field research in a present osier plantation during a representative period. Therefore, these variables can be included in the assessment and design through a probabilistic approach.

7.2.3. Recommendations for applying the research

In chapter 6 the outcomes of this research is already be implemented in a design for a wave damping plot with willows. Summary of the recommendations:

- Use of various types of willows, to reduce diseases

• Phased pruning of the plot, in strokes
• Pruning frequency of once per two years
• Regular inspection in (March) and before (September) the high water season, vegetation parameter check and treating of wounds
• Extra inspections during and after extreme circumstances, like high water, drought or storms
• In winter protection against animals, if they damage the willows
• Possibility of watering for new planted willows

The width of the vegetation plot depends on the effect of the exogenous threats and pruning strategy on the wave damping capacity. To avoid a reduction of the required wave damping, these effects should be stored in a buffer zone.
Recommended is to monitor the obtained wave damping during the first few years with pressure transducers in the total osier plantation and to frequent visible inspections focused on the probability and effects of exogenous threats. New data and insights can be retrieved by these monitor measurements and can be used in following designs, assessments and maintenance principles for wave damping vegetation.

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8

Appendices

Location Noordwaard: Fort Steurgat

Addition of vegetation to reduce the wave height at the toe of the dike is already been investigated by Deltares and implemented in the Noordwaard near Fort Steurgat. Fort Steurgat was the southernmost fort of the 19th century New Dutch Waterline. It is located close to the inflow opening of the polder Noordwaard at the edge of the watershed. The Noordwaard was part of a Room for the River project. The Noordwaard is depoldered what involves lowering of the flood defenses on the northeast side (inlet) and southwest side (outlet). The lowering took place over a length of two kilometers (inlet) and three kilometers (outflow opening). If the water in the river Nieuwe Merwede is higher than 2.0 meter + NAP the water can flow through the Noordwaard and will give a reduction in river water level (0.6 meter locally and 0.3 meter at Gorinchem) (Venema et al., 2014). The lowered primary flood defense is called the 'drempel (sill)'.

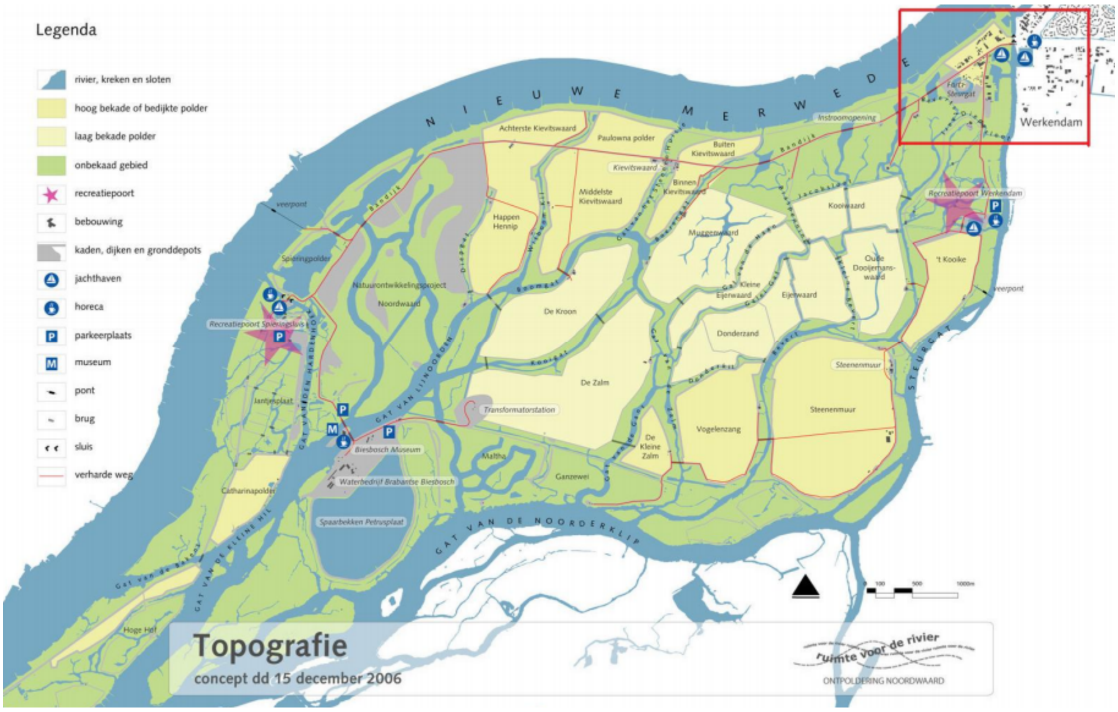


Figure 8.1: Topography of the Noordwaard (Deltares, 2014)

Due to lowering of the dike along the Nieuwe Merwede (to a level of 2.0 meter + NAP) the area around Fort Steurgat is flooded several times a year. From the trenches in the southwest a tidal movement is entering the area every day with a low water level of 0.4 meter + NAP and a mean high water level of 0.7 meter + NAP. This is also the average height of the ground in the catchment along the primary flood defense around the fort. So large parts of the ground in the catchment flooded daily. Measures will be taken to protect the fort against flooding.

To maintain the houses on the fort a dike between the fort and the basin is inevitable. The dike design conditions, requires a dike with a crest height of 5.0 - 5.5 meter + NAP if starting from a standard design. Residents of Fort Steurgat disagreed with these height of the dike, because they lose their view. To meet the needs of the residents a study has been done to promising designs of the flood defense with a lower crown height by use of innovative concepts and techniques. In the case Fort Steurgat is chosen for a hundred meters wide area with willows that will reduce the wave height. These trees meets the pre-made requirements and fulfill other benefits:

- Areas with willows belongs originally in the Noordwaard;
- A wide zone need to be planted, this is appropriate by willows;
- Management and maintenance is by machines, so fast and inexpensive.

Based on literature and experiments it was showed that a wave attenuation of 75% or more of the incoming wave height could be achieved by a hundred meter wide area with willows. As a result (for 80% wave reduction) the dike should be designed with a crest height reduction of 65 centimeters which corresponded with the required and desirable crest height (de Vries and Dekker, 2009).

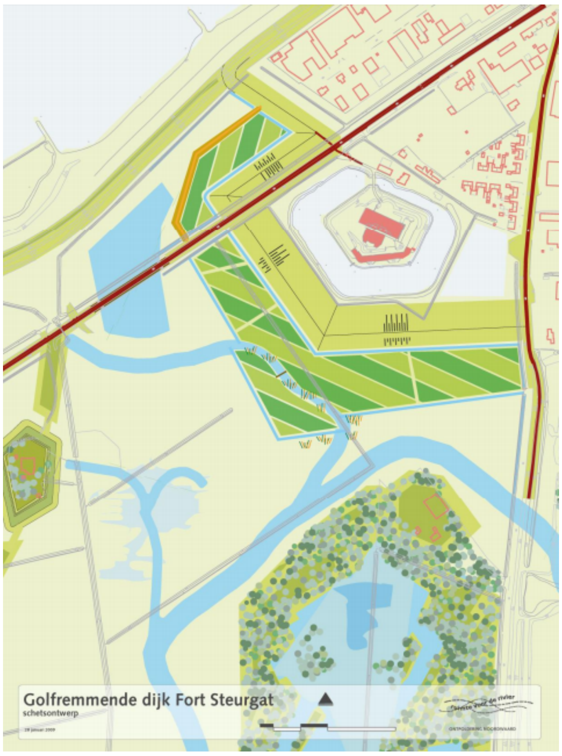


Figure 8.2: Top view of the dike which will reduce the waves at Fort Steurgat (Deltares, 2014)

Dike section Tiel - Waardenburg

Waterboard Rivierenland is currently reinforcing some dike sections along the Waal (on the route Tiel-Waardenburg) because these are rejected in the previous safety assessment. The flood defense is mainly disapproved on height. By limiting the heightening, the costs and required additional space for the heightening will reduced. Waterboard Rivierenland will investigate a number of innovative options to limit the heightening for the dike track Tiel-Waardenburg which is part of dike track 43. The track is shown in figure:

