

# Measuring ship induced waves and currents on a tidal flat in the Western Scheldt Estuary

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**Abstract**—In the Western Scheldt estuary a 45-day campaign took place to measure ship induced waves and currents on a tidal flat. It was established that the hydraulic loads due to the passing ships were large enough to play a major part in the erosion process of the tidal flat.

**Keywords**—component; Ship waves; erosion

## I. INTRODUCTION, SHIP INDUCED WATER MOVEMENT AS AN ERODING FORCE AND SAFETY LIABILITY IN ESTUARIES

Shipping lanes to major estuarial ports are steadily deepened and widened to allow access to larger ships. Furthermore, modern ships are equipped with more powerful engines and constantly redesigned to combine maximum cargo load with maximum speed. This leads to ever increasing waves and currents generated by ships in these areas. These waves and currents pose serious issues in terms of erosion, navigational safety and safety for recreation on beaches adjacent to tidal channels used by sea vessels.

Erosion due to ship induced water movement is a well known issue in rivers. It is one of the main factors to take into account in the design process of riverbank protection. The impact of shipping in estuaries however, is much less addressed and seldom taken into account in the design of coastal protection.

The area of interest in this paper is the Western Scheldt estuary, which is part of the Rhine-Scheldt delta in the Netherlands. It is the gateway to the North Sea for the harbors of Antwerp, Vlissingen, Ghent and Terneuzen.

The shipping lane to Antwerp harbor follows a wide bend in the river near the village of Bath. Along this bend, the foreshore at a dike (tidal flat) is eroding slowly but steadily over a length of 2 to 3 kilometers. This is an unwanted development, both from a safety perspective and from an ecological perspective.

Measures were designed to counter the erosion and reverse the process. The leading opinion was that the erosion is the effect of the meandering of the river caused by the tidal currents. Subsequently, the counter measure would be to reduce the current over the flat. In this case the designed counter measure consists of two low groynes on the flat.

The combined effect of waves and currents on the stability of a tidal flat is by far larger than the effect of either of these

separately. The principle behind this is that waves resuspend material which is then transported by currents.

The considered tidal flat is situated 50 km inland from the mouth of the Western Scheldt and is sheltered from swell from the North Sea and most wind induced waves. Therefore these waves are not considered to play a significant part in the erosion process. However, the number of ships passing the tidal flat is large. In this case the ship induced waves and currents could provide the forces that stir up sediment and contribute to the transport of sediment. This introduces a new perspective on the counter measure to be developed.

To acquire more insight in the dominant driving mechanism behind the erosion of a tidal flat a measurement campaign was set up, of which the setup and results are presented in this paper.

## II. SHIP INDUCED CURRENTS AND WAVES

### A. Primary wave pattern

Ship induced water movement consists of several distinctive parts. The complex of a front wave, a water level depression (or drawdown) and a stern wave are indicated as the primary wave. The return flow along the ship as the ship pushes away the water is directly associated with this primary wave. The primary wave more or less has the characteristics of a negative solitary wave and a length in the order of the ship's length.

The water depression and return currents in channels due to ships are a function of the ship's speed, draught, shape of the hull and the size and shape of the navigational channel. These were approximated by Schijf in 1949 [1] by using the Bernoulli equation and the continuity equation. One of the implicit assumptions in this approach is that the water level depression is constant over the whole width of the channel. In this case the channel is open on one side and has a wide tidal flat on the other. Therefore, this approach does not hold. Empirical corrections and estimations from scale models are available, but need to be adapted to the situation under study [2]. This was however not within the scope of this project. Therefore, the found results are presented "as is".

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This work was commissioned by the Dutch Ministry of Infrastructure and Environment.

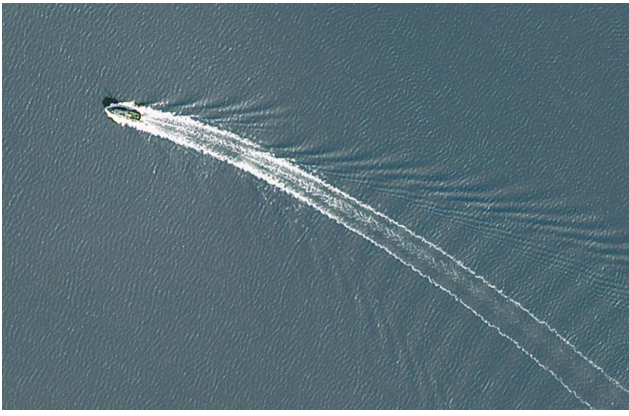


Figure 1. Kelvin wake pattern of a small ship in the Western Scheldt (Google Earth)

