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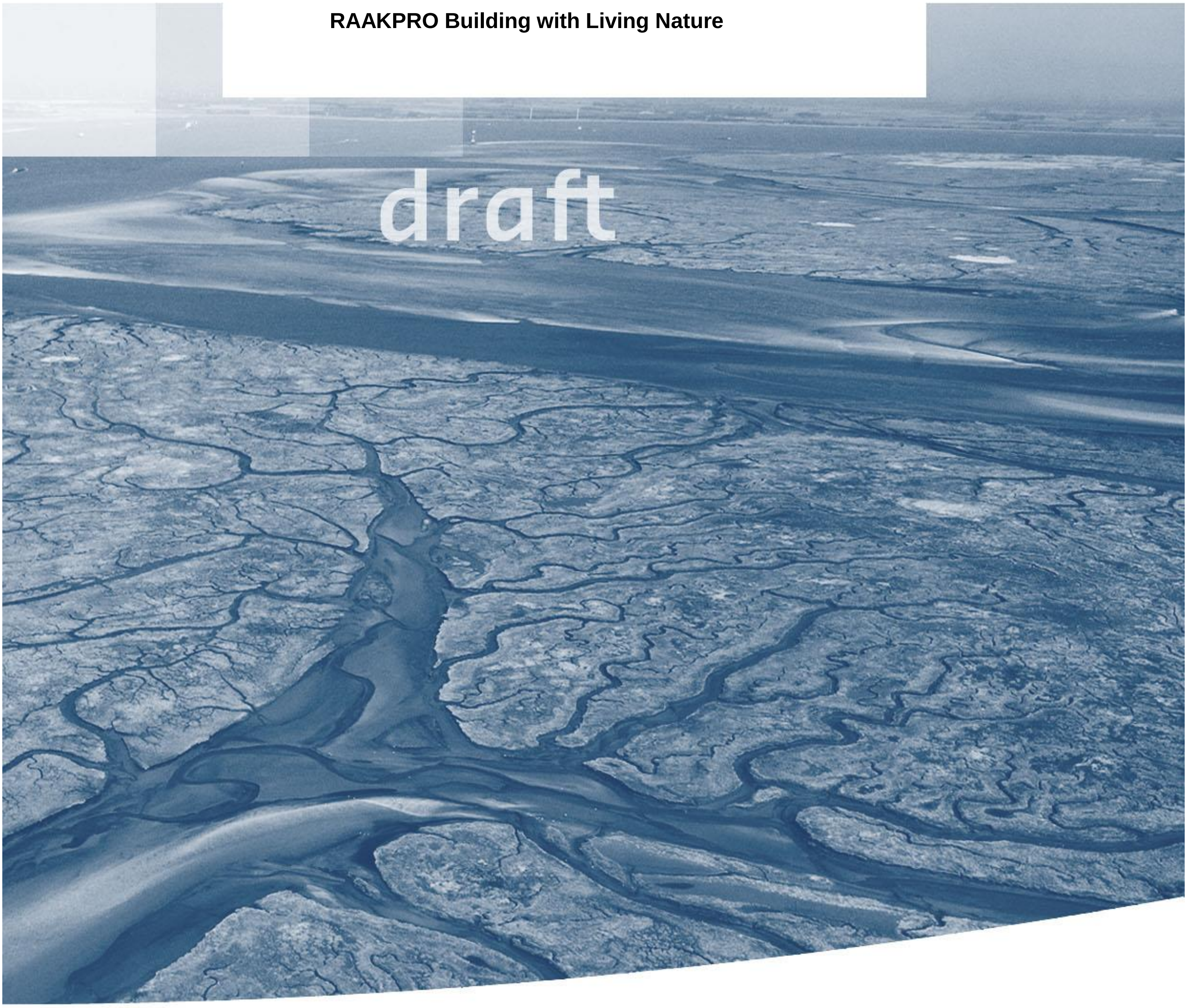
Oyster reefs in inter tidal areas

RAAKPRO Building with Living Nature



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RAAKPRO Building with Living Nature

E.W.J.Bergsma

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1 Introduction

In the framework of *Building with (Living) Nature* several research projects were launched to investigate more sustainable and nature-orientated solutions in hydraulic engineering. In the line of this research work, a pilot project was initiated in the Eastern Scheldt begin 2010. Three artificial oyster reefs are placed at two locations; Viane and de Val. The pilot project aims to gain insight in the hydrodynamic and morphological effects of the placement artificial oyster reefs. By placing the oyster reefs in front of flood defences, increased safety on flooding is intended. This improved safety is partially due to adapted flow regimes and reduced wave energy near the flood defences. Another related effect is the sediment trapping between the flood defences and the oyster reefs. The latter will not be subject of this report.

As part of the ultimate goal to implement natural and sustainable hydraulic solutions in human needs, engineers should have the tools to examine hydrodynamic and morphological consequences of placing the oyster reefs effectively. Development of this design tool is an ongoing process in which this particular project should be considered as a next step.

1.1 Aim

Further to physical research and a conceptual model[1] concerning wave dissipation on oyster reefs, currents over and around oyster reefs are subject for research. The focus in this report is on currents, as well tidal currents as wave-induced currents. *The aim is to determine relative impact introduced by an oyster reef under different flow regimes and reef dimensions. Furthermore, the aim is to asses the spatial reach of the observed changes.*

1.2 Approach

Applied variations in parameters are compared to a predefined base model. Time-series on bed shear stress are monitored in specific observation points. In these points, the relative changes in bed shear stress are related to the ratio reef height divided by water depth. Insight is gained in the sensitivity per parameter by comparing the spreading.

For the spatial reach, velocities perpendicular to the reef are plotted and assessed over predefined transects. The differences in depth average velocities represent a sheltered area or more exposed area. Where the velocities are comparable again is determined to be the spatial reach.

1.3 RAAKPRO Building with Living Nature

This research project will be part of the covering research RAAKPRO *Building with Living Nature*. The RAAKPRO *Building with Living Nature* research is divided in four packages;

1. “Development of concepts”
2. “Development of assessments”
3. “Execute knowledge extending experiments”
4. “Tools”

The numerical modelling of the oyster reefs in the Eastern Scheldt is part of two packages namely, **package two** and **three**.

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[1] *1D wave dissipation (conceptual) model deduced from field data by Bram van Prooijen and Nicolette Volp, 2011 (Delft University of Technology).*

1.4 Outline

After this introduction, the methodology elaborates the variation and evaluation of the applied parameters. Subsequently the numerical model domain is elaborated including boundary conditions. Chapter 3 gives the modelling results. The results are presented respectively in ratio of bed shear stress, wave influences and sheltered area behind and in front of the reef. The results are elaborated per varied parameter as described in chapter 2. This report concludes with conclusions, discussions and recommendations in chapter 4.

2 Methodology

The impact of oyster reefs on the bottom shear stress is assessed in this study by utilizing a numerical model, Delft3D. Reef dimensions and surrounding can be easily adapted in a numerical model. This allows verifying multiple combinations of dimensions and physical settings.

2.1 Variation in parameters

2.1.1 Base model

The baseline model simulates represents a situation with a reef of 0.2 metres high, 200 metres long and 10 metres wide. The applied slope is representative to the slope at *de Val* in the Eastern Scheldt: one on 600. The baseline model is exposed to a water level varying harmonically. The applied amplitude is 1.5 metres and the angular frequency is set on 28.984 degree per hour. The angular frequency is corresponding to a M2 tidal component.

2.1.2 Varying reef dimensions and surrounding

The dimensions of the reefs are expected to influence the effect and efficiency of the reefs in reducing erosion patterns. For this numerical assessment, only the length is kept constant on 200 metres. The variety of the reef dimensions is presented in Table 2.1 below:

Reef width	Reef height
2 metres	0.05 metres
4 metres	0.10 metres
6 metres	0.15 metres
8 metres	0.20 metres (base case)
10 metres (base case)	0.30 metres
16 metres	0.50 metres
20 metres	0.70 metres
30 metres	

Table 2.1 Applied variation in reef dimensions

Water level amplitude and the bottom slope are varied besides the reef dimensions. For the harmonic water level only the amplitude is varied, the angular frequency is kept constant on 28.984 degrees per hour. Independent on the bottom slope, the location and toe height of the oyster reef is kept constant for all slopes. The water level amplitudes are varying from micro to macro tidal ranges and presented in the table below:

Bathymetry slope	Water level amplitude
1 on 400	0.5 metres
1 on 600 (base case)	1.0 metres
1 on 800	1.5 metres (base case)
1 on 1000	2.0 metres
1 on 1200	2.5 metres
	3.0 metres
	3.5 metres

Table 2.2 Applied variation in water level amplitude and bottom slope

2.1.3 Base model with waves

As shown in the mentioned conceptual model, one can expect that the majority of the waves will dissipate energy on structures such as oyster reefs. A sheltered area is expected down drift the incoming wave direction. The period of the incoming wave is kept constant on 6 seconds. The directional spreading is fixed on 4 degrees. The significant wave height (H_s) is varied as presented in the table below:

Significant wave height
0.05 metres
0.10 metres
0.20 metres
0.50 metres

Table 2.3 Applied variation in significant wave height.

The maximum measured wave height in the Eastern Scheldt area is in the order of one metre. Waves with amplitudes of around one metre are physically unable to develop at water depths in the schematic model at average conditions. The extremes in reality occurring during extreme weather conditions in combination with water level setup.

2.2 Evaluation of parameters

2.2.1 Relative change in bottom shear stress

Assessing the impact of the oyster reefs is elaborated by tracking the relative change of the bottom shear stress in observation points. The spreading of the relative change gives an indication for the sensitivity of certain parameters. A reduction in bed shear stress is expected in the near surrounding of the reefs. On the reef itself, the velocities are expected to increase. This results in enhanced bottom shear stresses on the reef.

Transects of observation points perpendicular to the reef are introduced in the numerical domain. Per transect, one observation point is located on the reef. On both sides of the reef, an observation point is located at 10, 22, 45 and 85 metres off the reef (presented in Appendix 4.5A). For these points, the relative bottom shear stress is plotted against the relative water depth.

$$\text{relative } \tau_b < 1 \rightarrow \text{ Reduced bed shear stress}$$

$$\text{relative } \tau_b > 1 \rightarrow \text{ Enhanced bed shear stress}$$

A reduction of the bottom shear stress can be seen as a measure for erosion. A reduction of the bed shear stress means less erosion.

2.2.2 Reduced velocity magnitude

The velocities perpendicular to the reef are assessed over the same transects used above. Enhanced velocities on the reef are expected while down stream of the reef a shelter area with reduced velocities is supposed.

The reach of the sheltered area is quantified by a velocity difference between the base line model and the model including a reef of 0.03 m/s. Such a difference is assumed measurable in the field. This implies that velocities within smaller differences than 0.03 m/s compared to the base line model are considered equal meaning no influence.

2.3 Numerical implementation

The numerical model aims to simulate the effects of oyster reefs in inter tidal areas on (tidal) currents. Since one can expect mirrored flow patterns for the whole reef, only half of the reef is incorporated in the numerical domain. Hereby the model size is halve and computational more efficient.

