Impact of wave-current interaction on wind generated waves in low-land river systems

Progress report 2007

Report

January 2008
Impact of wave-current interaction on wind generated waves in low-land river systems

Progress report 2007

S.van Vuren, H.J. Verheij and J. I. Crebas

Report

January 2008
Crest levels of river dykes along the major rivers Rhine and Meuse are determined on the basis of the so-called ‘design water levels’ plus a freeboard height. The freeboard allowance is amongst others chosen on the basis of wave run up. Run up of wind generated waves mainly depends on local wave characteristics (wave height, wave period, wave steepness and wave direction), and the geometry and characteristics of the dyke and, if present, berms and foreshores.

In the present design method, the impact of currents on wave conditions at the toe of the river dyke is left out of consideration. Wave experts and results of reconnaissance research studies indicate that the influence of currents on wind generated waves could be of relevant importance. However, practical rules or guidelines to incorporate the impact of currents in the prediction of wave characteristics are still lacking. The issue of wave current interaction is addressed in an ongoing project. The main objective of the project is to develop a guideline for the influence of currents on the characteristics of wind generated waves during design flood conditions in order to design and check crest levels of dykes. The project is restricted to conditions in river systems, i.e. narrow water systems with short fetch length, complex geometry, and limited wind speeds.

This Progress Report presents the results of the activities carried out in 2007. The last-year project consists of a case study on a river section in the Waal, one of the Rhine branches in the Netherlands. The objective of this part of the project was to determine the importance of the various processes (viz. refraction, diffraction, breaking, wave-current interaction, reflection, and white-capping) that modify wave conditions. Moreover an expert gives his opinion on the suitability of SWAN in narrow fetch river systems.

It is recommended to continue the research in 2008 with 1) carrying out field or flume measurements to increase the insight into the impact of currents on waves and importance underlying mechanisms; 2) linking the present research project with research on wave-current interaction in other water systems, for instance in the Waddensee; 3) considering the proposed options to improve the suitability of SWAN in narrow fetch river systems; and 4) revising the sensitivity analysis of the present study after improving SWAN for narrow fetch river systems.
Contents

1 Introduction...........................................................................................................1–1
1.1 Background and problem definition .........................................................1–1
1.2 Objectives ..................................................................................................1–1
1.3 Activities in 2006.......................................................................................1–2
1.4 Summary of activities in 2007...................................................................1–2

2 Suitability of SWAN..............................................................................................2–1
2.1 Introduction................................................................................................2–1
2.2 Background of SWAN ...............................................................................2–1
2.3 Suitability and limitations for narrow fetch river systems .......................2–2
2.4 Options to improve SWAN for narrow fetch river systems.......................2–3
2.5 Conclusions and recommendations ...........................................................2–4

3 Sensitivity analysis ................................................................................................3–1
3.1 Introduction................................................................................................3–1
3.2 Wave-current interaction............................................................................3–1
3.3 Wave propagation and dissipation processes.............................................3–1
3.4 Conclusions and recommendations ...........................................................3–2

4 Planned activities for 2008 ...................................................................................4–1

5 References..............................................................................................................5–1

Appendix
A Memo: Sensitivity analysis..................................................................................A–1
A.1 Introduction...............................................................................................A–1
A.1.1 Background..................................................................................A–1
A.1.2 Research activities 2006 ..............................................................A–1
A.1.3 Objective of this memo................................................................A–2
A.2 Method: research area, models & sensitivity analysis ..............................A–3
A.2.1 Research area: Rhine in the Netherlands .....................................A–3
A.2.2 Coupling between a hydrodynamic and wave model ..................A–5
A.2.3 Set-up of the reference model...................................................A–5
A.2.4 Sensitivity analysis ......................................................................A–8
A.3 Wave-current interaction...........................................................................A–8
A.3.1 Introduction..................................................................................A–8
A.3.2 Flow results..................................................................................A–9
A.3.3 Results simulation with Delft3D and SWAN coupling.................A–11
A.3.4 Comparison with Bretschneider.................................A–23
A.4 Wave propagation and dissipation processes.........................A–25
A.4.1 Wave propagation processes........................................A–25
A.4.2 Wave dissipation processes.........................................A–32
A.5 Conclusions and recommendations ........................................A–37
A.5.1 Conclusions ..............................................................A–37
A.5.2 Recommendations.....................................................A–40
A.6 Annex 1: Effects of weirs in the wave model........................A–42
A.7 Annex 2: Settings of the SWAN-parameters...........................A–47
A.8 Annex 3: Detailed results of computations.............................A–49
A.8.1 Wave-modelling without (nc) and with (yc) current.........A–49
A.8.2 Comparison with Bretschneider.....................................A–50
A.8.3 Refraction .................................................................A–51
A.8.4 White-capping..........................................................A–52
A.8.5 Depth-induced breaking...............................................A–53
A.8.6 Bottom friction.........................................................A–54
1 Introduction

1.1 Background and problem definition

Crest levels of river dykes along the major rivers Rhine and Meuse are determined on the basis of the so-called ‘design water levels’ plus a freeboard height, needed to cope with, for instance, wind-wave run-up, wind set-up, settlement and soil consolidation, etc. In fact, the freeboard is a vertical safety margin between the design water level and the dyke crest level.

Run-up of wind generated waves mainly depends on local wave characteristics (wave height, wave period, wave steepness and wave direction), and the geometry and characteristics of the dyke and, if present, berms and foreshores. In the present design method, wave parameters are determined with the empirical Bretschneider wave growth formulae, see TAW (1985). The impact of currents on wave conditions at the toe of the river dyke is left out of consideration.

The issue of wave-current interaction on wave parameters during design conditions is addressed in a limited number of studies (i.e. Beyer et al., 2000, Van der Meer, 2004). The focus in these studies was mainly from a theoretical point of view. The studies indicate that the influence of currents on wind generated waves could be of importance. However, practical rules or guidelines to incorporate the impact of currents in the prediction of wave characteristics are still lacking. Insight in the influence of currents on wave conditions, and so on wave run-up, is of importance, since freeboard allowance is mainly chosen on the basis of wave run-up.

The problem described above was the reason for Rijkswaterstaat RIZA to commission WL | Delft Hydraulics to carry out a research project within the framework of Theme 1 Safety Questions of the Research funds of the Ministry of Verkeer & Waterstaat.

1.2 Objectives

The overall objective of the project is:

To develop a guideline for the influence of currents on the characteristics of wind generated waves during design flood conditions in order to design and check crest levels of dykes

The project will be restricted to conditions in river systems, i.e. narrow water systems with short fetch length, complex geometry, and limited wind speeds.

The research started in 2006 and is continued in 2007. This Progress Report presents the results of the activities carried out in 2007.
1.3 Activities in 2006

The project of 2006 resulted in 1) an overview of literature and 2) a reconnaissance case study on a river section in the Waal, one of the Rhine branches in the Netherlands.

From the activities in 2006 the following was recommended for 2007:

- investigate the suitability of SWAN in narrow fetch river systems and verify whether and which adjustments and modification of the wave model are required.

- perform a case study on the river Rhine using a coupling between the hydrodynamic model WAQUA and the spectral wave model SWAN, as performed by Beyer et al. (2000) and investigate not only the impact of currents on waves, but also the importance of the various processes that modify wave conditions, such as shoaling, refraction, diffraction, breaking, reflection and white-capping.

1.4 Summary of activities in 2007

During 2007 the following activities have been carried out in order to contribute to a better understanding of the influence of currents on wind generated waves:

1. Expert interview concerning the suitability of SWAN in narrow fetch river systems.

2. Investigation of the sensitivity during design flood conditions in the Dutch Rhine system to processes that modify wave conditions: 1) wave-current interaction; 2) wave propagation processes; and 3) wave dissipation processes.

The result of the first activity is presented in Chapter 2. The results of the sensitivity analysis are presented in Appendix A and summarised in Chapter 3. Conclusions of the R&D work in 2007 and recommendations for activities in 2008 are given in Chapter 4.

In the project proposal of the R&D work in 2007 it was also promised to address the importance of turbulence on wave propagation and dissipation from the main channel into the floodplain. This issue could not be included in the activities of this year, because the sensitivity analysis took most of the available time.
2 Suitability of SWAN

2.1 Introduction

From an expert meeting in 2006 (see Van Vuren & Verheij, 2006) it was concluded that the spectral model SWAN could be a model to assess wave-current interaction in shallow water systems.

SWAN is designed for the simulation of wave evolution over large distances, i.e. entire ocean basins and open coastal areas. In these modelling areas wave spectra are typically well-developed. SWAN calculates phase-averaged wave quantities, meaning that the wave information is averaged in time and space. Model parameters in SWAN are set on the basis of an intensive validation of SWAN in these large modelling areas.

In river systems, the evolution of waves is limited by the short fetches involved. SWAN is insufficiently validated for situations with such short fetches and young waves. It is therefore unclear whether SWAN in its present form and parameter setting can be applied to narrow water systems with short fetch length and complex geometry and whether such a phase-averaged approach is suitable at all.

The next sections describe the expert opinion of Jacco Groeneweg of WL | Delft Hydraulics on the suitability and limitations of SWAN in narrow fetch river systems. Recommendations for model improvement to make SWAN suitable for narrow fetch river systems are presented.

2.2 Background of SWAN

Over the past two decades, a number of advanced spectral wind-wave models, known as third-generation models, has been developed: WAM (WAMDI Group, 1988), WAVEWATCH III (Tolman, 1991), TOMAWAC (Benoit et al., 1996) and SWAN (Booij et al., 1999; freely available from http://www.fluidmechanics.tudelft.nl/swan/index.htm). These models solve the spectral action balance equation without any a priori restrictions on the spectrum for the evolution of wave growth.

