Experimental study of blockage of random waves by counter currents
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Experimental study of blockage of random waves by counter currents

Graduation thesis of M.P.C. de Jong

Committee:
Prof. Dr. Ir. J.A. Battjes
Ir. I.K. Suastika
Ir. G.J. Schiereck

TU Delft
Delft University of Technology
Faculty of Civil Engineering and Geosciences
Subfaculty of Civil Engineering
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My graduation project consisted of two parts: during the first two months, measurements were done in the Laboratory of Fluid Mechanics and during the last six months of the project, the processing of the measurements took place. During both periods I received supervision and assistance from a number of people.

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The special subject and good working atmosphere have made these months of working on my graduation project an interesting as well as a pleasant period.

Martijn de Jong
Summary

Introduction
From February to April 1999, wave-blocking experiments have been conducted at the Laboratory of Fluid Mechanics of the Faculty of Civil Engineering and Geosciences, Delft University of Technology, The Netherlands as a part of the Ph.D. research of I.K. Suastika.

Wave blocking is a special case of wave-current interaction. It can occur when waves are propagating against a counter of which the velocity is increasing in the wave propagation direction. Blocking occurs where the intrinsic wave group velocity \(c_g\) is equal, but opposite in sign, to the mean velocity \(U\):

\[
c_g + U = 0.
\]  
(S,1)

The counter current velocity at the blocking point is called the blocking velocity \(U_{bl}\). In this thesis the experiments are described and a part of the measurement data is analysed, especially the data concerning the blocking of irregular waves.

Research objectives
The first objective of this research is to acquire quantitative data on partial and complete blocking. The second objective is to develop a model for wave blocking. The model should describe the wave field in a situation where blocking occurs. So, for a given incoming (generated) wave field and counter current, the model should describe the wave field up to and at the blocking point. (And beyond, in cases of partial blocking.)

Theory of blocking
For free water waves there is a relation between the wave frequency and the wave number. This is the (linear) dispersion relation for free water waves:

\[
\sigma^2 = gk \tanh(kh)
\]  
(S,2)

in which \(\sigma\) is the intrinsic frequency (relative to the water), \(g\) is the acceleration due to gravity, \(k\) the wave number \((2\pi/\text{wave length})\) and \(h\) the water depth. In a situation with a (counter) current the dispersion relation is Doppler shifted:

\[
\sigma = \omega - \mathbf{k} \cdot \mathbf{U}
\]  
(S,3)

in which \(\omega\) is the absolute frequency (e.g. frequency of the wave maker) and \(\mathbf{U}\) is the velocity vector. After differentiating (S,3) to \(k\), the blocking condition (S,1), for a one-dimensional situation, can be derived.
When a wave faces a counter current with velocity smaller than that of the blocking velocity, the dispersion relation yields two solutions (for $k > 0$). One is associated with the incoming wave, the other, with a larger wave number, is associated with a reflected component.

**Experimental arrangement**

The key to the design of the experimental arrangement is a 12 m long measurement section in the central portion of a 35 m long flume in which discharge entering at one end is gradually withdrawn through the bottom and brought to zero at the other end. Large-scale turbulence and swirling motions in the inflowing current were dampened by using a honeycomb. At both ends the full flume width (0.8 m) and height (1.0 m) were available to the waves and the current, respectively, but with the aid of a vertical false wall and a false bottom the available width and height were reduced to 0.4 m and 0.7 m in the measurement section in the middle part of the flume. The measurement section was divided into six compartments of 2 m length each, with a false perforated bottom allowing withdrawal of discharge through this bottom into the adjacent dummy half of the flume, which in turn acted as a sump for six 10.0 cm inner diameter suction pipes, one for each compartment. (Along the entire 12 m long measurement section, the vertical false wall reached only to the false bottom, allowing lateral flow of water from underneath the false bottom into the adjacent dummy half of the flume; see figure for a detail of one suction section.)

Because the discharge decreased from maximal at one side of the measurement section to zero at the other side, a velocity gradient was achieved. Therefore, the waves that were generated at the downstream side of the flume were able to propagate into the flume until they reached a counter current strong enough to get blocked.

**Experimental program**
Before the actual blocking measurements, the velocity profiles in absence of waves were measured in order to determine the effectiveness of the experimental arrangement. Subsequently, experiments were done on blocking situations involving random and monochromatic waves. Furthermore, waves on still water were analysed in order to determine the dissipation due to internal friction and side wall resistance.

Results
The velocity measurements in absence of waves showed that the experimental arrangement worked very well: the six suction sections created a nearly constant velocity gradient and the velocity profile was reasonably depth uniform. The blocking experiments showed an incoming wave whose length decreased as it approached the blocking point, and it showed the reflected component which became shorter in the downstream direction. The crests of the reflected component still propagated in the upstream direction, but the energy of the waves was swept downstream by the counter current.

Waves with smaller periods were blocked by a counter current that was less strong than the counter current that was needed to block the longer waves. The amplitude influence was visible since the higher waves were blocked further upstream than lower waves with the same period.

Modelling
A model based on the wave action balance was developed which includes three kinds of energy dissipation: breaking (whitecapping), viscous damping and dissipation term due to wave-turbulence interaction.

Conclusions
The blocking experiment was successfully conducted: the experimental arrangement fulfilled its purposes and the measurements were speedily conducted. Even though there was little time available, many blocking situations (for random as well as monochromatic waves) were measured.

The modelling of the blocking phenomenon has proven to be very complicated. Partly because there are multiple mechanisms influencing the wave field when waves get blocked, and partly because regular analysis methods usually are not based on a situation which includes a current or a velocity gradient. The model, which was developed, is not able to predict the wave field in a blocking situation. With different calibration factors, the order of magnitude of the maximum significant wave heights can be estimated. However, the evolution of the significant wave height is not predicted well: the maximum wave height is calculated at a smaller co-ordinate than according to the measurements and the model shows a significant amount of energy which is not blocked, whereas the measured data show that almost the complete spectrum gets blocked.
Recommendations
The model has to be adapted/further developed in order to improve the results. In order to improve the agreement of the calculated blocking region with the measured locations, the wave propagation has to be calculated with a higher order dispersion relation. Other formulations or other dissipation mechanisms could be used in the model, so as to improve the calculated evolution of the significant wave height. Finally, the model can be adapted in order to include the reflected wave components. This means that the model will include more physical processes, which occur in the wave flume.
Samenvatting

Inleiding

Golf blocking is een bijzonder geval van golf-stromingsinteractie. Het kan optreden als golven zich voortbewegen op een tegenstroom van toenemende sterkte. Golf blocking treedt op waar de intrinsieke groep snelheid van de golven \( c_g \) gelijk wordt aan de gemiddelde snelheid \( U \) van de tegenstroom:

\[
c_g + U = 0 \quad (S,1)
\]

De stroomsnelheid op het blockingspunt wordt blockingsnelheid \( U_{\text{BL}} \) genoemd. In dit afstudeerverslag worden de blocking experimenten beschreven en wordt een deel van de gemeten data geanalyseerd, in het bijzonder de metingen van onregelmatige golven.

Onderzoeksdoel
Het onderzoek heeft een tweeledig doel: als eerste wil men met deze experimenten meetgegevens verzamelen voor gedeeltelijke en partiële blocking van golven. Daarnaast wil men een model opstellen voor het berekenen van de (variatie in de) golfhoogte in een blockings-situatie. Dus, voor een gegeven inkomend (of gegeneereerd) golfsspectrum, dient het model de evolutie van de golfhoogte te berekenen, naar het blockingspunt toe, op het blockingspunt en, in geval van partiële blocking, voorbij het blockingspunt.

Theorie van golfblocking
Voor vrije golven is er een relatie tussen de golfperiode en de golflengte. Dit is de (lineaire) dispersie relatie voor vrije oppervlaktegolven:

\[
\sigma^2 = gk \tanh(kh) \quad (S,2)
\]

waarin \( \sigma \) de intrinsieke frequentie, \( g \) de versnelling van de zwaartekracht, \( k \) het golfgetal \( (2\pi/\text{golflengte}) \) en \( h \) de waterdiepte is. In een situatie met een stroming geldt de dispersie relatie inclusief de Doppler verschuiving:

\[
\sigma = \omega - \vec{k} \cdot \vec{U} \quad (S,3)
\]
waarin $\omega$ de absolute frequentie (frequentie van het golfschot) en $\vec{U}$ de dieptegemiddelde snelheidsvector is. Na differentiëren van (S,3) naar k, kan voor een eendimensionale situatie de blockingsconditie (S,1) gevonden worden. Als de golven zich voortplanten op een tegenstroming met een absolute waarde van de stroomsnelheid die kleiner is dan de blockingsnelheid dan heeft de dispersierelatie twee wortels/oplossingen ($k>0$). De eerste wordt geassocieerd met de inkomende golf, de tweede, met het grotere golfgetal, met een gereflecteerde component.

Meetopstelling
Het hart van de meetopstelling was de 12 m lange meetsectie in het middelste deel van de 35 m lange golfgoot waarin het debiet dat aan één zijde van de goot binnenkwam geleidelijk werd afgezogen door de bodem en tot nul gebracht werd aan de andere zijde van de goot.

Een honingraat aan de bovenstroomse kant van de goot zorgde ervoor dat de grootschalige turbulente wervels werden gedempt. Aan de beide uiteinden van de goot was de gehele breedte (breedte goot: 0.8 m, hoogte goot 1.0 m) beschikbaar voor respectievelijk de golven of de stroming, maar met behulp van een vertikale wand en een verhoogde bodem werden de beschikbare hoogte en breedte gereduceerd tot 0.4 en 0.7 m in de meetsectie in het middelste deel van de goot. De meetsectie was opgedeeld in zes compartimenten van elk 2 m lengte met verhoogde geperforeerde bodems, die het mogelijk maakte het debiet door deze bodem af te zuigen naar de naastgelegen reserve helft van de goot, die op zijn beurt fungeerde als een put voor de zes afzuigbuizen (één per afzuigsectie) met elk een binnenwerks-diameter van 10 cm. (Langs de gehele 12 m lange meetsectie liep de vertikale wand in het midden van de goot tot op de verhoogde bodem, zodat het debiet onder de wand door naar de reserve kant gepompt kon worden, zie onderstaande figuur).
Omdat de stroomsnelheid van maximaal aan de ene zijde van de meetsectie afnam tot nul aan de andere zijde, werd een snelheidsgradiënt bewerkstelligd. Dus, de golven die gegenereerd werden aan de ene zijde van de goot konden de goot inlopen tot ze geblokkt werden op het blockingspunt.

**Meetprogramma**

Eerst werd het (longitudinale en vertikale) snelheidsprofiel bepaald, om de effectiviteit van de opstelling te bepalen. Vervolgens werden de blocking metingen verricht voor monochromatische en onregelmatige golven. Daarnaast werden ook golven op stil water gemeten om op die manier de dissipatie veroorzaakt door de wanden en geperforeerde bodem te kunnen bepalen. Als laatste werden ook turbulentie metingen gedaan.

**Resultaten**

De snelheidsmetingen gaven aan dat de meetopstelling goed werkte: de zes afzuigsecties realiseerden een constante snelheidsgradiënt met een redelijk uniforme snelheidsverdeling over de diepte.

De blocking experimenten lieten zien dat de golflengte van de inkomende golf langzaam afnam als de golf dichter bij het blockingspunt kwam, daarnaast lieten zij de gereflecteerde component zien waarvan de golflengte in stroomafwaardse richting afnam. De kammen van de gereflecteerde component propageerden wel stroomopwaarts, maar de energie van de golf werd stroomafwaarts getransporteerd door de tegenstroom.

Golven met kleinere perioden werden door een zwakkere tegenstroom geblokkt dan langere golven. Door de amplitude dispersie blockten de hogere golven verder stroomopwaarts dan de lagere golven.

**Modellering**

Een model is ontwikkeld gebaseerd op de balans van "wave action". In dit model zijn de volgende dissipatie mechanismen verwerkt: breken (whitecapping), visceuze demping door bodem en wanden van de goot en dissipatie door golf-turbulentie interactie.