2.3.1 Numerical model type (3D or 2DV)

In this case, a 2DV model is applied. The 3D model can represent a full logarithmic velocity profile over depth. The 2DV model is able to represent a fitted logarithmic velocity profile. The reef is numerical represented as reduced depths per grid cell. Processes around the reef are expected to be non-hydrostatic. Delft3D is a hydrostatic numerical simulation model; these non-hydrostatic processes are not simulated in either 3D or 2DV. To incorporate a sudden shift in the bottom profile, Delft3D allows using a different numerical scheme locally around the reef.

2.3.2 Applied grid

The highest resolution is required on and around the reefs since one expects deviating flow directions and magnitudes. In the far corners, the lowest resolution is applied. This results in grid cells of one square metre on and around the reef. The lowest resolution applied, is 300 square metres.

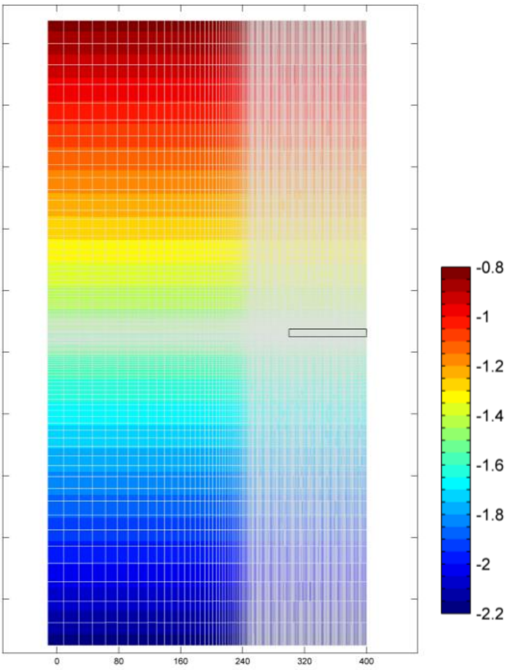

Figure 2.1 Applied grid and baseline bathymetry

2.3.3 Model boundaries

The Western, Northern and Eastern edge of the applied grid (Figure 2.1) are closed boundaries. On the Southern edge, a harmonic water level variation is introduced equidistant over the boundary. The harmonic water level variation follows the following expression over time;

$$\zeta(t) = A\cos\left(\omega t - \varphi\right)$$

In which A is the water level amplitude, in the base line model set to 1.5 metres. The angular frequency (Omega) and the phase lag (phi) are kept constant on respectively 28.984 degrees per hour and zero degrees.

2.3.4 Bottom roughness

For a depth average model, the bed shear stress is related to the depth average velocity. The Manning value for bed roughness is transformed into a Chézy value. From the Chézy value, a friction value (C_f) is deduced and used in the formula presented below:

$$\tau_b = c_f \bar{u} \left| \bar{u} \right|$$

Mature Oyster reefs are significantly rougher than for example mussel reefs (as well found in the Eastern Scheldt area). Several studies on oyster roughness state the hypothesis of the prevailing contribution to reduced velocities around a reef.

For the roughness, depth dependent Manning coefficients are applied. The muddy sand on the tidal flats is represented by a Manning value of 0.01. The Oyster reefs are corresponding to a Manning value of 0.03.

2.4 Essential numerical adjustments

In the schematic case, several numerical adjustments are implemented. These settings are required in order to simulate the flow at sloping inter tidal areas correctly. For reproduction of the numerical set-up, the essential adjustments are presented below.

2.4.1 Drying and flooding scheme

Hydraulic numerical models solve the mass balance and Navier-Stokes equations. Especially in the case of flooding, adaptations in the numerical scheme should be considered. The momentum in flow is entering a grid cell with centimetres of water depth gives high velocities. One can overcome this by introducing a certain minimum water level in a grid cell. However, in the case of the higher threshold, the flooding is jolty.

In order to overcome both problems a Flooding scheme is introduced in Delft3D. The scheme can be activated by modifying the following terms in the MDF-file to:

```
Dpsopt    =    #MAX#
Dpuopt    =    #MIN#
Momsol    =    #FLOOD#
```

The Delft3D manual explains this particular operation in more detail in chapter 10.8.

2.5 Key points

- Variations in parameters are assessed relatively to a base case,
- Variations comprise reef width and height, bottom slope, water level amplitude and significant wave height,
- Impact is assessed on change in bottom shear stress and reach of sheltered areas,
- The numerical model Delft3D is applied in 2DV mode.

3 Impact of oyster reefs

Numerical model results are elaborated and placed in perspective in the following section. In general, in respect to the flow direction behind the reef a lee area is developing. In the figure below, this is most clearly visible on the left-hand side. The ebb flow shows a nice and smooth spatial distribution of the flow magnitude. Velocities on the reef itself at enhanced while behind the reef the flow velocities are reduced.

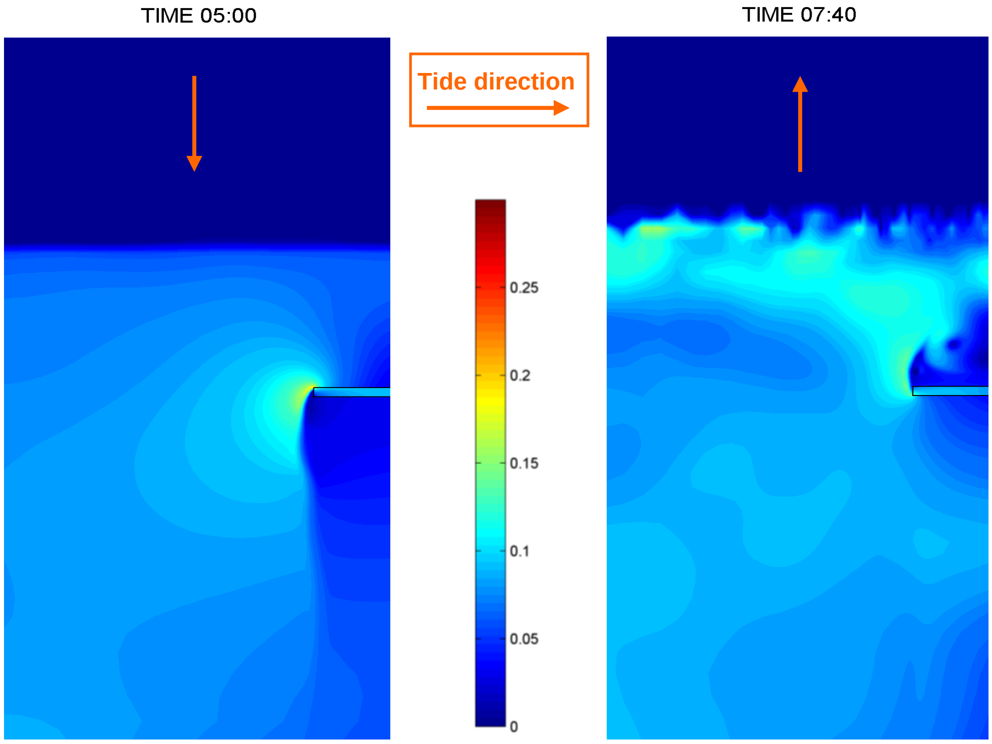

Figure 3.1 Velocity magnitudes during ebb flow (LEFT) and flood flow (RIGHT).

For the flood flow, a similar but joltier effect is simulated. The flow is entering inter tidal areas and behind the reef a shorter lee area is developing. This can be assigned to that the lee area is bounded by the decreasing depths during flood flow. During ebb flow, this limiting effect is less evident due to increasing depths.

3.1 Importance of oyster roughness

As shown above, the reefs induce a leeside with lowered velocities. The importance of oyster reef roughness in the size and decreasing velocities' magnitudes is elaborated below. On the tidal flats, the roughness is set to a Manning value of 0.01 representing sand. The oyster reefs are rougher, a representative Manning value is determined on 0.03. The higher the roughness value, the more kinetic energy is dissipated. This implies the higher the roughness of the reef the more effective it is in reducing flow velocities behind the reef. Figures below show the difference between a mussel reef (Manning 0.02) and an oyster reef (Manning 0.03).

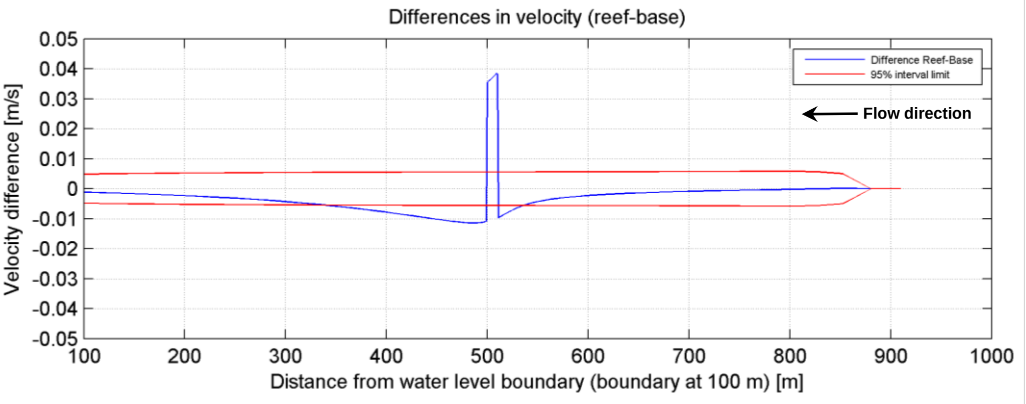

Figure 3.2 Reef roughness 0.02 (Manning) - Difference in depth averaged velocities perpendicular to the reef

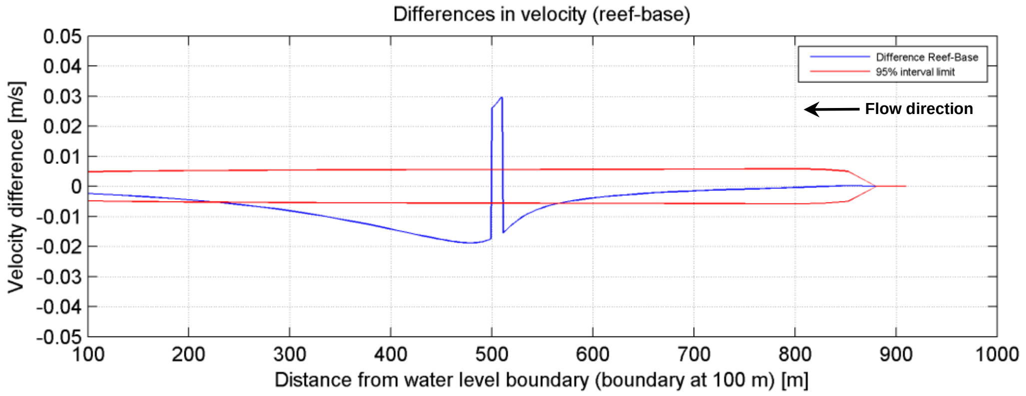

Figure 3.3 Reef roughness 0.03 (Manning) - Difference in depth averaged velocities perpendicular to the reef

Figure 3.2 and Figure 3.3 show velocity differences between the baseline and reef model. The sheltered area on the down drift side of the reef is in the figures above on the left side of the blue peak. The reef induces a topographical steering effect on the current. The flow velocity is enhanced on the reef. Sheltered areas develop down drift the reef where the flow velocity decreases.

