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Response of technical-biological bank protection to ship-generated wave actions – first results

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ABSTRACT: Growing awareness of the environmental aspects related to the transitional zone between land and water directs research into more ecologically sound, 'soft' engineering bank protections too. Considering this new set of boundary conditions, off-bank timber piling in combination with reed vegetation has been installed along the river Lys (Zulte, Belgium), a non-tidal, restricted waterway subject to heavy shipping traffic, in an attempt to reconcile both the technical and environmental requirements of a revetment. Since ship-induced water movements form the core threat to bank and vegetation stability, a subtle compromise between load and protection needs to be found. To determine and evaluate the ship-induced forcing, we designed an on-site prototype monitoring system to continuously acquire data of the impact of the ship wave climate on the bank protection. The first results indicate that the wave attack of the predominant primary ship wave system on the river bank is not sufficiently reduced by a single row of off-bank piling, in contrast with a 20% reduction of the secondary wave heights. Hence, questions arise whether this type of bank protection is a valuable alternative on these waterways. Ongoing research therefore addresses the twofold load reduction of this technical-biological bank protection, including the wave attenuation through a reed vegetation belt.

Keywords: Ship waves, Bank protection, Energy dissipation, Prototype monitoring

1 INTRODUCTION

Traditionally, river bank revetments are made of conventional, merely technology-based 'hard' protection materials like concrete, riprap, sheet piles etc. Nowadays, growing awareness of the environmental aspects related to this transitional zone between land and water directs research to more ecologically sound, 'soft' engineering bank protections too. Within this line of research, off-bank timber piling in combination with reed vegetation was installed in some sections along the navigable river Lys (Zulte, Belgium) to reconcile both technical and environmental requirements of a revetment. For a reasonable construction and maintenance cost, environmental benefits are increased and sustainable techniques are attained. Only little on-site research has however been devoted to experimentally investigate the assumption of wave load reduction, which is essential for better environmental circumstances (e.g. Coops et al., 1994; Kucera-Hirzinger et al., 2009). So the question remains how effective this technical-biological bank protection is in operation.

Failures of revetments, dikes or other bank protecting structures are known to be the result of tractive forces from currents, water level variations, wind-generated and ship-generated waves (Escarameia, 1998; Schiereck, 2001). With regard to restricted waterways subject to heavy shipping traffic, such as the river Lys, a good knowledge of the ship-generated wave actions on, and the geotechnical resistance of the bank protection is therefore essential for the proper design of embankment structures.