SWAN (acronym for Simulating WAves Nearshore) is a third-generation wave model for obtaining realistic estimates of wave parameters in coastal areas, lakes and estuaries from given wind, bottom and current conditions. However, SWAN can be used on any scale relevant for wind-generated surface gravity waves. The model is based on the wave action balance equation (or energy balance in the absence of currents) with sources and sinks. Good introductory texts on the background of SWAN are Young (1999) and Booij et al. (1999).

SWAN is an extension of the deep water third-generation wave models. It incorporates the state-of-the-art formulations for the deep water processes of wave generation, dissipation and the quadruplet wave-wave interactions from the WAM model. In shallow water, these processes have been supplemented with the state-of-the-art formulations for dissipation due to bottom friction, triad wave-wave interactions and depth-induced breaking. The wave propagation processes represented in SWAN are propagation through geographic space,
refraction due to spatial variations in bottom and current, diffraction, shoaling due to spatial variations in bottom and current, blocking by opposing currents, and transmission through, blockage by or reflection against obstacles. In addition, the wave-induced set-up of the mean sea surface as well as the wave-induced driving forces, based on the radiation stresses, can be computed in SWAN. However, wave-induced currents are not computed by SWAN. Wave-induced currents can be considered as a second order disturbance that could be computed when coupling SWAN with a hydrodynamic model such as WAQUA or Delft3D.

2.3 Suitability and limitations for narrow fetch river systems

SWAN can be used on any scale relevant for wind generated surface gravity waves. The model is suitable for oceans, seas and coastal areas, and even on laboratory scale. However, like any phase-resolving model, SWAN should not be applied in areas with strongly varying wave conditions. Phase-resolving models such as Boussinesq-type models or models based on the mild-slope equations solve wave-by-wave and should be applied when high resolutions are required, e.g. due to a strongly varying bathymetry, or when phase-information is required, e.g. for in cases of diffraction.

Waves on rivers are generally fetch-limited. As long as the bottom topography is gradually changing the assumption in SWAN of moderately-changing wave conditions will be fulfilled. Under normal conditions the presence of groins violates this assumption. If the groins are, partly, cutting the water surface, the long-crested waves will diffract around the groins. This aspect is modeled in SWAN in an approximate way by a phase-decoupled approach, as described in Holthuijsen et al. (2003), and is employed so that some qualitative behaviour of spatial redistribution and changes in wave direction is obtained. If the groin is submerged the change in bathymetry in cross-groin direction is so significant, that a resolution is required that is only a fraction of a typical wave length. In the presence of groins SWAN is not suitable to determine wave conditions along the river dikes under normal conditions.

Under extreme conditions, the water level might be so large that the presence of a groin only results in a small relative change in the total water depth. The wave conditions are only slightly affected. Under the restriction that the groins do not change the wave conditions significantly, SWAN might be applicable under extreme conditions of high water levels.

SWAN is calibrated and validated for large-scale areas and for depth- and fetch-limited situation. In river systems, the evolution of waves is limited by the short fetches involved. The waves are typically very young and are outside the range for which the model was validated. Comparison with measurements at locations in IJsselmeer (Bottema, 2006) show that SWAN overpredicts the amount of wave energy at fetches of the order of 1 km. A comparison between simulated and observed wave heights and periods at short fetches seems to point to an overestimation of the transfer of energy from the wind to the waves in the model for highly-forced, young wind sea. This has also been reported by Donelan et al. (2007) in experiments at Lake George, Australia, and by Graber (WISE Workshop 2006) and Jensen (WISE Workshop 2007) in simulations of Hurricane Katrina. Application of SWAN to bendy river systems would yield significant overpredictions of wave loads on river dikes.
Both under normal and extreme conditions current velocities become significant in comparison with the propagation velocity of the relatively young waves on rivers. Especially under extreme conditions the effect of an opposing or following current cannot be neglected in the determination of the wave conditions. Inclusion of following currents increases the wave age. Wave age is defined as the ratio between \( c_g + u \) (the group velocities of waves + the flow velocity) and \( u_{\text{wind}} \) (the wind velocity). Older waves grow less than in the same situation without waves and therefore the wave height and wave period are smaller. Inclusion in the computations of following currents is favourable for the wave load and amount of wave overtopping over a dike. The opposite is true for opposing currents. Then the wave age decreases. Besides, the strong steepening of the short-wave components leads to unrealistic energy levels at those components. The present dissipation mechanism in SWAN (white-capping) is not suitable to avoid the excessive growth of wave components near the blockage frequency, as was also concluded in WL (2007). Consequently, in its present state SWAN should be used with caution for determining the wave conditions on rivers in the presence of opposing currents.

\[2.4 \quad \textbf{Options to improve SWAN for narrow fetch river systems}\]

The limitations in SWAN for application to fetch-limited river systems are described in previous section and are related to wave growth, wave-current interaction and strongly varying wave conditions near groins. Since the stochastic wave model relies on moderate variations in the wave conditions, SWAN is not suitable if groin effects are significant. With respect to wave growth at short fetches and wave-current interaction some improvements (see below) have already been obtained. Further developments are foreseen in the SBW project.

For waves on opposing currents the conventional breaking formulation in SWAN is not sufficient to dissipate the wave energy near the blockage frequency. The application of a bore-based dissipation model by WL (2007), based on that of Battjes-Janssen (1978), as proposed by Ris (1997), has led to significant improvements of the computational results. As recommended in WL (2007) this expression should be developed and calibrated, based on more recent theoretical insights by Chawla and Kirby (1998, 2002) and Suastika (2004). In this respect also the implementation of an expression for amplitude dispersion in SWAN is recommended.

The suggestion made above is based on the history of stochastic wave modelling. In deep water the weak-in-the-mean formulation for white-capping performs very well. This dissipation mechanism is insufficient to reduce the amount of energy in the surf zone. Therefore, in SWAN a depth-induced breaking formulation (Battjes-Janssen, 1978) is included. Wave energy dissipation on counter-currents is a third mechanism, which has been modelled by means of a combination of the two existing breaker formulations in SWAN. It is not a priori evident whether that approach represents the physics correctly. For that purpose the effect of wave-turbulence interaction should be included.

Based on model comparisons with measurements Donelan et al. (2006), Graber (WISE Workshop 2006) and Jensen (WISE Workshop 2007) propose a limitation of the transfer of energy from the wind to the waves under highly forced conditions. In WL/Alkyon (2007) the effect of such a limitation of the energy transfer on the wave conditions has been
investigated. In SWAN the wind input term is capped above a certain level of wind forcing (given by $u^*/c$). The capping effect has been investigated for the Wadden Sea. The limitation in the amount of energy transfer from the wind to the waves at young wind seas significantly affects wave heights and periods at the lee of the barrier islands. It is recommended to calibrate and validate this approach, e.g. by means of the capping level, to make it applicable for more general situations.

In general, the performance of SWAN should be determined by comparing model results with either available or new measurements.

### 2.5 Conclusions and recommendations

Due to the restriction to moderately varying wave conditions SWAN is not applicable in river systems when the effect of groins is significant. Under extreme conditions the depth changes due to the presence of groins might not be significant.

Due to the short fetches and presence of an ambient current the performance of the present SWAN model in river systems is probably rather modest. The overestimation of the transfer of energy from the wind to the waves in the model for highly-forced, young wind sea yield inaccurate and unfavourable estimates for the wave conditions in the river systems. Also the effects of opposing currents near the blockage frequency are not taken into account properly in SWAN’s present version.

It is recommended to improve SWAN for narrow fetch river systems as soon as possible. Some of the proposed options for improvement have been implemented and tested for one or two situations in WL/Alkyon (2007, wind forcing) and WL (2007, wave-current interaction). Further calibration and validation, as well as investigation of further improvements are recommended.
3 Sensitivity analysis

3.1 Introduction

The objective of this sensitivity analysis is to investigate the importance of the various processes that modify wave conditions, viz.:

- wave-current interaction;
- wave propagation processes; and
- wave dissipation processes.

The previous chapter indicates that it remains to be verified to what extent SWAN in its present state is suitable for determining wave conditions in river systems with narrow fetches and strong currents. Although some doubts are raised on the suitability of SWAN, a case study on the river Rhine is performed in this using a coupling with a hydrodynamic model. Therefore the results should be interpreted with caution.

In principal a coupling between the hydrodynamic WAQUA model and SWAN was intended. However, since the standard Delft Hydraulics software makes a coupling with Delft3D easier than with WAQUA, a coupling between a hydrodynamic Delft3D model and a wave model SWAN was chosen.

To investigate the importance of the various processes, the processes are respectively switched on and off in the SWAN model. The results are presented in Appendix A.

3.2 Wave-current interaction

The impact of wave current interaction is investigated during design flood conditions in the Waal, the largest branch of the river Rhine in the Netherlands. During design flood conditions, the depth-averaged flow velocity varies between 1.3 and 2.5 m/s in the main channel of the Waal. The depth-averaged velocity drops below 1 m/s in the floodplain area. Near the toe of the dyke, the flow velocity is even less than 0.5 m/s.

3.3 Wave propagation and dissipation processes

The influence of other processes than wave-current interaction is addressed, namely the impact of 1) wave propagation processes and 2) wave dissipation processes.

The following wave propagation processes are represented in SWAN:

- refraction due to spatial variations in bottom and current
- shoaling due to spatial variations in bottom and current
- transmission through and reflection against obstacles
- blocking by opposing currents
The impact of blocking by opposing currents is addressed in the wave-current interaction. Under design conditions wave conditions are not influenced by the presence of groynes and levees in the floodplain, i.e. waves are fully transmitted. It is not possible to switch off the shoaling process. Therefore, from the wave propagation processes only the impact of refraction is addressed.

The following wave dissipation processes are represented in SWAN:

- white-capping
- depth-induced breaking
- bottom friction blocking by opposing currents

The impact of wave dissipation by the above-mentioned processes is assessed.