### B. Secondary wave pattern

As a ship progresses waves are caused by the discontinuities in the hull, which are found at the bow and the stern. These waves form a complex of diverging waves and a transverse wave also known as a Kelvin wake pattern (see Fig. 1). The interference of the waves causes a wave train for each discontinuity of which the one caused by the stern is usually dominant (see Fig. 2). In this paper these wave trains are indicated as the secondary waves. The wave periods of the wave trains are short and are related to the speed of the ship, as given by (1). The wave train progresses approximately at a 35 degree angle to the sailing line.

$$T = \cos 35^\circ v_s \frac{2\pi}{g} \quad (1)$$

With T the wave period [s],  $v_s$  the speed of the ship relative to the water [m/s] and g the gravitational acceleration [m/s<sup>2</sup>].

The height of secondary waves diminishes with the cubic root of distance in relatively deep water. The following empirical relation can be used as an estimation of the wave height:

$$\frac{H}{h} = \zeta \left( \frac{s}{h} \right)^{-1/3} \left( \frac{v_s}{\sqrt{gh}} \right)^4 \quad (2)$$

H is the wave height (m), h the local water depth (m) and s the distance of the wave to the sailing line of a ship (m). The shape of the ship (sleekness) is represented by  $\zeta$ . On a tidal flat this relation will only hold at high tide, but it gives insight in the parameters associated with the origination and propagation of these waves.

As seen in Fig. 1 part of the transverse waves and diverging waves follow behind a ship. The whole current and wave event of a passing ship, as observed from the bank, lasts in the order of a few minutes for a small ship up to 10 minutes for a large ship.

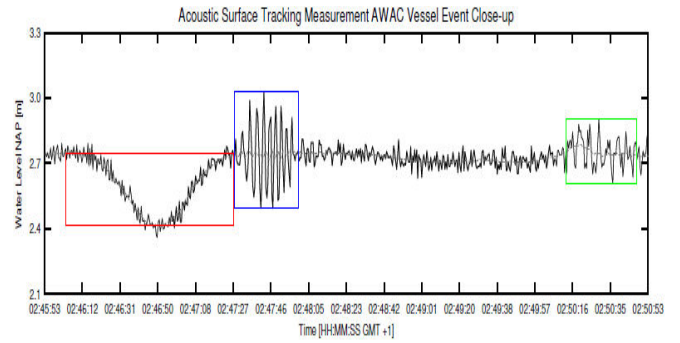


Figure 2. Water level excursion and waves generated by a passing container vessel in the Western Scheldt. The red, blue and green squares respectively box the primary wave, the first secondary wave and a second secondary wave. The measurement was performed at a few hundred meters distance from the ship.

## III. MEASUREMENT CAMPAIGN AT A TIDAL FLAT

In the summer of 2010 a measurement campaign of six weeks took place on the tidal flat at Bath. Measurements were performed of water levels, waves and current velocities, generated by wind, tide and passing ships.

### A. Measurement location and conditions

At the selected measurement location the river is 1600 meters wide at low tide and over 2500 meters wide at high tide (Fig. 3). The channel is 26 meters deep at its deepest. The channel wall is inclined at an angle of 1 to 4 on one side and at an angle of 1 to 25 at the other. The steepest side of the channel is reinforced by a revetment consisting of rubble. This stretches from 2 meters below sea level to 16 meters below sea level [3]. The top of the revetment is just above water at low tide. At high tide the top of the revetment is submerged by 5.3 meters.

The tidal flat next to the revetment consists of a layer of peat which has been swept clean of most sand and silt. At the time of construction this bare stretch of peat was 80 meters wide. Further away, the peat was covered by a 2 meter thick layer of sand and silt. At present the remaining layer of sand and silt has withdrawn 150 meters from the tidal channel and has reduced drastically in thickness up to 250 from the channel. This layer is still eroding.

The route through the channel which is to be used by the seagoing vessels is marked by buoys. The width of this path is 350 meters at the selected site. The marker buoys closest to the top of the revetment are only 30 to 50 meters away.