**Conclusies**

Het blocking-experiment is een succes: de meetopstelling heeft goed gewerkt en de metingen zijn goed verlopen. Ondanks dat er niet veel tijd beschikbaar was, zijn veel blockings-situaties doorgemeten (zowel voor onregelmatige als regelmatige golven).

Het modelleren van golf-blocking is lastig gebleken. Deels omdat er meerdere mechanismen zijn die het golffeld beïnvloedden als de golven worden geblokkt, deels omdat de reguliere analysemethoden niet gebaseerd zijn op een situatie met een stroming of een snelheidsgradiënt.
Het model dat ontwikkeld is kan (de veranderingen in) het golfveld niet goed voorspellen in een blockings situatie. Met verschillende versterkingsfactoren kan de orde van grootte van de maximale significante golflengte benaderd worden. De evolutie van de significante golflengte langs de goot daarentegen wordt niet juist berekend: de maximale significante golflengte wordt berekend bij een zwakkere tegenstroom dan volgt uit de metingen en het model berekent een relatief grote hoeveelheid energie die niet geblokkt wordt, terwijl de metingen laten zien dat bijna het gehele spectrum wordt geblokkt.

**Aanbevelingen**

Het model dient verder ontwikkeld/aangepast te worden om de resultaten te verbeteren. Om de overeenkomst van het berekende gebied van blocking met de gemeten lokatie te verbeteren dient de berekening van de golfvoortplanting gebaseerd te worden op een hogere orde dispersie relatie. Andere dissipatiemodellen en/of -mechanismen kunnen in het model worden opgenomen (een ander brekingsmodel bijvoorbeeld) om de berekende significante golflengten te verbeteren. Het model zou aangepast kunnen worden om de gereflecteerde golfcomponenten in de berekening te betrekken. Dit betekent dat het model meer in de goot optredende fysische processen weergeeft.
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1. Introduction

1.1 General

Wave-current interaction research
Waves have been studied for a long time. Usually laboratory research is focussed on waves without interaction with a current. Because this interaction between waves and currents occurs in many situations in the coastal region (e.g. waves interacting with an ebb current) and in rivers (e.g. waves interacting with a river flow), it is important to understand the underlying processes.

Reviews concerning wave-current interaction can be found in Peregrine (1976) and Jonsson (1993). In the last couple of years, more laboratory research has been done on wave-current interaction and in particular on wave blocking (see Lai et al. 1989, Chawla and Kirby 1998). The experiment of Lai et al. was on a rather small scale so viscosity and surface tension possibly had a significant influence. The experiment of Chawla and Kirby, of which the results were published at approximately the same time this experiment was set up, was on the same scale as this experiment, which is a part of the Ph.D. research of I.K. Suastika.

Influence of wave-current interaction
Because the interaction of waves and currents occurs very often, and the effects can be significant, it is important to include the effect of this interaction when (see Jonsson 1993):
- calculating wave heights from subsurface pressure recordings
- calculating refraction
- determining water particle velocities and accelerations for the calculation of forces on ocean structures
- determining energy spectra
- predicting extreme wave events
- calculating the effective fetch

Wave blocking
Wave blocking can occur when waves are propagating against a counter current of which the current velocity is increasing in the wave propagation direction. In such a situation, the waves can reach a point where the intrinsic group velocity ($c_g$) is equal (but opposite in sign) to the velocity of the counter current (U):

$$c_g + U = 0$$  \hspace{1cm} (1.1)

At this blocking point the absolute wave energy transport velocity equals zero: the waves cannot transport energy beyond this point, and blocking occurs. The theory of blocking will be treated in more detail in chapter 2.
1.2 Purpose of the study

Research objectives
The first objective of this research is to acquire quantitative data on partial and complete blocking. The second objective is to develop a model for wave blocking. The model should describe the wave field in a situation where blocking occurs. So, for a given incoming (generated) wave field and counter current, the model should describe the wave field up to and at the blocking point. (And beyond, in cases of partial blocking.)

Aspects
The model, which is to be developed, should include the following aspects:

1) Wave energy dissipation
Dissipation of wave energy due to
- viscous effects at the boundary layer along the side walls of the flume
- the water exchange through the perforated bottom (see for the experimental arrangement chapter 3) (especially for longer waves, when the pressure variations reach to the bottom)
- breaking of the waves: waves travelling on a non-uniform current can break when propagating against the current: the waves become higher and shorter (the waves become steeper).

2) Reflection of wave energy
Waves can be reflected at the blocking point. An aspect which is to be resolved here, is the discrimination of the reflected components from the incoming wave components.

Objectives of this thesis
Besides the description of the experiments, the focus in this graduation thesis is on wave energy dissipation. A model will be developed for irregular waves, which includes the wave energy dissipation due to wave breaking, due to viscous effects and wave turbulence interaction.
In order to describe the dissipation due to wave breaking, an adapted version of the Battjes-Janssen bore dissipation model will be used (see Battjes and Janssen 1978). For the dissipation due to viscous effects the model of Hunt (see Hunt 1952) will be used. The Rosenthal model will be used for dissipation due to wave-turbulence interactions (see Rosenthal 1989).
1.3 Outline of the report

In chapter 2 the underlying physics of wave blocking will be outlined. In chapter 3 the experimental arrangement and experimental procedures will be described. Observations made during the experiment are described in chapter 4. The results of the measurements are presented in chapter 5. Chapter 6 describes the models that were developed in order to describe the blocking situation. In the last chapter the conclusions and recommendations will be given.
2 Wave blocking

2.1 Introduction
In the first chapter wave blocking was already introduced as a special case of wave-current interaction. In this chapter the underlying physics of waves and wave blocking will be treated in more detail.

2.2 Dispersion relation
Intrinsic dispersion relation
For free water waves (i.e. without a forced period for a given wave number) there is a relation between the frequency and the wave number \( k = 2\pi/\text{wavelength} \), which is determined by the mass distribution and the equilibrium-seeking force. For free surface gravity waves this relation is:

\[
\sigma^2 = gk \tanh(kh) \tag{2.1}
\]

in which \( \sigma \) is the frequency of the wave, \( g \) is the acceleration due to gravity and \( h \) is the waterdepth. This linear dispersion relation is independent of the wave amplitude.
When using a third order (or higher) Stokes dispersion relation, the amplitude influence is introduced:

\[
\sigma^2 = gk \tanh(kh) \left[ 1 + \left( ka \right)^2 \left( \frac{8 + \cosh(4kh)}{8 \sinh(kh)^4} \right) \right] \tag{2.2}
\]

For a given wave number, the frequency will increase because of the amplitude influence.
In this chapter, the phenomenon of blocking is explained using the linear dispersion relation.

Doppler shifted dispersion relation
For waves on a (counter) current with a depth uniform velocity \( \vec{U} \) the dispersion relation for free waves is given by:

\[
\sigma = \omega - k \cdot \vec{U} \tag{2.3}
\]

in which \( k \cdot \vec{U} \) equals the Doppler shift of the frequency, which in a one dimensional case can be written as \( \sigma = \omega - kU \) in case of a counter current and as \( \sigma = \omega + kU \) in case of a following current, \( \omega \) is the absolute wave frequency (i.e. in these experiments the frequency of the wave maker) and \( \sigma \) is the wave frequency in a frame of reference moving with the current (intrinsic frequency).
Absolute frequency
For periodic waves, the absolute frequency is the same in every fixed point (e.g. location of a wave probe) even though the wave complies with the Doppler shifted dispersion relation and $\sigma$ may vary due to a nonuniform current. The reason for this is that when a wave propagates on a counter current, the wavelength and intrinsic period are smaller compared to a situation without a current, but, because of the counter current, the frame of reference is moving in the opposite direction so it takes the same time for a wave to pass a fixed point. This means that in a fixed frame of reference the absolute wave period does not change.

Roots of the dispersion relation
For different situations the dispersion relation yields different solutions/roots. The straight lines in figure 1 represent $\sigma = \omega - \vec{k} \cdot \vec{U}$ (derivative to $k$ equals -$U$). The intersections with the intrinsic dispersion relation $\sigma(k)$ are roots of the Doppler shifted dispersion relation ($\sigma(k) = \omega - \vec{k} \cdot \vec{U}$).

Figure 1: Doppler shifted dispersion relation
From figure 1 five different cases can be distinguished (for $k>0$):

a. $U = 0$ m/s. No current is present so $\omega = \sigma$. The horizontal line in the figure is used, which has one intersection with the intrinsic dispersion relation (one root).
b. \( U > 0 \, \text{m/s} \). Waves travel in the same direction as the current: wavelength increases compared to situation a.

c. \( U < 0 \, \text{m/s} \). In this situation the Doppler shifted dispersion relation has two roots: \( k_1 \) and \( k_2 \). The first solution (\( k_1 \)) represents a wave that propagates against the current with a wavelength that is smaller compared to the wavelength in the situation without a current. The second solution (\( k_2 \)) is associated with a reflected wave (see paragraph 2.5).

d. \[ \frac{d\sigma}{dk} = -U, \quad c_g + U = 0 \]

Border case for which wave blocking occurs. The two solutions coalesce (the tangent point). When waves are propagating on an increasing counter current, both solutions (\( k_1, \sigma_1 \) and \( k_2, \sigma_2 \)) from situation c approach the single solution which exists at the blocking point. This occurs when the counter current equals the blocking velocity (\( U_{BL} \)).

e. \( U + c_g < 0 \), no intersection with intrinsic dispersion relation: there are no roots. This means that waves cannot propagate into this region with relative high counter current velocity when originated at a location with a weaker counter current.

**Large scale current approximation**

Strictly speaking the Doppler shifted dispersion relation is only applicable for a uniform situation. Since the waves in the case of blocking are propagating on an increasing counter current, this is not the case.

By assuming that the time and length scales of the variations in the current are much larger than those of the waves (gradually changing current), the approximation can be used that the waves, at a point with certain flow characteristics, have the same characteristic values as a uniform wave train on a uniform current with the same flow characteristics. This is known as the "Large scale current" approximation (see D.H Peregrine 1979), or the "quasi-uniform wave" approximation. During the analysis and processing of the data this approximation is used.

This approximation can be effective when

\[ k \gg \max \left| \frac{1}{U} \frac{\partial U}{\partial x} \right| \quad \text{and} \quad \omega \gg \max \left| \frac{1}{U} \frac{\partial U}{\partial t} \right| \]  \hspace{1cm} (2.4)

This means that the current variations in space and time are small within a wave length and a wave period.

During the measurements a stationary situation was used, so the derivative with regard to time equals zero. This means that the second condition will be fulfilled. The
first condition is also fulfilled since our experimental arrangement produced a gradually changing current (small velocity gradient), compared to the mean velocity.

2.3 Blocking

Blocking condition
The condition for blocking can be acquired by differentiating (2.3). For a one-dimensional case, this yields:

\[ \frac{\partial \omega}{\partial k} = \frac{\partial \sigma}{\partial k} + U \quad \text{or} \quad C_g = c_g + U \quad (2.5) \]

In the second part of (2.5) \( C_g \) represents the absolute group velocity (relative to the flume) and \( c_g \) represents the group velocity of the waves relative to the water. At the blocking point, \( C_g \) equals zero so the condition for wave blocking is given by:

\[ c_g + U = 0 \quad (2.6) \]

which is situation d in paragraph 2.2. From (2.6) it can be seen that waves with a larger period, with a larger \( c_g \), require a stronger counter current to be blocked. When the influence of the amplitude is included in the dispersion relation, higher amplitudes also tend to increase the required counter current to block the waves.

The dispersion relation shows that when an incoming wave train propagates on an increasing counter current the intrinsic wave group velocity will decrease.

![Figure 2: Evolution of U and c_g](image)
An example is given in figure 2 for a regular wave with an absolute period of 1.1 s. The velocity of the counter current (solid line) in this figure increases from 0 m/s to about 0.4 m/s at the right side of the figure. The sum of \( U \) and \( c_g \) decreases until the point is reached where \( c_g + U = 0 \) and blocking occurs.