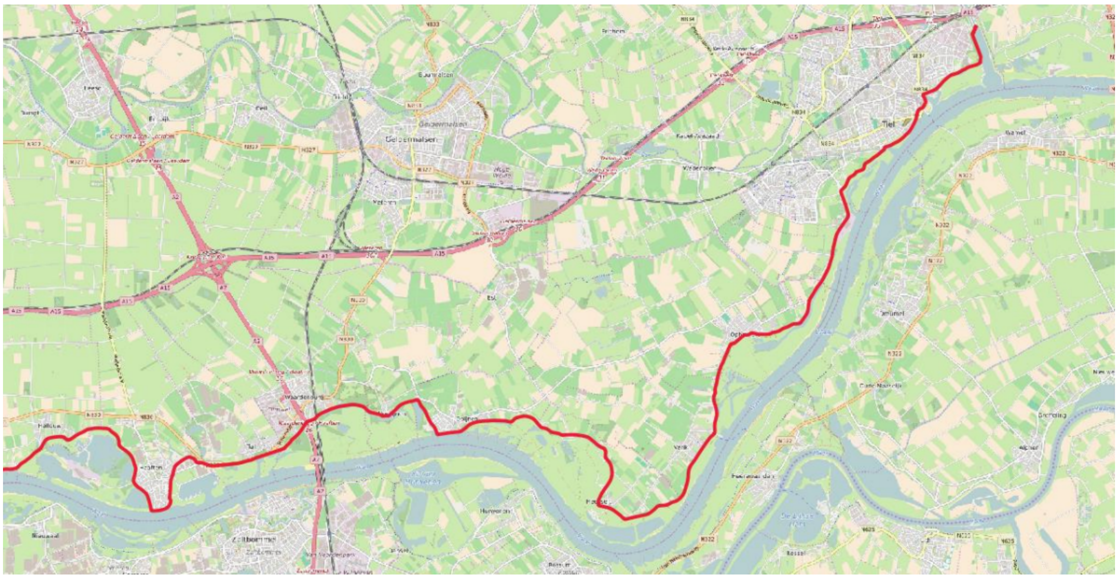


Figure 8.3: Dike section Tiel - Waardenburg along the river Waal (Deltares, 2015)

These height reducing innovations are:

- Temporary flood defenses (e.g. self closing barrier)
- Outer embankment
- Wave reducing vegetation on foreshores
- Permitting more wave overtopping by strengthening of the inner slope
- Inclusion of currents (currents reduce wave heights for example)

One of the innovative measures is the use of vegetation as wave reducing measure (Deltares, 2016b). In the quickscan study of Deltares there is analysed if vegetation is present in the leeward parts of the river and if these locations with vegetation acts with wave heights bigger than 0.5 meters. In the river basin of the Waal a number of locations met these requirements mainly at the dike section from Tiel to Waardenburg for example near Ophemert (figure 2.6).
Deltares has already done two studies to wave reduction by vegetation on this dike section Tiel - Waardenburg. The first study (Deltares, 2015) was only a brief survey to the contribution of wave damping by vegetated foreshores on dike heightening. Determined is the influence of the present vegetation on the wave height reduction on the floodplain Rijswaard. Wave reduction calculations are made in the model SWAN-VEG which was also used in the Fort Steurgat case.

In the second study (Deltares, 2016) the final product was a calculation formula to determine the required crest height with inclusion of vegetation. For this study two SWAN models were created for the section Tiel-Waardenburg. The inclusion of vegetation is integrated in the wave model by a reduction coefficient determined for different combinations of vegetation types and width. The wave reduction coefficients (and a calculation formula to discount the shift in failure probability contribution by reducing the wave height) will finally lead to the required crest height needed for the reinforcement design. Validation of the wave reducing effect of vegetation is not done for this dike section.

Model programs

There are various model programs available to model waves propagating over the foreshore to the river dike. Considered foreshore modules are the new foreshore model DaF, ENDEC module and wave models SWAN and SWASH. Each of these models has his own characteristics and active processes:

- SWAN
  The foreshore model SWAN uses dissipation mechanisms which can only be used for the analysis of wind generated waves. SWAN doesn't reduce only the wave height, but also the average wave period. Vegetation can be put in the model by giving all the parameters of the vegetation factor;

- ENDEC
  The ENDEC model included the processes wave upset and wind upset on the foreshore. This reduces the effect of reduction of the wave height what happens due to the vegetation on the foreshore. This wave damping vegetation is added in the model as bottom friction;

- DaF
  Most simple model. Wave reduction depends only on wave breaking and bottom friction;

- SWASH
  Non-hydrostatic model which can simulate the steep ship waves. SWASH solves the complete shallow water equations and vegetation can be put into the model such as in SWAN.

At the beginning of this study only SWAN and SWASH will be used for wave modelling. A detailed description of these programs are given in the following sections.

Non-hydrostatic wave-flow model SWASH

SWASH is a numerical tool for simulating non-hydrostatic, free-surface, rotational flows and transport phenomena, originally designed for wave transformation on shallow waters. The governing equations are the nonlinear shallow water equations including non-hydrostatic pressure and some transport equations, and provide a general basis for simulating:

- Wave transformation in both surf and swash zones due to nonlinear wave-wave interactions, interaction of waves with currents, interaction of waves with structures, wave damping due to vegetation, and wave breaking as well as run up at the shoreline;
- complex changes to rapidly varied flows typically found in coastal flooding resulting from e.g. dike breaks, tsunamis, and flood waves;
- density driven flows in coastal seas, estuaries, lakes, and rivers, and;
- large-scale ocean circulation, tides and storm surges.

The depth-averaged, non-hydrostatic, free-surface flow can be described by the nonlinear shallow water equations that, in turn, can be derived from the incompressible Navier-Stokes equations that comprise the conservation of mass and momentum. These equations are given by (swash. pdf)

$$\frac{\delta\zeta}{\delta t}+\frac{\delta hu}{\delta x}+\frac{\delta hv}{/}\delta y=0$$

$$\frac{\delta u}{\delta t}+u\frac{\delta u}{\delta x}+v\frac{\delta u}{\delta y}+g\frac{\delta\zeta}{\delta x}+\frac{1}{h}\int_{-d}^{\zeta}\frac{\delta q}{\delta x}dz+c_f\frac{u\sqrt{u^2+v^2}}{h}=\frac{1}{h}(\frac{\delta h\tau_{xx}}{\delta x}+\frac{\delta h\tau_{xy}}{\delta y})$$

$$\frac{\delta v}{\delta t} + u\frac{\delta v}{\delta x} + v\frac{\delta v}{\delta y} + g\frac{\delta \zeta}{\delta y} + \frac{1}{h}\int_{-d}^{\zeta}\frac{\delta q}{\delta y}dz + c_f\frac{v\sqrt{u^2+v^2}}{h} = \frac{1}{h}(\frac{\delta h\tau_{yx}}{\delta x} + \frac{\delta h\tau_{yy}}{\delta y})$$

Where:
t time
x, y directions located at the still water level
z direction pointing upwards
$/zeta(x, y, t)$ surface elevation measured from the still water level
$d(x, y)$ still water depth
$h = \zeta + d$ total water depth
$u(x, y, t)$ depth-averaged flow velocities in x- andy- direction
$v(x, y, t)$ depth-averaged flow velocities in x- andy- direction
$q(x, y, z, t)$ non-hydrostatic pressure
g gravitational acceleration
c_f dimensionless bottom friction coefficient
τ horizontal turbulent stress terms

In the SWASH model the non-hydrostatic mode is activated. The integral of the non-hydrostatic pressure gradient over the water depth can be expressed as follows (Stelling and Zijlema, 2003):

$$\int_{-d}^{\zeta}\frac{\partial q}{\partial x}dz = \frac{1}{2}h\frac{\partial q_b}{\partial x} + \frac{1}{2}q_b\frac{\partial(\zeta - d)}{\partial x}$$

with q_b the non-hydrostatic pressure at the bottom.

In this study the vegetation is the most important part in the model. Within the vegetation canopy, it is assumed that all energy of the mean flow is converted to turbulent energy due to the plant drag. The program SWASH used the Morison equation to determine the energy dissipation, see chapter .... In the SWASH model, vegetation (rigid plants) can be divided over a number of vertical segments and so, the possibility to vary the vegetation vertically is included. Each vertical segment represents some characteristics ofthe plants. These characteristics are:

height	the plant height per vertical segment (in m).
diamtr	the diameter of each plant stand per vertical segment (in m).
nstems	the number of plant stands per square meter for each segment.
drag	the drag coefficient per vertical segment.
INERTIA	indicates that the inertia force will be included.
C_m	virtual or added mass coefficient (i.e. one less than the inertia coefficient).

Wave model SWAN

SWAN is a wave-model which takes the nonlinear wave-wave interactions into account and use furthermore several parameterisations that is specific for shallow water. It is a model for wind-generated surface gravity waves in shallow waters. The wave model is based on the energy spectrum, $E = (\omega, \theta)$, of a wave field, which depends on frequency, ω, and direction, θ. The energy spectrum is described in the following balanced equation (WMO, 1998):

$$\frac{\partial E}{\partial t} + \nabla(c_g E) = S_{in} + S_{nl} + S_{ds}$$

S_{in} is the energy input generated from wind; S_{nl} represents the non-linear wave-wave interaction and represents the relocation of energy from one wave length to another wave length and all depends on the wave frequency and direction. The last term, S_{ds} is the wave energy dissipation and will be adjusted due to the vegetation. This 'new' dissipation term is in the SWAN VEG model, developed in 2009 by Delta res, added to the old formulation (Oude, 2010):

$$S_{ds,veg} = \int_0^\infty \int_0^{2\pi} \frac{8\sqrt{2}}{g\sqrt{\pi}} \rho C_D b_v N (\frac{gk(\omega)}{2\omega(\omega)})^3 \frac{\sinh^3(k(\omega)ah) + 3\sinh(k(\omega)ah)}{3k(\omega)\cosh^3(kh)} H_{rms}^3$$