### 3.4 Conclusions and recommendations

The sensitivity of wave-current interaction, wave dissipation and propagation processes on wave conditions near the toe of the dyke is assessed in the study. As mentioned before, the results should be interpreted with caution. The suitability of SWAN for riverine conditions with strong currents and narrow fetches remains to be verified.

In the present study, it appears that the largest differences in wave heights and in wave periods are induced by wave-current interaction. From the remainder processes, refraction of waves turns out to have an important influence on wave conditions. The effect of the other processes seems negligible.

Wave current interaction seems to have a significant impact on wave conditions in the main channel. The results show that waves increase in height and in length (in period) in adverse currents. Waves entering a region with counter-currents (or currents perpendicular to the wave field) increase in height due to current-induced steepening. Due to a steeper wave field, the water surface becomes more rough, resulting in perfect conditions for the wind to catch more surface area of the wave, and increasingly transferring energy to the waves. If the waves become too steep, energy dissipation in the form of wave breaking (white-capping) occurs, which yields a reduction of the wave height. In that case, part of the wave energy is dissipated and part is transferred to longer waves. This explains why waves become longer in adverse currents. Wave elongation is presumably also due to the blocking of the energy of wave components above a critical wave frequency that cannot propagate through the strong currents. Energy dissipation of the blocked wave components (the waves with high frequencies) results in an increase in the wave period. Normally, this goes along with a decrease in wave height. However, the wave heights turn out to increase (until the waves become too steep and break). This may have to do with the wave age: the young waves appear to grow, irrespective of wave blocking. As the result show, in part of the model area, waves are blocked completely in counter-currents (or currents perpendicular to the wave field) resulting in a decrease of the wave heights and periods.
The wave conditions near the toe of the dyke turn out to be less affected by wave-current interaction than the wave conditions in the main channel. The extent to which the wave conditions differ depends on the dyke location. Namely conditions near the toe of the dyke depend on 1) the degree of energy dissipation in the strong currents before they reach the dyke, and 2) the remaining fetch to the dyke location after energy dissipation took place. With respect to the former, a difference is noticed between waves that ‘cross’ the main channel, and waves that propagate alongside the main channel.

The difference in wave heights between a simulation with and without wave-current interaction amounts up to 0.1 m. An increase of the wave height from 0.4 m in a simulation without currents to 0.5 m in a simulation with currents at location 8, yields an increase in wave run up of 0.2 m (from approx. 0.8 m to 1.0 m). In absolute terms the differences in wave height and wave periods are small. Especially in comparison with the uncertainties and errors in wave conditions that are expected when applying SWAN to riverine situations.

Refraction has also a significant impact on the wave properties at the dyke locations. In general, it appears that due to refraction waves are refracted in the main channel due to differences in depth between inner and outer bend. Waves in the deeper outer bend have a higher propagation velocity than waves in the shallow inner bend. As a consequence waves are refracted from the outer bend towards the inner bend. It appears difficult for waves to penetrate outside the main channel. This is easier when refraction is switched off. Refraction has a lower impact on wave height that can amount up to 0.2 m.

Weirs have not been included in SWAN computations since the impact of weirs on the wave computations during design conditions seems unreliable. Test simulations show the crest levels of the weirs are a few meters below the water level: the submerged depth is at least factor 5 to 10 larger than the wave height. As a consequence, wave conditions should not be affected by the presence of weirs. The simulation results indicate however the opposite, i.e. a significant reduction in wave height. It is recommended to test this functionality and investigate the reason for the low wave transmission through. The transmission functionality was officially designed for breakwaters along the coast. Presumably, the functionality is not suitable for the weirs in river systems that are much smaller in size than these breakwaters.

An important aspect missing in this study is the availability of field data that could be used for verification of the SWAN computations. Reliable field measurements are required to obtain a better understanding of the various processes that modify waves, in particular the influence of currents on waves, in water systems like the river Rhine, with complex geometry, irregular geometrical boundaries, inhomogeneous bottom topography and narrow fetch conditions. It is recommended to carry out field measurements to increase the insight of the impact of currents on waves.
4 Planned activities for 2008

The difference in wave parameters near the toe of the dyke is so small that one can wonder whether the influence of currents on wave conditions should be taken into account. This is in contrast with the expectations of the wave experts. The results should be treated with caution, because SWAN is presumably limited suitable for narrow fetch river systems.

It is therefore recommended to improve SWAN for narrow fetch river systems as soon as possible. Some options to improve SWAN with respect to wave growth at short fetches and wave-current interaction are proposed by experts (see Chapter 2). The proposed options are partially implemented and tested within the project Strength and Loading of Water Defence Structures (SBW). Further calibration and validation, as well as investigation for further improvements is recommended.

The following is recommended for 2008:

- further improvements of SWAN for narrow fetch river systems;
- examination of the functionality wave transmission in SWAN for narrow fetch river systems;
- revision of the outcome of the sensitivity analysis after implementing, testing, calibrating and validating the improvements in SWAN;
- carrying out field or flume measurements that could be of use for verification of SWAN computations;
- cooperation and information exchange with other projects that address the subject of wave-current interaction, for instance the project Strength and Loading of Water Defence Structures (SBW).
5 References


A Memo: Sensitivity analysis

A.1 Introduction

A.1.1 Background

Crest levels of river dykes along the major rivers Rhine and Meuse are determined on the basis of the so-called ‘design water levels’ plus a freeboard height, needed to cope with, for instance, wind generated wave run-up, wind set-up, settlement and soil consolidation, etc. Run-up of wind generated waves mainly depends on local wave characteristics (wave height, wave period, wave steepness and wave direction), and the geometry and characteristics of the dyke and, if present, berms and foreshores.

In the present design method, the impact of currents on wave conditions at the toe of the river dyke is left out of consideration. Wave experts and results of reconnaissance research studies (i.e. Beyer et al., 2000, Van der Meer, 2004) indicate that the influence of currents on wind generated waves could be of relevant importance.

The objective of the present research project is to improve our understanding on the impact of currents on wind generated waves in narrow river systems with short fetch length, complex geometry, and limited wind speeds. The research started in 2006 and is continued in 2007.

A.1.2 Research activities 2006

Activities carried out in 2006 resulted in 1) an overview of literature and 2) a reconnaissance case study on a river section in the Waal, one of the Rhine branches in the Netherlands.

The literature review in Van Vuren & Verheij (2006) discussed a research study of Beyer et al. (2000) in which the impact of currents on the evolution of wind generated waves in the narrow fetched Waal river is investigated. To that end, a coupling between a hydrodynamic WAQUA model (developed for the computation of currents and water level) and a wave model, both wave models HISWA and SWAN, is made. The HISWA model contains more parameterisation with respect to the wave spectrum than the SWAN model\(^1\). Although the researchers were not familiar with SWAN and one of the first SWAN releases was used, the authors indicate to have more trust in the results obtained with SWAN than with HISWA. The SWAN computation showed that in counter currents waves become higher and longer. In other words, waves tend to grow both in height and in length in counter currents. This is an opposite effect to the Doppler effect, namely that waves become shorter in counter currents, accompanied by an increase in wave height.

\(^1\) The wave model HISWA belongs to the second-generation of wave models, the wave model SWAN to the third-generation of wave models. The main difference between the two models lies with the fact that in the third-generation wave models the direction and the frequency space are both discretised, whereas in second-generation models the spectral wave is parametrised in the frequency space.
In the reconnaissance study (Van Vuren & Verheij, 2006) a combination of Bretschneider and a Doppler type of dispersion relation is applied to assess the impact of currents on wave conditions. The study showed that the impact of currents on wave parameters is rather small. This is surprising, since other research studies showed the importance of currents. The Bretschneider approach neglects the effect of physical processes such as diffraction, refraction and reflection, complex non-uniform and unsteady flow conditions. Moreover it assumes zero dissipation and fetch-limited waves reaching river dykes as shallow water waves. This may induce an unrealistic view of the influence of currents on waves. The conclusion could either be that currents are of minor importance in river systems like the Rhine, or that the Bretschneider approach is too simple to draw this conclusion.

From the work in 2006 the following activities are recommended for 2007:

- investigate the suitability of SWAN in narrow fetch river systems and verify whether and which adjustments and modification of the wave model are required;

- perform a case study on the river Rhine using a coupling between the hydrodynamic model WAQUA and the spectral wave model SWAN, as performed by Beyer et al. (2000) and investigate not only the impact of currents on waves, but also the importance of the various processes that modify wave conditions, such as shoaling, refraction, diffraction, breaking, reflection, white-capping, turbulence, etc.

**A.1.3 Objective of this memo**

The objective of this memo is to investigate the importance of the following processes that modify wave conditions:

- wave-current interaction;
- wave propagation processes; and
- wave dissipation processes.

To that end, a case study on the river Rhine is performed using a coupling between a hydrodynamic and wave model. To investigate the importance of the various processes, the processes are respectively switched on and off.

The research method, amongst which the study area, the reference model, and the model versions used, is described in Chapter A.2. Chapter A.3 discusses the impact of wave current interaction. The influence of other processes such as wave propagation and wave dissipation is shown in Chapter A.4. Conclusions and recommendations are given in Chapter A.5.
A.2 Method: research area, models & sensitivity analysis

A.2.1 Research area: Rhine in the Netherlands

The Rhine is a large river in Western Europe and has a total length of 1,320 km. It rises in Switzerland as a snowmelt-fed mountain river and eventually debouches as a rain- and snowmelt-fed lowland river in the North Sea in the Netherlands.

In the 19th and early 20th centuries, the Rhine was heavily trained for the purpose of safe discharge of water, sediment and ice, and of a better navigability. The large-scale river training resulted in the ‘present-day’ appearance of the river (Figure A.1): fixed planform, non-permeable groynes, a single main channel intensively used for navigation, low levees (‘summer dykes’) that protect floodplains from frequent flooding, silted up flat floodplains used as meadows and high dykes acting as a main flood defence. These dykes protect a dense riparian population.