Reflection and dissipation
At the blocking point the energy flux of the waves becomes zero, so the blocking point acts like a "vertical wall" for the waves. Because the energy cannot pass this barrier, it has to be dissipated or reflected. Since the waves become steeper when they approach the blocking point, energy will be dissipated through e.g. whitecapping (breaking of waves due to the existence of a maximum steepness).
Energy which is not dissipated can be reflected in the form of a second wave component with a larger wave number than the incoming wave (downstream of the blocking point). How much of the incoming energy is dissipated and how much is reflected is not known yet.

Reflected wave component
Because the reflected wave is a free wave, it has to comply with the (Doppler shifted) dispersion relation. In paragraph 2.2 the possible (positive) roots of the Doppler shifted dispersion relation were shown. In what was called situation c (the situation with a counter current velocity whose magnitude is smaller than the magnitude of the blocking velocity) two solutions were found: solution \( k_1 \), which corresponded with the incoming wave propagating towards the blocking point, and solution \( k_2 \), which was associated with the reflected wave.
At the downstream side of the blocking point, the phase velocity \( (c = \alpha/k) \) of this reflected component is larger than the absolute value of the counter current \( (|U|, \text{see figure 3}) \), so the crests of the reflected wave component travel upstream. However, the group velocity \( (c_g = d\alpha/dk) \) of the reflected wave at this location is smaller than absolute value of the counter current so \( c_g + U < 0 \), which means that the wave-energy is being swept downstream by the current, away from the blocking point.

This transporting mechanism can be elaborated through the following example which uses the same characteristics for the incoming wave as in figure 2. The group velocity of the reflected wave which is associated with this incoming wave, the average velocity \( (U) \) and the sum \( c_g + U \) are plotted in figure 4. The wave group velocity of the reflected wave can only be calculated in a region with a counter current: the second solution of the Doppler shifted dispersion relation \( (k_2) \) goes to infinity when the reflected wave reaches a region of still water.
From figure 4 it can be seen that the sum of \( c_g \) (of the reflected wave) and \( U \) is negative at each point downstream of the blocking point, which is located at approximately \( x = 8 \) m. This shows that the energy of the reflected wave component is transported from the blocking point in the downstream direction.
Figure 3: Phase velocity and group velocity of second component

Figure 4: Evolution of $c_g$ and $U$ for the reflected wave

Wave numbers
In case of wave reflection by a vertical wall in a constant water depth, the wave number of the reflected wave will be equal but opposite in sign to the wave number of the incoming wave. The reflected wave transports wave-energy away from the wall with its group velocity. Because the wavelengths of both waves are equal, a standing wave (clapotis) can form in front of the wall.
In a blocking situation, on the other hand, the wavelengths (wave numbers) of both waves are equal only at the blocking point (where in fact only one wave occurs). Further downstream, the two wavelengths are not equal so a standing wave cannot occur. The evolution of the wave numbers of the two solutions can be illustrated by the following situation (see figure 5): again a regular wave with a period of 1.1 s is used with the same counter current as in figure 4.

In the upstream direction (increasing counter velocity), the incoming wave will become shorter (increasing wave number) until it reaches the blocking point. The reflected wave will become shorter (increasing k) in the downstream direction until it reaches still water where $k_2 = \infty$ so the theoretical wavelength equals zero. Breaking and viscosity will dissipate the energy of the reflected wave long before this situation arises.

![Graph showing wave numbers](image)

*Figure 5: Evolution of the wave numbers of the incoming and reflected wave*

### 2.3 Wave energy

*Period and wave height*

In this study the blockage of both monochromatic and random waves is investigated. A monochromatic wave has a period (T) and an amplitude (a). A random wave field is a combination of an infinite number of sine wave components each with a different frequency, phase and amplitude (and direction in case of a multi directional wave field).

A random wave field is described by an energy (or variance) density spectrum, which is usually characterised by the peak period (period with the highest energy density) and the significant wave height ($H_s$ or $H_{1/3}$ average of the one third highest waves). The wave height is defined as the highest elevation of the crest and of the lowest
through between two consecutive zero down or up crossings (crossing of mean water level).

Variance density spectrum
A variance density spectrum of a measured signal can be obtained by assuming that the measured signal is equal to a sum of a large (theoretically infinite) number of cosines, with different amplitudes, frequencies and phases:

$$\eta(t) = \sum_{n=1}^{N} a_n \cos(2\pi f_n t + \alpha_n)$$  \hspace{1cm} (2.7)

in which $\eta$ is the surface elevation and $a_n$, $f_n$ and $\alpha_n$ respectively represent the amplitude, the frequency and the phase of the $n^{th}$ component.

In case a continuous function is determined (in stead of using a discrete number of components), the ratio of the variance of the components in a small frequency band, to the bandwidth $\delta f$ which equals:

$$\frac{\sum_{f}^{1} a_n^2}{\delta f}$$  \hspace{1cm} (2.8)

is used. This ratio converges to a finite value when the width of the frequency band ($\delta f$) goes to zero. The continuous spectrum (variance density spectrum) is therefore defined as:

$$E(f) = \lim_{\delta f \to 0} \frac{1}{\delta f} E\left\{ \sum_{f}^{1} a_n^2 \right\}$$  \hspace{1cm} (2.9)

The area under the variance density spectrum ($m_0$) is the total variance of the surface elevation ($\eta$), which equals $E\left\{ \eta^2 \right\}$ and since $\rho g E\left\{ \eta^2 \right\} = E_{\text{total}}$ (total amount of energy per unit area), the energy density spectrum can be calculated by multiplying the variance density spectrum with $\rho g$.

### 2.5 Wave action
In presence of a current, wave energy is not conserved (see Bretherton and Garreth, 1969):

$$\frac{d}{dx} \left( E(c_g + U) \right) \neq 0$$  \hspace{1cm} (2.10)
in which $E = 1/2 p g a^2$: the wave energy density. However, the wave action ($N$) defined as:

$$N = \frac{E}{\sigma}$$

(2.11)

is conserved (see Bretherton and Garrett, 1969). The wave action balance can be derived from the momentum conservation formula, combined with the energy balance (see Jonsson 1993). This balance reads:

$$\frac{d}{dx} \left( \frac{E}{\sigma} (c_g + U) \right) + \frac{D}{\sigma} = 0 \quad \text{or} \quad \frac{d}{dx} \left( N (c_g + U) \right) + \frac{D}{\sigma} = 0$$

(2.12)

in which $D$ represents the rate of wave energy dissipation per unit area. When a wave propagates on an increasing counter current, $(c_g + U)$ decreases and $\sigma$ increases. This results in an increase of wave energy which, when dissipation is not taken into account (i.e. $D = 0$), reaches infinity at the blocking point according to equation (2.12) which, however, is not valid in that region because of rapid spatial variations in the wave field.
3 Experimental arrangement

3.1 Description of the experimental arrangement

In order to make further studies of wave blocking, the occurrence of breaking and/or reflection, and the damping of the ongoing waves, experiments have been conducted at the Laboratory of Fluid Mechanics of the Faculty of Civil Engineering and Geosciences, Delft University of Technology, The Netherlands.

General description

The key to the design is a 12 m long measurement section in the central portion of a 35 m long flume in which discharge entering at one end is gradually withdrawn through the bottom and brought to zero at the other end. (See figure 8 with the layout of the experimental arrangement.) This measurement section had a constant cross section (A). This means that the velocity gradient (dU/dx) was solely caused by the variation of the discharge (Q(x)). The blockage of waves can therefore be measured without the influence of a varying cross section.

The false bottom of the measurement section consisted of perforated plates. This perforated bottom can cause more dissipation than a regular bottom (i.e. a smooth bottom of a flume), because the waves can "pump" water in and out the suction sections through the perforated plates which causes higher turbulence intensity. This could be reduced by using short waves (deep water waves, short wavelength with respect to the depth). The pressure variations and orbital movement of these deep water waves do not reach the bottom plates, so dissipative effect of the perforated plates is reduced.

More reduction of the dissipative effect of the perforated plates was achieved by mounting plywood "lids" over the suction sections: the volume of the sections was thereby fixed and the amount of water the waves were unable to pump through the bottom plates was reduced considerably.

The flume is equipped with a wave generator at one end (to the right in the longitudinal view and plan view in figure 8), with permeable wave damping material at the opposite end where also a flow of water could be let into the flume with controlled discharge. Large-scale turbulence and swirling motions in the inflowing current were dampened by a honeycomb.

Division of flume's width

At both ends the full flume width (0.8 m) and height (1.0 m) were available to the waves and the current, respectively, but with the aid of a vertical false wall and a false bottom the available width and height were reduced to 0.4 m and 0.7 m in the measurement section in the middle part of the flume.
In order to obtain a smooth inflow, both the false bottom and the false wall at the upstream end of the flume were streamlined, forming a gradual decrease of the available cross-section in the flow direction. At the upwave end of the flume, a concreted sloping bottom formed a gradual transition between the original flume bottom and the false bottom in the measurement section. The false wall at that end was not streamlined but instead acted as a splitter wall, so as to allow undisturbed wave propagation into the measurement section. The remaining energy propagated into the dummy half of the flume where it was dissipated there on a 1:10 gravel spending beach.

**Suction sections**

The 12 m long measurement section was divided into six compartments of 2 m length each, with a false perforated bottom allowing withdrawal of discharge through this bottom into the adjacent dummy half of the flume, which in turn acted as a sump for six 12.5 cm inner diameter suction pipes, one for each compartment. (Along the entire 12 m long measurement section, the vertical false wall reached only to the false bottom, allowing lateral flow of water from underneath the false bottom into the adjacent dummy half of the flume; see figure 6 for a detailed view of one suction section.)

![Diagram](image)

*Figure 6: Detail of suction section (measures in m)*

Each suction pipe was mounted vertically in the dummy half of the flume and connected to a horizontal conduit provided with a control valve and discharge meter. These six conduits in turn led via two manifolds to two pumps from which the water was returned through two pressure pipes and delivered to the upstream end of the flume.

In order to better control the longitudinal discharge variations (i.e., to prevent longitudinal short-circuiting), the six 2 m long compartments were separated by vertical plywood plates normal to the flume length axis, occupying the entire flume cross-section except the reduced area available for the current and the waves. In this
manner it was guaranteed that each of the six suction pipes would withdraw water from only the 2 m long compartment adjacent to it.

**Wave maker**
Downstream of the measurement section with variable discharge, a region existed where the discharge and therefore the cross-sectionally averaged current velocity was zero. In this stagnant region, waves were generated by a wave generator, through horizontal translation of a vertical wave paddle. The motion of the paddle was controlled with electronic signals generated by Auke-stir2C, a wave generation package developed within WL | Delft Hydraulics. This package is capable of generating regular waves of different periods and heights, and irregular waves with different target energy spectra, with second-order control to prevent spurious harmonics. It also has an automatic reflection absorption capability.

**Video recordings**
Video recordings have been made to show the experimental set-up, to visualise some physical processes occurring in the flume (such as the occurrence of the short reflected wave), and to allow quantitative analysis of some visually observable phenomena.

### 3.2 Co-ordinates
In figure 8 the origin of the co-ordinate system is located at the start of the slowly rising bottom at still water level where x is positive in wave propagation direction (from right to left) and z positive upwards.

The measurements were done in a section from \(x = 9.0 \text{ m}\) to \(x = 25.0 \text{ m}\) (see figure 7). This part of the flume had a constant cross section (height and width).