The SWAN wave model is used to analyse the effect of vegetation on waves at the case locations. In SWAN the energy dissipation formulation of Dalrymple is implemented:

$$\frac{\partial E c_g}{\partial x} = -\frac{1}{2\sqrt{\pi}} \rho C_d b_v N (\frac{kg}{2\sigma})^3 \frac{\sinh^3(kah) + 3\sinh(kah)}{3k\cosh^3(kh)} H_{rms}^3$$

$E = (1/8)\rho g H_{rms}^2$ Wave energy per square meter
C_g Group velocity
ρ Water density
g Gravity
H_{rms} Root-mean-square height
x Distance in direction of wave propagation
a Vegetation height relative to the waterdepth
h Water depth
k Wave number
σ Wave frequency

In this formulation the horizontal and vertical distribution of the vegetation is used to determine the wave reduction. For this purpose the vegetation is described as a collection of strains/branches per surface area, wherein for several heights the diameter, resistance and number of the strains/braches can be varied. The degree of energy dissipation per square meter vegetation determines the calculated wave height.
In the Dalrymple-formula vegetation is described in three parameters: diameter (b_v), number of branches per m^2 (N) and the resistance coefficient C_d. For rigid circular cylinders the C_d coefficient has a value of 1. The three parameters can be multiplied which produce the vegetation factor Vf:

$$Vf = C_d b_v N$$

Vf Vegetation factor
C_d Average drag coefficient
b_v Plant stem diameter perpendicular to incoming wave
N Vegetation density, number of stems/plants per square meter

This vegetation factor can be implemented in de wave model SWAN. In the model a higher vegetation factor results in a bigger wave height reduction. Further, contains this factor a lot of uncertainties. The parameters, diameter and number of branches, can be measured but varies through the years and seasons, so should be averaged. Second, the exact value of the resistance coefficient C_d cannot be easily measured and calculated because there is no good scientific theory. In the field the vegetation parameters b_v and N are often measured in two layers, a lower layer and an upper layer. To get at the end an average drag coefficient for the vegetated foreshore the lower layer can be rated with the high coefficient value (rigid stems) and the upper layer with the low coefficient (flexible branches).

Old versus young willows

The dissipation of energy due to vegetation depends on the vegetation factor 2.3.3:

$$Vf = C_d b_v N$$

The plot with young willows has a high density of branches, while the plot with old willows has stems to a height of seventy centimeters with big diameters. The drag coefficient is for both willows unknown, but is set at $C_d = 1$ for each section of height.
The maximal water depth will be two meters above the crates or bigbags. The vegetation factor will be:

height (m)	b_v (m)	N	Vf
< 0.7	0.15	1	0.15
0.7 - 1.8	0.0098	46	0.45
1.8 - 4.0	0.0080	80	0.64

(a) Old willows

height (m)	b_v (m)	N	Vf
< 0.6	0.0084	190	1.60
0.6 - 1.2	0.0065	190	1.24
1.2 - 1.5	0.0038	190	0.72

(b) Young willows

Table 8.1: The diameter, density per m^2 and vegetationfactor for $C_d = 1$ per section of height for the old and young willows

Results old willows

In this section the results of the plot with old willows are elaborated. Following figures and tables gives all outcomes of the measurements and calculations.
The next figure shows the outcomes of the two outer pressure transducers of one burst of seven minutes. The outcome of the measured pressures is a graph with the amplitudes in meters of all the waves in the burst.

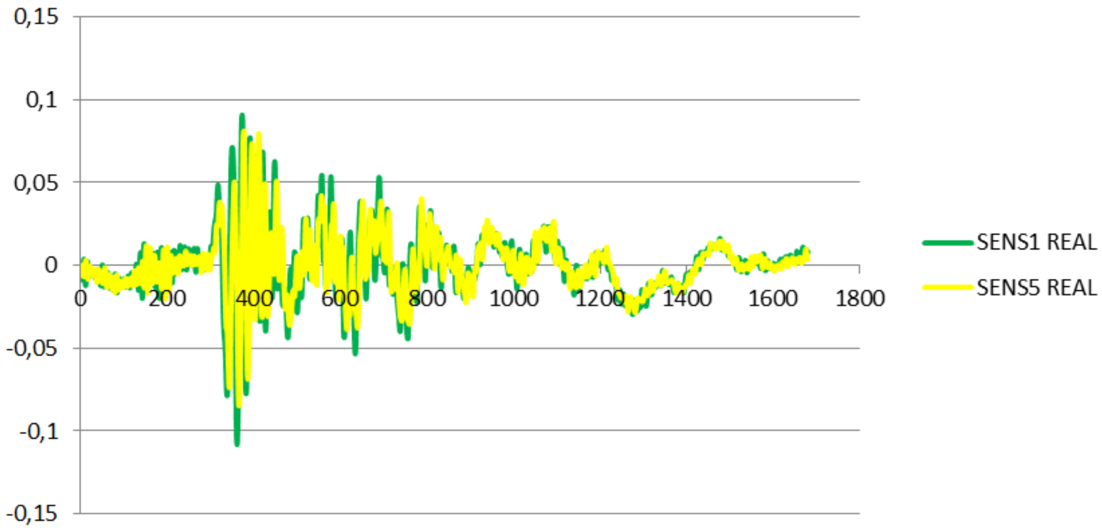


Figure 8.4: Wave attenuation in the plot with old willows measured with sensor 1 (close at the riverside) and sensor 5 (located at 6 meter) of one burst

In the figure the amplitudes of the waves measured by sensor 5 have different peakheights or are shifted relative to the incoming waves (sensor 1). The waves are distorted. A continuous reduction of the waves in the burst between sensor 1 and 5 is not explicit visible.

Relation between wave attenuation and the incoming wave height

The analyzed waves from the water level time series shows also for the old willows a clear wave attenuation over the vegetation plot. As well as for the young willows the highest incoming waves give the biggest wave reduction in %/m. The mean wave reduction for all the waves is about 2.5% of the incoming waveheight per meter 'plot'.

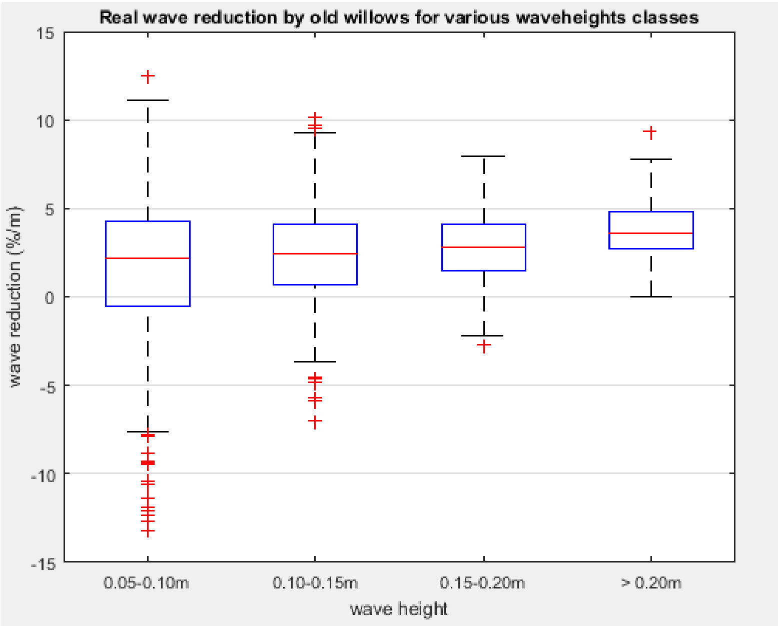


Figure 8.5: Wave attenuation over the plot with old willows between sensor 1 and 5 in %/m for incoming waves divided in various classes of waveheights

Relation between wave attenuation and the locations of the pressure transducers

In the plot with old willows (5 x 5 willows) the sensors are attached to the stem of each willow trough the middle of the plot perpendicular to the river. In between sensor 2 and 3 the wave reduction was almost nothing. For the other parts between the sensors there was a clear reduction of the waves. The reduction was even as for the young willows bigger at the end of the plot further away from the river.

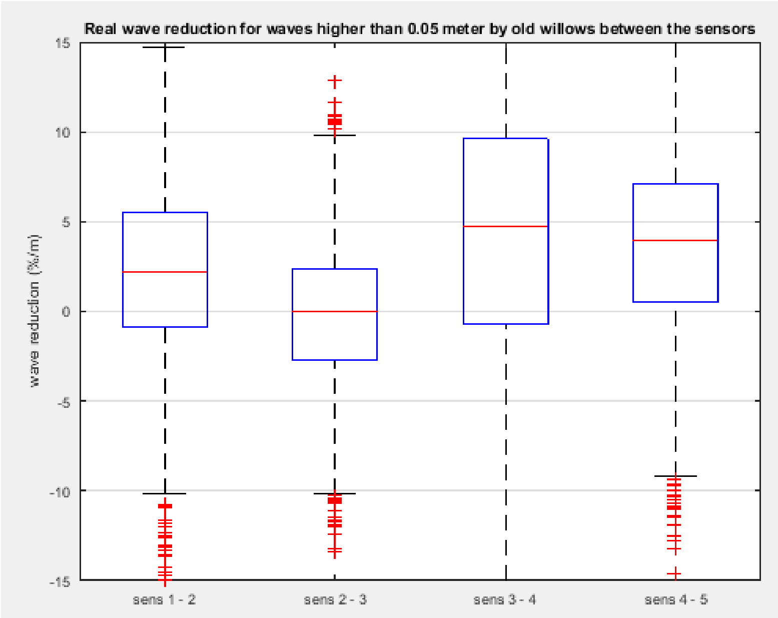


Figure 8.6: Wave attenuation over the plot with old willows in %/m for waves in the areas between the five sensors

This bigger reduction between the last sensors is again clearly visible in the graph which plots the significant waveheight per sensor.