Figure A.1 The Rhine branches in the Netherlands

In accordance with Beyer et al. (2000) the impact of currents on wave conditions is analysed for a 25-km long river section of the Waal (one of the branches of the Rhine in the Netherlands) between Tiel and Zaltbommel, see Figure A.2. This river section is characterised by large variations in geometry, variation in bend radius of curvature and crossings between opposite bend. Strong confinements of floodplains with narrow and wide section alternately located at the left and right side of the river. For the sensitivity analysis ten representative locations near the toe of the dyke are selected, see Figure A.2.
Figure A.2 River section of the Waal between Tiel and Zaltbommel
A.2.2 Coupling between a hydrodynamic and wave model

In order to investigate the importance of the various processes that modify wave conditions, a coupling is made between a hydrodynamic model and a wave model. In principal a coupling between the hydrodynamic WAQUA model and SWAN was intended. However, since the standard Delft Hydraulics software makes a coupling with Delft3D easier than with WAQUA, a coupling between a hydrodynamic Delft3D model and a wave model SWAN was chosen. Because of the large similarities between WAQUA and Delft3D, we do not expect that the Delft3D model yields different results.

The coupling concerns a one-way coupling, implying that first the Delft3D computations are performed and then the wave computations. Although it can be done, effects of waves on currents are neglected. The reason for this is that concerns a second-order disturbance and therefore of minor importance in this research.

Hydrodynamic computations are carried out with Delft3D version 3.54.23.00, and wave computations are carried out with SWAN version 40.51A. It should be mentioned that the suitability of SWAN in its present state for river systems with narrow fetches and strong currents is not clear and remains to be verified. Therefore the results should be interpreted with caution.

A.2.3 Set-up of the reference model

For the model schematisation of the hydrodynamic and wave model the same database is used. The following schematisation aspects are addressed below: the grid resolution, the Delft3D model schematisation, the SWAN model schematisation and the boundary conditions.

Grid resolution

The computation grid is a curvilinear grid, with an average grid size in the main channel of 20 m in longitudinal direction and 6 m in transverse direction. The resolution of the computation grid in the floodplain is somewhat smaller, up to at most 13 m in transverse direction and 30 m in longitudinal direction, as indicated in the figures below.
For the schematisation of the hydraulic roughness, the bed topography, the groynes, summer levees and steep obstacles in the floodplains, an official database program of Rijkswaterstaat is used (Baseline version 3.3, see Van Vuren et al. 2007). For the Baseline projection the reference schematisation of the PKB Room for the River studie (see Van Vuren et al. 2007) has been used.

The bathymetry dates from singlebeam soundings of 1997. Groynes, levees and steep obstacles in the floodplain are schematised as 2D-weirs. Floodfree areas that do not drown at high discharges are schematised as thin dams.

An adapted version of the Van Rijn (1984) roughness predictor is used to schematising the hydraulic roughness in the main channel. The predictor accounts for variation in the
hydraulic roughness induced by bed forms that develop during high discharges and affect the bottom roughness.

The hydraulic roughness in the floodplain is related to the various ecotypes and their spatial distribution over the floodplains. Nikuradse roughness coefficients are chosen with the help of roughness tables.

**SWAN model schematisation**

The basic parameter setting of the spectral wave model SWAN is derived from a SWAN model of the Slotermeer (Bottema et al., 2002). For a detailed overview of the parameter settings in the SWAN model reference is made to Appendix 2.

The wave transmission over a structure, such as a summer levee or a groyne can in principle be computed with SWAN. To that end, the files describing the weirs and thin dams have to be re-defined, since the required format deviates from the file format in Delft3D.

When a wave propagates over an weir the wave will reduce in height if the submerged depth (~ the difference between the water level and the crest level of the weir) is small with respect to the wave height. For the transmission of a wave passing over a weir in SWAN the expression of Goda et al. (1967) is used. The Goda forula is designed for wave breakers along the coasts. The expression reads:

\[
K_t = \begin{cases} 
1 & \text{if } \frac{h-d}{H_i} < -\beta - \alpha \\
0.5 \cdot \left(1 - \sin\left(\frac{\pi}{2\alpha} \left(\frac{h-d}{H_i} + \beta\right)\right)\right), & \text{if } -\beta - \alpha \leq \frac{h-d}{H_i} \leq \alpha - \beta \\
0 & \text{if } \frac{h-d}{H_i} < \alpha - \beta 
\end{cases}
\]

where \(h\) represents the crest level of the weir with respect to reference level (NAP), \(d\) the water level with respect to reference level (NAP), \(H_i\) the significant wave height, and \(\alpha\) and \(\beta\) coefficients that depend on the shape of the weir. The default setting is used for coefficients \(\alpha (~2.6)\) and \(\beta (~0.15)\). The transmission coefficient \(K_t\) is the ratio of the wave height at the downwave side of the weir over the wave height at the upwave side.

During design conditions in the Rhine, the difference between the crest level of the weirs and the design water levels, i.e. the submerged depth, is in the order of 4 to 7 m. So according to Eq. A-1 waves with a significant wave heights of 0.3 to 0.7 m ar not effected by the submerged weirs. A test simulation with a SWAN model including weirs shows however an opposite view, see Appendix 1. The wave properties are significantly influenced by the presence of the weirs. Presumably, this functionality is not suitable for riverine conditions. Therefore, weirs are not included in the SWAN model.

Thin dams have not been included in the wave-computation either, since they hardly occur in the research area.
Boundary conditions

Crest heights of river dykes are determined on the basis of the so-called ‘design water levels’, plus a freeboard height, mainly chosen on the basis of wave run-up. The boundary conditions in the Delft3D-SWAN model of the Waal are based on design conditions. The following three boundary conditions are included:

- a stationary design discharge at the upstream boundary;
- a design water level at the downstream boundary; and
- a design wind speed.

The hydrodynamic boundary conditions are derived from a hydrodynamic simulation with the hydrodynamic model that is officially used for design water level predictions. The design discharge at Lobith where the Rhine enters the Netherlands is 15,000 m$^3$/s. At the upstream boundary of the Delft3D model of the Waal this corresponds with a discharge of 9,500 m$^3$/s. The downstream water level is set to 7.98 m+NAP. The water level and flow pattern resulting from the Delft3D model are used as boundary conditions in the SWAN model.

During design conditions the windspeed varies between 9 and 13 m/s (Beaufort 6), depending on the wind direction, see TAW (1985). For simplification a windspeed of 13 m/s from the southwest direction (225º nautical convention) is applied. Wind is imposed both in the Delft3D and the SWAN model.

A.2.4 Sensitivity analysis

The sensitivity of wave conditions to wave-current interaction, wave propagation processes and wave dissipation processes is investigated by means of a sensitivity analysis. In this analysis the sensitivity of the wave properties is investigated by systematically and deterministically varying model input values one by one, and estimating their impact on the model results. Meanwhile, the other variables are held constant at their pivot value.

In most cases the sensitivity of the various processes is assessed by switching the processes respectively on and off.

A.3 Wave-current interaction

A.3.1 Introduction

In this Chapter the impact of wave current interaction is addressed. Section A.3.2 presents the flow result: water levels, water depths and flow velocities. In Section A.3.3 the impact of currents on wave conditions is discussed. A comparison with the Bretschneider results of Van Vuren & Verheij (2006) is given in Section A.3.4.
A.3.2 Flow results

Figure A.5 to Figure A.7 show respectively the computed water levels, depth-averaged flow velocity and water depth during a design discharge in the Waal. The flow results are used in the wave computations to investigate the impact of currents on wave conditions. As can be noticed, the depth-averaged flow velocity varies between 1.3 and 2.5 m/s in the main channel, whereas in the floodplain, the velocity drops below 1 m/s. Near the toe of the dyke, the flow velocity is less than 0.5 m/s.

Figure A.5  Water levels in the Waal during the design discharge
Figure A.6  Depth-averaged flow velocities in the Waal during the design discharge

Figure A.7  Water depth in the Waal during the design discharge
A.3.3 Results simulation with Delft3D and SWAN coupling

The impact of currents on wave conditions is investigated in this section. Figure A.8 shows the significant wave height in the model area for a simulation including and excluding currents. Figure A.9 presents the difference between the two simulations. Figure A.10 & Figure A.11 and Figure A.12 & Figure A.13 show the same type of figures for the mean wave length and the mean wave period $T_{m01}$, respectively.

Wave current interaction appears to have a significant impact on wave conditions in the main channel. The largest difference is noticed in the situation with counter currents, i.e. in the stretch between location 5 and 8 (see Figure A.2). Waves become up to 0.3 m larger in a situation with adverse currents. This results in wave heights up to 0.7 m. The mean wave periods become approximately 1.5 sec larger in a situation with counter currents. The latter yields an increase in wave lengths.

As discussed by Van Vuren & Verheij (2006), when investigating the impact of currents on wave conditions use can be made of the Doppler type of dispersion relation. If a wave enters a region with a counter-current and no energy dissipation occurs due to current-induced steepening of the waves, based on Doppler shift alone, the wave is expected to become higher and shorter. The figures show however also an elongation of waves in adverse currents.
Figure A.8  Significant wave height in the Waal for a simulation with and without currents

Figure A.9  Difference in significant wave height in the Waal between a simulation with and without currents
Figure A.10  Mean wave length in the Waal for a simulation with and without currents
Figure A.11  Difference in mean wave length in the Waal between a simulation with and without currents

Simulation with currents
Impact of wave-current interaction on wind generated waves in low-land river systems

Figure A.12  Mean wave period $T_{m01}$ in the Waal for a simulation with and without currents

Figure A.13  Difference in mean wave period $T_{m01}$ in the Waal between a simulation with and without currents
The effect of an increase in height and length of waves in counter currents can also be noticed from the results of Beyer et al. (2000). For a better understanding, Figure A.14 shows the results of the wave computations near location 2 in detail, for a simulation with and without currents.