The access to the Antwerp harbor is not limited by the conditions at this particular site but by sills and bends at other places along the Western Scheldt. There is a guaranteed clearance at all times for ships with a draught up to 13.5 meters. High tide allows for significantly more draught. The present limitation on the length of the ships travelling to Antwerp is 360 meters.

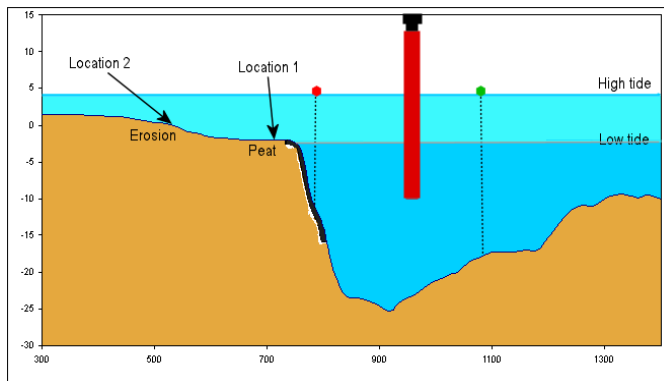


Figure 3. Tidal channel at Bath. On the left is the tidal flat which slowly erodes. The red block represents a ship, the red and green dots are the marker buoys.

### B. Measurement set-up

The measurements took place at two locations on the tidal flat using bottom mounted equipment. The first location was 30 meters from the edge of the navigational channel. At this location the tidal current is still strong and the ship waves will hardly have reduced. The second location was 230 meters from the channel in slightly shallower water. This location was within the area of the tidal flat where most of the erosion takes place, see Fig. 1 and 3. At this distance the tidal current will have reduced significantly and a reduction of ship induced currents and waves was expected as well. Both locations fell dry during low tide and were submerged during high tide with a maximum water column of 5.3 meters.

Close to the shipping lane an acoustic Doppler current meter equipped with an inverted echo sounding beam was mounted (1 Mhz Nortek AWAC). At the location furthest from the channel the measurements were performed using a point current velocity meter with an integrated pressure sensor (10 Mhz Nortek Vector ADV), see Fig. 4. The AWAC was set up to measure in bursts of 17 minutes to obtain wave data using the echo beam and one velocity cell. This burst was followed by a 2 minute burst measuring a full current profile, with

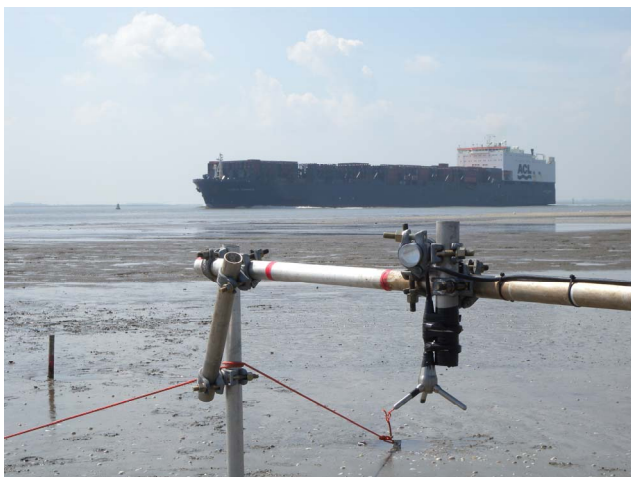


Figure 4. ADV in a frame on the tidal flat. The peat is visible in the background. The container ship "Atlantic Companion" in the background. Picture taken by Jarno Terwindt.

cell sizes of 0.5 meters. This was repeated every 20 minutes. After each profile measurement the internal software of the instrument evaluated the cell size and cell position to use for the next "wave" burst. During this campaign this cell size switched between, 0.5 and 0.9 meters depending on the available water depth. The ADV measured continuous. Both instruments put out data at 2 Hz.

Measurements in the tidal channel itself were planned to establish the wave and currents before coming onto the tidal flat. However, a measurement on the revetment would be disturbed by reflection of the waves on the rumble. Putting instruments in the shipping lane was not possible, which left the possibility of measuring on the opposite side of the shipping lane. Unfortunately time and available instruments were restricted and no measurements were performed.

Wind information was supplied from a nearby measurement station of the Royal Netherlands Meteorological Institute (KNMI).