Besides the topographical effects, the higher roughness of the reef affects the water body up and down drift. Reefs become more effective in slowing down the current with higher roughness. This effectiveness induces a higher gradient in the velocity differences. The reduced momentum around the reef radiates and amplifies the sheltered area. Lower velocities in the sheltered areas mean lower bed shear stresses and more settling time for the suspended sediment.

3.2 Reef – tidal current interaction

The effect on the bed shear stress induced by the presence of a reef structure can be found in a run without roughness differences. A general trend of the presence of a reef can be deduced. In Figure 3.4 the bed shear stress is tracked on the reef in the middle. The representation below is the result of the base model.

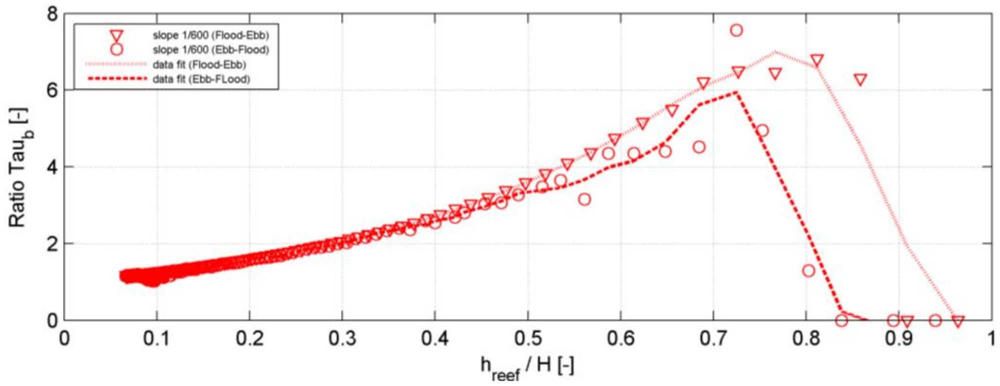

Figure 3.4 Relative bottom shear stress on top of the reef over one tidal cycle (constant roughness whole domain).

During the ebb flow, the bed shear stress gradually increases. The discharge in the model domain is a function of the water level variation. Since the water depth is reduced at the reef, the velocity enhances and thereby the bed shear stresses. When the water level reaches the top of the reef, the velocities drop relatively quickly.

The amplification of the bed shear stress during flood flow follows the same trend as during the ebb flow. The magnitude is slightly lower compared to the ebb flow. A delay in the flow over the reef is induced by the reef itself and flow routes around the reef. The bed shear stresses become significant at a greater depth. Around a water depth of 2.5-3 times the reef height, the ratios are laying on top of each other. For the coming variations, only the ebb flow is elaborated.

3.2.1 Slope variation

Figure 3.5 shows as the water depth decreases the ratio between the bed shear stresses increases. The ratio in bed shear stress starts at an amplification of ten. This can be assigned to the topographical effect and in particular the reef roughness. Around water depths of 2-2.5 times the reef height, spreading in ratio begin to enhance. The steeper the gradient, the more amplification in bed shear stress is simulated on the reef.

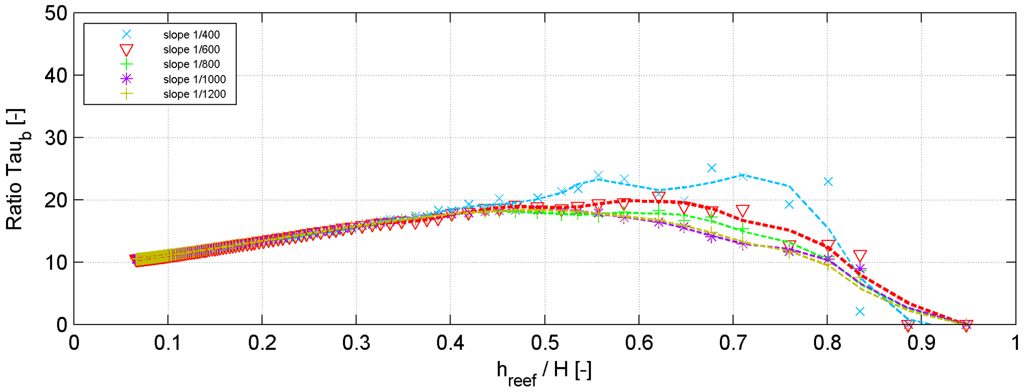

*Figure 3.5 Relative bottom shear stress **on the reef** in case of varying bed slopes.*

There could be generally two reasons. On the one hand, there is less dissipation of kinetic energy in the surroundings of the reef. Which can be explained since the depth is limiting the depth average velocity closer to the reef. This seems to be an unlikely explanation. More convenient might be the slope of the reef itself, following the bottom slope. Under the assumption of a sloped reef, the numerical model simulated 30% more amplification compared to the base line model (red line in Figure 3.5).

The bottom gradients of 1:1000 and 1:1200 show practically similar amplifications. In terms of percentage, the declining bed gradient difference becomes smaller. Logically, smaller differences results in simulation outcomes that are more similar. However, this can be placed in the same perspective of the explanatory hypothesis above.

At the lee side of the reef, the velocities are expected to reduce due to the presence of a reef. A direct consequence is reduced bed shear stresses at the lee side as shown in Figure 3.6. Variation in bed gradients seems to have a significant impact in shallower areas (relative to the reef height) as the water depth reaches 2-2.5 times the reef height.

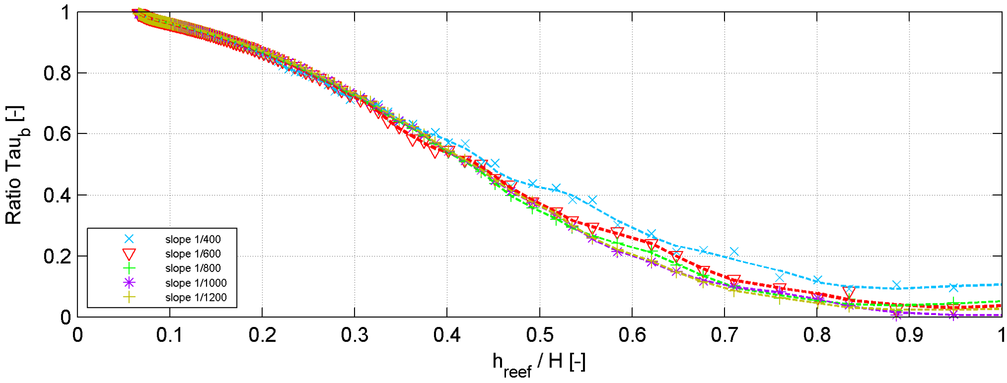

*Figure 3.6 Relative bottom shear stress **behind the reef** in case of varying bed slopes.*

Maximum spreading is found around a factor of 12 in amplification. This factor corresponds to 50% of the maximum amplification. The maximum spreading is particularly found in the regions of a water depth of around 1.20 to 2.25 times the reef height. At larger water depths, the slope in combination with the presence of the reef is considered of minor influence on the bed shear stress. Behind the reef, smaller offsets are found of around 10% of the maximum ratio.

3.2.2 Water level amplitude variation

The case of a variety in water level amplitude the whole range of micro to macro tidal environments is implemented. This implies for a micro tidal environment: 0 – 2 metres mean tidal range. For meso tidal environment: 2 – 4 metres mean tidal range. All ranges larger than four metre tidal range is considered macro tidal. In Figure 3.7, a reef is numerically implemented in a range of water level amplitudes.

The amplitude, implemented as explained in section 2.3.3, varies and the angular frequency is kept constant. Logically, this implies higher flow velocities. Thereby higher bed shear stresses are simulated, as presented in Figure 4.3. However, the ratios in bed shear stresses are quite similar.

The individual points are almost overlaying. The spreading in the data fit line could be mainly assigned to the lack of data points in that region. Less data points are available in the region where the water depth becomes close to reef height. This has to do with the relative differences between data points in the form h_{reef} / H. In addition, the vertical velocity plays a role, in the reduced number of data points.

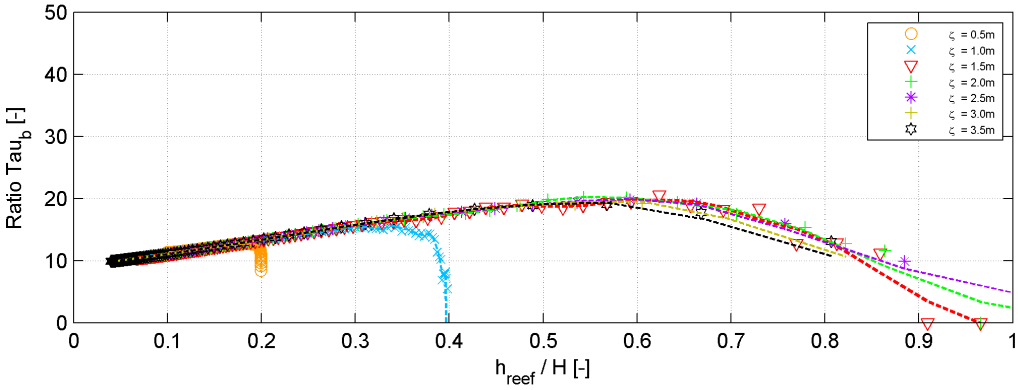

*Figure 3.7 Relative bottom shear stress **on the reef** in case of varying water level amplitudes.*

The smallest amplitudes (0,5metres and 1,0metres) are respectively presented in Figure 3.7 by the blue and orange line. The reef is placed at 1.5metres below MSL, which is zero. With a water level amplitude of 0.5metre there is at minimum one metres water depth. This water depth is equivalent to 0.2 h_{reef} /H. The blue and orange line represents this in both, Figure 3.7 and Figure 3.8.

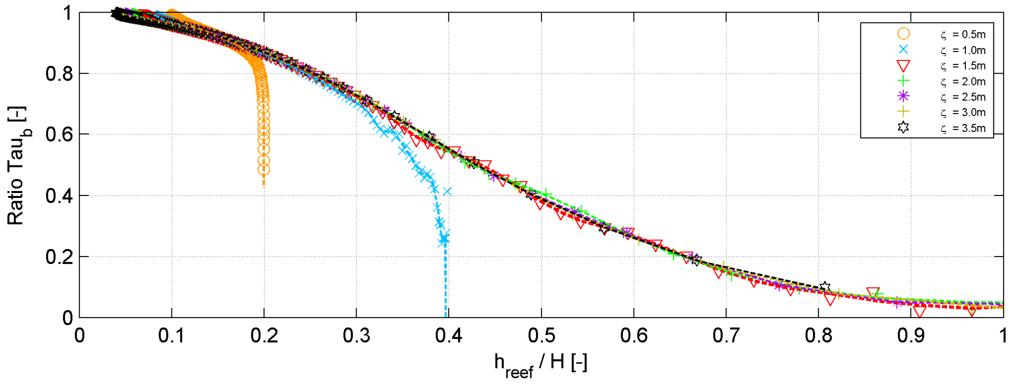

*Figure 3.8 Relative bottom shear stress **behind the reef** in case of varying water level amplitudes.*

Also for the ration in bottom shear stress behind the reef, the trends are overlying. Figure 3.8 indicates that in the near surroundings of the reef, independent on the tidal environment a bottom shear stress ratio appears.