The simulation without wave-current interaction (see the left panels of figure A.14) shows the following. When wind begins to blow across the surface from the southwest direction, small rounded waves with short wave periods and wave lengths begin to form. These wave dimensions are relative small as compared with the water depth in the floodplain, i.e. the young waves are considered as deep water waves. With the generation of young waves, the water surface becomes more rough, resulting in perfect conditions for the wind to catch more surface area of the wave, and increasingly transferring energy to the waves and transfer of wave energy to lower frequencies. As a result, young waves grow over its fetch in height and length. If wind acts sufficiently long on the water surface, the fetch-limited waves become well-developed. The size of the fetch-limited waves increase in the direction of the toe of the dyke of the opposite floodplain.

The simulation with wave-current interaction gives a different view (see right panels of figure A.14). The current is directed perpendicular to the wind direction. Perpendicular to the flow direction, the waves start to increase in height and in length. Eventually, towards the outer bend in the main channel with the strongest currents, waves cannot penetrate any further and are ‘blocked’ by the strong current. Wave blocking is a phenomenon in wave-current interaction that may occur for waves meeting an adverse current of which the velocity increases in upstream direction (Suastika, 2004). When blocking of wind-generated waves occurs, energy dissipation takes place. In that case, energy of wave components above a critical wave frequency cannot propagate through the strong currents and is dissipated. In principle, wave blocking goes along with a decrease in wave heights and an increase in wave period. Figure A.14 shows both an increase in wave height and in wave period. Presumably, a combined effect is noticed of 1) wave blocking yielding in larger wave periods; and 2) the wave age resulting in the growth of the heights of young waves in counter currents. The figure illustrates that eventually a substantial part of the wave energy is dissipated in the outer bend due to the fact that the current becomes too strong. This results in a decrease of the wave height and period.

Next to energy dissipation due to wave blocking, energy is dissipated by white-capping. White-capping is wave breaking due to wave steepening. Part of the wave energy is dissipated and part of the energy is transferred to longer waves. The upper limit of the wave steepness height can be written as (Miche, 1944):

\[
\frac{H_s}{L} = \frac{1}{7} \cdot \tanh\left(\frac{2\pi d}{L}\right) \tag{A-2}
\]

in which L represents the wave length, d the water depth and \( H_s \) the significant wave height. In deep water Eq. A.2 boils down to:

\[
\frac{H_s}{L} = \frac{1}{7} - 0.14 \tag{A-3}
\]

This implies that white-capping occurs when waves become steeper than 0.14.
Impact of wave-current interaction on wind generated waves in low-land river systems

Wave height in simulation without currents
Wave height in simulation with currents
Wave period in simulation without currents
Wave period in simulation with currents
Steepness in simulation without currents
Steepness in simulation with currents
Wave direction (cartesian conv) in sim without currents
Wave direction (cartesian conv) in sim with currents
As illustrated in Figure A.14 waves become steeper in the simulation with currents. Downstream the spots with the highest steepness in the main channel, the wave height is smaller in the simulation with currents than in the simulation without. This indicates that part of the wave energy is probably dissipated due to wave-induced steepening. At these spots also the wave direction is shifted 90º (note that the wave direction is given in cartesian convention). This means that wave propagate locally in the direction as the flow. Waves become longer and reduce in height.

Figure A.15 gives a similar picture for river section near location 3 and 8. Wave-current interaction yields an increase in wave height and wave period over the entire fetch.
Impact of wave-current interaction on wind generated waves in low-land river systems

- Wave height in simulation without currents
- Wave height in simulation with currents
- Wave period in simulation without currents
- Wave period in simulation with currents
- Steepness (ratio of wave height and length) in simulation without currents
- Steepness (ratio of wave height and length) in simulation with currents
Figure A.15  Impact of currents on wave conditions near location 8

As can be noticed from Figures A.8 to A.15, the wave conditions near the toe of the dyke turn out to be less affected by wave-current interaction than the wave conditions in the main channel. This is presumably due to the fact that currents are less strong in the floodplain area, and so near the toe of the dyke. Moreover, wave generation (wind forcing) is less in the floodplain area than in the main channel. This is due to lower water depths in the floodplain
(see Figure A.7, the water depth is approximately 5 m lower in the floodplain area than in the main channel).

Figures A.16 to A.18 illustrate the impact of wave-current interaction on wave conditions at locations near the toe of the dyke. The figures illustrate that at some dyke locations the wave height increases, whereas at other locations they decrease. This has probably to do with differences in energy dissipation and remaining fetches after energy dissipation. Regarding the former, a difference is noticed between the waves ‘crossing’ the main channel (viz. location 2) and waves ‘propagate alongside’ the main channel (viz. location 8). For dyke location 2, a significant part of the wave energy is dissipated in the main channel by wave blocking and white-capping. The remaining fetch to the toe of the dyke is too short to get waves of the same dimensions as in the simulation without wave-current interaction. The wave properties near dyke location 8 are not affected by energy dissipation.

Including wave-current interaction in wave computations yields at maximum a 0.1 m higher wave height and a 0.8 sec larger wave period. The question is whether this is a lot with respect to the design of river dykes. The crest level of dykes along the Waal is determined by the design water level plus a wave run up with a minimum of 0.5 m plus subsidence.

Wave run up can be computed as follow:

\[ z_{2\%} = 8 \tan(\alpha)H_s \]

in which \( z_{2\%} \) represents the 2% wave run up, \( H_s \) the significant wave height, \( \alpha \) the slope of the dyke. With an average slope of 1:4, i.e. \( \tan \alpha = 0.25 \), Eq. A.4 boils down to:

\[ z_{2\%} = 2.4H_s \]  

According to Eq. A.5 an increase of the wave height from 0.4 m in a simulation without currents to 0.5 in a simulation with currents at location 8, yields an increase in wave run up of 0.2 m, from 0.8 m to 1.0 m.

In absolute terms this is rather small. Especially in comparison with the uncertainties and errors in wave conditions derived with SWAN, when applying SWAN to riverine situations.
Figure A.16  Significant wave height for the locations near the toe of the dyke in a simulation with and without wave-current interaction

Figure A.17  Mean wave period for the locations near the toe of the dyke in a simulation with and without wave-current interaction
A.3.4 Comparison with Bretschneider

In Van Vuren & Verheij (2006) a combination of the Bretschneider formula and a Doppler type of dispersion relation is applied to assess the impact of currents on wave conditions.

For the Bretschneider computations information on water depths and currents during design conditions is obtained from a simulation with a WAQUA model driven by a design discharge of 16,000 m³/s. For the water depth an average constant depth over the entire fetch or an average constant depth in the floodplain area is taken, depending on the location. According to TAW (1985), local deep parts in the floodplain do not affect the wave conditions. An average constant depth over the entire fetch is taken for locations close to the main channel, viz. location 4, 5, 7, 8 and 9. For the remainder locations, the average depth in the floodplain area is taken. The same is done for current velocity and current direction.

The empirical Bretschneider formula has the following disadvantages:

- Bretschneider does not account for the complex geometry with irregular geometrical boundaries and inhomogeneous bed topography
- The effect of physical processes such as refraction, diffraction and reflection is not included in Bretschneider
- With the application of Bretschneider, constant water depth and current information is used to estimate wave conditions, whereas in reality non-uniform and unsteady flow conditions occur.
• In the Bretschneider it is assumed that the waves at the toe of the dyke are well-developed over its limited fetch. The impact of wave blocking (resulting in larger wave periods) and the impact of wave age (the growth of young waves in height, irrespective of wave blocking) is not included.

This section compares the results of Van Vuren & Verheij (2006) with those of the present study. Figure A.19 gives the significant wave height of both methods for the ten dyke locations. Figure A.20 shows the ratio between the wave heights derived with Bretschneider and SWAN.

In Bretschneider the effect of the compartment of the floodplain area by summer levees and other levees is ignored. According to Section A.2.3 this is a valid assumption, since approximately 100% wave transmission over the weirs in the floodplain area is expected. Bretschneider yields similar results as the SWAN computations, Bretschneider performs reasonably well for the major part of the dyke locations. Apart from dyke location 3, 8 and 10, the differences in wave height between the methods are rather small.

For dyke locations 3, 8 and 10, the difference in wave height as predicted by Bretschneider and by SWAN, varies between 0.1 and 0.2 m (25% - 40%). In the wave computations with SWAN when including wave-current interaction, the wave height increases in the counter-currents. Since the wave properties near dyke location 8 and 10 are not affected by energy dissipation by blocking and white-capping and the fetch after energy dissipation is long enough for location 3 to let the waves well-develop, the wave heights are larger for SWAN computations than for the Bretschneider computations.

Figure A.19 Significant wave height for the locations near the toe of the dyke in a reference SWAN simulation with wave-current interaction and with a Bretschneider computation

2. Note that in the previous study a windspeed of 12 m/s was applied (13 m/s in the current study). The wind direction is 225 degrees (southwest).
A.4 Wave propagation and dissipation processes

In this section the influence of other processes than wave-current interaction is addressed, namely the impact of 1) wave propagation processes and 2) wave dissipation processes.

A.4.1 Wave propagation processes

The following wave propagation processes are represented in SWAN:

- refraction due to spatial variations in bottom and current
- shoaling due to spatial variations in bottom and current
- transmission through and reflection against obstacles
- blocking by opposing currents

If a wave approaches water that is gradually becoming shallower and the wave crest makes an angle to the depth contours, the wave will refract. The part of the wave crest that is already in shallower water has a lower propagation celerity and will bend. The angle between the depth contours and the wave crest will diminish. This process is called refraction.

Shoaling occurs as waves travel toward a shore in shallow water. Shoaling is the changes in wave characteristics that occur when a wave reaches shallow water. The decreasing depth
causes a decrease in wave celerity and wave length. The conservation of energy results in more energy forced into a smaller area, i.e. in an increase in wave height.