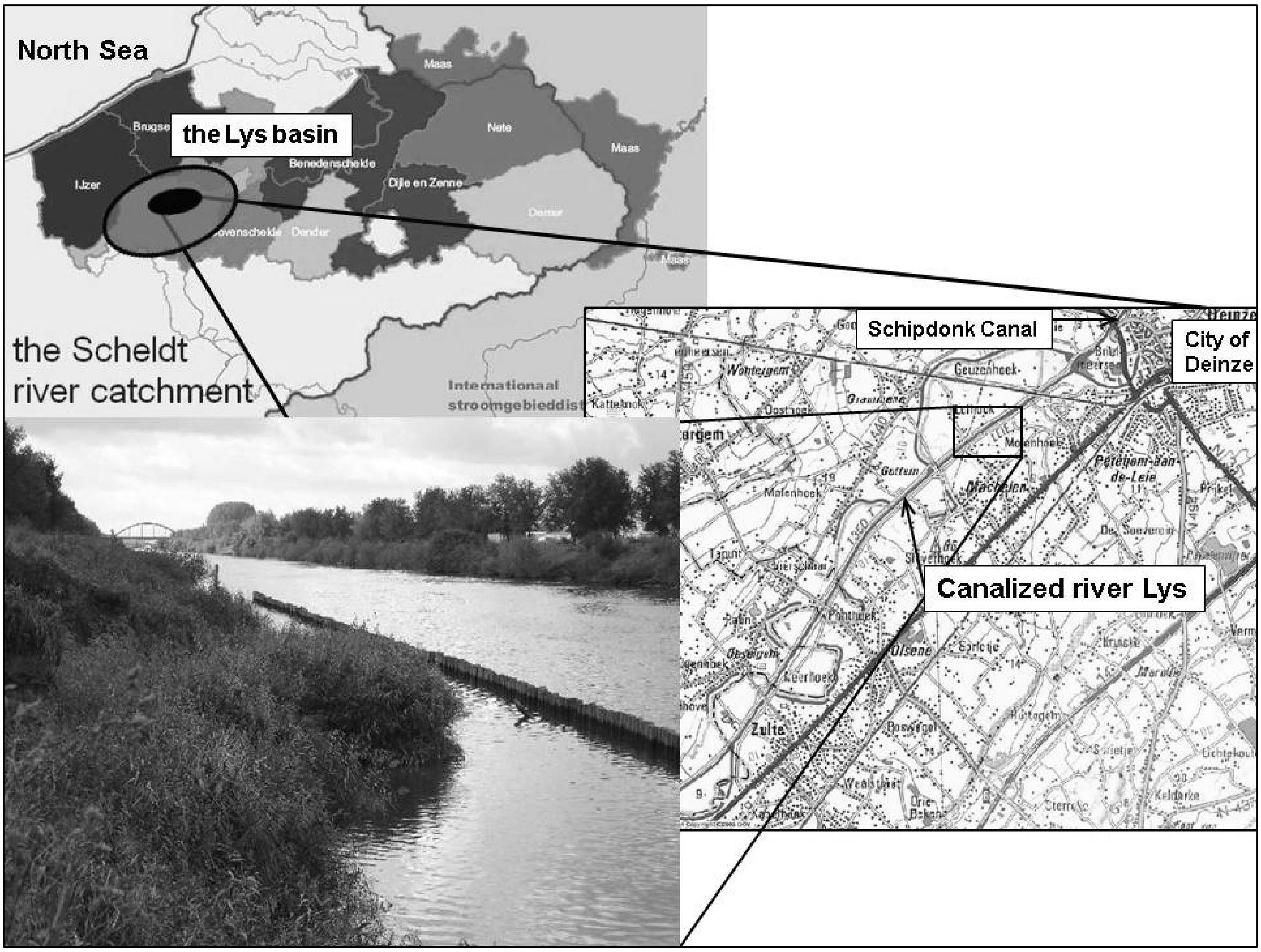

Figure 1 Location of the Lys basin in the Scheldt river catchment, zooming in on the measurement site with close-up of the monitored technical-biological bank protection, consisting of off-bank timber piling in combination with (reed) vegetation.

Navigating ships generate a specific pattern of bank-directed surface waves. Its characteristics, such as propagation directions, wave heights, and wave periods alter with ship design (different types, draught, speed) (e.g. Johnson, 1958; Sorensen, 1973) and navigation orientation and interact with topographic boundaries and local hydraulic conditions (e.g. Bhowmik & Mazumder, 1990). As a result, theoretical calculations and simulations of the ship-induced loads on a specific embankment are not straightforward. Field measurements thus provide a welcome alternative for the determination of these forces and the response of the bank protection to the ship-generated wave actions.

Objective of the present study is to analyse the energy dissipation through a single row of off-bank timber piles, designed to act as a wave reductor. The paper outlines the first, quantitative results, and points to some interesting conclusions in contrast with the current assumptions.

2 STUDY SITE

The prototype monitoring system is installed on a cross section of the river Lys (Zulte, Belgium), which is situated in the north-western part of the Scheldt river catchment. In the seventies, the watercourse was straightened and canalized to allow inland navigation up to CEMT-class IV. The use of larger (and faster) ships however prompted the waterway administration to allow vessels up to CEMT-class Va. This permission is a provisional measure, in anticipation of a further deepening of the profile to gain a narrow (one-way traffic) profile for vessels up to CEMT-class Vb. With, on monthly average, 1500 barges passing through the lock of Sint-Baafs-Vijve, the river Lys is categorized as a waterway subject to heavy shipping traffic.