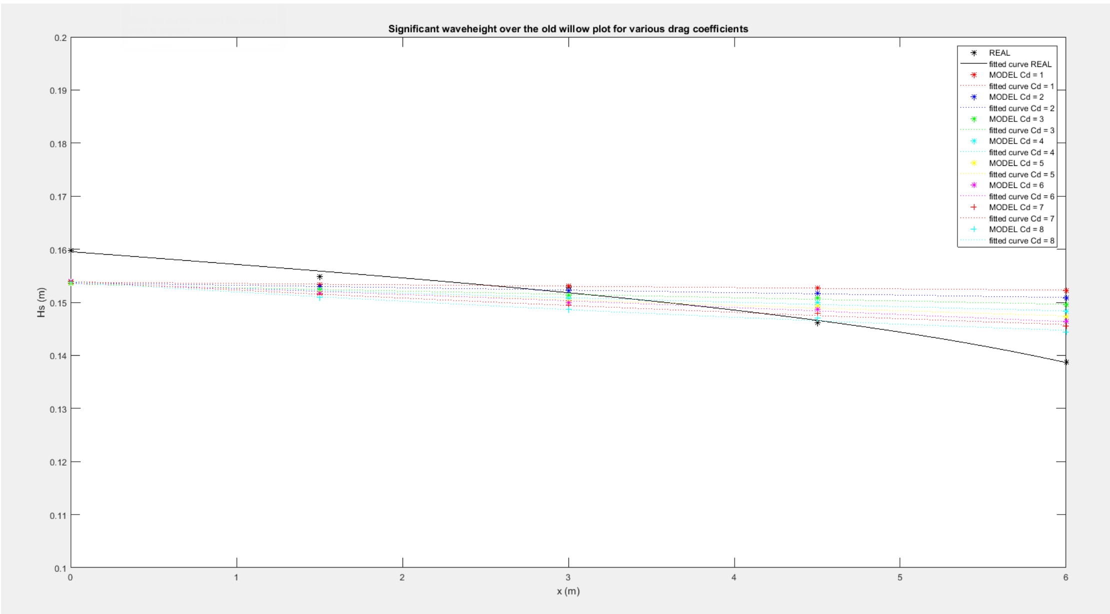


Figure 8.7: Reduction of the significant waveheight over the plot with old willows in horizontal direction, determined at the locations of the pressure transducers

Relation between wave attenuation and water level

The wave attenuation of the plot with old willows is depended on the water level, which is visible in the next table.

water depth (m)	wavereduction (%/m)	number of bursts
0.8 - 1.0	1.71	18
1.0 – 1.2	2.41	9
1.2 – 1.4	1.99	34
> 1.4	2.13	12

Table 8.2: The average wave attenuation by the old willows for various water depths in %/m

There is no clear relation between the water depth and wave reduction. Probably this depends on the shape of the willows. The stem with a diameter of fifteen centimeters reach a height of 0.7 meter. From there on till a height of 1.8 meter there are approximately 46 branches per square meter.

Calibrated drag coefficient for numerical model with and without elevation of the bottom

The drag coefficient C_D is calibrated for each burst. The best correspondence between the measurement data and outcomes of the SWASH model, for various drag values, was obtained. To determine the drag coefficient of vegetation during storm conditions also the Reynolds number of each burst is calculated. Extended explanation about the Reynolds number can be found in chapter 2.1.1. A river dike is designed on storm conditions, also named as design conditions. An higher Reynolds number is equivalent to a turbulent waterflow, which occur during storm. By plotting the calibrated drag coefficient and Reynolds number for all bursts an extrapolation can be made to determine the drag coefficient of the willows for design conditions.

The drag coefficient is calibrated for each burst in both models with and without elevation of the bottom. In the following figures the spread of the markers in the scatterplot is big. For the model with crates on the bottom the spread is bigger than for the model with flat bottom. For this last model, the average calibrated C_D is also lower. The averaged calibrated coefficient is somewhere between 1 and 4 in stead of 3 and 7 for the model with crates.

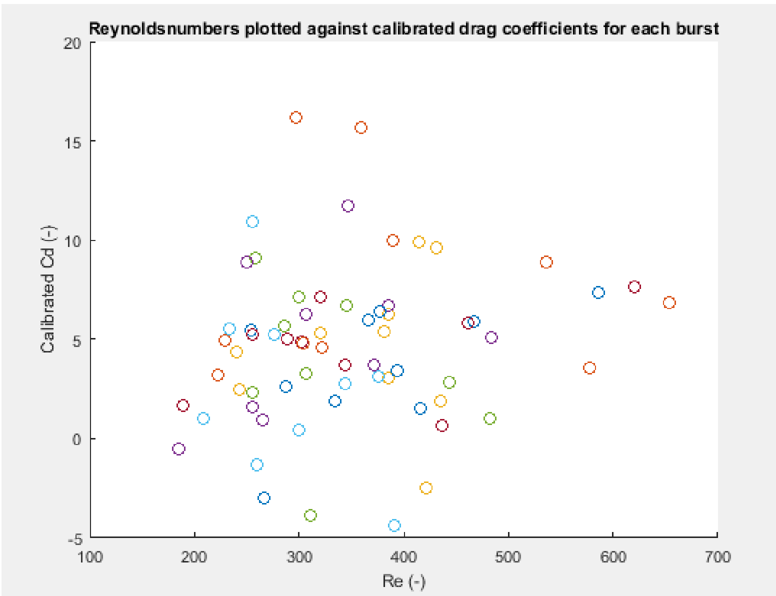


Figure 8.8: including elevation of the bottom

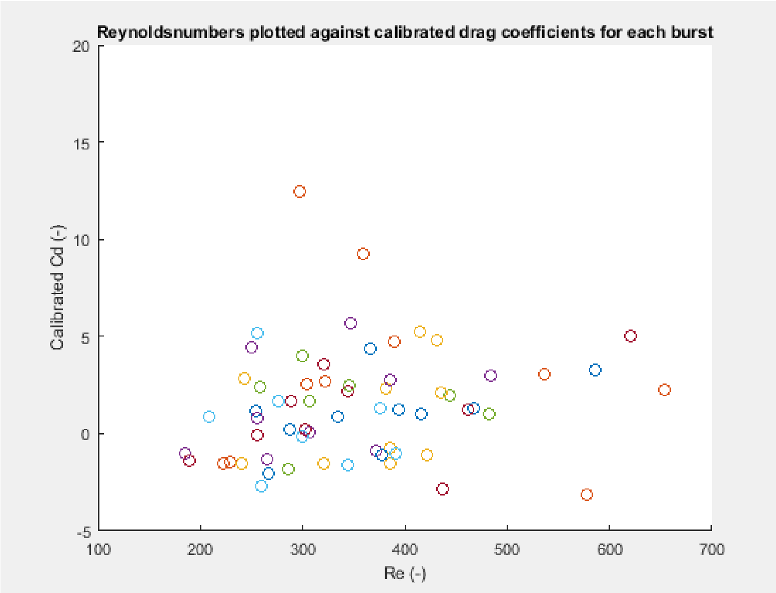


Figure 8.9: Flat bottom

For high Reynolds numbers the difference in C_D-value for the two models is clear. For the model with flat bottom this value is approximately 3 versus $C_D = 8$ for the other model. For a flat bottom the spread is less and the average calibrated drag coefficient is closer to 1, which it have to do for high reynold numbers. Therefore the model with flat bottom is better.
Both values are relatively high in comparison with drag coefficients for vegetation which are determined in relately new researches (Yusof et al., 2017). The models give for normal C_D vegetation values less wave reduction than what was obtained by the measuring set. For a higher value of the drag coefficient the reduction became slightly larger.

Flat bottom versus elevation of the bottom by crates

Because of the suddenly elevation (by the crates and bigbags) waves can be deformed which could make other dissipation mechanisms more important. This has impact on the wave damping only by the willows. Therefore a second case is made including the elevation by crates and bigbags as bottom. SWASH cannot handle vertical elevations, so the elevation of fourty centimetres for the crates is create with a slope of 1:0.5 even as the elevation of eighty centimetres for the bigbags.