### C. Instrument performance

Measuring ship induced currents and waves differs slightly from measuring wind waves, orbital motion and tidal currents. Measuring the long primary waves ( $T=20-90$  s) requires an instrument able to follow this slow water level excursion. For significant resolution of the wavelength of secondary wave trains a sample period at least 4 times shorter than the shortest expected wave period (2 s) is preferable. The techniques traditionally used for these type of measurements in shallow water are a point velocity meter and a pressure sensor. In deeper water Doppler profilers have the potential to do the same job.

In this specific setup the AWAC's inverted echo sounder has some clear advantages over a bottom mounted pressure sensor; first of all that the pressure sensor cannot register short waves when the water column gets large due to attenuation of the waves. The correction to apply for this attenuation when using pressure sensors and measuring ship wakes, is still a matter of discussion [4], although a correction using linear wave theory is common and applied here. Secondly, velocities along the pressure sensor can result in a pressure and therefore be mistaken for excursions of the water surface. A drawback of the inverted echo sounder is that in shallow water, during breaking wave conditions, the acoustic beam does not track the surface correctly [5]. This is due to entrained air and sediment. At this location the data from the tracking became reliable when the instrument was submerged by a meter and a half.

The standard error in the velocity measurements of the AWAC velocity data (in wave mode) varies between 7 cm/s and 22 cm/s depending on the size of the measurement cell, while the ADV measurements have a standard error of a few millimeters per second.

The instruments more or less performed as expected in this calm shallow water setup: The AWAC acoustic surface tracking gave clear and reliable data on the water level and wave heights. The pressure sensor gave good data on both the water levels and wave heights. The secondary wave heights calculated from the pressure sensor were corrected for

attenuation due to the water depth. The ADV velocity measurement clearly showed both velocities associated with the primary and the secondary waves of which the second were again slightly attenuated by depth (see Fig. 5). The velocity measurements by the AWAC have intrinsic high uncertainties when measuring at 2 Hz. A moving average with an averaging interval of 3 seconds was applied. In the resulting signal the secondary waves were no longer distinguishable. The velocities due to the primary wave were distinguishable but with a high

uncertainty.

In hindsight the profiler should not have measured in bursts. Due to the 3 minute gap in the surface information the signal of many ship passages was partly lost.