For the water level amplitudes, the maximum spreading is around 5 in amplification ratio. This factor corresponds to 25% of the maximum amplification. This maximum spreading is particularly found in the regions with little water depth on top of the reef. Corresponding amplifications are found in regions with larger water depth, the spreading is negligible. Especially behind the reef, almost no spreading is observed; all the cases give good alignment. This indicates that the tidal environment does not have a strong effect on the bed shear stress in case a reef is implemented.

3.2.3 Reef width variation

The reef width is varied between 2metres and 30metres, as described in section 2.1.2. The bed shear stress is tracked in the middle of the reef for all situations. On the one hand, the distance to the reef edge is enlarging. On the other hand, in the point behind the reef the distance to the reef edge reduces. This can be important in analysing the results in the view of bottom shear stress ratios.

Figure 3.9 shows the enhanced bottom shear stress ratio on top of the reef. For the widest reef, this ratio has a negative slope as the water level reduces. The ratio is starting at 10 due to the topographical effect but especially because of the applied reef roughness. The negative slope indicates that due to the reef width the velocities in the middle of the reef are constantly reduced. In other words, the velocity is over the tidal cycle lowered instead of enhanced.

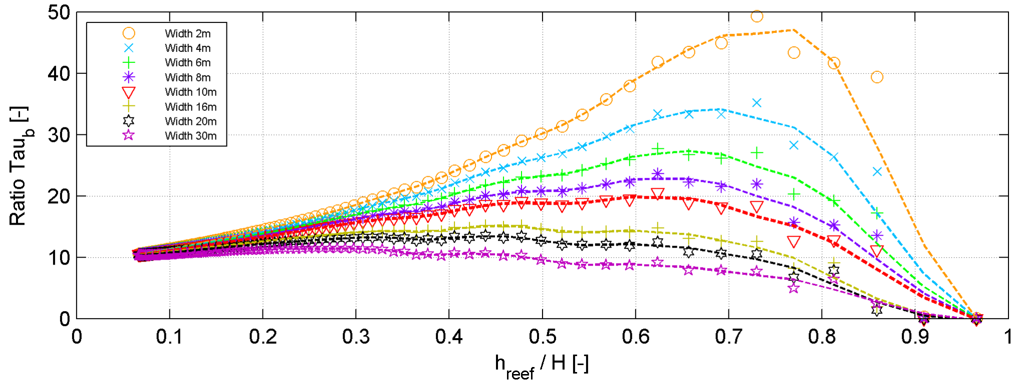

*Figure 3.9 Relative bottom shear stress **on the reef** in case of varying reef widths.*

Contrary to the widest reef, the smallest reef shows an enhancement of around 45 times in bed shear stress. As mentioned, the edge of the reef is closer to the observation point. It is likely that the sudden change in bed level has the largest impact at the reef edges. As the reefs become wider, more energy is dissipated over the width. Thereby the maximum bed shear stress ratio in the observation point in the middle of the reef becomes lower. Possibly, comparable amplifications of the bottom shear stress ratio are found on all reef edges.

Therefore one can argue whether the impact of the reef width is isolated represented in the Figure above. In the smallest reefs, the reef width is too small to become asymptotic to its roughness related bed shear stress, illustrated in Figure 3.10. Although Figure 3.9 gives a nice overview of the sensitivity, one should bear in mind that for the smallest reefs the topographical effects of a reef are prevailing.

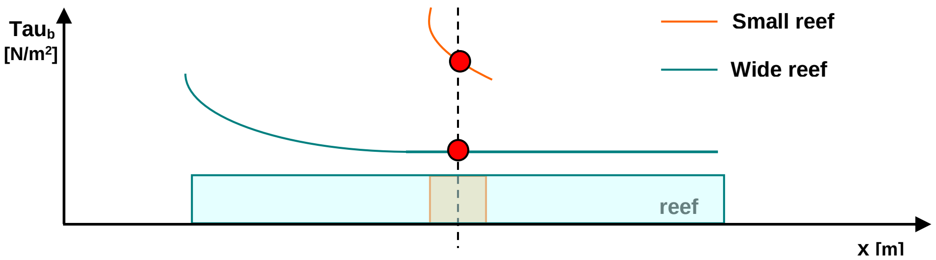

Figure 3.10 Schematic representation of the bed shear stress over a reef (flow in positive x-direction)

Relatively much spreading in the ratio in bed shear stress is found in Figure 3.9 and Figure 3.11. This spreading indicates the sensitivity of the bed shear stress to the width of the reef. The patterns in Figure 3.11 can be assigned to two issues. On the one hand, a wider reef dissipates more energy so the ratio behind the reef is lower, reduction of bed shear stress at the lee side. On the other hand, the distance from the reef determines the trend of the lines.

The observation point from the reef is varied, as presented in Figure C.1. Independent of the distance to the reef, the trends are fairly similar. Relative to each other there is less reduction in bed shear stress closer to the reef. Since the reef is slowing down the velocities at the lee side, the impact of a wider reef is larger. This is clearly shown in Figure 3.11. The gradient until 2.5-2.8 times the reef height is steeper in case of wider reefs. At some point, the water depth becomes dominating since the water cannot cross freely over the reef anymore. Probably the twist of the lines around 2.8 times the reef indicates this point.

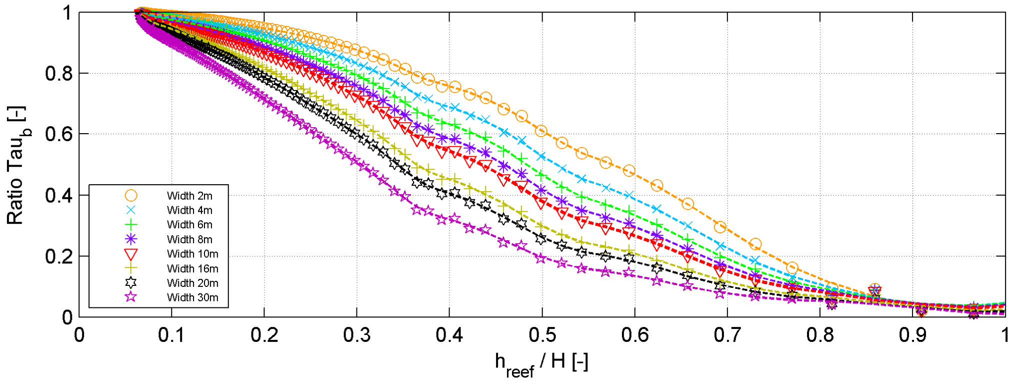

*Figure 3.11 Relative bottom shear stress **behind the reef** in case of varying reef widths.*

The maximum spreading found for the reef width variation is fairly high, around 85% on the reef. The maximum amplification found is around a factor 50. As pointed out above, the large spreading is mainly found because of the large amount of dissipated kinetic energy. Behind the reef a spreading of around 40% is found. The reef width does not seem to have a particular region for the spreading.

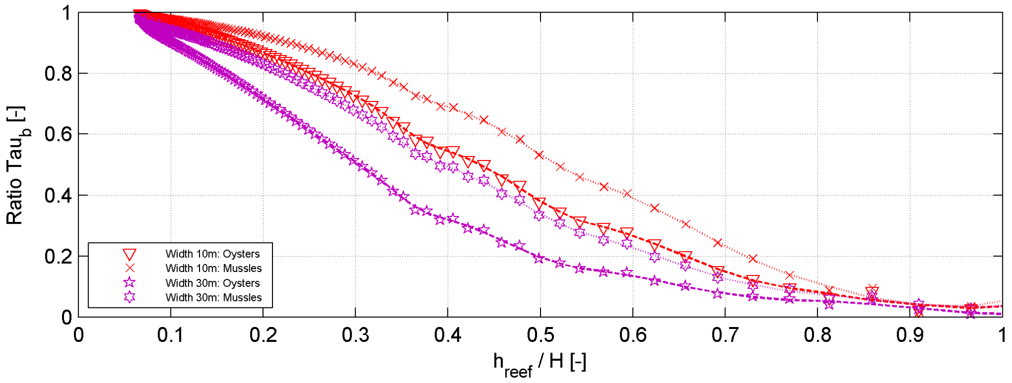

*Figure 3.12 Relative bottom shear stress **behind the reef** in case of varying reef widths and **roughness**.*

Roughness is important in the dissipation of kinetic energy. Figure 3.12 show that roughness differences have an effect behind the reef. Reefs with higher roughness are more effective in reducing the bottom shear stress behind the reef. As shown in section 3.1, more reef roughness induces a higher rate of dissipation around the reef. This is clearly presented in Figure 3.12, a 30metres wide mussel reef reduces with around a similar rate the bed shear stress as an oyster reef.

3.2.4 Reef height variation

Variations are introduced varying from reef height of 0.05metres to 0.7metres. At the start the water level reaches +1.5metres. For the different reefs, specific water depths are introduced. For this reason the start and end per reef height differs along the x-axis. Figure 3.13 shows similar trends for the range 0.05metres to 0.2metres. Although the reef height is 4 times larger in the base line model, the ratio is similar when the water level is around 2 times the reef height.

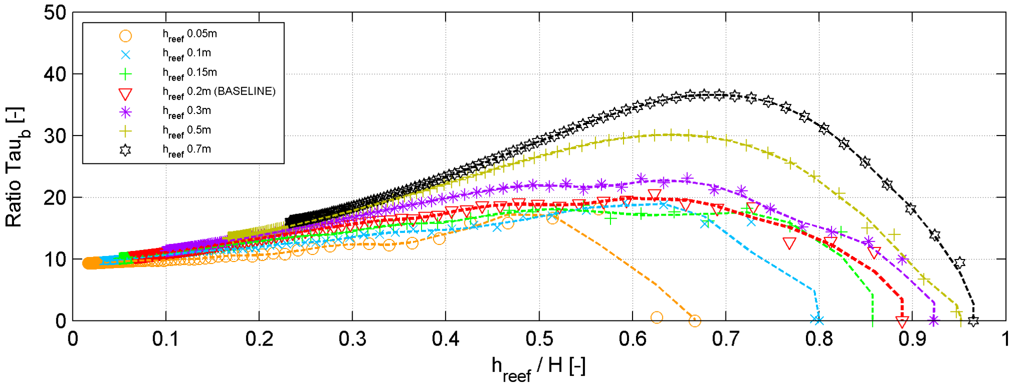

Figure 3.13 Relative bottom shear stress ***on the reef*** *in case of varying reef heights.*

Another trend is observed at the other side of the variation; enlargement of the reef height. While the absolute difference in reef height enlarges, the maximum enhanced ratio in bed shear stresses follows the same trend. With some imagination, the absolute difference in reef heights of 0.3, 0.5 and 0.7metres result in the same increment in maximum ratios; ~23, ~30 and ~37.