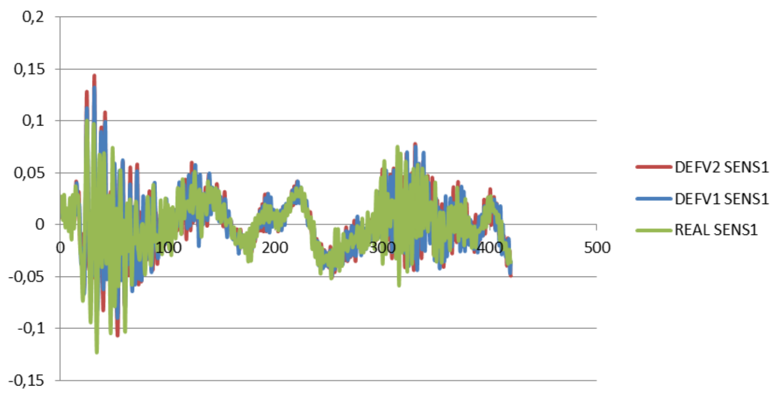
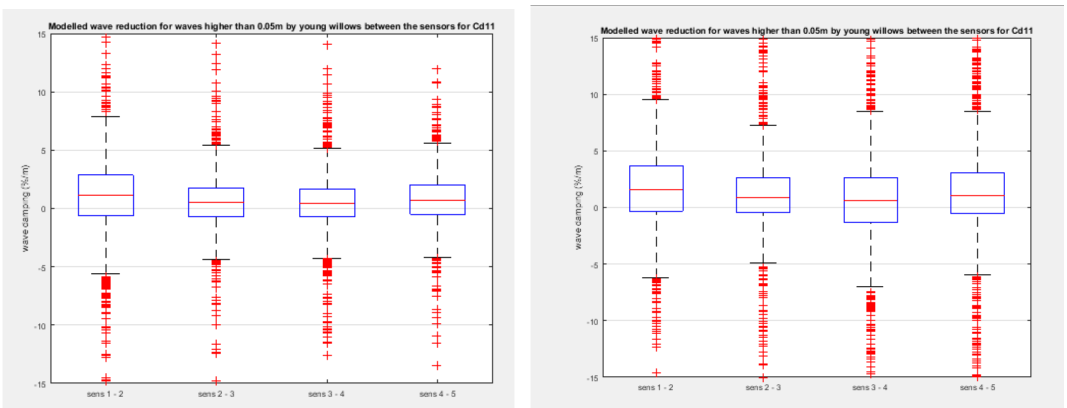


Figure 8.10: The real measured timeserie (green) at the first pressure transducer at the riverside of the plot with young willows versus the modelled timeserie at the same location for a bottom with the elevation by the crates (DEFV1) and with a flat bottom (DEFV2) when the real measured timeserie was used as input in the SWASH model

There are some slightly differences in wave reduction between the two types of bathymetry. For the model with the flat bottom the reduction in %/m is over the total plot higher than for the model with bottom elevation. This increase is highest between sensor 1 and 2. Another striking element is the variation in wave reduction. This is greater for the model without elevation for all parts of the plot.



(a) Including elevation of the bottom (b) Flat bottom

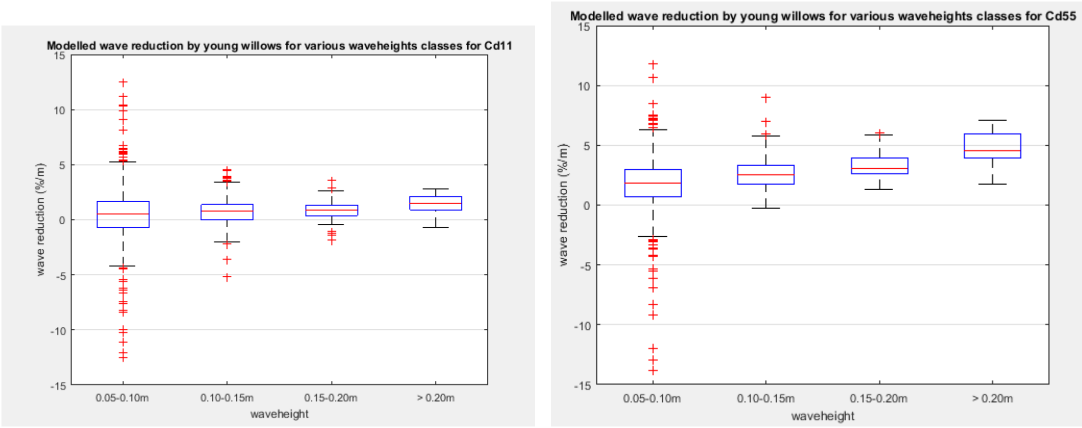
Figure 8.11: Wave reduction between the sensors in %/m for two bathymetries

Sensitivity drag coefficient

In theory a drag coefficient of 1 is normal for stiff beams which is comparable with a stem of a willow. For the young willows this could be a lower value, because the branches are flexible. However, with calculations of the wave reduction it seemed that a drag coefficient of 1 does not give the wave reduction that is obtained by the actual plot with young willows. So the sensitivity of the drag coefficient is theorytically determined by analyzing of the wave reduction boxplots for $C_d = 1$ and $C_d = 5$.

Including elevation of the bottom

The figures show a clear difference between the model with a drag coefficient of 1 or 5. The wave reduction is for all classes of waveheights higher, however for the highest waves the reduction is bigger than for the lower waves.



(a) Cd = 1 (b) Cd = 5

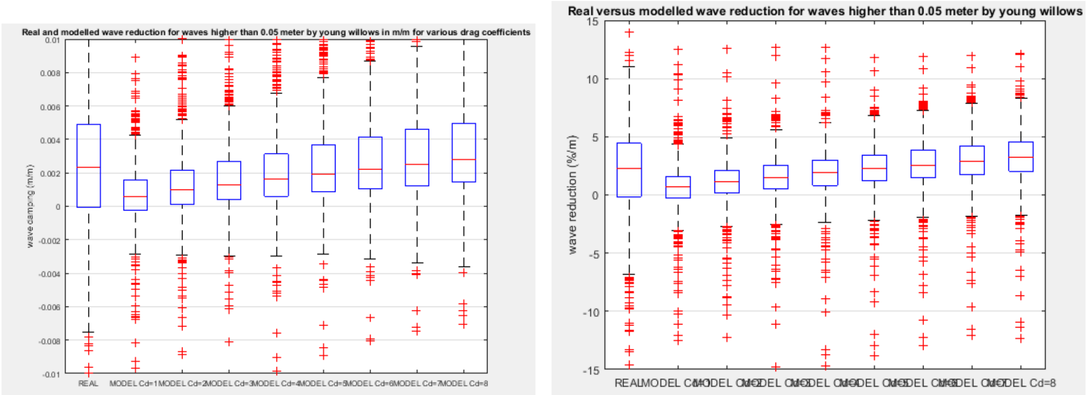
Figure 8.12: Wave reduction for $C_d = 1$ and $C_d = 5$ for various wave height classes in %/m for model including elevation of the bottom

Calibration drag coefficient

The drag coefficient for young willows is calibrated for the model with and without elevation of the bottom. The coefficient is calibrated on the actual measured wave damping. First, boxplots are showed for the actual measured reduction and the reduction of the model with a drag coefficient varied from 1 to 8. Second, the drag coefficient is determined by plotting the actual mean wave reduction and the modelled mean wave reduction. The intersection point gives the drag coefficient.

Including elevation of the bottom

The wave reduction in m/m give the reduction of the incoming wave height in meter per horizontal meter of willows. With the measuring setup a reduction is calculated of 2.5 milimeters per meter willows. So if a reduction of ten centimeters is needed a plot with a width of fourty meters should be created. In the model the same reduction in m/m is reached for $C_d = 6-7$ and for the reduction in %/m for $C_d = 5-6$.



(a) Wave reduction in m/m

(b) Wave reduction in %/m

Figure 8.13: Actual wave reduction in the plot with young willows versus the modelled wave reduction for various drag coefficients for model including elevation of the bottom

The drag coefficient is determined by the intersection point of the actual mean wave reduction and the modelled mean wave reduction for various drag coefficients. The 25%-quantile and 75%-quantile are also plotted. The calibrated drag coefficient has for the bottom including elevation a value of $C_d = 4.3$. The quantiles shows a variation in the drag coefficient value from 1.8 to 7.5.