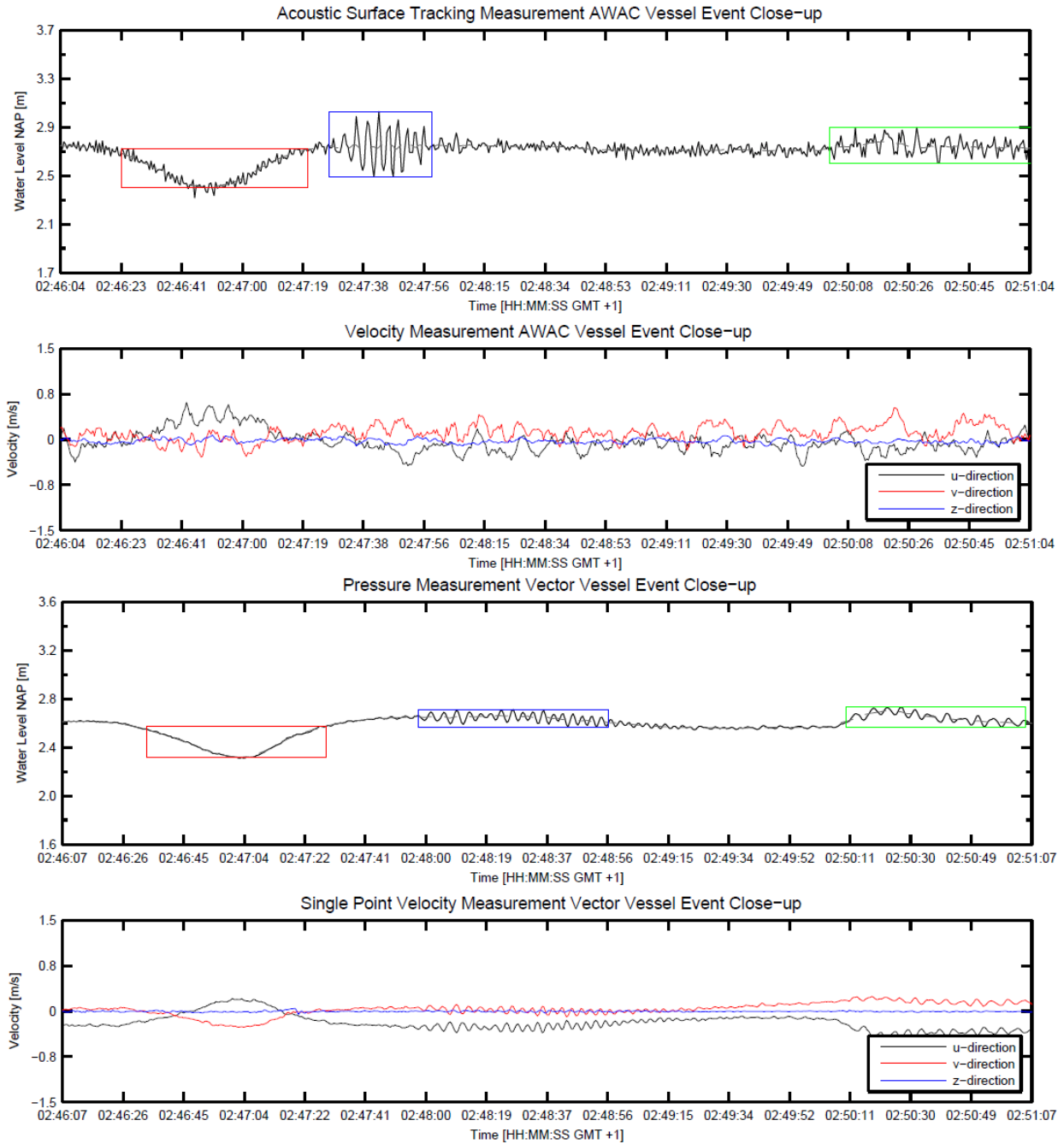


Figure 5. Water levels and currents during the passages of container vessel “JAZAN”. The top window: waterlevel as recorded by the acoustic surface tracking of the AWAC at location 1. The second window from the top: the current at location 1 as measured by the one measurement cell of the AWAC. The bottom windows: water level and current by ADV at location 2.

IV. ANALYSIS OF THE FIELD MEASUREMENTS

During the 45-day campaign, nearly 4000 seagoing ships passed the measurement site, including 170 ships over 250 meters length. The characteristics of these passing ships were supplied by the Scheldt River Coordination Centre (SRCC). The speeds of the ships were estimated from the time of passages of certain waypoints. These speeds were accurate within 10% (validated using data from the Automatic Identification System (AIS) logged at the SRCC).

The ship induced waves and currents were well distinguishable from the background. This can be seen in Fig. 5, which shows the water level displacement and the velocities as registered at both locations during the passage of the 305-metre long container vessel “Jazan”.

The measurements were analyzed for a selection of 60 ships. These ships are categorized in 3 classes (20 for each category).

A. Wave heights and wave periods

The wave height of the primary wave increases with the speed of the ship and the length of the ship as shown in Fig. 7. Ships shorter than 100 meters did not produce a primary wave which could be detected at the measurement locations. The measured wave period of the primary wave is on average slightly shorter than generated wave period estimated by  $2 L_{\text{ship}}/V_{\text{ship}}$  (see Fig. 8). In which  $L_{\text{ship}}$  is the length of the ship.

The primary waves at location 1 and location 2 are comparable in wave period and wave heights for water level depressions up to 40 cm. For larger water level depressions the depression was 10 to 30 cm larger at location 2 than at location 1. The largest growth occurred when the water level at location 2 was less than a meter. This indicates shoaling. However, the phenomenon is closer to a bore and seen more often when a ship wave flows on to a beach with a small slope. It occurs when the water from higher up on the slope is still flowing downwards and out of the sand due to the water level depression while the water filling up the depression is coming in.

The relations of the measured secondary waves with the characteristics of the passing ships are more complex. The speed of the ship is the dominant variable for the height of the secondary wave. The measured wave heights of the secondary wave show some relation to the ship’s speed (Fig 9), but not a clear relation as expected and given by (2).

The wave height of the secondary waves on average reduces by 45% between locations 1 and 2. A diminishing wave height in the order of 30% was indicated by (2). Considering the uncertainties in the empirical relation (1) the measured reduction is not an unexpectedly large.

Based on (1) there should be a linear relation between the measured wave periods and the ship’s speed (indicated by the line in Fig. 10). The found correlation between the two parameters is low. This is mainly explained by the fact that the ships are not sailing in a straight line at the measurement site but in a curve. With each ship following it’s own path through the river bend. Secondly at lower water levels the secondary

waves are prone to some refraction while coming from the channel onto the tidal flat. Both effects will change the periods of the waves.