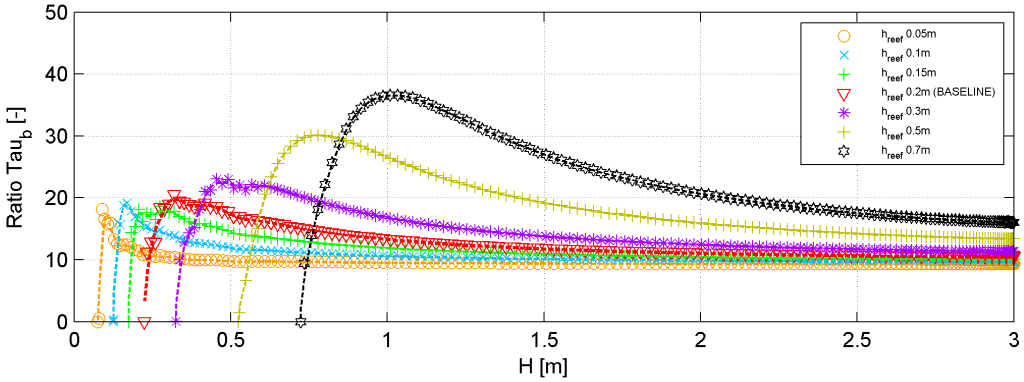

Figure 3.14 Relative bottom shear stress ***on the reef*** *against the* ***water depth*** *in case of varying reef heights*

Although Figure 3.13 gives a nice dimensionless representation, the reef height is as well present in the axis as the data. Figure 3.14 shows the same increasing impact with higher reefs, of a maximum amplification of around factor 40. It shows that there is an impact at greater water depths for the highest reefs. The influence of the lower reefs is rather limited at larger water depths at the trend lines converge to their specific minimum (roughness and height dependent).

For the impact behind the reef a similar plot, ratio Tau$_b$ against the water depth, is created. Figure 3.15 shows reduced bed shear stresses mostly concentrated at shallower waters for the lower reefs. The lower reefs are relatively quick asymptotic to one. The gradient from a ratio Tau$_b$ close to zero is steepest in case of lower reef heights. This implies that the impact of the lower reefs for larger depths is limited. In addition, that the influence is reducing relatively quickly while the influence of largest reef is significant over a larger range of water depths.

For the highest reef, at a water depth of around one metre the maximum gradient is reached in bed shear stress ratio. This corresponds to the maximum bed shear stress on the reef as shown in Figure 3.14.

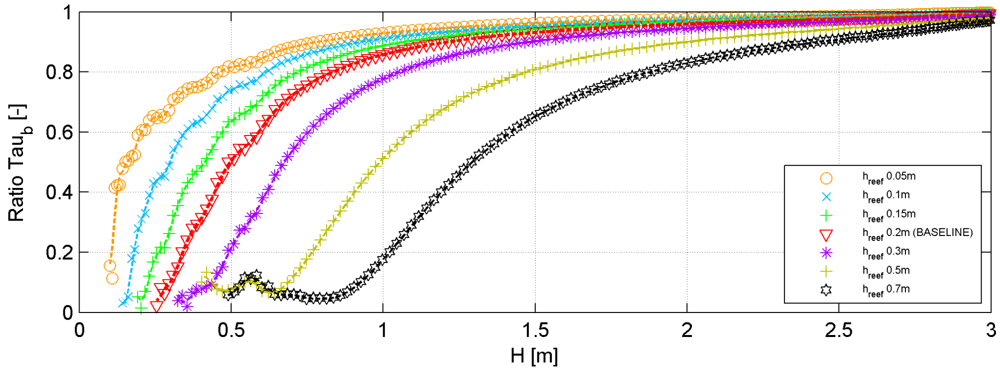

Figure 3.15 Relative bottom shear stress ***behind the reef*** *in case of varying reef heights.*

Considering a target of 80% reduction of the bed shear stress at the leeside of the reef, the most effective solution is the highest reef. It reduces the bed shear stress by to 80% or more of the baseline model behind the reef over a water depth range of zero to almost two metres. The smallest reef is only effective in a range of zero to half a metre water depth. For engineering practices, an optimum can be found for range of water depth, reef height and reef costs.

3.3 Reef – tidal current interaction and waves

As described in the introduction, artificial oyster reefs are placed in the Easter Scheldt in the framework *Building with Nature*. Measurements around the oyster reefs are analysed resulting in a conceptual model (Prooijen and Volp, 2011) for describing wave dissipation around a reef. The conceptual model applied in the Eastern Scheldt at Viane West is shown in the figure below.

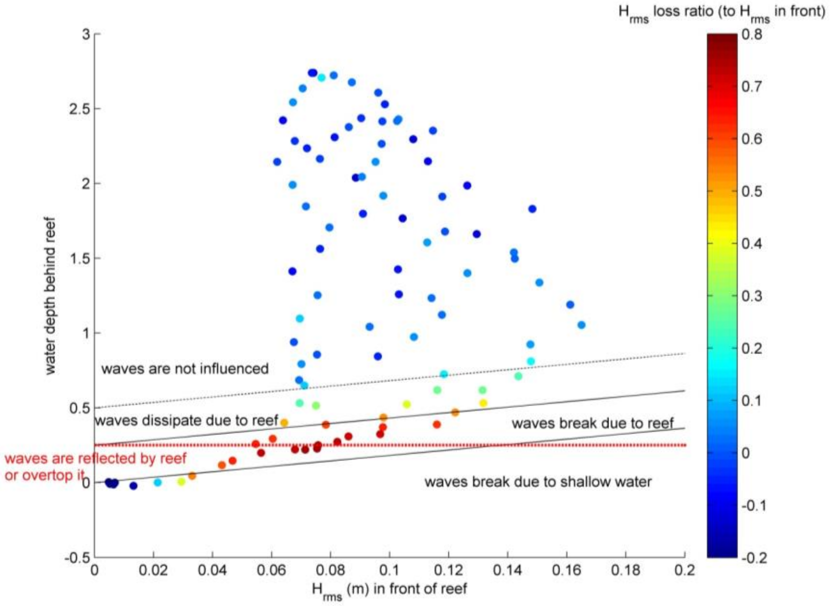

Figure 3.16 Conceptual model deduced from field data (Modified from Prooijen and Volp, 2011).

For the numerical computation, a wave model (SWAN) is introduced. Figure 3.18 shows a spatial distribution of the significant wave height. Waves entering the numerical domain at the Southern boundary are travelling up North. The wave height reduces gradually as the water depth decreases. Behind the reef on the right side, a lee area of reduced wave heights is simulated. Following the simulation, the reef makes the waves dissipate energy at this particular depth.

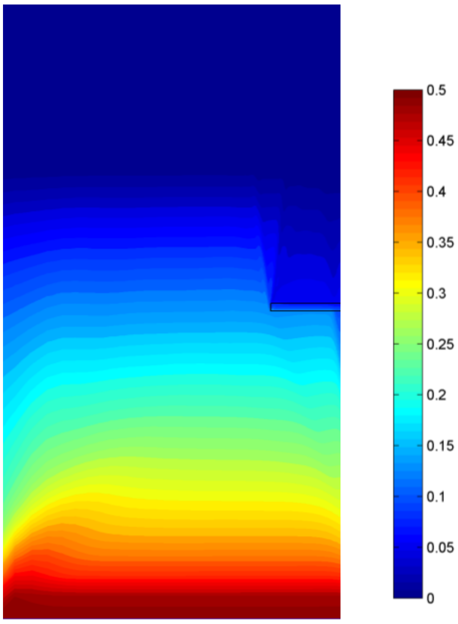

Figure 3.17 Spatial distribution of the significant wave height in case of H_s = 0,5metres at the boundary

At different water depths, different dissipation rates hold (shown the conceptual model). Figure 3.17, shows this difference in significant wave height in front, on and behind the reef. In front of the reef, 65-70% of the significant wave height at the boundary is left at larger water depths. As the water depth decreases the wave heights decline. Towards a water level at the same level of the top of the reef, the waves are fully dissipated.

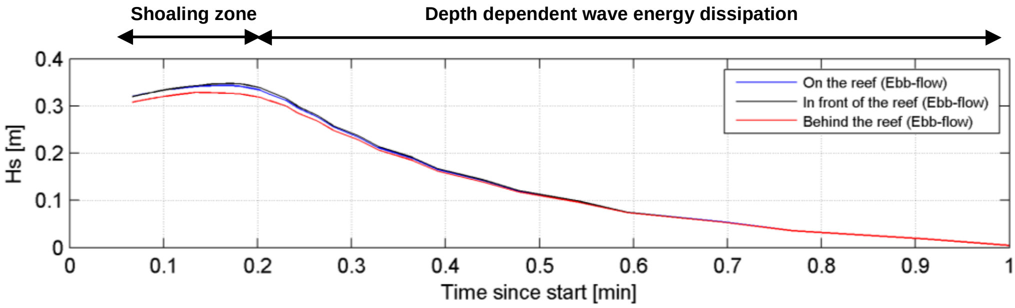

Figure 3.18 Significant wave height in time at different location – Boundary H_s = 0,5metres

The difference in significant wave height between the blue/black line and the red line represents the wave height loss over the reef. At the larger water depths, the wave height is reduced by around 10%. The maximum difference is found at water depths of around 6 times the reef height. Closer to a h_{reef}/H ratio of one, the significant wave heights are close to zero and dissipation over the reef is becoming less.

Dissipated energy can be expressed in the energy loss over the reef, as presented in Figure 3.19. As described above; after a peak around water depths of 6 times the reef height (for a H_S of 0.5metres), the dissipation of energy decreases as the water depth decreases. At water depths of around twice to 2.5 the reef height, the energy loss is less than 5% of the maximum loss.

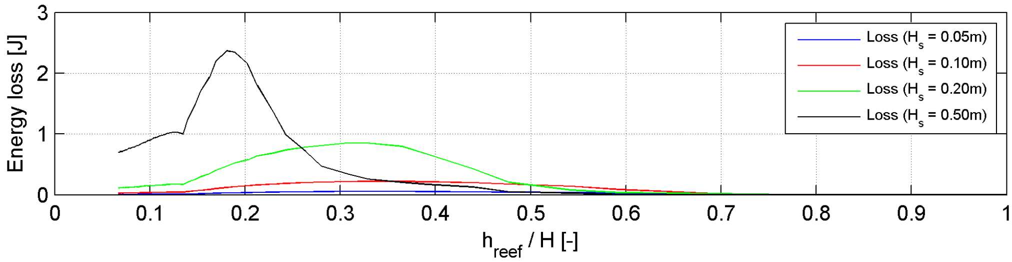

Figure 3.19 Wave energy loss over the reef in time in case of different wave heights at the model boundary.

Figure 3.19 shows a logical effect of lower maxima in energy loss over the reef in case the significant wave heights at the boundary are lower. The energy loss is more peaked in case of waves that are more energetic. The trend shows an increasing energy loss at first. This is due to the shoaling effect, subsequently the energy loss decreases since the waves become depth limited in front of the reef. The variance increases as the significant wave height decline. The lower energetic waves encounter less energy dissipation but continue to dissipate at shallower water.

A maximum energy dissipation rate found is around 0.2-0.3 J/m. Compared to the conceptual model (around 0.8 J/m) this is significantly lower. In this perspective, the oyster reefs are considered not yet well integrated in the SWAN model. On the one hand, SWAN might not be that suitable for these shallow water applications. On the other hand, SWAN as such accounts more for the depth changes. To overcome this, the roughness parameterisation can be implemented more closely to reality by applying a vegetation module.