Furthermore, the river Lys has a fixed water level which is maintained during normal weather conditions, and a small cross-sectional width (50.2

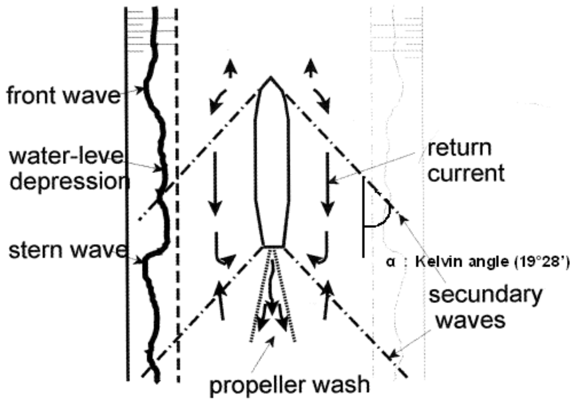

Figure 2 Primary and secondary wave system around a navigating ship (adapted from Schiereck, 2001)

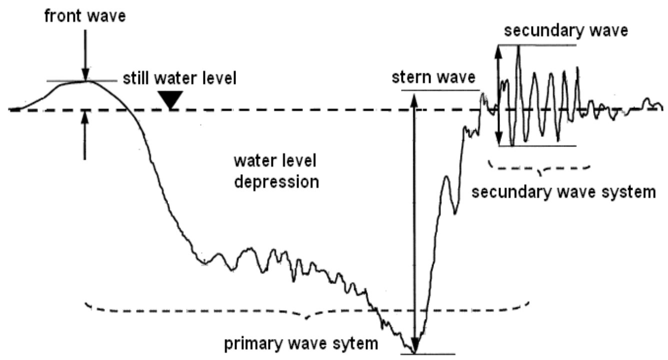

Figure 3 Parameters of the ship wave pattern for a ship navigating at subcritical speed.

m on the still water level) and depth (3.5m), making it a restricted, non-tidal waterway.

High embankments, the small cross-sectional width and trees along the crest of the dikes limit the fetch length for generation of significant wind waves. Consequently, it is believed that ship-generated waves contribute the largest amount of erosive energy to the river bank in normal weather conditions, i.e. non-flow dominated situations.

Site selection was guided by the need to find a location where (1) the technical-biological bank protection is applied, and (2) the waterway has a sufficiently long straight section. This setup allows limit (maximum) speed for displacement ships, and cruising ship speed in case of planing ships and hence, is representative of maximum ship-induced forcing on the river bank.

Armoured concrete revetment originally protected the river bank but cumulative physical processes undermined this rigid structure and led to progressive bank erosion, resulting in the presence of a vertical cut-bank. At its base a very gentle sloping beach of eroded sediment is found, partly colonized by (reed)vegetation. A row of off-bank timber piles is placed in front of the bank to act as a first wave reductor.

3 SHIP WAVE BASICS

Ship-generated waves have their distinct characteristics in comparison with wind-generated waves. Navigating ships generate specific patterns of surface waves, which can be separated into the primary and secondary wave system of a ship. Although the duration of the wave train of a ship is very limited at a given location, it is a complex wave pattern, consisting of different components which are frequently superimposed.

The primary wave system, propagating in the navigation direction, is characterised by a significant water level depression along the hull of the ship. It is initiated with a front wave at the bow of the ship, travels as a drawdown wave along the ship and ends with the stern wave (Schiereck, 2001). Associated with these characteristics is the return current. In order to overcome its resistance, the navigating ship transfers energy to the water body in the form of a water displacement from the front to the back of the ship, inducing a return current (Sorensen, 1973).

Transverse and diverging secondary waves, propagating under an oblique angle to the sailing line of the ship, are caused by the dynamic pressure distribution due to discontinuities in the hull profile. The secondary wave train usually consists of two higher waves followed by 10 to 15 smaller waves. Lord Kelvin (1887) was the first to analytically investigate this wave pattern. Later on, his work was extended by Havelock (1908).