B. Wave generated currents and tidal currents

Apart from the wave height and wave period the occurring velocities were studied. The maximum velocities were directly attributed to the primary wave as show in Fig. 6 for location 2. At location 2 these velocities reached values up to 1.4 m/s while the tidal current at this location was 0.35 m/s at its maximum and 0.1 cm/s on average.

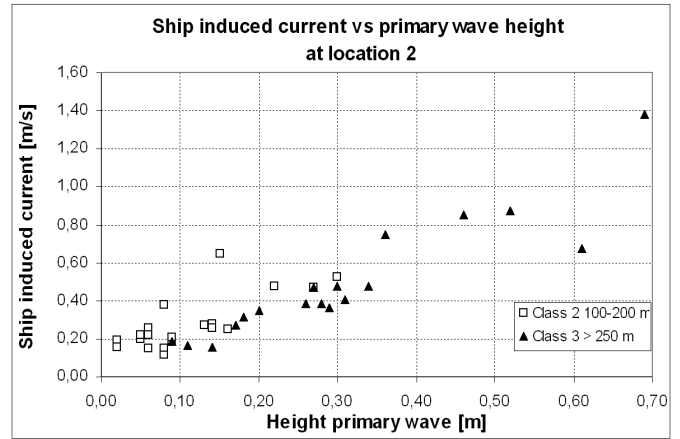


Figure 6. Ship induced current as a function of the height of the primary wave at location 2

C. Shear stress and erosion

At location 1, close to the channel, the surface consists of peat which is sometimes covered with some silt. At location 2 the surface consists mostly of fine sand and mud. However, part of the tidal flat at this distance from the channel consist of consolidated material dating back a few ages. The exact composition of the material has yet to be verified by samples of the local material. Table I shows the critical shear stresses associated with a number of sediment types.

TABLE I. CRITICAL SHEAR STRESS ( $\tau_{\text{crit}}$  [N/m<sup>2</sup>]) FOR DIFFERENT TYPES OF SEDIMENT

Sediment type	Critical shear stress ( $\tau_{\text{crit}}$ [N/m <sup>2</sup> ])	
	Incipient motion	Transport of suspended material
Sand (D50 = 100 $\mu\text{m}$ )	0.14	0.2
Sand (D50 = 250 $\mu\text{m}$ )	0.19	0.5
Sand (D50 = 400 $\mu\text{m}$ )	0.23	0.7
Sand with 50% slit (nonconsolidated)	0.3 – 0.8	-
Sand with 50% slit (consolidated)	0.5 – 1.0	-

The shear stresses on the bottom are calculated from the measured wave heights and tidal velocities. In table II the occurring maximum shear stresses are given for the combined stress of tidal current and wind waves and separately for the primary and secondary waves for each ship class.

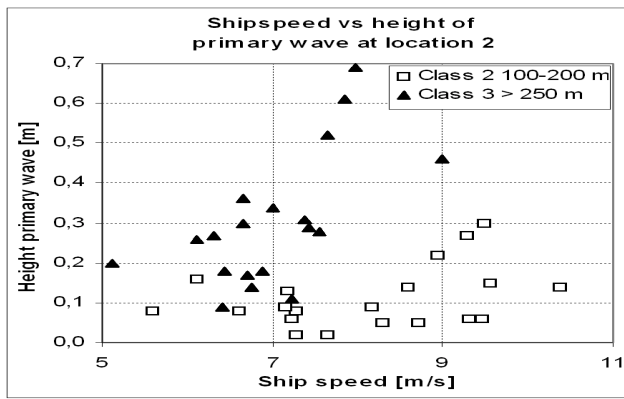


Figure 7. Estimated heights of the primary waves at location 2 as function of the ship's speed for the different classes.

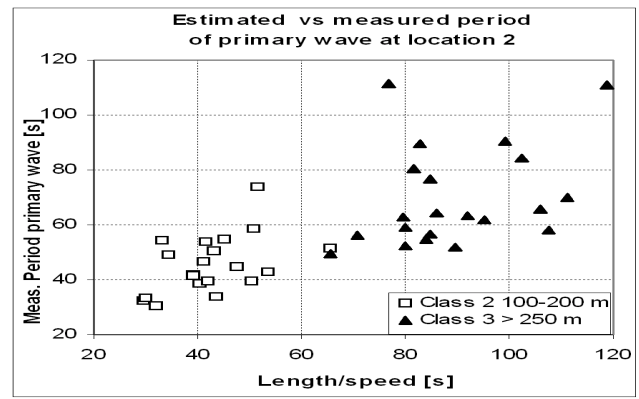


Figure 8. Wave period of the primary wave measured at location 2 as a function of the period estimated by  $2L_{ship}/V_{ship}$ .