![Figure 7: Measuring section with co-ordinates](image)

### 3.3 Experimental procedure

#### 3.3.1 Positioning the probes
With the aid of a cart, which could be moved easily on two rails along the flume, it was possible to position the measurement probes at any location along the measurement section.
Experimental arrangement

Longitudinal section

Plan view

Coordinates measuring section

Section AA'

Section BB'

Experimental arrangement

Experimental study of blockage of random waves by counter currents

M.Sc. thesis of M.P.C. de Jong

Hydromechanical Engineering

Scale 1:50 [1:50]

Dimensions in m

Experimental Arrangement

Waveblocking experiment

CAD te
The flow velocity was measured by using EMF (or EMS) and LDA probes. The surface elevation was measured by using capacitance type wave gauges. The spatial resolution was chosen 80 cm (near the wave maker) to 10 cm (near the blocking point) for both regular and irregular waves.

Two types of EMF probes have been used: the first to measure $u$ and $w$ (velocity in $x$, $z$ direction) simultaneously and the second to measure $u$ and $v$ (velocity in $x$, $y$ direction). An LDA probe has been used to check the velocity measurements done by using the EMF probes. Furthermore, the LDA probe was used for the purpose of turbulence monitoring since it is capable of producing a higher resolution in space and time, i.e. a smaller measurement volume and higher sample rate than the EMF.

3.3.2 Description of the probes

**LDA probe**
The LDA probe uses two intersecting laser beams (or three when measuring velocities in two directions simultaneously). At the intersection region they form a measuring volume. As a particle passes the measuring volume, the laser light will be scattered. A sensor detects the scattered laser light, whereas the other beam is detected to function as a reference. The scattered laser light has shifted in phase because of the Doppler effect. By comparing the reflected beam and the reference beam, the velocity of the particle can be calculated. When there are not enough particles in the water (i.e. the water is “too clean”) a special seeding can be added to the water.

**EMF probe**
The EMF or EMS probe measures the velocity of the water by means of an electromagnetic field. The passing water generates a so-called Electro-Motive Force, which the probe can detect. The measured voltage is a measure of the velocity of the water, so after calibration the voltage can be converted to a current velocity.

**Wave height probe**
Wave heights were measured with capacitance type probes, which measure a changing resistance over a steel rod positioned in the water. This resistance is measured as a potential difference (Voltage) which exists over the steel rod. After calibration, these measured voltages can be converted to surface elevations.

3.3.3 Wave generation

**Duration of the signals**
The record length of the regular wave measurements was 180 s; this was sufficiently long to determine the (mean) regular wave height ($H$) after the small fluctuations were filtered from the signal. All irregular wave measurements on the other hand were done with a record length of 330 s. The record length of the measurements of
irregular waves was longer because a reliable estimate of the parameters which describe the wave field had to be derived from the signal. These signals were processed by using a Fast Fourier Transform (FFT, see paragraph 5.4.2) which uses $2^n$ values. This meant that by increasing the initial record length of 300 s (which was originally used) to 330 s, the complete signal could be used. The sample rate was set to one hundred samples per second, so each measurement consisted of 33,000 samples. For the FFT the value of $n$ was set to 15, which means that 32,768 of the 33,000 samples could be used.

The irregular wave signal of the wave maker also had a duration of 330 s, which was continuously repeated. In doing so, the input signals during measurements have the same statistical characteristics, even though they are shifted in time. Any change in measured wave height is therefore due to (wave-current interaction) processes in the flume and not due to a different input signal because it is a different part of a longer wave maker signal (with different characteristics).

\textit{Variance density spectra}

The irregular wave field is described by a JONSWAP (Joined North Sea Wave Project, see Hasselmann et al. 1973) variance density spectra were used as a target. The basic case for the irregular waves was a wave field with a peak period ($T_p$) of 1.1 s and a significant wave height ($H_s$) of 0.05 m.

The characteristics of the spectrum at $x = 9.0$ m, i.e. the start of the measurement section, are slightly different from the characteristics used for the generation of the waves by the wave maker. This is partially because the wave maker does not create a spectrum with exactly the prescribed characteristics, and partially because the waves travel approximately 10 meter before they reach the point $x = 9.0$ m. In this area the waves dissipate energy and they shoal because of the slowly elevating bottom.

For this standard case, the significant wave height ($H_s$) of the measured field at $x = 9.0$ m is decreased to 0.043 m and the peak period is 1.16 s. The measured spectra at $x = 9.0$ m (see figure 9 for a typical example) were used as input for further analysis. Measurements were done using spectra that were (almost) completely blocked and spectra that were partially blocked. In the latter case, the longer waves travelled beyond the point of maximum counter velocity. That is why extra measurements were done beyond $x = 25.0$ m, beyond the original measuring section. Because the cross section beyond $x = 25.0$ m was no longer constant, these data-series had to be treated separately.
Figure 9: Variance density spectrum at x = 9.0 m (T_p = 1.1 s and H_mo = 0.05 m)
4 Observations

4.1 Wave characteristics

The influence of the counter current was clearly visible when dealing with regular waves. This influence resulted in a decrease of the wave length: in still water at the start of the measurement section the wave lengths were of the order of magnitude of 1.5 m (for $T = 1.1$ s) and near the blocking point the wave lengths were of the order of 0.40 m.

The wave heights increased as the waves approached the blocking point. Because the waves became higher and shorter, the steepness increased, and the waves break.

In a region of about one meter in front of the blocking point, the wave height rapidly reduced from a maximum to zero at and beyond the blocking point, which resulted in a rather spectacular sight.

4.2 Location of the blocking points

Not only for the irregular, but also for the regular waves, the blocking point was not located at a fixed point for a certain combination of wave characteristics because the waves became groupy (groups with larger and smaller wave heights) as they approached the blocking point. This caused the blocking point to move back and forth in a region of about half a meter.

Longer waves resulted in a shift of the blocking point further upstream. Larger wave heights also moved the blocking point upstream, because of the amplitude influence in the dispersion relation.

4.3 Reflected wave

The reflected wave that, according to the theory, could be responsible for energy transport away from the blocking point, has in fact been observed during the measurements. The existence of the reflected wave was most visible when the wave maker was started or turned off.

When the wave maker was started, a single wave component was visible. Some time after the incoming wave had reached the blocking point and wave energy had started to reflect, a shorter component became visible on the longer incoming wave in areas some distance downstream of the blocking point.

When the wave maker was turned off, the last part of the incoming wave propagated towards the blocking point. Because the incoming waves had stopped, the front of the reflected waves was visible, which slowly moved downstream. This also shows the mechanism by which the reflected wave component transports energy away from the blocking point.
5 Measurements

5.1 Experimental program

Currents without waves
In order to determine the effectiveness of the suction sections to produce a slowly varying counter current with a constant gradient, the current velocities were measured in absence of waves. These measurements were done at four elevations: \( z = -0.05 \text{ m}, -0.20 \text{ m}, -0.35 \text{ m} \text{ and } -0.50 \text{ m} \), with an interval of \( \Delta x = 0.45 \text{ m} \).
Along one suction section more detailed measurements were done to examine the current velocity near the perforated bottom and the velocity distribution along a suction section.

Blocking of irregular waves
For the blocking measurements two different discharges were used: 120 l/s and 78 l/s. The larger discharge blocked most of the energy in the energy density spectrum whereas the use of the smaller discharge resulted in a situation of partial blocking.

Because of the influence of the perforated bottom plates, the peak period could not be chosen too long. When longer periods were used \( (T_p > 1.5 \text{ s}) \), the waves would no longer be on deep water and the orbital movement would reach the plates. The periods could also not be chosen shorter than one second because oscillations perpendicular to the propagation direction became very pronounced for these short waves.

For the small discharge of 78 l/s only the 1.1 s peak period was used because almost all the energy of the spectra with higher peak periods would not have been blocked. The steepness of the waves was varied by using different initial \( H_s \): measurements were done using \( H_s \) of 0.02, 0.05 and 0.08 m. For the large discharge the same wave heights were used but now the steepness was also varied by means of different peak periods: \( T_p = 1.1 \text{ s} \text{ and } T_p = 1.4 \text{ s} \).

Blocking of regular waves
The cross flume oscillations were most pronounced for the regular waves. But, by choosing the periods of the waves larger than one second, this could largely be reduced. Only the waves with large amplitudes \( (H_s \geq 0.08 \text{ m}) \) showed these oscillations when a period of over one second was used. So for the regular waves, the largest amplitude was chosen 0.07 m in stead of 0.08 m. For the small discharge only the 1.1 s period was used. For the large discharge, measurements were done for a 1.1, 1.2 and 1.4 s period. Because only one component is used, only complete blocking had to be examined.
Waves on still water
Experiments on waves propagating on still water have also been conducted to investigate the energy dissipation due to viscous effects. All the combinations of wave parameters (both for the large and for the small discharge) which were used for the blocking measurements have also been used in these experiments.

Turbulence measurements
Extra measurements were done for turbulence monitoring. Irregular waves were used with a peak period of 1.1 s in combination with the small discharge of 78 l/s. The amplitudes used were: 0.02, 0.05 and 0.08 m. (These results will be analysed at a later time.)

Water surface
The drop of the free surface elevation between the measurement section and the dummy sections was determined before the lids were installed. From these measurements the energy dissipation due to the perforated plates can be determined. The longitudinal profile of the free water level in the measurement section was measured too.

5.2 Vertical profile of longitudinal velocity component U
Detailed velocity measurements were done in one suction section with a high resolution in x (Δx = 0.20 m) and in z (Δz = 0.05 m from z = -0.05 m to -0.50 m and at z = -0.025 m and z = -0.525 m). These measurements showed that the velocity u was reasonably uniform over the vertical except for the regions near the surface and the bottom (see figure 10). The distortion, which is visible near the surface, is ascribed to secondary flows in the flume. These flows transport fluid with a relatively low forward velocity (small momentum) along the walls of the flume to the surface. At the surface this low momentum fluid mixes with the surrounding water, and thus reduces the velocity locally.
These measurements showed that the velocity measurements using the EMF probe yielded approximately the same results. This meant that the influence of the metal bottom plates on the EMF probe was not strong and previous velocity measurements using the EMF probe could be used for further analysis.
5.3 Longitudinal profile of longitudinal velocity component

The first velocity measurements were done in the centreline of the measurement section using the EMF probe. At every location (see paragraph 5.1) a measurement of five minutes was done. The average of each recorded signal was used in order to determine the mean velocity of the flow (without turbulent fluctuations). The streamwise variation of the vertically averaged velocity in the centreline (U) for the high-discharge case ($Q = 120 \text{ l/s}$) is shown in figure 11.
From this figure it is clear that the experimental arrangement worked very well. The current strength measured at the central plane of the flume increased almost linearly from approximately 0 m/s at x = 11.0 m (start of suction sections) to 0.65 m/s at x = 23 m (end of suction sections).

The average velocity measured in the centreline of the flume is not exactly equal to the discharge divided by the wetted area (Q(x)/A). This is because the velocity is higher in the centre of the cross section (at y = 0 m) than the average velocity. The velocity at x = 11.0 m is not exactly zero because of a small secondary flow, which arose at the start of the first suction section: this section not only extracted its discharge from the two meter of the section itself, but, at the bottom, it extracted water from the downstream side of the section too. This secondary flow could have been overestimated because the accuracy of the EMF probe is not high enough to measure the small velocities that are created in this region.

5.4 Blocking experiments

The blocking experiments were conducted with maximum velocity of approximately 0.55 m/s and a maximum velocity of 0.35 m/s (both based on Q/A). Measurements were done on both regular and irregular waves, although the emphasis in this thesis will be on irregular waves.

5.4.1 Regular waves

For measurements on regular waves, the wave maker was set to produce a sine wave. The basic case for blocking of regular waves was a wave with a period (T) of 1.1 s and an initial wave height (H) of 0.05 m. In figure 12, the evolution of wave heights along the flume for three different starting wave parameters have been plotted. The theoretical blocking point is located at approximately 20.5 m (using Q/A). The amplitude dispersion is visible since the higher waves block further upstream. In order to compare the relative growth of the wave heights, the wave heights have been normalised by the incoming wave height at x = 9.0 m. Figure 13 shows that the wave height for H₀ = 0.02 m increases towards the blocking point by more that 100 percent. The two other waves (H₀ = 0.05 and 0.07 m) show a smaller increase in wave height. These waves are steeper at the start of the measuring section (larger amplitudes combined with the same wave lengths), so the wave height cannot increase much, since the waves start to break if their steepness reaches a certain value (H/L ≈ 8%).
Wave periods

In paragraph 2.3 it was already pointed out that the absolute wave period is constant (equal to the period of the wave maker) even though the wave length and intrinsic wave period decrease in the direction of increasing counter current. From the measured signal of regular waves, the wave period was derived by determining the periods between the consecutive zero-up crossings, of which the average value was determined for each 180 s long signal.