3.4 Tidal currents, sheltering effect

In the near surroundings of the reef, a sheltered area expected. The reach is expressed in the distance from the reef where reduced velocities are present. In absolute value, the occurred velocities are around 0.3-0.4 metres per second in the baseline model. The differences in velocities between the baseline model and the reef models are one order of magnitude lower. In order to determine whether an area experiences a significant difference, the boundary is set to 0.03m/s. If the difference in absolute value is larger than 0.03m/s, the area is considered influenced by the reef.

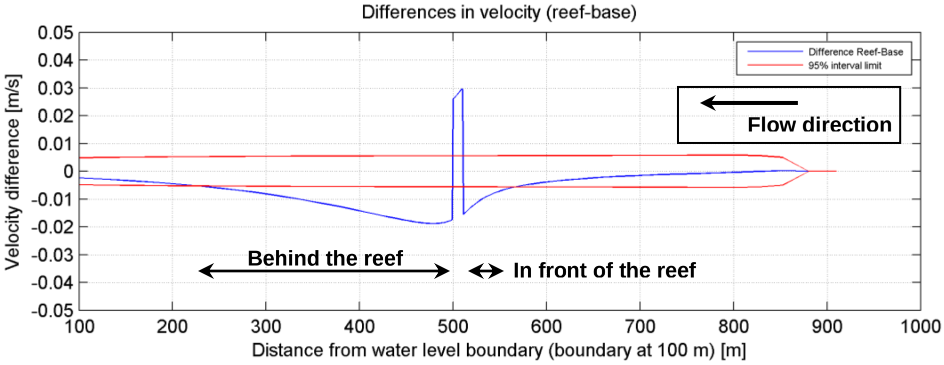

Figure 3.20 Influenced areas around an oyster reef.

The flow direction is leading in the determination whether an area is in front or behind a reef. Figure 3.20 shows this flow dependent determination during ebb flow. During flood flow for example, the flow direction is opposite. For this report, the influenced distance is elaborated during the ebb flow. The different lines in the figures represent the specific variation.

In time during ebb flow, the velocities increase and subsequently decrease again. The influenced distance is depending on the occurring velocity difference and occurring velocity magnitudes. It can be expected that the higher velocities give higher velocity differences.

3.4.1 Slope variation

The area behind the reef is influenced for all applied slopes around a similar time from the simulation start. A maximum influenced area of around 200-250metres behind the reef is relatively similar for slope more gentile than 1/600, as shown in Figure 3.21. The steeper slopes show more variation in maximum length. Due to the more rapid increase of depth behind the reef, the influences decline.

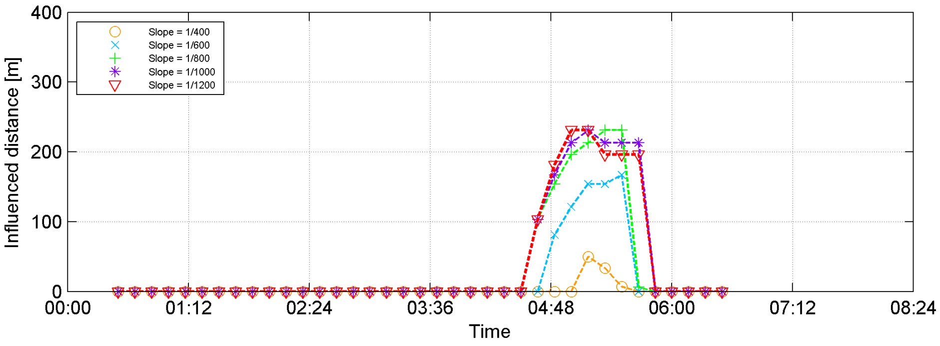

*Figure 3.21 Influenced distance **behind** the reef in case of slope variations*

Figure 3.22 shows the influenced area in front of the reef. Maxima are found at similar time points referring to the maximum simulated velocities. The maxima are significantly lower, around 80 metres for the gentlest slope.

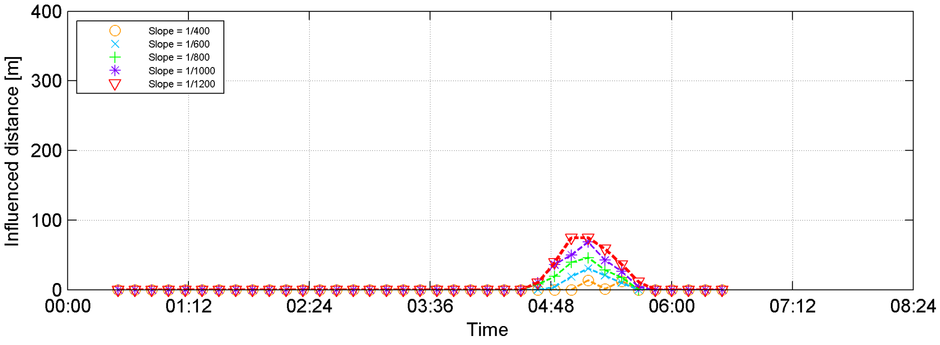

*Figure 3.22 Influenced distance **in front** of the reef in case of slope variations.*

In order to weight the impact the area underneath the influenced differences is integrated per minute. A trend of decreasing influenced area is found for the increasing slope angles. Only the two gentlest slopes show similar integrated areas. As the slope angle declines the influence increases and tend to reach a maximum, shown in Figure 3.23.

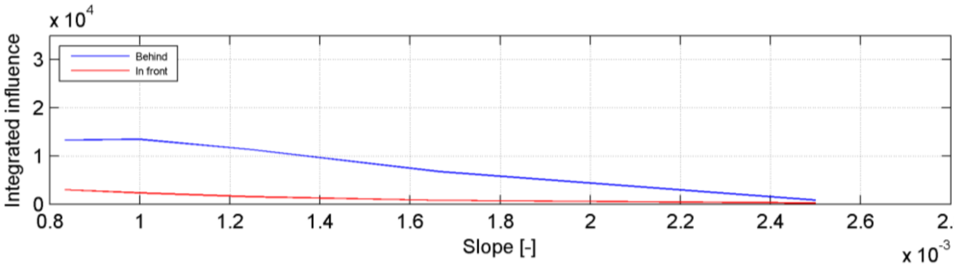

Figure 3.23 Integrated trend lines of influenced areas per minute time for slope variations

In the previous section is shown that there is not much spreading in bed shear stress ratio for varying bed slopes. Compared to the influenced distance this means that the reduced bed shear stress extents significantly more far at gentile slopes and has therefore greater impact.

3.4.2 Water level amplitude variation

Logically influenced distance behind the reef is a function of the reef dimension but certainly also of the occurring flow velocities. Since the amplitude is larger but the angular frequency is higher, the velocities are higher; the reef dries quicker and visa versa. The influence area should be larger but last shorter for the larger amplitudes, compared to the small amplitudes. As shown in Figure 3.24, the maximum influenced area (around 350 metres) is larger for greater amplitudes and declines gradually as the amplitudes decrease. On the other hand, the time that the area is influenced is larger. For the amplitudes, 1 to 0.5 metre the influenced area is not present.

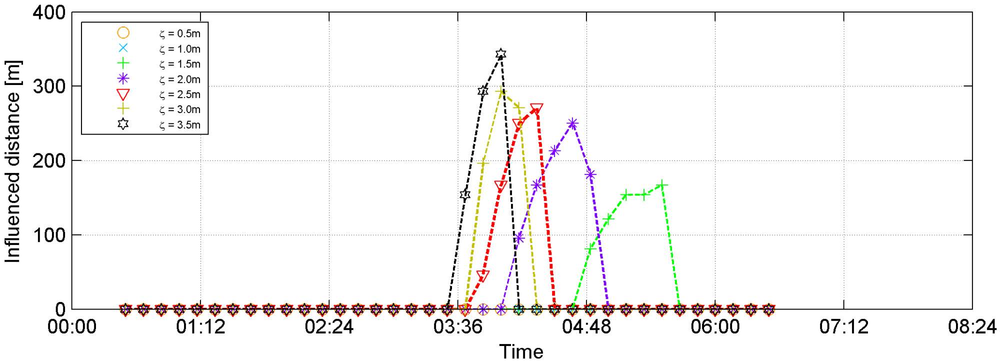

Figure 3.24 Influenced distance ***behind*** *the reef in case of slope variations*

In front of the reef, the influenced area is also not present for the two lowest amplitudes. For the three highest amplitudes, the maxima are surprisingly similar (around 100 metres). As the amplitudes decline, the maximum influenced length in front declines corresponding.

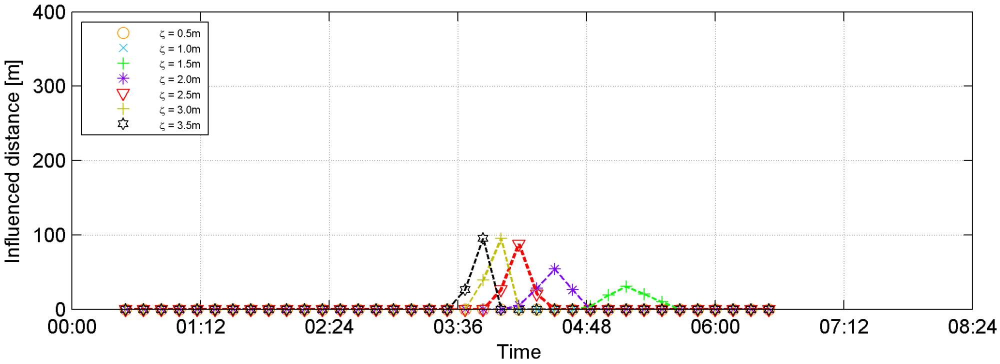

Figure 3.25 Influenced distance ***in front*** *of the reef in case of water level variations.*

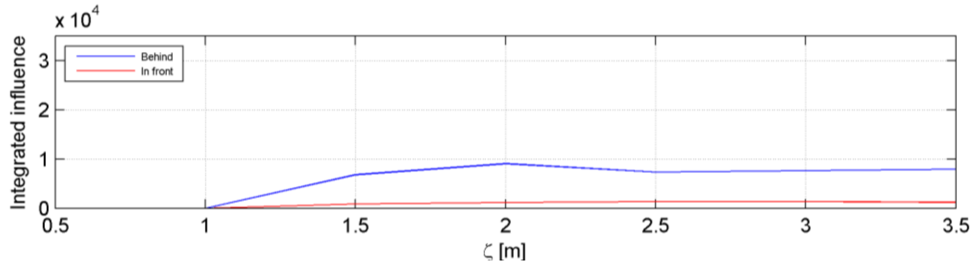

Figure 3.26 Integrated trend lines of influenced areas per minute time for water level amplitude variations

As mentioned above, the maxima of the influenced area are higher but last shorter. The integration per minute of the trend lines shows this interaction between time and maximum distance. After the two amplitudes with no lee area, the influenced area increases gradually to a maximum at a water level elevation of two metres at stays more or less constant.

3.4.3 Reef width variation

The reef width determines greatly the amount of kinetic energy dissipation. Logically, the influenced area enhances when the reef width increases. This shown in the figure below; the distance increases gradually in correspondence with the reef width. The maximum of the widest reef (~320metres) is almost three times the smallest reef (~120metres). Not only the maximum is higher, the influence last longer as well.