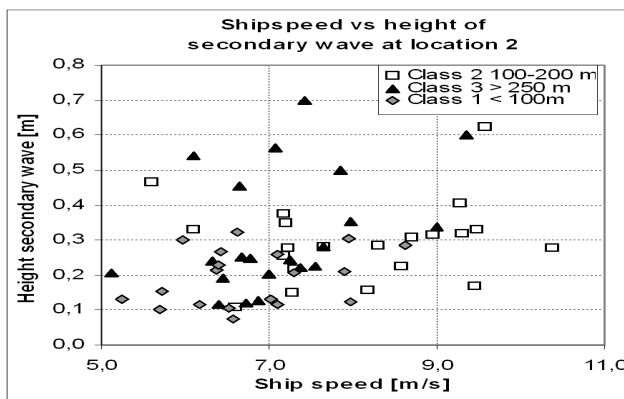


Figure 9. Maximum heights of the secondary waves at location 2 as function of the ship's speed for the different classes.

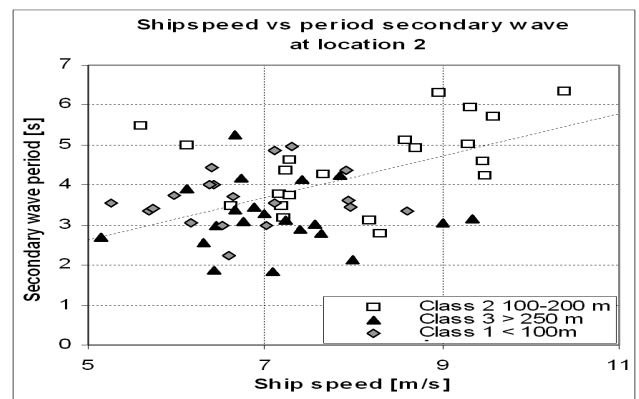


Figure 10. Periods of the secondary waves at location 2 as function of the ship's speed for the different classes.

At location 1, about thirty meters away from the navigational channel, the peak stresses due to tidal currents and wind waves were about  $2.5 \text{ N/m}^2$ . This is strong enough to suspend silt and sand, but not strong enough to cause erosion of the underlying layer of peat. About 25% of the time the shear stress reached a value over  $0.4 \text{ N/m}^2$  at this location, which indicates that fine sand and silt can stay suspended and be transported. At this location the peak stress due to the secondary ship waves up to  $5.5 \text{ N/m}^2$  occur, caused by the ship class over 250 meters length.

The peak load due to tidal current and wind waves at location 2, 230 meters away from the channel, did not exceed  $0.6 \text{ N/m}^2$ . These peaks are still high enough to suspend the local sand/mud bottom if it is not consolidated. 25% Of the time the shear stress reached a value over  $0.2 \text{ N/m}^2$  at this location, which indicates that suspension of the finest sand fractions is possible. However, only the peaks are enough to instigate some motion if the material is consolidated. The stress due to secondary ship waves is on average lower at location 2 than location 1 due to the lower wave heights, but the peak stress still reaches the value of  $5.5 \text{ N/m}^2$ . Shear stress due to the primary ship wave, which is low, at location 1 grows up to  $2.7 \text{ N/m}^2$  at location 2 due to the shallower water.

Location 2 is within the present area of erosion. At this location the shear stress due to the ship waves is strong enough to erode even consolidated material. Furthermore, the largest ship class produces such a large current that in absence of tidal flow the ship induced movement by itself is large enough to suspend material and carry it away. Given the frequency of passing ships and the tide, it is estimated that ship waves provided an impact at this site for about 5% of the time. This duration appears to be a small, but due to the large stresses the impact on the site can be significant.