In figure 14 the determined periods are shown. The figure shows that the absolute wave period remains constant up to about one half meter before the blocking point is reached.
Near the blocking point the signal is influenced by the fact that the blocking point is not stationary, that may be the cause of the slight increase of the wave period just in front of the blocking point. The measurements upstream of the blocking point are not shown in figure 14. Because of the intermittent behaviour of the blocking point, the measured wave period reduces strongly beyond approximately \( x = 22.5 \) m.

![Figure 14: Measurements of \( T \) for \( T = 1.1 \) s \( H = 0.07 \) m](image)

### 5.4.2 Irregular waves

In case of an irregular wave field, the waves do not get blocked at the same location because the wave field is a combination of many wave components, each with a different period. For the analysis of the measurements of irregular waves, a blocking region is defined: the region where most of the energy of the wave field gets blocked i.e. the region with the largest decrease of wave energy.

**Variance density spectra**

For each combination of wave characteristics (see paragraph 5.1) spectra have been computed using a Fast Fourier Transformation (FFT) method, which uses a finite number of cosine wave components (necessary Matlab files were written by Gert Klopman, used by kind permission). Because the blocking point is not located at the same co-ordinate for all the combinations of wave characteristics, spectra are plotted at different locations for each combination. In figure 15 the spectra are plotted for the basic case for irregular waves: \( T_p = 1.1 \) s and \( H_{mb} = 0.05 \) m, which will be treated here to show some typical results. (The other spectra can be found in appendix A.)
The solid line represents the spectrum at $x = 9.0 \text{ m}$, the start of the measuring section (used as a reference). At $x = 13.0 \text{ m}$, the energy of all components has increased (because of wave action flux conservation). At this location the counter current is not very strong and breaking will not be very pronounced (breaking source term in wave action conservation balance very small or absent). The spectrum for $x = 20.6 \text{ m}$ shows that the high frequency components have been blocked by the increasing counter current. They have been reflected or their energy has been dissipated. The energy of the lower frequencies is still increasing. At the blocking region breaking (whitecapping) becomes very intensive (especially for the initially steeper waves) and the energy of the lower frequencies is dissipated or reflected.

**Benjamin-Feir instability**

In the blocking region energy shifts from a higher to a lower frequency. This effect is ascribed to the Benjamin-Feir instability (see Benjamin and Feir 1967). Because of this instability, side bands are generated. This effect becomes very pronounced when waves propagate on a counter current. Partly because the waves steepen in a blocking situation (wave length shortens and the wave height increases), which increases the intensity of non-linear phenomena like the Benjamin-Feir instability, and partly because in a blocking situation the net energy transport is relative slow, especially near the blocking point where $c_g + U$ is nearly zero. The energy therefore, can be transferred to other frequencies, even over small spatial differences. This effect has also been observed in experiments by Lai et al. (1989) and by Chawla and Kirby (1998).
The Benjamin-Feir instability can be illustrated by examining the spectra of locations just in front of the blocking point with a higher frequency resolution. Because of this higher resolution it is possible to determine different peaks in the spectrum.

The local increase of energy (in frequency space) cannot be the direct result of the increase of wave energy due to wave action flux conservation. If this was the case, the increase of wave energy would not have been limited to a relative narrow frequency band.

In figure 16 three spectra are plotted for $T_p = 1.1$ s en $H_s = 0.05$ m. The first, at $x = 21.1$ m, shows a peak at 0.9 Hz (peak frequency of the incoming spectrum).

![Figure 16: Evolution of side bands](image)

The second spectrum (for $x = 21.6$ m) shows two peaks, one at 0.9 Hz and another at 0.8 Hz, so energy has been shifted from the peak frequency to a lower frequency. In the last spectrum (for $x = 22.0$ m) only the new peak at 0.8 Hz remains, the other peak with a higher frequency has already been blocked.

**Wave heights**

Significant wave heights for $T_p = 1.1$ s and $Q = 120$ l/s are shown in figure 17. The fluctuations in the significant wave height in the region downstream of the blocking point are caused by the reflected waves, which interfere with the incoming waves. The blocking region is located near $x = 21.5$ m for $H_s = 0.02$ m, near $x = 22.5$ m for $H_s = 0.05$ m and near $x = 23.0$ m for $H_s = 0.08$ m. The blocking point of the peak period, on the other hand, is located at $x = 20.4$ m according to the linear dispersion relation with $U = Q/A$. The differences can be explained by the fact that almost half
the energy of the spectrum is located at frequencies lower than the peak frequency. The energy of these low frequency waves increases until they are blocked, which is at a location beyond the blocking point of the peak period. From figure 17, it can be seen that increasing amplitude causes the blocking point to move further upstream, which complies with the theory (third order Stokes dispersion relation).

![Figure 17: Measurements of $H_s$ for $T_p = 1.1$ s](image)

In order to compare the relative growth of the waves, significant wave heights normalised by the incident significant wave height at $x = 9.0$ m are shown in figure 18. (The other figures can be found in appendix B.)

![Figure 18: Measurements of $H_s(x)/H_s(x = 9.0$ m$)$ for $T_p = 1.1$ s](image)
The relative growth of the amplitude is largest for the small amplitudes (over 100 percent). These waves are least steep because the peak period of the three wave fields is the same. When $H_s = 0.08$ m is used, the growth of the amplitude is only in the order of ten percent. These waves will dissipate more energy (breaking / whitecapping) because they are already more steep at the beginning of the measuring section compared to the waves with $H_s = 0.02$ m.

**Mean periods**
The mean period of the spectrum is defined as

$$T_m = \frac{\int E(f) df}{\int f \cdot E(f) df} = \frac{m_0}{m_1}$$

(5.1)

In figure 19 mean wave periods are plotted for $H_s = 0.02$ m, 0.05 m and 0.08 m with $T_p = 1.1$ s. (the other figures with mean periods for the other wave characteristics can be found in appendix C.)

Because the counter current increases from $x = 11.0$ m the mean period increases at first, as expected. However, between $x = 15.0$ and $x = 21.0$ m ($H_s = 0.02$ m) or $x = 22.5$ m ($H_s = 0.05$ and 0.08 m) the mean wave period decreases. This can be explained by the fact that in this region the energy of the high frequency components increases more than the energy of the lower frequency components. This is because a large growth of wave energy occurs just before each component reaches its blocking point.

This causes a shift of the mean period towards the higher frequencies. From $x = 22.5$ m to the blocking point the mean period increases again, especially for $H_s = 0.02$ m, because now the higher frequencies are blocked and the energy of the lower frequency components is still increasing.
5.5 Waves on still water

Because the attenuation of the waves had to be determined, experiments were also performed for waves propagating on still water. In doing so, it is possible to determine the dissipation of wave energy caused by the flume’s walls and (perforated) bottom because of e.g. viscous effects. During the analysis, the attenuation of the incident wave heights was modelled as (according to the Hunt formula, see paragraph 6.2.3):

\[
\frac{a(x)}{a(x_0)} = e^{-k(x-x_0)} \quad \text{or} \quad \frac{da}{dx} = -Ka(x)
\] (5.2)

The value of K is estimated as follows. Because the wave field consists of incoming and reflected waves, these have to be separated first. For this purpose the wave field is modelled as a superposition of exponentially decaying incoming and reflected wave components. In order to estimate the value of K, the model is fitted to the data by using a least square error fitting method.

In Table 1 the results of the analysis are shown. Since the Hunt formula is based on a linear theory, there is no dependency of K on the wave height. The estimated values for the parameter K do depend on the wave heights. The values for K, which were determined from the experimental data, are larger than those calculated with the Hunt formula. This is ascribed to the perforated bottom, which also explains why the ratio of K / \(K_{\text{Hunt}}\) increases with increasing period: the influence of the perforated bottom plates is stronger for longer waves, whose orbital movement and pressure fluctuations are more influenced by the bottom.
Table 1: Results of the analysis of waves on still water

<table>
<thead>
<tr>
<th>T (s)</th>
<th>H_{initial} (m)</th>
<th>K (m^{-1})</th>
<th>K_{Hunt} (m^{-1})</th>
<th>K/K_{Hunt}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>0.02</td>
<td>0.011</td>
<td>0.0047</td>
<td>2.34</td>
</tr>
<tr>
<td>1.1</td>
<td>0.05</td>
<td>0.021</td>
<td>0.0047</td>
<td>4.47</td>
</tr>
<tr>
<td>1.1</td>
<td>0.07</td>
<td>0.025</td>
<td>0.0047</td>
<td>5.32</td>
</tr>
<tr>
<td>1.2</td>
<td>0.02</td>
<td>0.013</td>
<td>0.0041</td>
<td>3.17</td>
</tr>
<tr>
<td>1.2</td>
<td>0.05</td>
<td>0.025</td>
<td>0.0041</td>
<td>6.10</td>
</tr>
<tr>
<td>1.2</td>
<td>0.07</td>
<td>0.029</td>
<td>0.0041</td>
<td>7.07</td>
</tr>
<tr>
<td>1.4</td>
<td>0.02</td>
<td>0.013</td>
<td>0.0033</td>
<td>3.94</td>
</tr>
<tr>
<td>1.4</td>
<td>0.05</td>
<td>0.033</td>
<td>0.0033</td>
<td>10.00</td>
</tr>
<tr>
<td>1.4</td>
<td>0.07</td>
<td>0.040</td>
<td>0.0033</td>
<td>12.12</td>
</tr>
</tbody>
</table>

For the models, which are described in chapter 6, no calibration factor was used because the enhancement factors shown in Table 1 are based on measurements on still water. In case of the blocking experiments the wave lengths reduce significantly as the waves approach the blocking point. This means that the influence of the plates will not be as strong as estimated.
6 Modelling

6.1 Introduction

The second objective of this study is to develop a model that can describe the wave field in a blocking situation. Two models based on a wave action balance (see paragraph 2.5) have been developed. A relatively simple single frequency model was developed at first. Because the data were not reproduced very well by this model, a second model has been developed which is based on a spectral computation. For the modelling of the blocking phenomenon the cross-sectionally averaged velocity has been used \( \langle Q(x)/A \rangle \), even though the velocity is not uniformly distributed (especially near the free water surface).

Both models use the "large current" (or "quasi-uniform" wave) approach and do not include diffraction of wave energy. This allowed the development of relatively simple models. Reflection is also not included in the models. In these models the energy of a component which is blocked is set to zero. This causes a (numerical) type of energy dissipation, because this energy is actually not dissipated at the blocking point but is reflected and transported away from the blocking point.

Near the blocking point, the wave parameters do not change gradually in space, which means that the "Quasi-uniform wave" approach formally can not be used there. Nevertheless, the "Quasi-uniform wave" approach has been used for the model in order to calculate the evolution of the significant wave height along the complete measurement section, also near the blocking point.

By comparing the results of the models to the measured data, it is possible to determine whether these assumptions/simplifications can be used.

6.2 Single frequency model for random waves

6.2.1 Single frequency model formulation

Balance equation

In the absence of currents the wave energy balance can be used. The energy balance reads:

\[
\frac{\partial P_x}{\partial x} + D = 0
\]  

(6.1)

in which \( P_x \) represents the energy flux: \( E^*c_g \). \( D \) represents the sink terms, such as due to breaking of waves (whitecapping) and viscous energy dissipation.