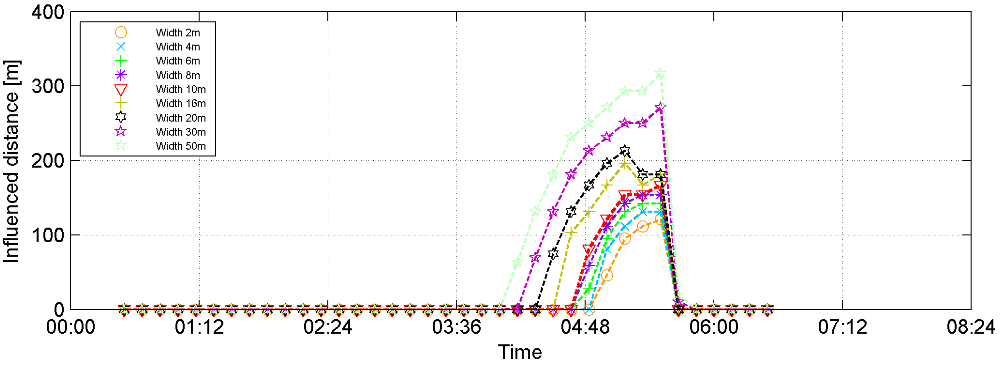

*Figure 3.27 Influenced distance **behind** the reef in case of slope variations*

A quite similar trend is found for the influenced area in the front of the reef although the maxima are significantly lower (around 50metres). In both figures, skewness in the signal is present; an increase followed by more rapid overlaying descends.

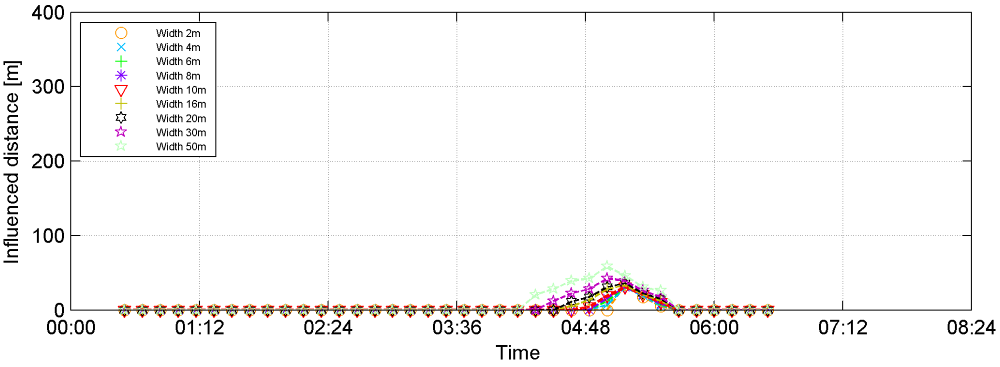

*Figure 3.28 Influenced distance **in front** of the reef in case of reef width variations.*

As the increase in influenced distance starts earlier in time and the descend stays similar, the integration will give increasing values as the width increases. This is clearly shown in Figure 3.29, a gradually increasing value for the integrated area per minute. Compared to the similar figures for the bed slope and water level amplitude, the integrated value is around twice for the maximum in case of reef width.

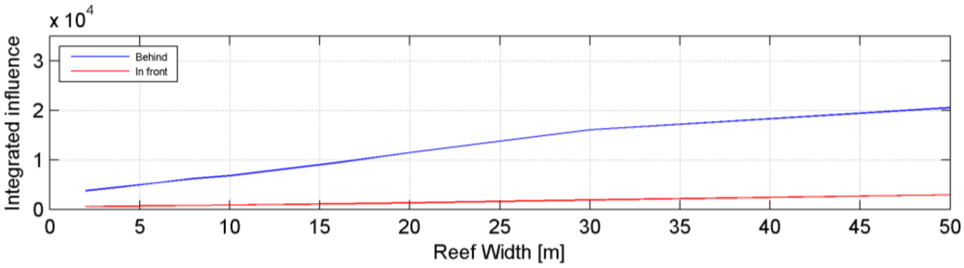

Figure 3.29 Integrated trend lines of influenced areas per minute time for reef width variations

3.4.4 Reef height variation

Skewness as found at the reef width variations is also found for the reef heights. The reef height show the highest maximum values (around 470metres) of the influenced area compared to all other variations. As shown in the sections above, the bottom shear stress is most sensitive to the reef height. The same is found for the influenced areas. The highest reef has also the largest time slot wherein a lee area is developed.

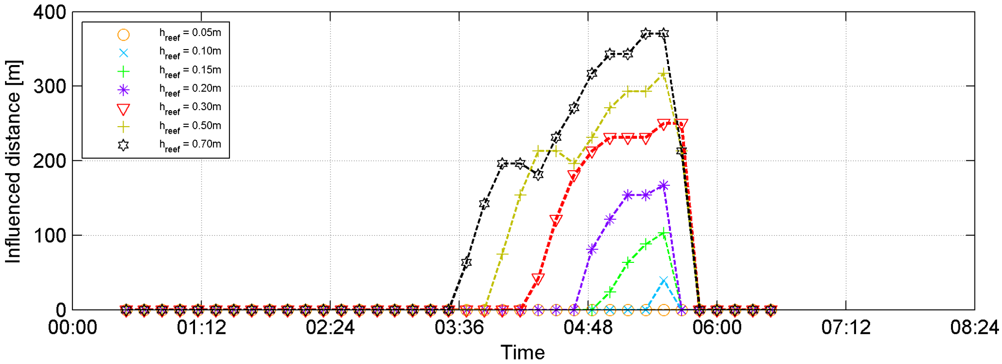

*Figure 3.30 Influenced distance **behind** the reef in case of slope variations*

The influenced area in front of the reef shows a maximum of around 100 metres. The trends in front of the reef show skewness with more rapid increase in influenced distance than the decline. Figure 3.31 show an increased area under the trend line with enhancing reef heights.

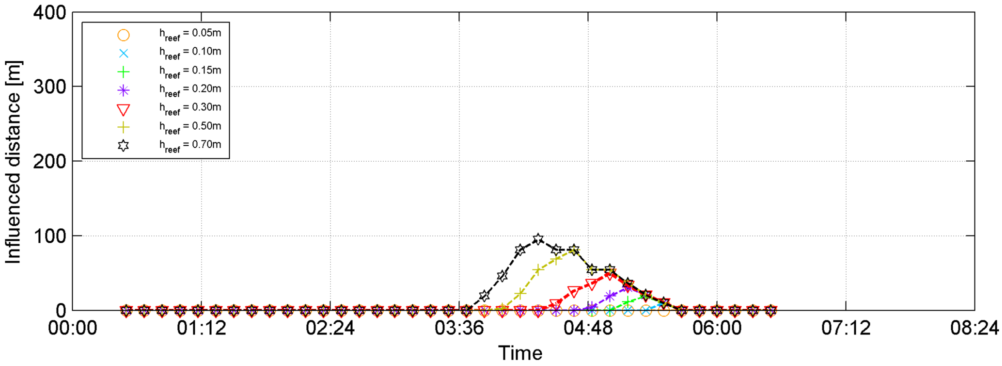

*Figure 3.31 Influenced distance **in front** of the reef in case of reef height variations.*

The influenced distance integrated per minute, shows similar trends. For the reef height, the integrated area reaches the absolute maximum compared to all the variations.

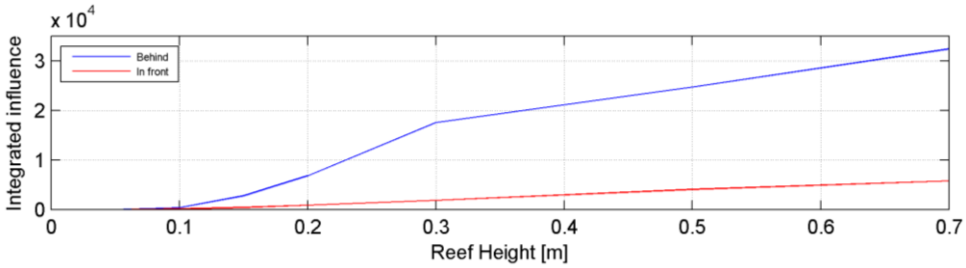

Figure 3.32 Integrated trend lines of influenced areas per minute time for reef height variations

3.5 Key points

- Bed shear stress ratio more sensitive to reef dimensions and relative less sensitive to the surrounding environment
- The influenced area is most sensitive to reef dimensions
- Besides the highest sensitivity on the reef height, the reef height also induces the greatest lee areas behind the reef.
- Utilising SWAN as such, does not represent the dissipation of waves over the reef in acceptable accuracy. The vegetation module should be implemented.
- Influenced area behind the reef for currents influenced by waves is not yet assessed and should be elaborated after implementation of the vegetation module.
- Determine a critical bed shear stress for healthy oyster reefs in order to access the allowed amplification in bed shear stress.

4 Conclusions

Up to amplifications of a factor of 50 are found in the simulation results. This amplification has to be placed in perspective; nothing times a lot is still nothing. The focus in the conclusions is therefore more on the spreading in the results. The spreading indicates the dependency on the specific parameter.

4.1 General

The dependency or significance of a parameter is determined on basis of its spreading. The maximum spreading varies from 25% to 85%; starting from the largest spreading; Reef width (85%), Reef height, (50%), slope (50%) and tidal amplitude (25%). As well, the absolute amplification of the bed shear stress gives the same order. The reef width can be seen as the parameter that influences the bed shear stress the most in the middle of the reef.

4.1.1 Critical shear stress and shape of the reef

Behind the reef, lowering of the reef induces corresponding lower bed shear stresses behind the reef. This is mainly due to the low impact of a small reef and is therefore not really an effective solution. Widening is a more effective solution. The amplification reaches factors of around 50. Information on maximum allowable bed shear stress for a healthy reef would be required in a design tool to determine the allowable reef width.

The possible impact is more sensible to the reef dimensions compared to the local environment. For now, the form of the reef is rectangular. Different shapes, more close to natural forms, would be interesting to investigate.

4.2 Bottom shear stress

The first section of the results shows the impact of the placement of oyster reefs on the bottom shear stress. For the oyster reefs, higher bed roughness values are assigned for the bed. The bottom shear stress is linearly, related to the bed roughness.

4.2.1 Hydraulic environment

Two parameters are varied in this study concerning the hydraulic environment, namely the water level amplitude and the bed slope. Depending on this variation, the maximum spreading found is around 50% for the slope variation. These relative large spreading is especially found in regions of a water depth equal to 1.20 to 2.25 times the reef height. The maximum amplification is around a factor of 24. Besides this spreading, the overall trends are similar.

Trends that are found for different water level amplitudes are nearly overlaying. Especially for the larger water depths, the spreading is close to zero. Independent of the tidal environment, the reef has the same amplification in bed shear stress. This off course does not mean that similar values of bed shear stress are found. For the variation in slopes, the larger impacts are found for the larger bed gradients. This is mainly due to the slope dependent energy dissipation on top of the reef.

With maximum amplification between 20 and 25, the impact is relative to the dimension variation; moderate.

4.2.2 Reef Dimensions

For the reef dimensions, also two parameters are varied namely the reef width and height. The dimensions show more absolute spreading of respectively 40 and 19 in amplification factor. In percentages, this means a spreading of around 85% and 50% of the maximum amplification. The maximum amplification factors found are respectively around 48 and 37.