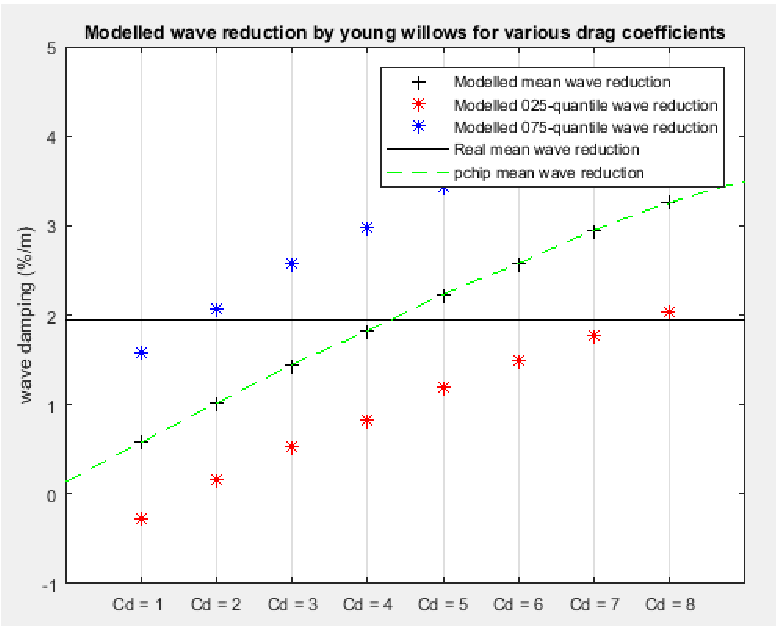


Figure 8.14: Modelled wave reduction (mean, 25-quantile and 75-quantile) in %/m for various drag coefficients for a model with a bottom including elevation, and the actual measured mean wave reduction for young willows

Discussion model young willows flat and elevated

Obviously, there is a bigger wave damping in the model by higher drag values. The differences between the model with and without elevation of the bottom are clearly visible. In the figures below the significant waveheight of the sensors in the actual situation and model (for various drag coefficients)

are plotted. The plot with willows started at $x = 0$, the asterisks gives the significant waveheight at the sensor locations. In the actual situation a parabollic line is visible with at the end of the plot a bigger reduction of the significant waveheight per meter width than at the first meters of the plot with willows.
In the model the significant waveheight at sensor 1 is already lower than the height in the actual situation. A parabola is not visible, only (almost) straight lines. The biggest reduction in significant waveheight is in the model between sensor 1 and 2, while in the actual situation this was at the end of the plot.
The average angle of the fitted curve for the actual situation, which say something about the reduction of significant waveheight over the plot, is closest to the angle of the line with a drag coefficient value of 6 for the model with elevation of the bottom.

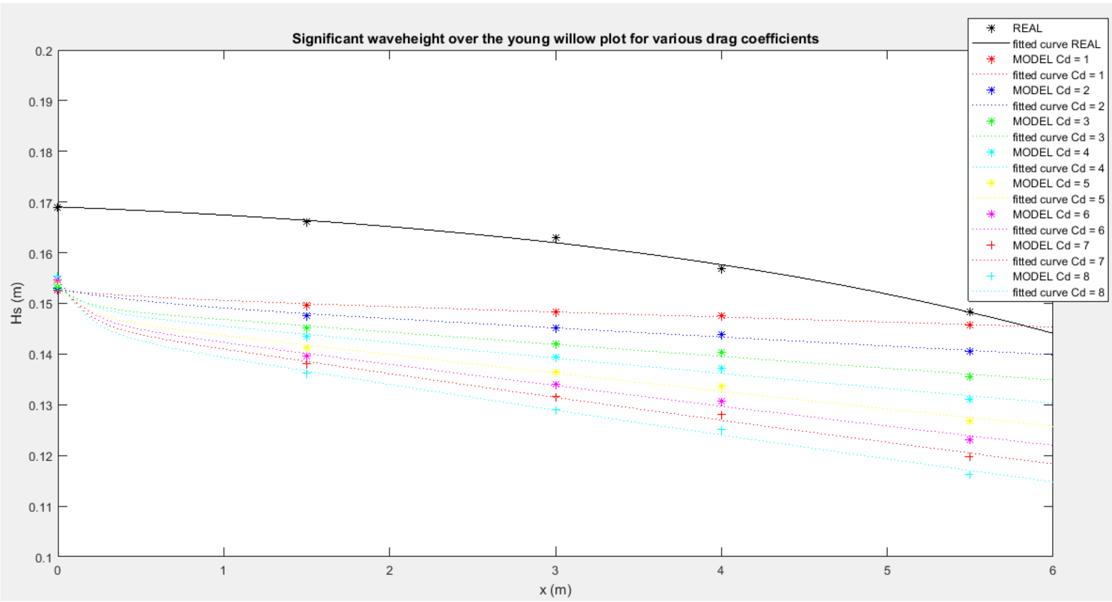


Figure 8.15: Reduction of the significant waveheight in the model with bottom elevation over the plot with young willows in horizontal direction, determined at the locations of the pressure transducers

The model with the flat bottom shows different curves for the significant waveheight over the sensors. At sensor 1 the significant waveheight is also lower than the height at the actual situation. Furthermore, this waveheight is lower than the modelled height for the model with bottom elevation.

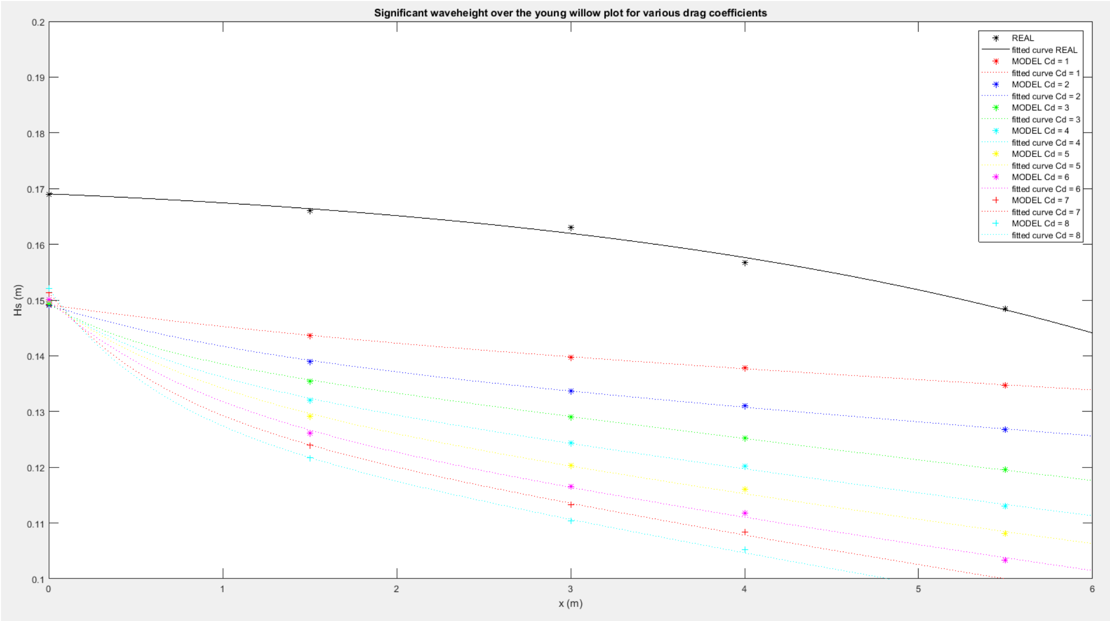


Figure 8.16: Reduction of the significant waveheight in the model with flat bottom over the plot with young willows in horizontal direction, determined at the locations of the pressure transducers

However, for this model with flat bottom the ’curved’ line fitted for $C_d = 3$ has almost the same wave reduction over the plot than for the actual situation. The curved line is only visible at the begin of the plot with willows, which was the same as for the plots with elevation of the bottom.

Conclusion is that the bottom elevation results in a higher significant waveheight over the plot and less reduction due to the vegetation. Probably other dissipation mechanisms have effect on this reduction.

Control and temporary measures

Effects of the exogenous threats can be reduced by control or temporary measures. In the following paragraphs, possible control measures for the scenarios are described as well as temporary measures.

Reduction of scenario effects

Most important is the prevention of large impacts by scenarios by performing regular inspections of the wave damping willows. Consequences can be significantly reduced if the management is attentive. The wave damping willows should always reduce the waves enough to meet the safety requirements. This is why regular checks and a good management and maintenance plan are vital for safety.

Replantation

If willows are about to die, or whenever the total achieved wave damping does not meet the requirements, replantation is required. Willows at the riverside should be replaced first, because they contribute the most in wave height reduction within the osier plantation. It is preferable to plant new willows in the winter season, from November to the beginning of March.

Diseases and insects

An infectious disease, such as the watermark disease, spreads quickly through the air. To prevent further spread of the disease, selective harvesting should take place. If a willow shows some characteristics of a disease, the tree must be cut. Inspection rounds should take place at the beginning of February, so new willows can be planted in Februari-March and grow before the next storm season. Insects can be combated with natural pesticides. However, the damage create by the insects will remain. It is important to know if the damage has effect on the wave damping capacity or not. For example, tunnels in the stem can make willows fragile, which increase the risk of uprooting. In order to prevent damage by diseases and insects, the tree must be prevented for damages or be treated with a wound covering agent (Interview).

Beavers and other animals

The beaver is a protected species, so it is not allowed to catch or harm these animals. The effects of a beaver family in the Heesseltsche Uiterwaarden is on short-term small, but is assumed to increase the upcoming 50 years. Moreover the largest damage is caused by the digging of beavers which affects the stability of the dike and not the wave damping vegetation. This has mainly effect on the stability of the dike and less on the wave damping vegetation.
In winter, measures can be taken to prevent damage of beavers and other animals, if they are active at the Heesseltsche Uiterwaarden. For example, fences can be placed.

Flooding

Flooding during the growth period cannot be controlled. It is therefore important to monitor the conditions of the willows after the flood and take action whenever willows are injured. Selective harvesting can be an option to keep the biggest part of the wave damping intact.

Storm

If a heavy storm dauses a lot of damage to branches, the wave damping capacity should be investigated to ensure it still meets the damping required during high water conditions. Storms are often occur during the high water season. Temporary measures can be used to increase the crest level, ensuring the critical overtopping discharge is not reached.
During growth season in the early spring, new branches will grow and the vegetation density will increase again after being cut. If willows are uprooted, new willows will be planted.