When waves are interacting with a current, the wave action balance applies (as was pointed out in paragraph 2.5):
\[
\frac{\partial}{\partial x} \left( \frac{E}{\sigma} (U + c_g) \right) + \frac{D}{\sigma} = 0
\] (6.2)

In this single frequency model, both wave propagation and dissipation calculations are based on a single characteristic wave period (e.g. peak period of the incoming spectrum at \(x = 9.0\) m) so \(\sigma, c_g\) and \(k\) are calculated once for each location from the (linear) dispersion relation.

### 6.2.2 Breaking of waves

The first dissipation (sink or negative source) term is derived from the Battjes-Janssen bore based model (see Battjes and Janssen, 1978). In this model the wave energy dissipation due to breaking of waves is calculated by assuming the dissipation of a breaking wave to be like that in a bore.

**Probability of breaking**

All waves that break or are broken are assumed to have the same wave height, which equals the maximum wave height sustainable by the given depth at a certain point \((H_m)\). This implies that the probability that at a given point a wave height is associated with a breaking or broken wave \((Q_b)\) equals:

\[
Q_b = Pr\{H = H_m\}
\] (6.3)

Assuming a Rayleigh distribution for the heights of the non breaking waves, this probability can be rewritten in terms of a function of \(H_{rms}/H_m\):

\[
Q_b = f\left(\frac{H_{rms}}{H_m}\right)
\] (6.4)

\(Q_b\) therefore represents the fraction of waves which at one point are breaking or broken, in terms of the ratio of the root mean square wave height actually present, to the maximum wave height which the given depth can sustain. The maximum wave height \(H_m\) is calculated from Miche's criterion for the maximum wave height for periodic waves of constant form:

\[
H_m \approx 0.14L \tanh\left(\frac{2\pi h}{L}\right) \approx 0.88k^{-1}\tanh(kh)
\] (6.5)

For this model a factor of 0.60 has been used in stead of the 0.88 because waves tend to break at a lower steepness when they are propagating on a counter current.
(see Chawla and Kirby 1998). The wave number (k) in (6.5) is calculated using the dispersion relation based on the peak period of the wave spectrum.

**Energy dissipation due to breaking (whitecapping)**

The power dissipated in a bore per unit span (D') can be calculated using the conservation of mass and momentum across the bore. This yields (see Lamb, 1932):

$$D' = \frac{1}{4} \rho g (Y_2 - Y_1)^3 \left( \frac{g(Y_1 + Y_2)}{2Y_1Y_2} \right)^{\frac{1}{2}}$$  \hspace{1cm} (6.6)

in which $Y_1$ and $Y_2$ represent the water depth at either sides of the bore (see figure 20).

![Figure 20: Definition sketch of a bore](image)

For application to breaking progressive waves, expression (6.6) is modified by assuming:

$$Y_2 - Y_1 \approx H$$  \hspace{1cm} (6.7)

and

$$\left( \frac{g(Y_1 + Y_2)}{2Y_1Y_2} \right)^{\frac{1}{2}} \approx \left( \frac{g}{h} \right)^{\frac{1}{2}}$$  \hspace{1cm} (6.8)

This yields for $D'$ (power dissipation per m$^2$ crest):

$$D'_RJ \approx \frac{1}{4} \rho g H^3 \left( \frac{g}{h} \right)^{\frac{1}{2}} \left[ \text{W/m}^2 \right]$$  \hspace{1cm} (6.9)

For a regular (periodic) wave the average power dissipation per unit area can be calculated by:

$$D_RJ = \frac{D'_RJ}{L} = \frac{D'_RJ k}{2\pi} = \frac{C_RJ}{2\pi} \rho g H^3 \left( \frac{g}{h} \right)^{\frac{1}{2}} k \left[ \text{W/m}^2 \right]$$  \hspace{1cm} (6.10)
In which $C_{BJ}$ is a calibration factor, used to fit the model to the measured data. (This calibration factor was set to unity for the single frequency model, whereas for the spectral model this factor was used to fit the model to the data.)

\textit{Average dissipation in wave field}

The dissipation only has to be applied to the breaking waves so (6.3) and (6.10) combined yields the average rate of energy dissipation of the wave field:

$$D_{BJ} \approx \frac{C_{BJ}}{8\pi} Q_s \rho g H_m \left( \frac{g}{h} \right)^{\frac{1}{2}} k \quad [\text{W/m}^2] \quad (6.11)$$

\subsection{6.2.3 Dissipation due to viscous damping}

The viscous dissipation of energy caused by the walls and bottom of the flume was modelled using the formula of Hunt (see Hunt 1952) for waves on still water:

$$\frac{a(x)}{a(x_0)} = e^{-K(x-x_0)} \quad \text{or} \quad \frac{da}{dx} = -Ka(x) \quad (6.12)$$

with damping modulus

$$K = \left( \frac{2k}{b} \right) \left( \frac{\nu}{2\sigma} \right)^{\frac{1}{2}} \left( \frac{k b + \sinh(2kh)}{2kh + \sinh(2kh)} \right) \quad [\text{m}^{-1}] \quad (6.13)$$

in which $\nu$ is the kinematic viscosity and $b$ is the width of the flume. The change in wave energy flux because of viscous dissipation can be written as ($c_g$ constant):

$$D_{Hunt} = -\frac{d}{dx}(Ec_g) = -\frac{d}{dx} \left( \frac{1}{2} \rho g a^2 c_g \right) = -\rho ga \frac{da}{dx} c_g \quad (6.14)$$

When (6.12) and (6.14) are combined, this yields:

$$-D_{Hunt} = -\rho ga K c_g \quad \text{or} \quad D_{Hunt} = \rho g a K c_g = 2KEc_g \quad (6.15)$$

The viscous damping due to the walls and the bottom (which is assumed to be impermeable) can be written as (when assuming $a = 1/2 H_{rms}$):

$$D_{Hunt} = \frac{1}{4} K \rho g c_g H_{rms}^2 \quad [\text{W/m}^2] \quad (6.16)$$
6.2.4 Complete single frequency model

The single frequency model consists of the wave action balance (6.2) based on the peak period of the spectrum. The source terms, which are included in the model, are the dissipation due to breaking (6.11) and the dissipation due to viscous damping caused by the walls and the bottom of the flume (6.16). Both dissipation terms are also based on the peak period of the spectrum.

The spectral model, which is introduced in paragraph 6.3, also includes a source term based on wave-turbulence interactions. The single frequency model does not include this source term because this model is rejected because of its erroneous prediction of abrupt blocking.

As input the measured significant wave height at \( x = 9.0 \) m has been used. The action balance in integrated numerically with discrete spatial steps of \( \Delta x = 0.20 \) m.

6.2.5 Model results

Location blocking point

In figure 21 calculated \( H_{s} \)-values are shown for \( T_{p} = 1.1 \) s and \( H_{p} = 0.05 \) m. The most striking feature in this figure is the sudden cut-off of the wave height. This is because the propagation of all the wave components is based on one frequency: according to the model the complete spectrum gets blocked when this (peak) frequency gets blocked. The blocking point according to the measurements is further upstream. This is because approximately half the energy of the wave field is at lower frequencies than the peak frequency.

Wave heights

In figure 21, the dashed line represents the model with only breaking as a source term (\( D_{b,j} \)). The wave heights are overestimated by this model. The solid line represents the model that also includes viscous dissipation (\( D_{b,j} \) and \( D_{v,unl} \)). The latter model yields better results for order of magnitude the maximum wave heights.
6.3 Spectral model for random waves

6.3.1 Spectral model formulation

In the spectral model the propagation and the evolution of the wave action of each spectral component is calculated using the frequency of the component itself. The wave action flux balance for frequency $f_n$ is:

$$\frac{d}{dx} \left( \frac{E_n}{\sigma_n} (\varepsilon_n + U) \right) + \frac{D_n}{\sigma_n} = 0$$

(6.17)

in which $E_n$ is the energy of the $n^{th}$ component, given by:

$$E_n = \rho g \int_{f_n}^{f_n+M} E(f) df$$

(6.18)

Because each component has a different frequency, the components do not all get blocked at one location: the high frequency components get blocked by a relatively weaker counter current strength than those with lower frequencies.

6.3.2 Source terms

**Dissipation of a component**

The determination of the total dissipation rate is based on a single period (frequency). At a given point a characteristic wave period is determined (i.e. $m_r / m_0$) using the local variance density spectrum. The dissipation can therefore be calculated until, theoretically, the complete spectrum gets blocked.
In order to avoid dependency on the chosen frequency resolution, the total dissipation is determined first. The dissipation per component is determined by:

\[
D_w = \frac{E_w}{E_{\text{tot}}} D_{\text{tot}}
\]  
(6.19)

in which \( E_{\text{tot}} \) is the total amount of energy of the wave field. The total dissipation equals the integral of dissipation over all components:

\[
\int_{f=0}^{f=\infty} \frac{E(f)}{E_{\text{tot}}} D_{\text{tot}} df = D_{\text{tot}}
\]  
(6.20)

which is independent of the chosen frequency resolution.

**Dissipation due to breaking (whitecapping)**

In this model the power dissipation due to breaking (whitecapping) is also determined by the Battjes-Janssen bore based model (equation 6.11). After fitting the model to the data, best results were found for a calibration factor of 1.6.

**Dissipation due to viscous damping**

The viscous dissipation in this model is determined by the Hunt formula introduced in paragraph 5.2.3. No calibration factor was used for the Hunt formula because this mechanism uses less uncertain variables than the other two dissipation mechanisms.

**Dissipation due to wave-turbulence interactions**

The third energy dissipation mechanism that has been implemented in this model is the energy dissipation due to wave-turbulence interactions. This source term is given by:

\[
D_{\text{turb}} = -\rho \frac{A}{4} g k^4 a^4 \left\{ \frac{\coth(2kh)}{\tanh(kh)} + \frac{kh}{\sinh^2(kh) \tanh(kh)} \right\} \quad \text{[W/m}^2\text{]} \]  
(6.21)

in which \( A \) is the turbulent eddy viscosity, estimated as \( C_T U_{\text{max}} h \). Through \( A \) the influence of the current velocity is introduced. At first the local current velocity was used, but this resulted in an underestimation of the dissipation. In later calculations, the calculation of turbulence dissipation along the complete measurement section was based on the maximum counter current velocity. This is based on the assumption that the turbulence which is generated in the region of maximum counter current velocity will be swept downstream into the region with a weaker current. \( C_T \) represents a calibration factor, which was determined after curve fitting. Best results were found when this factor was set to 1.2.
6.3.3 Complete spectral Model

The complete model is formed by the wave action balance (6.17) for each frequency, in which the source terms (based on a local characteristic period: \( m_1/m_0 \)) are the Battjes-Janssen breaking mechanism (6.11, \( D_{Bl} \)) with a calibration factor of 1.6, viscous damping due to walls and bottom (6.16, \( D_{Hun} \)) with a calibration factor set to unity and wave energy dissipation due to wave-turbulence interactions (6.21, \( D_{Turb} \)) for which a calibration value has been used of 1.2. The dissipation of one component (\( D_n \)) is calculated from eq. 6.19. The calibration factors were determined by means of visually fitting the model to the measured data.

As input the spectrum at \( x = 9.0 \) m has been used. This spectrum was derived from a Fast Fourier Transform of which the first 600 components, which contained the wave energy, were used. The differential equation (6.17, wave action balance per component) has been numerically integrated with discrete spatial steps \( \Delta x = 0.20 \) m. The source code of the numerical model can be found in appendix D.

6.3.4 Model results

Peaks in model results

The peaks that are visible in the figure 23 to 31 are the result of the discretisation used for the measured spectra at the start of the measurement section. The discrete components, which are used to calculate the evolution of the complete spectrum, show a significant increase of wave energy near their blocking point (according to the model). So, when the spectrum is calculated at a location where one of the components is just in front of its blocking point, this spectrum will show a significant increase of wave energy for this component.