TABLE II. MAXIMUM SHEAR STRESS [ $\text{N/m}^2$ ]

Maximum Shear Stress [ $\text{N/m}^2$ ] at location 1				Maximum Shear Stress [ $\text{N/m}^2$ ] at location 2			
Tidal current and wind waves	Ship class	Primary wave	Secondary wave	Tidal current and wind waves	Ship class	Primary wave	Secondary wave
	100-200 m	0.3	5.6		100-200 m	0.5*	3.8
	> 250 m	1.0	5.5		> 250 m	2.7*	5.5

\*It is suspected that the shear stress at location 2 due to the primary wave is underestimated for those occasions where a steep wave front occurs.

## V. CONCLUSIONS

The presented research shows the ship induced waves and currents on the tidal flat at Bath. The chosen measurement setup performed well for the given location and the given purpose. The AWAC acoustic surface tracking and the ADV gave good and clean signals. The use of an ADV in a bottom mounted frame is limited by the attenuation of short waves. The AWAC supplies an alternative for locations with a water depth over 1.5 meters although the velocity resolution is limited. For ship wave analysis it is recommended not to use the wave mode of the AWAC as its burst mode leads to loss of data.

The measured primary waves reach heights of 70 cm and extended far from ship. These waves do not show attenuation during their passage over the tidal flat and increase in height on the slope which is subject to erosion. In several cases a bore is seen as part of the primary wave. The associated currents reach values exceeding a meter per second. The secondary waves heights reach values up to one meter close to the channel and reduce by a factor 2 over 200 meters. The larger wave heights of both secondary waves and primary waves and the higher currents are caused by the larger ships.

Within the present area of erosion at the tidal flat the shear stress due to the ship waves is strong enough to erode even consolidated material. Furthermore, the largest ship class produces such a large current that in absence of tidal flow the ship induced movement by itself is large enough to suspend material and carry it away.

Concerning erosion of the tidal flat over time the following hypothesis is given: the original tidal flat consisted of consolidated material a few centuries old. This material slowly eroded due to tidal currents and the outward meandering of the river bend. This process was sped up by the increasing loads of ship waves and induced currents over the last decades. Since 1997 the tidal channel is fixed in its position by the revetment, therefore the tidal flow does not increase outward anymore (or only slowly as the depth increases on the tidal flat). And it is no longer strong enough to eat away at the old layers on the tidal flat far from the channel. However, these layers get pounded by ship waves turning it into unconsolidated material. This material can then be transported either by ship induced currents or tidal current. This hypothesis depends largely on the assumption of the origin and age of the materials that make up the tidal flat. This and the erosion pattern over the last 40 years will be subject to further study.

A counter measure designed to reduce flow will reduce the load on the tidal flat and slow the erosion. However, it will not reduce the much larger, although shorter, impact of the ship waves, which in itself is large enough to suspend and transport material. This implies that a stop to the erosion and the desired reversal is not guaranteed. A counter measure designed to reduce both waves and currents should therefore be considered.

Antwerp harbor aims at the admittance to the Western Scheldt of the largest container vessels presently in existence.

These measure 400 meters and have a draught of 15.5 meters. At the time this paper was written the shallowest parts of the river were being dredged and widened, thereby making Antwerp accessible for these larger ships in the near future. A subsequent increase in the loads is expected on tidal flats and the river system as a whole. From the measurements and insights gained from this campaign it is possible to extrapolate the expected increase in load and act upon it.

Field data of ship induced waves and currents in coastal zones are scarce. The only documented measurements in the Western Scheldt date back to 1991. The present study showed that easy and accurate measurements are possible with present day equipment.

### A. Further work

This study was performed to estimate loads on the tidal channel and not to gain more insight in the physics of ship induced water movement. However, the data set is extensive and all needed parameters are available (although not all used in this study) to further such knowledge.

The given estimates of measured wave heights, wave periods and resulting loads have relatively large uncertainties. These can be reduced by developing new data processing algorithms and making use of all available data. One of these data sources is AIS which contains more accurate estimates of ship speeds and the distance of these ships while passing the measurement site.

Based on the measurements on the tidal flat much insight was gained on the occurrence of strong currents and steep fronts of the waves that follow the water level depression. These types of waves are a major problem for recreation on beaches along the Western Scheldt and have led to accidents in the summer of 2010. A new study was set up to measure explain the occurrence of these waves on the beaches in order to take the right measures to prevent them in the future.

## ACKNOWLEDGMENT

The authors would like to thank Gert-Jan Liek, Olivier Sinke, Jan van 't Westende, Marco Schrijver and Dick de Jong at Rijkswaterstaat Zeeland for their cooperation and feedback throughout the project and the fieldwork.

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