Transmission resembles the process that when a wave passes through or over an obstacle part of the wave energy will be dissipated. Reflection implies that when a wave approaches a bottom slope with a steep profile like a dam or a dyke, the wave will partly break and reflect. The steeper the bottom slope, the greater the reflection.

The phenomena that energy of wave components above a critical wave frequency cannot propagate through the strong counter currents and is dissipated, is called wave blocking. Wave blocking causes a decrease in wave heights and an increase in wave period.

The impact of wave-current interaction and the influence of wave blocking in counter-currents is addressed in Section A.3.3. Under design conditions waves are not influenced by the presence of groynes and levees in the floodplain, i.e. wave are fully transmitted (see Section A.2.2.). It is not possible to deactivate shoaling in the SWAN. The effect of reflection is not investigated. This section addresses only the impact of refraction of the wave propagation processes.

To show the effect of refraction on a river with wave-current interaction, the refraction process is deactivated in the SWAN model. With respect to refraction it is important to model the bathymetry with sufficient detail. In a first attempt, a computation grid with an average grid size of 60 m in longitudinal direction and 20 m in transverse direction was used. A simulation with this grid did not have a large impact on the wave properties. Therefore the grid was refined to a grid with an average grid size of 20 m in longitudinal direction and 10 m in transverse direction. Figure A.21 shows the resulting bathymetry of the river bed near dyke location 3 and 8.

Deactivation refraction in a computation with the new grid has a significant impact on the wave properties at the dyke locations, see Figure A.22 and Figure A.23. Figure A.24 and figure A.25 give a 2-D overview of the significant wave height with and without refraction, and the difference between the two simulations. In general, it appears that due to refraction waves are refracted in the main channel due to differences in depth between inner and outer bend. Waves in the deeper outer bend have a higher propagation velocity than waves in the shallow inner bend. As a consequence waves are refracted from the outer bend towards the inner bend. It appears difficult for waves to penetrate outside the main channel. This is easier when refraction is switched off. Refraction has a lowering impact on wave conditions, see Figure A.25. The largest differences are noticed near Tiel (location 4, 5, 9 and 10). Figure A.26 shows a detailed overview of the wave conditions with and without refraction near Tiel.
Figure A.21  Bathymetry of the river bed near dyke location 3 and 8

Detail picture of the groyne section:
Figure A.22  Significant wave height for the locations near the toe of the dyke in a reference SWAN simulation with refraction and without refraction.

Figure A.23  Mean wave period for the locations near the toe of the dyke in a reference SWAN simulation with refraction and without refraction.
Impact of wave-current interaction on wind generated waves in low-land river systems

Figure A.24 Significant wave height $H_{\text{sig}}$ in the Waal for a simulation with (upper panel) and without (lower panel) refraction.
Figure A.25 Difference in significant wave height $H_{\text{sig}}$ in the Waal for a simulation with and without refraction
Impact of wave-current interaction on wind generated waves in low-land river systems

Wave height in simulation without refraction

Wave height in simulation with refraction

Wave period in simulation without refraction

Wave period in simulation with refraction

Steepness (ratio of wave height and length) in simulation without refraction

Steepness (ratio of wave height and length) in simulation with refraction
A.4.2 Wave dissipation processes

Examples of wave dissipation processes represented in SWAN are:

- dissipation by white-capping
- dissipation by depth-induced wave breaking
• dissipation by bottom friction

Wave breaking can be induced by various causes, such as breaking induced by wave steepening and depth-induced breaking.

Wave breaking occurring when a wave becomes too steep, is known white-capping. As a rule of thumb, it is assumed that white-capping occurs when the steepness (i.e. the ratio between $H_s$ and $L$) exceeds the limit of 0.14. In SWAN the process can be deactivated or the rate of white-capping can be adjusted. Because decreasing the rate of white-capping to zero is not realistic, the rate of white-capping is decreased by 10 % to investigate the effect of white-capping.

Depth induced breaking occurs when waves reach shallow water and the wave height is large when compared with the water depth. As a rule of thumb, it is assumed that depth-induced breaking takes place when the ratio between wave height and water depth exceeds 0.5. To show the effect of depth-induced breaking, the depth-induced breaking process is deactivated in the SWAN model.

For incorporating the effect of bottom friction, the JONSWAP option has been used in the SWAN model. The JONSWAP option is deactivated in the SWAN model to investigate the effect of bottom friction.

**White-capping**

To investigate the effect of white-capping, the coefficient for determining the rate of white-capping has been decreased by 10 % (Komen, parameter $cds2 = 2.124E-5$). In the figures below show the wave height and the mean wave period for the reference simulation and the simulation with the decreased white-capping rate, for the dyke locations. Figure A.27 shows the ratios between the wave parameters derived with the reference simulation and a simulation with a reduced white-capping rate.

At all dyke locations a reduction of the rate of white-capping results in an increase of the wave height and wave period. Decreasing the rate of white-capping causes less energy loss and higher waves.
Figure A.27 Significant wave height for the locations near the toe of the dyke in a reference SWAN simulation and a simulation with a reduced white-capping rate.

Figure A.28 Mean wave period for the locations near the toe of the dyke in a reference SWAN simulation and a simulation with a reduced white-capping rate.
Impact of wave-current interaction on wind generated waves in low-land river systems

The depth-induced breaking is switched off to investigate the effect of wave dissipation by depth-induced breaking. Figure A.30 and Figure A.31 show the impact on wave height and wave period respectively. It becomes clear that switching off wave induced breaking does not affect the results. When analysing the ratio between wave height and water depth in the simulation with depth-induced breaking, it appears that in the entire river area this ratio is smaller than 0.5. This means there is no depth-induced breaking in the model area.

**Depth-induced breaking**

![Figure A.30](image-url)

Significant wave height for the locations near the toe of the dyke in a reference SWAN simulation and a simulation without depth-induced breaking
Figure A.31  Mean wave period for the locations near the toe of the dyke in a reference SWAN simulation and a simulation without depth-induced breaking.

**Bottom friction**

To investigate the effect of bottom friction, a simulation of the wave model has been carried out without bottom friction. In the reference case the JONSWAP option was applied to simulate bottom friction. The figures below show the impact of bottom friction on the wave properties. Bottom friction turns out to hardly affect the wave properties. This counts for the dyke locations, but also for the main channel section.

Figure A.32  Significant wave height for the locations near the toe of the dyke in a reference SWAN simulation and a simulation without bottom friction.
A.5 Conclusions and recommendations

A.5.1 Conclusions

The sensitivity of wave-current interaction, wave dissipation and propagation processes on wave conditions near the toe of the dyke is assessed in the study. As mentioned before, the results should be interpreted with caution. The suitability of SWAN for riverine conditions with strong currents and narrow fetches remains to be verified.

The impact of switching on and off processes on the significant wave height is summarised in Figure A.34 and Figure A.35. The impact on the mean wave period is summarised in Figure A.36 and Figure A.37.

In the present study, it appears that the largest differences in wave heights and in wave periods are induced by wave-current interaction. From the remainder processes, refraction of waves turns out to have an important influence on wave conditions. The effect of the other processes seems negligible.

Wave current interaction seems to have a significant impact on wave conditions in the main channel. The results show that waves increase in height and in length (~ in period) in adverse currents. Waves entering a region with counter-currents (or currents perpendicular to the wave field) increase in height due to current-induced steepening. Due to a steeper wave field, the water surface becomes more rough, resulting in perfect conditions for the wind to catch more surface area of the wave, and increasingly transferring energy to the waves. If the waves become too steep, energy dissipation in the form of wave breaking (white-capping) occurs, which yields in a reduction of the wave height. In that case, part of

Figure A.33 Mean wave period for the locations near the toe of the dyke in a reference SWAN simulation and a simulation without bottom friction
the wave energy is dissipated and part is transferred to longer waves. This explains why waves become longer in adverse currents. Wave elongation is presumably also due to the blocking of the energy of wave components above a critical wave frequency that cannot propagate through the strong currents. Energy dissipation of the blocked wave components (the waves with high frequencies) results in an increase in the wave period. Normally, this goes along with a decrease in wave height. However, the wave heights turn out to increase (until the waves become too steep and break). This may have to do with the wave age: the young waves appear to grow, irrespective of wave blocking. As the result show, in part of the model area, waves are blocked completely in counter-currents (or currents perpendicular to the wave field) resulting in a decrease of the wave heights and periods.

The wave conditions near the toe of the dyke turn out to be less affected by wave-current interaction than the wave conditions in the main channel. The extent to which the wave conditions differ depends on the dyke location. Namely conditions near the toe of the dyke depend on 1) the degree of energy dissipation in the strong currents before they reach the dyke, and 2) the remaining fetch to the dyke location after energy dissipation took place. With respect to the former, a difference is noticed between waves that ‘cross’ the main channel, and waves that propagate alongside the main channel. The difference in wave heights near the toe of the dyke between a simulation with and without wave-current interaction amounts up to 0.1 m. An increase of the wave height from 0.4 m in a simulation without currents to 0.5 m in a simulation with currents at location 8, yields an increase in wave run up of 0.2 m (from approx. 0.8 m to 1.0 m). In absolute terms the differences in wave height and wave periods are small. Especially in comparison with the uncertainties and errors in wave conditions that are expected when applying SWAN to riverine situations.

Refraction has also a significant impact on the wave properties at the dyke locations. In general, it appears that due to refraction waves are refracted in the main channel due to differences in depth between inner and outer bend. Waves in the deeper outer bend have a higher propagation velocity than waves in the shallow inner bend. As a consequence waves are refracted from the outer bend towards the inner bend. It appears difficult for waves to penetrate outside the main channel. This is easier when refraction is switched off. Refraction has a lower impact on wave height that can amount up to 0.2 m.
Figure A.34  Significant wave height for the locations near the toe of the dyke in a reference SWAN simulation and simulations in which processes are switched off

Figure A.35  Ratio between the significant wave height for the locations near the toe of the dyke in a reference SWAN simulation and simulations in which processes are switched off
A.5.2 Recommendations

Weirs have not been included in SWAN computations since the impact of weirs on the wave computations during design conditions seems unreliable. Test simulations show the crest levels of the weirs are a few meters below the water level: the submerged depth is at least factor 5 to 10 larger than the wave height. As a consequence, wave conditions should not be affected by the presence of weirs. The simulation results indicate however the opposite, i.e.
a significant reduction in wave height. It is recommended to test this functionality and investigate the reason for the low wave transmission through. The transmission functionality was officially designed for breakwaters along the coast. Presumably, the functionality is not suitable for the weirs in river systems that are much smaller in size than these breakwaters.