Ice

Just as during storms, ice can break twigs and branches. Again cutting of branches in spring is a good control measure. For thick river ice, the only possible measure at the end of the frosty period is cutting down the willows at ground level to prevent crooked growth of new branches (Venema et al., 2014). It is assumed that this scenario happens before the growing season. Therefore willows are recovered enough to provide wave height reduction in October, when the high water season starts. Whether or not this is sufficient to be assessed.

Drought

Drought causes only causes damage to newly (re)planted willows during their first and second year of growth. The management should keep an eye on the waterlevel in the river and the groundwater level in the foreshore. If the water level is critical, the freshly planted osier bed should be watered. Additional watering can also be required for replaced individual willows as their roots are not deep enough yet to reach the deeper ground water resources and the older willows withdrawing groundwater nearby.

Fire

The path of a fire is most important, because this can have a big influence on the wave damping capacity of the osier plantation. The fire affected path or area will have to be replaced by new willows during in spring and summer. Moreover if a part of the plot is burned during the high water season, temporary measures will have to be deployed in order to guarantee the safety requirements.

Temporary measures

At the case location, temporary measures that can be considered are measures which increases the crest level of the dike causing a decrease of the wave overtopping discharge. Emergency temporary measures like sand bags, Dutchdam or the Block-IT (van Damme et al., 2016) can resist a water level of approximately one meter. This is enough to withstand the calculated scenario effects in respect to the required increase of elevation on the crest. Fast wave breaking measures are not possible at this location, because of the large water depth on the floodplain.

Interviews

Interview den Hertog

Marc den Hertog
Den Hertog Tuinplanten Boskoop

Hoofdvragen (kan misschien makkelijker worden beantwoord na het beantwoorden van de deelvragen):
- Welk type/welke typen wilg zijn het meest geschikt? (De takken moeten voor maximale golfdemping minstens 5 meter hoog zijn op deze locatie)
Mijn favoriete wilg voor dit soort toepassingen is de Salix triandra. De juiste hoogte halen ze wel, ook al duurt dat wellicht even, maar dit is een toepassing die heel erg lijkt op plekken waar ze in de natuur voorkomen. Ze zijn naar mijn ervaring dus ook helemaal aangepast aan veel problemen die voorkomen langs de waterkant van rivieren. Andere wilgen hebben dat in meer of mindere mate ook wel, maar de Salix triandra naar mijn mening het meest. Salix alba is zeker ook geschikt, en verder zou de Salix viminalis ook wel voldoen. Maar Salix triandra heeft mijn voorkeur langs de waterkant.
Als het ook uitheems mag zijn zou ik ook de bekende Gele Treurwilg eens overwegen. Salix sepulcralis 'Chrysocoma' Die groeit veel sneller dan de andere genoemde soorten, heeft bijna geen last van ziektes en aantastingen in Nederland en maakt door zijn tegelijk opgaande en neergaande groeiwijze een enorme hoeveelheid gewas en takken. Extra voordeel is dat de neergaande takken ook snel wortelschieten als ze de grond raken zodat er snel een enorme dichte bosschage zou kunnen ontstaan.

- Welke eigenschappen heeft deze wilg? Waarvoor is de wilg gevoelig en wat is de kans daarvan? (Kans kan bijvoorbeeld worden beschreven als: 1x in de 2 jaar/1 op de 200/< 1/10 jaar) De Salix triandra Amandelwilg heeft relatief klein blad en dunne takken. Zeker als hij net uitloopt. Maar hij heeft een heel erg dichte groeiwijze en maakt veel meer takken dan andere wilgen in dezelfde omstandigheden. Voor mijn gevoel bijna 3 keer zoveel, maar dat heb ik nooit berekend. Ik heb verspreid over kwekerij exemplaren staan die we elk jaar knotten voor stek, en als je vergelijkt wat de opbrengst aan takken is in vergelijking met andere wilgen is dat ongeveer drie keer zoveel. Zoveel zelfs dat ik hem wel eens aan heb willen melden voor gebruik als biomassa, maar de keuze voor Salix alba was toen al gemaakt. Die maakt wel langere takken, maar veel minder in aantal.
De takken zijn extreem soepel en breken vrijwel nooit. Ze zijn daardoor ook nooit helemaal recht, maar het hout is wel taai en sterk. En kan veel weerstaan.

Hij heeft de neiging om in eerste instantie snel om te vallen en op die manier te beginnen met groeien in de breedte. Iets wat hij ook veel sneller doet dan de Salix alba. Zijn natuurlijke groeiwijze is al heel snel ruim anderhalf keer zo breed dan hoog en alle takken die de grond raken kiemen ook weer direct zodat er snel een dichte griend ontstaat in de vorm van een soort mangrove. Dit doet hij vooral zonder dat er gesnoeid wordt. In het rapport staat de suggestie dat er elk jaar gesnoeid moet worden, dat kan ook bij deze soort, maar ik durf de stelling wel aan dat je deze Amandelwilg beter helemaal met rust kunt laten omdat de aldus ontstane groeiwijze elk jaar steviger en dichter wordt, en dus structureel voor demping van de golven kan zorgen. Bij elk jaar snoeien krijg je echt een griend, en op die manier wordt deze soort veel dichter dan de andere Salixen, dus het kan ook op die manier.

De bast van de Amandelwilg lijkt als enige wilg een beetje op die van de Plataan. De bast valt dus regelmatig af en er zit dan weer een nieuwe bast onder het afgevallen stuk. Een handige en ongewone eigenschap voor een wilg, maar bruikbaar omdat alle vervuiling op de bast regelmatig verdwijnt zodat er altijd zuurstof bij het Cambium kan en bij het zachte hout eronder.

Wij werken op ons bedrijf zonder chemische middelen. Ik vind ziektes ook niet heel interessant en ken ze dus ook niet allemaal. Bij wilgen speelt daarnaast dat die eigenlijk altijd wel ziek zijn. Vrijwel doorlopend worden alle wilgen geteisterd door allerlei aantastingen, insecten, schimmels en wat er maar bestaat. Ook logisch naar mening omdat de meeste inheemse wilgen in vrijwel elk deel eetbaar zijn en daarom belangrijk als voedselvoorziening voor veel grote en kleine dieren. Wilgen zijn dus een heel belangrijke voedselbron in de natuur, ook voor alle organismen die wij ziektes noemen. Doordat de wilgen die we hier bespreken van nature in moerassen voorkomen waar van nature heel erg veel gebeurt, zijn ze al die veranderingen en aanvallen ook gewend en geven ze er naar mijn mening niets om. Ze zijn hier zo op aangepast dat ze bijna overal een antwoord op hebben, behalve op extreme en zeer langdurige droogte.

In onze ervaring op veengrond komt vrijwel geen watermerkziekte voor, maar elk jaar hebben ze wel last van luizen en allerlei kleine aantastingen van het blad.Verder krijgen examplaren die wat ouder zijn, vanaf ongeveer 5 jaar en ouder, vaak last van de enorme rupslarven die uiteindelijk de spectaculaire grote wilgenhoutvlinder oplevert. Deze grote rupsen doen er een jaar of 4-5 over om uiteindelijk vlinder te worden, en in al die tijd maken ze grote gangen in het hout van wilgen en hollen ze de wilgen op die manier uit. Wilgen hebben hier op zich geen last van, want alles wat bast heeft groeit door, maar op veengrond zien we deze rupsen veel. Op andere grondsoorten, zoals de klei op dijken zal dat veel minder zijn. Daar houd die vlinder niet van dacht ik.

Deelvragen:

- Gevoeligheid voor ziekten (bacteriën/insecten/schimmels): hoeveel kans? Kans als hoeveel procent wordt er ziek per jaar? Welke ziekten? Hoe snel verspreidt het? Al snel zichtbaar/te behandelen? Is het goed te managen als er 1x in de 2 maanden iemand langs de wilgen loopt om te kijken, of is dat te weinig? Hoe behandelen (kappen/gif)?

Nogmaals, wilgen zijn eigenlijk altijd wel ziek, maar juist daarom zo sterk en taai. Ze gaan nooit dood van een aantasting, en blijven nieuwe takken leven op alles wat een bast heeft. Mijn eigen advies zou zijn om hier helemaal niet op te letten, omdat het geen tot nauwelijks effect zal hebben op de groeiwijze en op het effect dat jullie willen bereiken. Snoeien van wilgen mag altijd, maar gif zou ik niet gebruiken. Totaal zinloos, aantastingen horen gewoon bij wilgen langs de waterkant, maar zullen ze nooit slopen.

- Gevoeligheid voor wind/golvend water: Breken takken snel af?