Even though wave energy gets dissipated, this local increase in wave energy results in a peak in the calculated evolution of the significant wave height (when no dissipation is taken into account, the peaks are more pronounced). At the next location where the spectrum is calculated (one spatial step further upstream), the local peak of wave energy is dissipated or the component is blocked. Both effects result in the reduction of the peak in the calculated wave height evolution.
Figure 22: Model results for $H_s = 0.05 \text{ m and } T_p = 1.1 \text{ s (} \Delta x = 0.05 \text{ m)}$

In case of smaller spatial and frequency resolutions an increase is found of the number of calculated peaks (see figure 22 for a typical example). The magnitude of each peak on the other hand reduces.

**Calibration factors**

The influence of each source term is examined by the use of different calibration factors for each source term. In figure 23 to 25 the results of the calculation are shown for the standard case of $H_s = 0.05 \text{ m and } T_p = 1.1 \text{ s.}$ The solid line in each figure represents the situation without dissipation i.e. a calibration factor equal to zero.
Figure 23: Influence of the Battjes-Janssen source term

The influence of the Battjes-Janssen source term is represented in figure 23. At the location where the waves exceed the maximum sustainable steepness, the breaking mechanism is activated. In the region of maximum counter current (where the velocity of the counter current remains constant) the waves stop steepening, which causes the dissipation due to breaking to become zero (according to the model).

Figure 24 shows that the influence of the viscous damping is much weaker than the influence of the Battjes-Janssen source term. This dissipation mechanism dissipates energy along the complete length of the flume, hence the decrease of wave energy along the complete measurement section (also beyond \( x = 23.0 \) m).
The results of the calculations using the turbulence dissipation source term are shown in figure 25. The influence of the steepness of the waves is very large for this source term via \((ka)^4\). This explains that the dissipation of wave energy at the start of the measurement section is virtually absent, because of the relatively low steepness of the waves. As with the Battjes-Janssen mechanism, the dissipation of wave energy is larger in regions where waves have steepened due to the counter current. When the source terms are compared using a calibration factor set to unity, this mechanism dissipates the most energy.

Figure 25: Influence of the turbulence source term
**Model results compared to data**

For $T_p = 1.1$ s, three cases have been examined (initial significant wave heights): $H_s = 0.02$ m, 0.05 m and 0.08 m. For each set of wave characteristics calculations were made with source terms: Battjes-Janssen, subsequently Battjes-Janssen and Hunt and finally with Battjes-Janssen, Hunt and wave turbulence interactions. For these calculations, the same calibration factors have been used: 1.6 for Battjes-Janssen, 1.0 for Hunt and 1.2 for the wave - turbulence interaction source term (as was stated in the previous paragraph). The results are shown in figure 26 to 28. In these figures, the solid line represents the calculation without any source terms taken into account.

![Graph showing comparisons of model results to data](image)

*Figure 26: Results for $H_s = 0.02$ m and $T_p = 1.1$ s*

For $H_s = 0.02$ m, the dissipation due to breaking (whitecapping) is not activated according to the model because the steepness does not exceed the maximum sustainable steepness (see next paragraph). Because the steepness of the waves is relatively low, the dissipation due to wave-turbulence interaction is not very strong. The increase in wave height (over 100%) which the measured data show, can be approached when all source terms are used, but only by use of curve-fitting. The model shows a large amount of wave energy which is not blocked, whereas the measurements show that almost all wave energy gets blocked. In the case of $H_s = 0.05$ m (see figure 27), most dissipation is caused by the wave turbulence interaction and breaking.

Even though the calibration factors are used and the order of magnitude of the maximum wave height is calculated correctly, the model is not able to calculated the occurring blocking region and according to the model a significant amount of wave
energy does not get blocked, whereas the measurements show almost a complete blockage of wave energy.

**Figure 27: Results for $H_s = 0.05\ m$ and $T_p = 1.1\ s$**

For $H_s = 0.08\ m$ (see figure 28), the same situation occurs: the model does not predict the wave height evolution well, and too much energy passes the point of maximum counter current velocity, i.e. does not get blocked.

**Figure 28: Results for $H_s = 0.08\ m$ and $T_p = 1.1\ s$**
Source terms
In the previous paragraph, measurements were compared to the calculations done with the spectral model based on the wave action balance. In figure 29 to 31 (different vertical scales), the amount of energy dissipated by each mechanism (according to the model) is plotted for the calculations which used all three dissipation mechanisms.

Figure 29: Energy dissipation for $H_s = 0.02 \text{ m}$ and $T_p = 1.1 \text{ s}$

Figure 29 shows that, in case of relatively low waves, the Battjes-Janssen source term is not activated (as was already mentioned in the first part of this paragraph.) The dissipation due to viscous effects of the wall and bottom of the flume occurs, of course, along the complete length of the flume. The wave-turbulence interaction mechanism, on the other hand, only dissipates energy in the region where the steepness of the waves is sufficiently large.

The calculated dissipation terms for $H_s = 0.05 \text{ m}$ are shown is figure 30. In this case too, the dissipation due to wave-turbulence interaction is the dominant dissipation mechanism.

Compared to the situation with $H_s = 0.02 \text{ m}$, the waves are steeper, which results in an increase of dissipation due to wave-turbulence interaction. As the steepness of the waves tends to exceed the maximum steepness, the breaking mechanism is activated.

The last case which is examined ($H_s = 0.08 \text{ m}$, see figure 31) shows an increase of energy dissipation especially for the breaking and wave-turbulence mechanisms. The overall situation is the same as in the previous case: the wave-turbulence interaction
has the largest dissipative effect and most dissipation occurs in the region where the waves have steepened while propagating towards the blocking region.

![Energy dissipation for $H_s = 0.05 \, m$ and $T_p = 1.1 \, s$](image1)

**Figure 30:** Energy dissipation for $H_s = 0.05 \, m$ and $T_p = 1.1 \, s$

![Energy dissipation for $H_s = 0.08 \, m$ and $T_p = 1.1 \, s$](image2)

**Figure 31:** Energy dissipation for $H_s = 0.08 \, m$ and $T_p = 1.1 \, s$

**Spectra**

In order to further analyse the differences between the model and the measurements, spectra are plotted at multiple locations (see figure 32 for $T_p = 1.1 \, s$ and $H_s = 0.02 \, m$, the other spectra can be found in appendix E).

The spectra at $x = 15.40 \, m$ show relatively little differences, which is understandable, since the waves only face a weak counter current and only a small increase of wave
energy has occurred for all components, which the model is able to produce. At $x = 18.20$ m, the model shows that the energy of the high frequency components is blocked. The components that are almost at their blocking point show a large increase in wave energy according to the model. This local peak of wave energy, concentrated at a few wave components, may be spread over a range of frequencies due to non linear processes, which are not included in the model.

Especially near the blocking point, the wave parameters change very rapidly over one wave length. This means that the assumption that changes occur over long distances relative to the wave length is no longer valid in the region near the blocking point: the "Quasi-uniform wave" approximation is not valid for that region of the flume. A large local increase in wave height will be spread out over a larger area due to e.g. diffraction of wave energy.

This would explain why the model is able to reproduce the changes in the spectra at the beginning of the measurement section, but is unable to do so near the blocking point.

![Graphs showing variance density spectra](image)

*Figure 32: Variance density spectra ($T_p = 1.1$ s, $H_s = 0.02$ m)*

The calculated spectrum for $x = 21.00$ m shows the same concentration of wave energy in a narrow frequency band. The model can predict the location of the wave
energy, but the energy of the components below the "cut-off" is overestimated, whereas the energy of higher frequency components is underestimated. According to the model, the wave energy of these higher frequency components is zero since they are blocked, but the measurements show that these components still contain wave energy.

In the last figure (x = 22.80 m) the model still shows a large amount of wave energy, whereas the measurements show that almost all the wave energy has been blocked.

For the two other situations, $H_s = 0.05$ m and $H_s = 0.08$ m, similar have been found: at the beginning of the measuring section, the model is able to predict the variance density spectrum reasonably well, but near the blocking point, the agreement is not good due to the "cut-off" in the frequency domain.
7 Conclusions

7.1 Introduction
For this research, monochromatic and random waves (partially) blocked by a counter current, have been studied. Different wave characteristics have been used, i.e. different periods and wave heights, as well as different discharges. Waves were also measured propagating on still water, in order to determine the dissipation caused by the flume walls and (perforated) bottom. Furthermore, video recordings were made. In these recordings, the experimental arrangement, experimental procedure and the observations of the witnessed phenomena are shown (figures of these recordings can be found in appendix F).

7.2 Experiments
The blocking experiments were a success: the experimental arrangement fulfilled its purposes and the measurements were completed rapidly, after a troubled start. Even though there was little time available, many blocking situations were measured.

Observations
The observations showed the incoming waves steepen (wave length became shorter, while the wave height increased) while approaching the blocking point. They also showed the short reflected waves, which became longer and higher towards the blocking point. At the blocking point, an impressive phenomenon could be witnessed: wave trains that cannot propagate further upstream, which caused the wave heights to be reduced from maximal to zero over less than one meter.

Measurements
The measured data have not only served as a database for this research project, but will also provide data for research projects to come. The findings of these research projects can be integrated in numerical models in order to predict the influence of currents on waves. In doing so, a more accurate estimate can be made of maximum wave heights that occur at sea or in estuaries. These maximum wave heights can in fact be much larger than calculated by a model which does not take wave current interaction into account.
7.3 Modelling

The modelling of the blocking phenomenon has proven to be very complicated. Partly because there are multiple mechanisms influencing the wave field when waves get blocked, and partly because the wave numbers and current velocity are not constant in the area of interest, i.e. in this case, along the wave flume.

Single frequency model for random waves

Two models were developed, both based on the wave action balance. The first model was a single frequency model, in which both wave propagation and wave action dissipation were calculated using a single (characteristic) frequency. The order of magnitude of the maximum wave heights was reproduced reasonably well, but the location of the blocking point was determined at a location with a much weaker counter current than the measurements showed. This was caused by the single frequency approach: approximately half of the energy of the wave field was located at frequencies lower than the peak frequency. These lower frequency components can propagate further upstream before they face a counter current strong enough to get blocked.

Spectral model for random waves

In this model the wave propagation was based on the frequency of the wave component itself. The total dissipation rate is still based on a characteristic frequency (e.g. mean period), but in this model the local value of the characteristic frequency is determined from the local variance density spectrum. In doing so, it is possible to calculate the evolution of the wave field until it is completely blocked.

Even though this model is not based on a single frequency, the model is not able to predict the wave field in a blocking situation. With different calibration factors, the order of magnitude of the maximum significant wave heights can be estimated. However, the evolution of the significant wave height is not predicted correctly: the maximum wave height is calculated further downstream than according to the measurements and the model shows a significant amount of energy which is not blocked, whereas the measured data show that almost the complete spectrum gets blocked.

Since the calculation of wave propagation is based on the linear dispersion relation, the wave components can propagate further upstream than the model determines. This results in differences between the model and the data, especially for the initially higher waves. Because of this effect, the best results were found for the case with the smaller wave heights ($H_s = 0.02 \text{ m}$).
The calculated spectra show large concentrations of wave energy for the components which are just in front of their blocking point. These local peaks of wave energy concentrated at a few wave components may be spread over a range of frequencies due nonlinear processes, which are not included in the model. Especially near the blocking point, the wave parameters change very rapidly over one wave length. This means that the "Quasi-uniform wave" approximation is not valid near the blocking point. A large local increase in wave height will be spread out over a larger area due to diffraction of wave energy, which is not included in the model.

7.4 Recommendations

The model has to be adapted/further developed in order to obtain satisfactory results. In order to improve the agreement of the calculated blocking region with the measured locations, the wave propagation has to be calculated with a higher order dispersion relation. In doing so, the influence of the wave height on the wave propagation can be included in the model.

Other formulations for the dissipation mechanisms should be incorporated into the model (e.g. another formulation for breaking, Hunt formulation only for the flume walls, dissipation due to the perforated plates separately), so as to improve the calculated evolution of the significant wave height.

The local peaks in the calculated spectra could be avoided by the use of a diffraction mechanism. When this mechanism is used, the differences between the calculated and measured spectra will probably be reduced.