Figure 2 depicts the primary and the secondary ship wave system of a ship. All observable parameters of the ship wave pattern for a ship navigating at subcritical speed are illustrated in Figure 3. The magnitude and thus, relevance of these parameters varies with the characteristics of the navigating ship and the local geometry of the waterway.

4 MATERIALS AND METHODS

4.1 *Ship wave measurements*

During a two and a half month survey (August, 7 - October, 24 2009), ship wave characteristics were registered using pressure sensors (Druck PTX 1830, GE Sensing & Inspection Technologies), which continuously recorded the water level fluctuations at a sampling frequency of 10 Hz.

The pressure sensors were laboratory calibrated via a progressive stepwise hydraulic pressure generation with a pressure calibrator, determining the scaling and offset parameters of each sensor. Out-

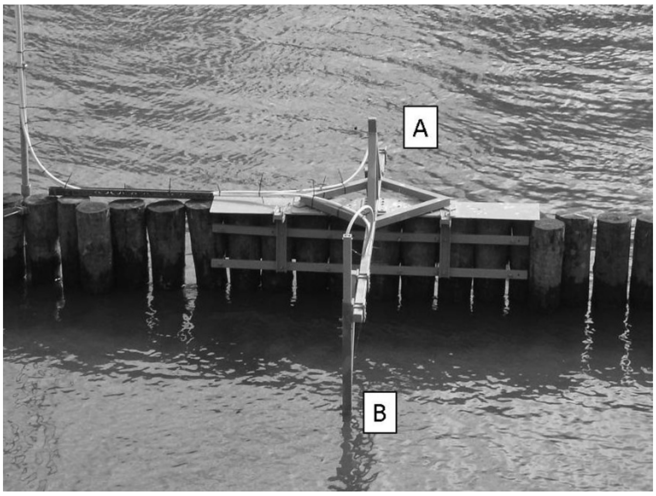

Figure 4 Experimental test setup on a single row of timber piles along a cross section of the river Lys, consisting of two pressure sensors mounted on the bottom end of a steel suppporting structure (A: pressure sensor alongside the fairway ; B: pressure sensor alongside the river bank).

put voltages at fixed pressures were recorded for 100 bursts and averaged. The pressure sensors operate a factory set measurement range from 0 to 1 bar. They have a six times permissible overpressure and the signal precision to linearity is specified to be ±0.06% of full-scale of the best straight line.

Figure 4 depicts the experimental test setup on a single row of timber piles along a cross section of the river Lys at Zulte (Belgium). Two pressure sensors are deployed in a cross-shore array, mounted on the bottom end of a steel supporting structure. Both devices are fixed at the same relative depth to each other. In order to monitor the incident and transmitted ship waves, pressure sensor A is located in the fairway, at a distal point of 15 m from the river bank and 1.5 m before the off-bank timber piling. Pressure sensor B is placed 2 m behind the off-bank timber piling, alongside the river bank.

The measured pressure time series provides the necessary data for investigation of the local wave climate, affected by the waterway geometry and the heavy shipping traffic.

4.2 *Ship wave analysis*

Signal analysis of the ship waves is handled using a self-designed program implemented in Labview (National Instruments), which carries out the data (pre-) processing as well as the data analysis.

In this way, the subsurface water pressure time series is converted to a time series of surface water elevations by correcting the pressure signal for depth attenuation using the linear wave theory (Ellis et al., 2006). Ship wave events are identified and selected based on pre-defined minimum criteria for peak detection and peak interval time. In the frequency domain, filtering is additionally applied to distinguish the primary and secondary wave system from one another by their respective wave periods, i.e. more than 10 s for the primary wave system and the interval period between the primary wave system and the wind-generated waves for the secondary wave system.

Once the primary and secondary wave signals are extracted, their relevant wave parameters are processed making use of the zero down-crossing method.