Salix triandra heeft de meest soepele takken van alle wilgen in mijn beleving. Je kunt bij eenjarige takken de hele tak rondbuigen en er een knoop in leggen zonder dat ze breken. Ze kunnen bijzonder goed tegen structureel veel wind. Ze zijn dat in de natuur ook gewend en komen voor tot bijna aan de kust. Door de soepelheid zakken de takken vaak wel snel opzij en kiemen dan opnieuw door afleggen. Daarna wordt het geheel alleen maar sterker. Oudere takken breken soms bij de basis af als het hout is verzwakt, maar groeien altijd weer gewoon verder omdat ze vrijwel nooit zomaar helemaal afbreken. Golvend water doorstaan ze naar mijn beeld ook wel, ook al hebben wij daar in Boskoop weinig ervaring mee. Door de soepelheid van de takken lijkt het me geen enkel probleem.

- Gevoeligheid voor overstroming: Na hoeveel dagen gaan wilgen echt dood als ze onder water staan, zodat je ze (allemaal) moet vervangen? Wat is de kans dat ze echt doodgaan? Hoelang duurt het voordat je ziet dat ze beschadigd zijn (en vervangen moeten worden)?

Als de overstroming in de herfst of winter plaatsvindt kunnen ze zeker 4 tot 5 maanden zonder veel problemen onder water staan. Er is dan geen verdamping van bladeren en de sapstroom staan dan ook stil. In die fase is hij bijzonder taai. Mocht er toch schade zijn ontstaan dan zie je dat niet in de winter zelf. Pas als hij uit gaat lopen zal er effect zichtbaar zijn. Maar omdat wilgen vrijwel als enige gewas in Nederland de mogelijkheid hebben on na een overstroming gewoon vanuit de bast nieuwe wortels te maken zal dit niet zomaar dood zijn. Hij blijft dat eerst een hele tijd opnieuw proberen. Door deze bijzondere eigenschap verwacht dat wilgen eigenlijk nooit vervangen hoeven te worden na een overstroming in de wintermaanden. Tijdens de groeiperiode in de zomer is de gevoeligheid wat groter denk ik. Als een overstroming dan langer dan drie / vier weken duurt zal dat groeivertragingen geven en zullen de bomen daar last van kunnen krijgen. Vooral omdat er op een gegeven moment geen zuurstof meer bij de wortels komt waardoor er verstikking optreed. In de zomer zul je na een echt lange overstroming vrijwel direct effect binnen een maand. Ook al zal hij er niet direct dood van gaan. Als dat wel gebeurt zal dit in de zomer ongeveer twee maanden volledig onder water moeten staan. Maar zelfs dan verwacht ik dat er delen zijn die een nieuwe doorstart proberen te maken. Het blijft een echte moerasboom, en overstromingen horen daarbij. Deze wilgen zijn daar volledig op aangepast.

- Beheer en onderhoud: Wanneer en hoe vaak moet je snoeien? (Hoe snel groeit het aan? – We willen in het hoogwater seizoen van november t/m maart de maximale hoogte hebben!) Gevarieerd/gedoseerd snoeien? Random of in banen?

Mijn advies zou zijn helemaal nooit snoeien. Deze amandelwilg is vooral geschikt voor de beschreven taak als hij helemaal kan verwilderen. Snoeien creeert een andere soort groei en dan gaan de wilde eigenschappen voor een deel verloren. Als er toch gesnoeid moet worden zou ik dat bij deze wilg alleen halverwege de zomer doen. Ongeveer vanaf de langste dag half juni. Hij verdraagt elke vorm van snoei en reageert met een dubbele hoeveelheid takken na elke snoeibeurt. Daarnaast doet snoeien echt groeien bij Amandelwilgen. Hij probeert na snoei in extreem korte tijd dezelfde hoogte direct weer met jonge takken te compenseren. In de natuur van levensbelang, en in uw geval alleen maar handig denk ik. Door snoei ontstaan er wel veel meer takken dicht op elkaar dan normaal in de natuur. Daardoor kunnen er veel takken door te weinig zonlicht in het jaar erna wegvallen. Op zich een natuurlijk proces. Na snoei kunnen ze in een groeiseizoen lange nieuwe takken maken van ongeveer drie meter hoog, soms iets meer. Als u toch wilt snoeien zou ik daar vooral gebruik van maken, van die eigenschap. Maar niet snoeien heeft een beter effect vindt ik. Tegen mijn klanten zeg ik wel eens dat er ook niemand in de natuur een zaag heeft. Toch kunnen planten allerlei nuttige taken vervullen.

- Aanbeveling voor toepassen van wilgen als golfdempende vegetatie – bijvoorbeeld hoe kunnen de wilgen het beste worden geplant voor golfdemping? Hoe is een wilgenperceel goed te beheren? Zijn wilgen nog ergens anders gevoelig voor?

Deze vraag heb ik al deels beantwoord, maar nog een keertje geeft niet. Ik zou ze aanplanten met jonge staken van ongeveer twee meter. Dit kan het beste bij een hoge grondwaterstand. En natuurlijk alleen in de wintermaanden. januari en februari zijn de beste maanden hiervoor. Hierna gewoon afwachten en daarna de planten helemaal hun eigen natuurlijk vorm laten krijgen met zo min mogelijk beheer. Het zal ongeveer twee of drie jaar duren voordat ze ver genoeg zijn om echt te een succes te kunnen zijn, en na ongeveer 5 jaar en meer krijgen ze de natuur op die plek ongeveer in hun greep en zullen ze de golfslag dempen zoals u voor ogen hebt. Daarna zo min mogelijk meer aan doen. Waar u nog wel extra op moet letten is vraat van de grotere grazers. Herten etc, maar ook hazen en konijnen. Deze zijn allemaal verzot op het blad, de jonge takken en de bast. En in de winter is vooral de bast echt belangrijk wintervoedsel, maar zonder bast gaan zelfs wilgen uiteindelijk dood. Voor een succes bij het dempen van golven zal vooral dit effect goed in de gaten moeten worden gehouden, Het zal ook niet elk jaar een risico zijn, maar in de koudere winters kan de bast van wilgen opeens het enige voedsel zijn voor veel dieren wat er nog is. Voorkomen moeten worden dat die bast op echt grote schaal gegeten zal worden. Verder zal bij alle moeraswilgen langdurige droogte in combinatie met een lage waterstand een probleem kunnen zijn. Het zijn nu eenmaal bomen die graag veel water om zich heen hebben. Dit geldt voor alle genoemde wilgen uit moerasgebieden.

Interview Bontekoe

Peter Bontekoe
Salixkwekerij Bontekoe, Boskoop

Hoofdvragen: Welk type/welke typen wilg zijn het meest geschikt? (De takken moeten voor maximale golfdemping minstens 5 meter hoog zijn op deze locatie)
Salix Viminalis

Welke eigenschappen heeft deze wilg? Waarvoor is de wilg gevoelig en wat is de kans daarvan?
Sterke wilg, maakt goede lengte en heeft zich in de historie bewezen. Er zijn echter meerdere soorten denkbaar e mijn advies is om meerdere soorten door elkaar te gebruiken. Goed tegen de ziektegvoeligheid, biv Salix Smithiana. (Kans kan bijvoorbeeld worden beschreven als: 1x in de 2 jaar/1 op de 200/< 1/10 jaar)

Deelvragen: Gevoeligheid voor ziekten (bacteriën/insecten/schimmels): hoeveel kans? Kans als hoeveel procent wordt er ziek per jaar? Welke ziekten? Hoe snel verspreidt het? Al snel zichtbaar/te behandelen? Is het goed te managen als er 1x in de 2 maanden iemand langs de wilgen loopt om te kijken, of is dat te weinig? Hoe behandelen (kappen/gif)?
Bovengenoemde soorten krijgen net als elke andere wilg last van luis en kevertjes. Als je meerdere soorten wilgen plant heb je meer biodiversiteit en daardoor een beter biologische ziekte bestrijding. Chemisch is uit den boze.

Gevoeligheid voor wind/golvend water:
Breken takken snel af? Nee

Gevoeligheid voor overstroming: Na hoeveel dagen gaan wilgen echt dood als ze onder water staan, zodat je ze (allemaal) moet vervangen? Wat is de kans dat ze echt doodgaan? Hoelang duurt het voordat je ziet dat ze beschadigd zijn (en vervangen moeten worden)?
Wilgen kunnen heel lang(aantal maanden) tegen in het water staan mits de beworteling goed is.

Beheer en onderhoud: Wanneer en hoe vaak moet je snoeien? (Hoe snel groeit het aan? – We willen in het hoogwater seizoen van november t/m maart de maximale hoogte hebben!) Gevarieerd/gedoseerd snoeien? Random of in banen?
Eens in de drie jaar snoeien uiterlijk, 2 jaar is beter. 5 mtr groei per jaar is geen probleem.

Aanbeveling voor toepassen van wilgen als golfdempende vegetatie – bijvoorbeeld hoe kunnen de wilgen het beste worden geplant voor golfdemping? Hoe is een wilgenperceel goed te beheren? Zijn wilgen nog ergens anders gevoelig voor?
Wilgen waren honderden jaren geleden al goed voor de doelen waar ze voor werden gebruikt en er is nog steeds geen verbetering gevonden. In Boskoop(boomkwekersdorp) hebben ze in de historie drainage uitgevonden met wilgentakken. Horizontale afwatering van je perceel. Dit soort dingen leer je niet in Wageningen, jammer, de historie biedt veel meer wijsheid dan men voor kan stellen.