Finally, the model can be adapted in order to include the reflected wave components. This means that the model will include more physical processes which occur in the flume.
References

# List of Symbols

**Roman letters**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Wetted area (width of measuring section · waterdepth)</td>
<td>m²</td>
</tr>
<tr>
<td>a</td>
<td>Wave amplitude</td>
<td>m</td>
</tr>
<tr>
<td>(a_n)</td>
<td>Amplitude of the (n)th wave component</td>
<td>m</td>
</tr>
<tr>
<td>(C_{BJ})</td>
<td>Calibration factor for the Battjes-Janssen source term</td>
<td>-</td>
</tr>
<tr>
<td>(c_g)</td>
<td>Intrinsic group velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>(C_g)</td>
<td>Absolute group velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>(C_T)</td>
<td>Calibration factor for the wave-turbulence interaction source term</td>
<td>-</td>
</tr>
<tr>
<td>D</td>
<td>Power dissipation per unit area</td>
<td>W/m²</td>
</tr>
<tr>
<td>(D')</td>
<td>Power dissipation per unit span</td>
<td>W/m¹</td>
</tr>
<tr>
<td>(E{X})</td>
<td>Expected value of (X)</td>
<td>Varies</td>
</tr>
<tr>
<td>(E(f))</td>
<td>Variance density as function of frequency (f)</td>
<td>m²/Hz</td>
</tr>
<tr>
<td>(E)</td>
<td>(Wave) Energy density</td>
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</tr>
<tr>
<td>(E_n)</td>
<td>Energy density of (n)th wave component</td>
<td>J/m²</td>
</tr>
<tr>
<td>(E_{tot})</td>
<td>Total energy density in wave field</td>
<td>J/m²</td>
</tr>
<tr>
<td>(f)</td>
<td>Frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>(f_n)</td>
<td>Frequency of the (n)th wave component</td>
<td>Hz</td>
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<tr>
<td>(H)</td>
<td>Wave height</td>
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<tr>
<td>(H_m)</td>
<td>Maximum wave height</td>
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</tr>
<tr>
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<td>Significant wave height based on (m_0)</td>
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</tr>
<tr>
<td>(H_{ms})</td>
<td>Root mean square wave height</td>
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<tr>
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</tr>
<tr>
<td>(k)</td>
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<tr>
<td>(m_0)</td>
<td>Area of variance density spectrum</td>
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</tr>
<tr>
<td>(N)</td>
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<tr>
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<tr>
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<tr>
<td>(U)</td>
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<tr>
<td>(U_{BL})</td>
<td>Mean velocity at blocking point</td>
<td>m/s</td>
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<tr>
<td>(U_{max})</td>
<td>Maximum mean velocity (at x = 23.0 m)</td>
<td>m/s</td>
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<tr>
<td>(v)</td>
<td>Lateral velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>(w)</td>
<td>Vertical velocity</td>
<td>m/s</td>
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### Greek Letters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>η</td>
<td>Surface elevation</td>
<td>m</td>
</tr>
<tr>
<td>ν</td>
<td>Kinematic viscosity</td>
<td>m²/s</td>
</tr>
<tr>
<td>ρ</td>
<td>Mass density of water</td>
<td>kg/m³</td>
</tr>
<tr>
<td>σ</td>
<td>Intrinsic frequency</td>
<td>rad/s</td>
</tr>
<tr>
<td>ω</td>
<td>Absolute frequency</td>
<td>rad/s</td>
</tr>
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Appendix A: Measured variance density spectra

$Q = 78 \text{ l/s}$
$Q = 120 \text{ l/s}$

**Variance density spectra ($T_p = 1.1 \text{ s}, H_{rd} = 0.02 \text{ m}$)**

- $x = 9.0 \text{ m}$
- $x = 13.0 \text{ m}$
- $x = 20.6 \text{ m}$
- $x = 22.0 \text{ m}$

**Variance density spectra ($T_p = 1.1 \text{ s}, H_{rd} = 0.05 \text{ m}$)**

- $x = 9.0 \text{ m}$
- $x = 13.0 \text{ m}$
- $x = 20.6 \text{ m}$
- $x = 22.0 \text{ m}$

**Variance density spectra ($T_p = 1.1 \text{ s}, H_{rd} = 0.08 \text{ m}$)**

- $x = 9.0 \text{ m}$
- $x = 13.0 \text{ m}$
- $x = 20.6 \text{ m}$
- $x = 23.1 \text{ m}$
Wave-current interaction: Wave blocking

M.Sc. thesis of M.P.C. de Jong

Variance density spectra ($T_p = 1.4$ s, $H_{eq} = 0.02$ m)

- $x = 9.0$ m
- $x = 19.0$ m
- $x = 22.0$ m
- $x = 23.0$ m

Variance density spectra ($T_p = 1.4$ s, $H_{eq} = 0.05$ m)

- $x = 9.0$ m
- $x = 13.0$ m
- $x = 22.0$ m
- $x = 23.0$ m

Variance density spectra ($T_p = 1.4$ s, $H_{eq} = 0.08$ m)

- $x = 9.0$ m
- $x = 13.0$ m
- $x = 22.0$ m
- $x = 24.0$ m
Appendix B: Wave heights (blocking experiment for irregular waves)

Q = 78 l/s

Q = 120 l/s
Appendix C: Mean periods (blocking experiment for irregular waves)

$Q = 78 \text{ l/s}$

![Graph showing mean wave period for $Q = 78 \text{ l/s}$]

$Q = 120 \text{ l/s}$

![Graph showing mean wave period for $Q = 120 \text{ l/s}$]
Appendix D: Source code of numerical model (spectral model for random waves) (Matlab version 5.2)

clear all;
%constants
h=0.55;
g=9.81;
rho=1000;
b=0.4;
u=1e-6;
w=1;
% 1) Hs = 0.02 m, 2) Hs = 0.05 m, 3) Hs = 0.08 m
% (in order to load the appropriate data file)

%Calculation area and step size
startx=9;
endx=25;
deltax=0.2;
E=ones(600,((endx-startx)/deltax+1)); %Reservation of memory for results matrix (x,f)

%Enhancement factor of dissipation applied to Battjes-Janssen bore based model
alpha=1.4;

%Enhancement factor of dissipation applied to Hunt viscous dissipation model
beta=1;

%Enhancement factor of dissipation applied to Turbulence dissipation model
gamma=0.8;

%boundary conditions
type=w;
typestr=num2str(type);
df=0.0031;
eval(['load ' F'.typestr',' .asc']);
eval(['load ' P'.typestr',' .asc']);
eval(['F=F'.typestr, ',']);
eval(['P=P'.typestr, ',']);
xa(1,1)=startx;
x=startx;
E(:,1)=P;
n=1;

ka=4*ones(1:600);

% Calculation of first wave parameters
[U]=vel(x);
for f=1:600
    T=1/F(f,1);
    Eold=E(f,1)*df*rho*g;
    kold=ka(f,1);
    [k,s,cg]=dispm3(T,h,U,kold);
    cg(f,1)=cg;
    U(f,1)=U;
    s(f,1)=s;
    actionfluxold(f,1)=Eold/s(f,1)*(cg(f,1)+U(f,1));
    ka(f,1)=k;
end
kdiss=4;
for x=(startx+deltax):deltax:endx
  n=n+1;
  (endx-startx)/deltax-(n-1) %on screen counter of remaining spatial steps
  xa(n,1)=x;
  m0=0;
  m_1=0;
  m1=0;
%Calculation of Tchar from spectrum (n-1) and Dtot for location n
for j=1:600
  m0=m0+(E(j,(n-1))/df;
  m_1=m_1+(E(j,(n-1))/F(j,1))*df;
end
T=m_1/m0;
Ta=(n-1),1)=T;
[U]=vel(x);
kold=kdiss;
Etot=m0*rho*g;
H=sqrt(8*m0);  %Hrms
a=H/2;
[k,s,cg] = dispmod3(T,h,U,kold);
if k>0;
  %calculation of source terms
  Etota(n-1,1)=Etot;
  kdiss=k;
  kdissa(n,1)=k;
  Hm=0.5/k*tanh(k*h);
  [Qb]=Q(H,Hm);
  Qba(n,1)=Qb;
  Db0=alpha*1*(8*pi)*Qb*rho*g*Hm^3)*sqrt(g/h)*k;
  Dbja(n,1)=Dbj;
  K=(2*k/b)^sqrt(nu/(2*s))^((k*b+sinh(2*k*h))/(2*k*h+sinh(2*k*h)));
  Dhunt=beta*(2*Etot*K*cg);
  Dhunta(n,1)=Dhunta;
  %Array with Hunt source term values
  A=gamma*-55*h;
  Dturb=(4*rho*g*K^4*a^4........
  ((coth(2*k*h)/(tanh(k*h))+k*h/((sinh(k*h))/(2)*tanh(k*h)));
  Dturb(n,1)=Dturb;
  %Array with Turbulence source term values
%Calculation of spectrum at location n
for f=1:600
  if E(f,(n-1))>0;
    T=1/F(f,1);
    Eold=E(f,(n-1))*df*rho*g;
    kold=ka(f,1);
    [k,s,cg] = dispmod3(T,h,U,kold);
    ka(f,1)=k;
    if k>0
      actionfluxnew(f,1)=actionfluxold(f,1)-(Eold/Etot)*Dturb*deltax;
      E(f,n)=actionfluxnew(f,1)*s/(cg+U)*(df*rho*g);
      actionfluxold(f,1)=actionfluxnew(f,1);
    else
      E(f,n)=0;
      actionflux(f,1)=0;
    end
  else
    E(f,n)=0;
  end
end

end
end
else
  Ta(n,1)=0;
  Dbja(n,1)=0;
  Dhunta(n,1)=0;
  kdisse(n,1)=0;
  Etoala((n-1),1)=0;
  for f=1:600
    E(f,n)=0;
  end
for r=1:min(size(E))
  r
  for t=1:600
    if imag(E(t,r))>=0
      E(t,r)=0;
    end
    if real(E(t,r))<=0
      E(t,r)=0;
    end
  end
end
for n=1:length(xa)
  hulp=0;
  for f=1:600
    hulp=hulp+E(f,n)*df;
  end
  m0a(n,1)=hulp;
end
Hs=4*sqrt(m0a);
figure,plot(xa,Hs,'k');
hold;
end
Appendix E: Model spectra compared to measurements

Solid line: spectral wave blocking model, dashed line: measured data

\[ T_p = 1.1 \text{ s}, \quad H_s = 0.02 \text{ m}, \quad Q = 120 \text{ l/s} \]
$T_p = 1.1 \text{ s}, \ H_s = 0.05 \text{ m}, \ Q = 120 \text{ l/s}$
$T_p = 1.1 \text{ s, } H_s = 0.08 \text{ m, } Q = 120 \text{ l/s}$

\begin{align*}
\text{Model} & \quad \text{Data} \\
\end{align*}
Appendix F: Figures from the video recordings

*Experimental arrangement*

![Figure 1: Longitudinal view](image1)

Figure 1: Longitudinal view

![Figure 2: Suction section](image2)

Figure 2: Suction section

![Figure 3: Perforated bottom plate](image3)

Figure 3: Perforated bottom plate
Figure 4: Width of flume divided into two sections

Figure 5: Flume seen from the upstream direction, streamlined inflow

Figure 6: Splitting point in front of the wave maker.
Left: measurement half, Right: dummy half
Figure 7:
Suction pipes

Figure 8:
Suction pipes, three connected to each pump

Figure 9:
Honeycomb at the upstream side of the flume
Figure 10: Suction pump with manifold for three suction pipes

Figure 11: Manometers

Figure 12: Wave maker
Figure 13:
LDA velocity probe

Figure 14:
Cart for moving measurement probes
Waves

Figure 15:
Incoming wave just after starting wave maker (reflected energy has not reached this location yet)

Figure 16:
Incoming wave + shorter reflected wave

Figure 17:
Incoming wave + reflected wave
Figure 18: Waves steepening on the counter current

Figure 19: Waves approaching the blocking point

Figure 20: Blocking point