An important aspect missing in this study is the availability of field data that could be used for verification of the SWAN computations. Reliable field measurements are required to obtain a better understanding of the various processes that modify waves, in particular the influence of currents on waves, in water systems like the river Rhine, with complex geometry, irregular geometrical boundaries, inhomogeneous bottom topography and narrow fetch conditions. It is recommended to carry out field measurements to increase the insight of the impact of currents on waves.
A.6  Annex 1: Effects of weirs in the wave model

To investigate the effect of weirs in the wave-computation, the model was executed with and without weirs. The results of the computations are shown in the figures below.

Wave height without weirs

Wave height with weirs
Mean wave length without weirs

Mean wave length with weirs
Mean wave period without weirs

Mean wave period with weirs
Results of wave-modeling without (n\_wrs) and with (y\_wrs) weirs.

Output quantities:
- d: depth (m)
- Hs: significant wave height (m)
- Dir: mean wave direction (degrees w.r.t. north, clockwise)
- Tp: peak period (s)
- Tm\_01: mean absolute wave period (s)
- Dspr: directional spreading of the waves (degrees)

<table>
<thead>
<tr>
<th></th>
<th>n_wrs</th>
<th>y_wrs</th>
<th>n_wrs</th>
<th>y_wrs</th>
<th>n_wrs</th>
<th>y_wrs</th>
<th>n_wrs</th>
<th>y_wrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>6.66/</td>
<td>6.66/</td>
<td>5.16/</td>
<td>5.16/</td>
<td>4.33/</td>
<td>4.33/</td>
<td>4.90/</td>
<td>4.90/</td>
</tr>
<tr>
<td>Hs</td>
<td>0.41/</td>
<td>0.26/</td>
<td>0.32/</td>
<td>0.19/</td>
<td>0.39/</td>
<td>0.29/</td>
<td>0.17/</td>
<td>0.17/</td>
</tr>
<tr>
<td>Dir</td>
<td>221.13/</td>
<td>236.92/</td>
<td>245.80/</td>
<td>224.47/</td>
<td>202.56/</td>
<td>211.76/</td>
<td>218.80/</td>
<td>224.17/</td>
</tr>
<tr>
<td>Tp</td>
<td>2.10/</td>
<td>1.63/</td>
<td>1.85/</td>
<td>1.26/</td>
<td>2.10/</td>
<td>1.85/</td>
<td>1.43/</td>
<td>1.26/</td>
</tr>
<tr>
<td>Tm_01</td>
<td>1.69/</td>
<td>1.34/</td>
<td>1.33/</td>
<td>1.01/</td>
<td>1.87/</td>
<td>1.63/</td>
<td>1.82/</td>
<td>2.09/</td>
</tr>
<tr>
<td>Dspr</td>
<td>52.86/</td>
<td>38.65/</td>
<td>36.93/</td>
<td>36.58/</td>
<td>35.88/</td>
<td>35.11/</td>
<td>45.56/</td>
<td>37.21/</td>
</tr>
</tbody>
</table>

Summer dikes and other dikes in the floodplain of the Waal-model are schematized by weirs. As can be seen from the results above, these weirs, included as obstacles in the wave-model, have a significant (lowering) impact on the significant wave height at the locations in general. This is not realistic because the minimum water depth at the station locations is greater than two times the significant wave height and therefore the wave height should not be affected by the weirs. Below the difference in wave height for each station is shown in a graphical way.
Wave height comparison

![Wave height comparison chart](chart)

- **Wave height comparison**
- **Station**
- **Hs (m)**
- Without obstacles
- With obstacles
## A.7  Annex 2: Settings of the SWAN-parameters

The settings of the SWAN-parameters are listed in the table below.

<table>
<thead>
<tr>
<th>CIR</th>
<th>spectral directions cover the full circle</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>mdc = number of subdivisions of the 360 degrees</td>
</tr>
<tr>
<td>0.08</td>
<td>flow = lowest discrete frequency used in calculation (Hz)</td>
</tr>
<tr>
<td>1.70</td>
<td>fhigh = highest discrete frequency used in calculation (Hz)</td>
</tr>
<tr>
<td>24</td>
<td>msc = one less than # frequencies (sigma space df/f = 0.1358)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GEN3</th>
<th>SWAN runs in third generation mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>KOM</td>
<td>linear growth (default)</td>
</tr>
</tbody>
</table>

| BREaking | adjust depth induced wave breaking in shallow water |
| CONSTANT | constant breaker parameter to be used |
| 1.00 (default) | alpha: proportionality coefficient of the rate of dissipation |
| 0.73 (default) | gamma: the ratio of maximum individual wave height over depth |

| FRICTION | activate bottom friction |
| JONswap | use semi-empirical expression derived from the Jonswap results for bottom friction dissipation |
| 0.0670 (default) | cfjon: coefficient of the Jonswap formulation |

| TRIAD | activate triad wave-wave interaction using the LTA method |
| 0.1000 | trfac: proportionality coefficient αB (default: 0.05) |
| 2.2000 | cutfr: controls maximum frequency considered in triad computations (default: 2.5) |
| 0.2 (default) | urcrit: critical Ursell number appearing in expression for biphase |
| 0.01 (default) | urslim: if actual Ursell number below this value, triad interactions are not computed |

| LIMiter | de-activate permanently quadruplets when actual Ursell number exceeds [ursell] |
| 10 (default) | ursell: upper threshold for Ursell number |
| 1 (default) | qb: threshold for fraction of breaking waves |

<p>| NUMeric | adjust numerical properties of SWAN |
| DIRimpl | adjust numerical scheme for refraction |
| cdd= 0.50 (default) | cdd = 0: central scheme; cdd = 1: first order upwind scheme |
| SIGIMimpl | controls accuracy of computing frequency shifting and stopping criterion for SIP solver (currents involved) |
| css= 0.50 (default) | css = 0: central scheme; css = 1: first order upwind scheme |</p>
<table>
<thead>
<tr>
<th>NUMeric</th>
<th>adjust numerical properties of SWAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACCUR</td>
<td>adjust criterion for terminating the iterative procedure</td>
</tr>
<tr>
<td>0.010</td>
<td>drel: fraction of local mean wave period</td>
</tr>
<tr>
<td>0.010</td>
<td>dhoval: fraction of average mean wave period (of all wet grid points)</td>
</tr>
<tr>
<td>0.010</td>
<td>dtoval: fraction of average mean wave period (of all wet grid points)</td>
</tr>
<tr>
<td>98.000</td>
<td>npnts: percentage of all wet grid points where conditions must be fulfilled</td>
</tr>
<tr>
<td>50</td>
<td>maximum number of iteration steps</td>
</tr>
</tbody>
</table>
### A.8 Annex 3: Detailed results of computations

#### A.8.1 Wave-modelling without (nc) and with (yc) current

Output quantities:
- **d**: depth (m)
- **Hs**: significant wave height (m)
- **Dir**: mean wave direction (degrees w.r.t. north, clockwise)
- **Tp**: peak period (s)
- **Tm01**: mean absolute wave period (s)
- **Dspr**: directional spreading of the waves (degrees)

<table>
<thead>
<tr>
<th>Location</th>
<th>nc</th>
<th>yc</th>
<th>nc</th>
<th>yc</th>
<th>nc</th>
<th>yc</th>
<th>nc</th>
<th>yc</th>
<th>nc</th>
<th>yc</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.63</td>
<td>5.63</td>
<td>5.27</td>
<td>5.27</td>
<td>4.32</td>
<td>4.32</td>
<td>4.98</td>
<td>4.98</td>
<td>4.69</td>
<td>4.69</td>
</tr>
<tr>
<td>2</td>
<td>0.42</td>
<td>0.39</td>
<td>0.33</td>
<td>0.33</td>
<td>0.38</td>
<td>0.38</td>
<td>0.45</td>
<td>0.45</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>3</td>
<td>214.58</td>
<td>219.50</td>
<td>248.90</td>
<td>246.62</td>
<td>186.22</td>
<td>201.87</td>
<td>191.70</td>
<td>192.77</td>
<td>202.33</td>
<td>209.08</td>
</tr>
<tr>
<td>4</td>
<td>2.39</td>
<td>2.39</td>
<td>2.10</td>
<td>2.10</td>
<td>1.85</td>
<td>1.85</td>
<td>2.39</td>
<td>2.39</td>
<td>2.39</td>
<td>2.39</td>
</tr>
<tr>
<td>5</td>
<td>1.60</td>
<td>1.65</td>
<td>1.63</td>
<td>1.54</td>
<td>2.06</td>
<td>1.63</td>
<td>1.78</td>
<td>1.86</td>
<td>2.03</td>
<td>2.03</td>
</tr>
<tr>
<td>6</td>
<td>36.78</td>
<td>36.99</td>
<td>36.99</td>
<td>36.99</td>
<td>34.02</td>
<td>34.02</td>
<td>39.50</td>
<td>39.50</td>
<td>34.02</td>
<td>34.02</td>
</tr>
<tr>
<td>7</td>
<td>36.78</td>
<td>36.99</td>
<td>36.99</td>
<td>36.99</td>
<td>34.02</td>
<td>34.02</td>
<td>39.50</td>
<td>39.50</td>
<td>34.02</td>
<td>34.02</td>
</tr>
<tr>
<td>8</td>
<td>34.23</td>
<td>35.06</td>
<td>36.47</td>
<td>60.77</td>
<td>29.73</td>
<td>37.23</td>
<td>27.35</td>
<td>35.97</td>
<td>26.62</td>
<td>36.33</td>
</tr>
<tr>
<td>9</td>
<td>1.64</td>
<td>0.79</td>
<td>0.82</td>
<td>1.56</td>
<td>2.35</td>
<td>1.81</td>
<td>2.10</td>
<td>1.82</td>
<td>2.58</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>34.23</td>
<td>35.06</td>
<td>36.47</td>
<td>60.77</td>
<td>29.73</td>
<td>37.23</td>
<td>27.35</td>
<td>35.97</td>
<td>26.62</td>
<td>36.33</td>
</tr>
</tbody>
</table>
A.8.2 Comparison with Bretschneider