The variety in reef dimensions does not give a particular region of large spreading, over all water depths the spreading exists. As the water depth decreases, the spreading increases until the water depth reaches one to 1.10 times the reef height. With respect to the hydraulic environment, reef dimensions have similar to twice as much impact.

4.3 Sheltered area

Lee sides area developing in the most of the applied scenarios. Only the lowest reef height and low energetic water level amplification of one and half a metre shows no sheltered area. The largest distances are developing in the timeslot with highest velocities. The maximum simulated distance is with a reef height of 70 centimetres and reaches around 370 metres. Behind the reef, the lee area length is for all simulations with a lee area development in the order of hundred of metres.

4.4 Discussion

In the following discussion, the absolute reduction of the oyster reefs and application on larger scales is elaborated and placed in perspective.

4.4.1 Flow velocities and morphology

Occurring velocity magnitudes are depending on the tidal range and wave influences. In general, in the intertidal areas, the tidal variation is prevailing in the generation of currents in respect to waves. The maximum simulated velocity magnitudes for 1.5m water level amplitude are around 0.3 – 0.4 metres per second. The reef induced velocity difference is an order of magnitude lower.

Reduction of the flow velocities might be considered limit in absolute value. The bed shear stress is quadratic related to the velocity. This implies that as the velocity enhances, the bed shear stress amplifies double. In addition, considering suspended sediment transport, which is current driven, is in the order to the 4th to 5th power of the velocity.

In the field, an important factor in accumulation or erosion of sediment is the tidal asymmetry. As just mentioned, suspended transport of sediments is to the 4th or 5th power related to the flow velocity. The difference in ebb and flood flow velocities prevail in suspended sediment morphology. Relative reduction of flow velocities will be present at both sides of the oyster reef and will enhance the sediment.

4.4.2 Large scale application of oyster reefs

The oyster reefs induce a reduced velocity magnitude, thus bed shear stress, behind the reef. On the larger scale, the application of oyster reefs in intertidal areas is limited since adaption in regional flow regimes occur. Reasonable change in regional system can be expected. The reefs dissipate kinetic energy. On the one hand, this dissipation of energy leads to a concentration of the current to the main gullies. On the other hand, it leads to sedimentation due to oyster reefs on the flats and can lead to too much accumulation of sediments and severe hydraulic changes in the regional domain.

4.5 Recommendations

The recommendations are summed below:

- Implement the reef roughness in SWAN by utilising the vegetation module of SWAN,
- Comparison with the conceptual model after implementation of SWAN' vegetation module,
- Investigate the influence of different reef shapes. More natural shapes such as elliptic shapes, varying heights and top of the slopes,
- Determine a critical bed shear stress for a healthy oyster reef,
- Extent the graphical information in this report to relation between integrated area (A), varied parameter (Width), reef height (h_{reef}) and tidal amplitude (H):

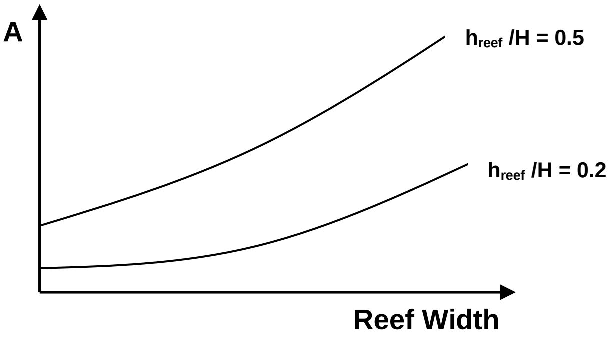

Figure 4.1 Illustration of possible engineering tool.

- A could also be replaced with bed shear stress (Tau_b),
- The model domain might be extended in length until 600 a 700 metres from the reef.

A Observation points

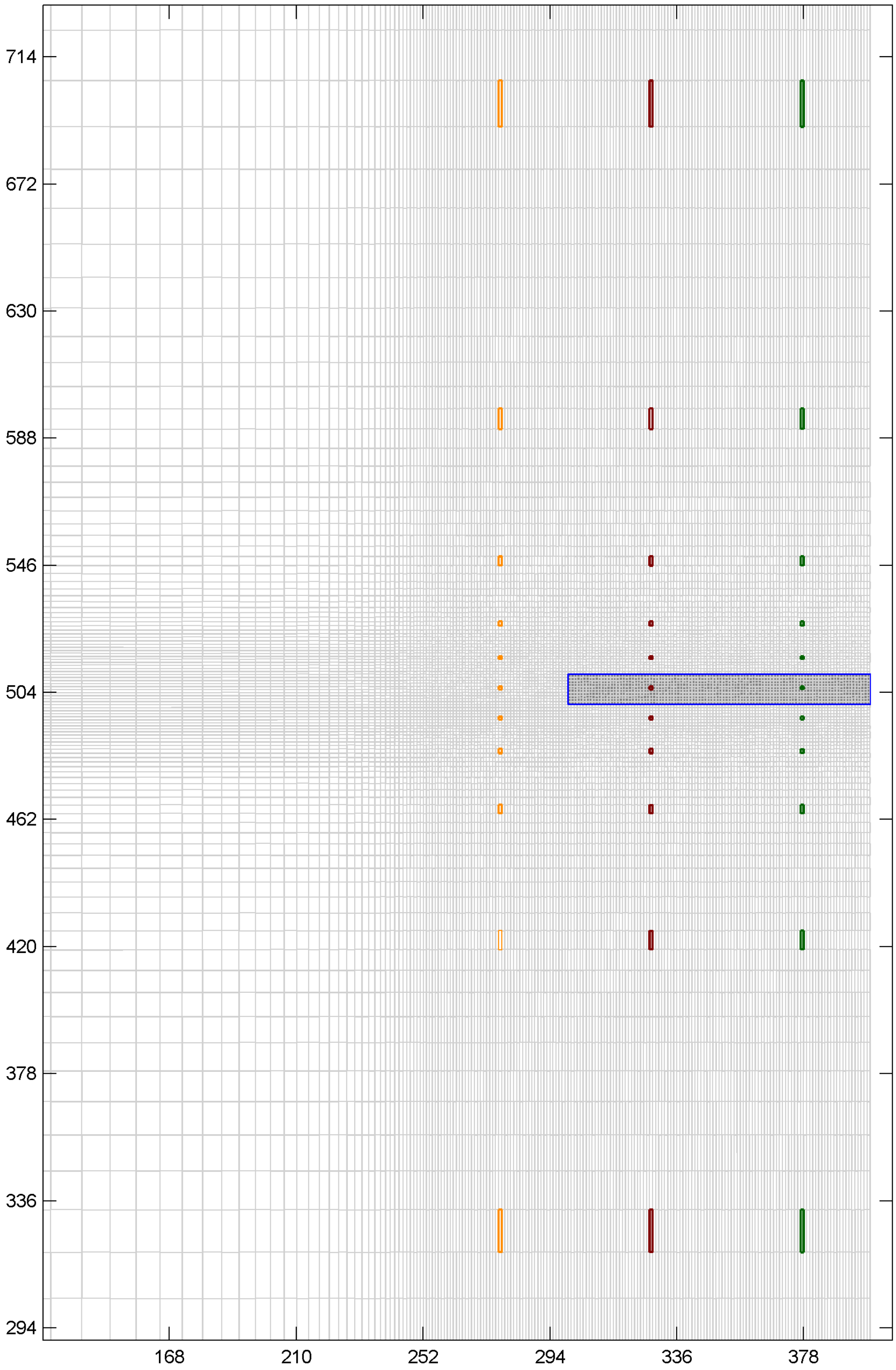

Figure 4.2 Observation positions

B Water level amplitudes

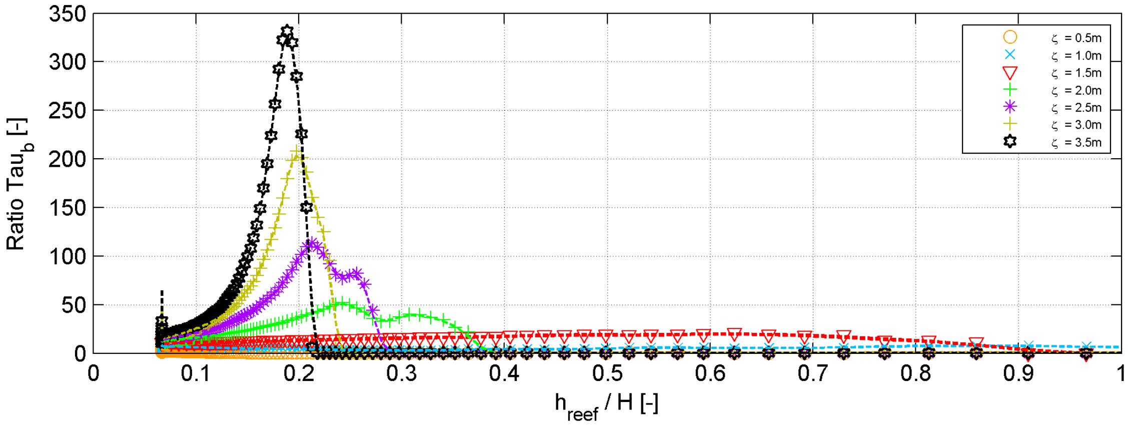

Figure 4.3 Relative bottom shear stress ***on the reef*** *in case of varying water level amplitudes (rel. to base line).*

C Reef width variation

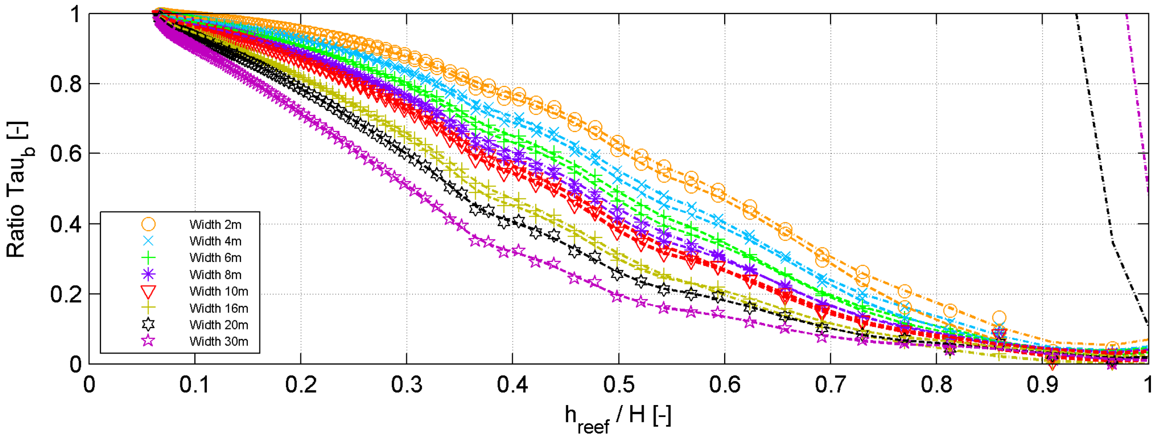

*Figure C.1 Relative bottom shear stress **behind the reef** in case of varying reef widths. (-.- 10m from reef), (- - 20m)*