ds: delft3d/swan (without current)
bs: bretschneider

<table>
<thead>
<tr>
<th></th>
<th>ds</th>
<th>bs</th>
<th>ds</th>
<th>bs</th>
<th>ds</th>
<th>bs</th>
<th>ds</th>
<th>bs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.42/0.42</td>
<td>0.43/0.37</td>
<td>0.38/0.25</td>
<td>0.39/0.30</td>
<td>0.52/0.42</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.34/0.32</td>
<td>0.11/0.12</td>
<td>0.41/0.38</td>
<td>0.51/0.41</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
A.8.3 Refraction

<table>
<thead>
<tr>
<th>ref</th>
<th>no-rf</th>
<th>ref</th>
<th>no-rf</th>
<th>ref</th>
<th>no-rf</th>
<th>ref</th>
<th>no-rf</th>
<th>ref</th>
<th>no-rf</th>
</tr>
</thead>
<tbody>
<tr>
<td>d=</td>
<td>6.66/5.63</td>
<td>5.16/5.27</td>
<td>4.33/4.32</td>
<td>4.90/4.98</td>
<td>4.77/4.69</td>
<td>6.45/6.01</td>
<td>8.65/8.72</td>
<td>3.77/3.83</td>
<td>4.05/3.99</td>
</tr>
<tr>
<td>Hs=</td>
<td>0.41/0.45</td>
<td>0.32/0.34</td>
<td>0.42/0.43</td>
<td>0.29/0.46</td>
<td>0.46/0.56</td>
<td>0.38/0.36</td>
<td>0.14/0.12</td>
<td>0.46/0.47</td>
<td>0.42/0.53</td>
</tr>
<tr>
<td>Dir=</td>
<td>220.01/211.35</td>
<td>245.50/238.64</td>
<td>200.23/186.52</td>
<td>212.48/188.07</td>
<td>209.43/204.23</td>
<td>237.73/247.63</td>
<td>223.35/233.38</td>
<td>211.38/228.17</td>
<td>212.74/223.73</td>
</tr>
<tr>
<td>Tp=</td>
<td>2.10/2.39</td>
<td>1.85/1.85</td>
<td>2.10/2.39</td>
<td>1.43/2.71</td>
<td>2.71/2.71</td>
<td>2.10/1.85</td>
<td>1.11/0.98</td>
<td>2.10/2.39</td>
<td>2.39/2.71</td>
</tr>
<tr>
<td>Tm01=</td>
<td>1.69/1.78</td>
<td>1.34/1.40</td>
<td>1.96/2.10</td>
<td>1.90/2.31</td>
<td>1.95/2.29</td>
<td>1.63/1.60</td>
<td>0.87/0.93</td>
<td>2.21/2.35</td>
<td>1.99/2.26</td>
</tr>
<tr>
<td>Dspr=</td>
<td>50.93/31.28</td>
<td>36.91/36.15</td>
<td>35.09/26.69</td>
<td>45.79/25.76</td>
<td>33.75/23.95</td>
<td>34.96/33.24</td>
<td>52.76/40.47</td>
<td>39.12/29.67</td>
<td>35.20/28.28</td>
</tr>
</tbody>
</table>
### A.8.4 White-capping

<table>
<thead>
<tr>
<th>Location</th>
<th>d</th>
<th>Hs</th>
<th>Dir</th>
<th>Tp</th>
<th>Tm01</th>
<th>Dspr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.63/5.63</td>
<td>5.27/5.27</td>
<td>4.32/4.32</td>
<td>4.98/4.98</td>
<td>4.69/4.69</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.39/0.41</td>
<td>0.33/0.34</td>
<td>0.45/0.47</td>
<td>0.30/0.34</td>
<td>0.48/0.51</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>219.50/218.59</td>
<td>246.62/247.23</td>
<td>201.87/201.25</td>
<td>192.77/187.21</td>
<td>209.08/208.52</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2.10/2.10</td>
<td>1.85/2.39</td>
<td>2.39/2.39</td>
<td>1.63/2.71</td>
<td>2.39/2.39</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.65/1.67</td>
<td>1.36/2.06</td>
<td>2.10/1.78</td>
<td>1.85/2.03</td>
<td>2.06/2.06</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>38.51/38.74</td>
<td>36.99/37.65</td>
<td>34.02/34.28</td>
<td>39.50/39.92</td>
<td>33.60/33.71</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>6.01/6.01</td>
<td>8.72/8.72</td>
<td>3.83/3.83</td>
<td>3.99/3.99</td>
<td>5.60/5.60</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.39/0.40</td>
<td>0.12/0.13</td>
<td>0.50/0.52</td>
<td>0.47/0.49</td>
<td>0.58/0.61</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>235.25/236.37</td>
<td>226.01/231.74</td>
<td>212.41/212.89</td>
<td>217.37/218.99</td>
<td>237.92/238.55</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1.85/2.10</td>
<td>0.98/0.98</td>
<td>2.39/2.39</td>
<td>2.39/2.71</td>
<td>2.39/2.39</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.64/1.65</td>
<td>0.82/0.86</td>
<td>2.35/2.36</td>
<td>2.10/2.12</td>
<td>2.58/2.60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>35.06/35.88</td>
<td>60.77/61.78</td>
<td>37.23/37.62</td>
<td>35.97/36.78</td>
<td>36.33/36.61</td>
<td></td>
</tr>
</tbody>
</table>
A.8.5 Depth-induced breaking

<table>
<thead>
<tr>
<th>Location</th>
<th>d</th>
<th>Hs</th>
<th>Dir</th>
<th>Tp</th>
<th>Tm01</th>
<th>Dspr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.65/</td>
<td>0.39/</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.65/</td>
<td>0.39/</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.65/</td>
<td>0.39/</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.65/</td>
<td>0.39/</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.65/</td>
<td>0.39/</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>6.01/</td>
<td>0.39/</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>6.01/</td>
<td>0.39/</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>6.01/</td>
<td>0.39/</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>6.01/</td>
<td>0.39/</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>6.01/</td>
<td>0.39/</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

location 1
location 2
location 3
location 4
location 5
location 6
location 7
location 8
location 9
location 10
A.8.6 Bottom friction

<table>
<thead>
<tr>
<th>Location</th>
<th>(d)</th>
<th>(H_s)</th>
<th>(\text{Dir})</th>
<th>(T_p)</th>
<th>(T_m01)</th>
<th>(D_spr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.63/5.63</td>
<td>0.39</td>
<td>219.50/219.48</td>
<td>2.10/2.10</td>
<td>1.65/1.65</td>
<td>38.51/38.60</td>
</tr>
<tr>
<td>2</td>
<td>5.27/5.27</td>
<td>0.33</td>
<td>246.62/246.90</td>
<td>1.85/1.85</td>
<td>1.36/1.37</td>
<td>36.99/37.05</td>
</tr>
<tr>
<td>3</td>
<td>4.32/4.32</td>
<td>0.45</td>
<td>201.87/201.62</td>
<td>2.39/2.39</td>
<td>2.06/2.08</td>
<td>34.02/34.05</td>
</tr>
<tr>
<td>4</td>
<td>4.98/4.98</td>
<td>0.45</td>
<td>192.77/191.89</td>
<td>2.39/2.39</td>
<td>2.06/2.08</td>
<td>34.05/34.05</td>
</tr>
<tr>
<td>5</td>
<td>4.69/4.69</td>
<td>0.31</td>
<td>209.08/208.87</td>
<td>2.39/2.39</td>
<td>2.03/2.05</td>
<td>33.60/33.47</td>
</tr>
<tr>
<td>6</td>
<td>6.01/6.01</td>
<td>0.39</td>
<td>235.25/235.62</td>
<td>1.85/1.85</td>
<td>1.65/1.65</td>
<td>35.06/35.10</td>
</tr>
<tr>
<td>7</td>
<td>8.72/8.72</td>
<td>0.12</td>
<td>226.01/226.68</td>
<td>2.39/2.39</td>
<td>2.08/2.08</td>
<td>60.77/60.80</td>
</tr>
<tr>
<td>8</td>
<td>3.83/3.83</td>
<td>0.50</td>
<td>212.41/212.45</td>
<td>2.39/2.39</td>
<td>2.06/2.08</td>
<td>37.23/37.11</td>
</tr>
<tr>
<td>9</td>
<td>3.83/3.83</td>
<td>0.51</td>
<td>217.37/217.56</td>
<td>2.39/2.39</td>
<td>2.08/2.08</td>
<td>37.11/37.11</td>
</tr>
<tr>
<td>10</td>
<td>3.99/3.99</td>
<td>0.47</td>
<td>237.92/237.93</td>
<td>2.39/2.39</td>
<td>2.08/2.08</td>
<td>35.97/35.97</td>
</tr>
<tr>
<td></td>
<td>5.60/5.60</td>
<td>0.48</td>
<td>237.92/237.93</td>
<td>2.39/2.39</td>
<td>2.08/2.08</td>
<td>36.33/36.19</td>
</tr>
</tbody>
</table>