A detailed description of the practical analysis methodology can be found in De Roo & Troch (2010a).

4.3 *Energy dissipation through timber piles*

Forces in waves are important when dealing with erosion and protection. The working principle of the applied technical-biological method relies on the reduction of the excessive kinetic wave energy by a single row of timber piles (debarked impregnated pine) in front of the bank down to a manageable level in the water strip behind, where wave energy is further dissipated due to (1) bottom friction, (2) wave breaking and (3) wave attenuation through a (reed) vegetation belt before reaching the river bank.

A wall that consists of vertical piles can act as a wave reductor if there is little space between the piles (Schiereck, 2001). Part of the wave energy will then be absorbed because the water has to flow through the construction. Another way of absorption, the internal 'work' in structures, is carried out by the bending (reed) vegetation belt, but this method is not considered here.

The effectiveness of the wave reducing piling is easily quantified by means of the transmission coefficient C_T:

$$C_T = {H_T}/{H_I} \tag{1}$$

where H_T and H_I are respectively the transmitted and the incident wave height [m].

Equivalent is the use of the energy density:

$$E = \frac{1}{8}\rho\gamma H^2 \tag{2}$$

were ρ is the fluid density [kg/m³], g represents the acceleration of gravity [m/s²] and H the wave height [m].

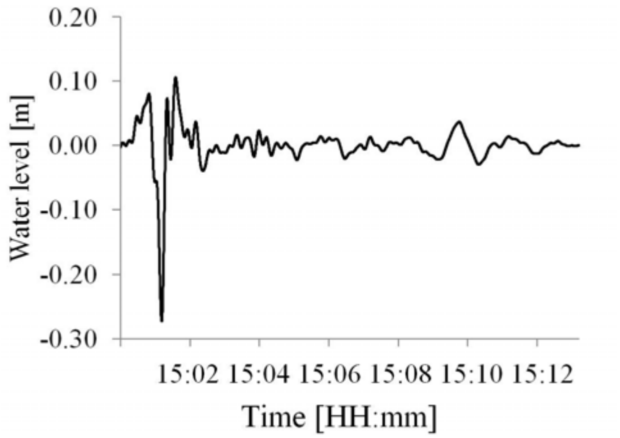

Figure 5 Example of the primary ship wave system

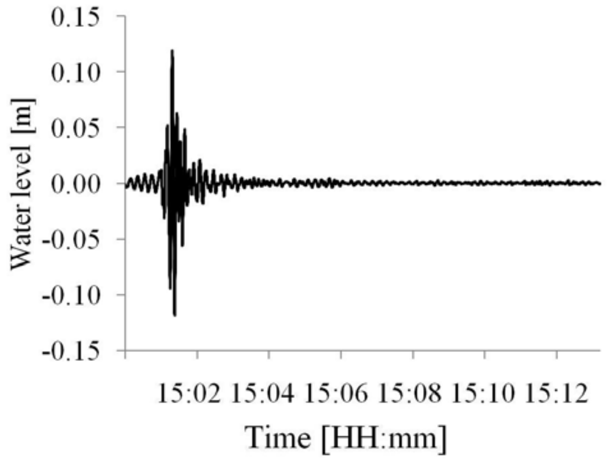

Figure 6 Example of the secondary ship wave system

The transmission coefficient and wave energy ratio between incident and transmitted waves are calculated per ship wave event for the primary and secondary wave individually. Like in various previous research, a.o. Ellis et al. (2002); Hofmann et al. (2008), the maximum wave height in both wave systems serves as criterion for the determination of load reduction through the row of timber piles.

5 RESULTS

5.1 *Ship-generated waves*

The measurement campaign resulted in the selection of 3718 ship wave events. Taking into account that 3945 ships passed through the lock of Sint-Baafs-Vijve, located 8 km upstream of the measurement site, it can be said that 94% of the shipping traffic is detected by the software. However, this holds just a rough estimation of the accuracy of detected ship passages because recreational boat traffic can bypass the lock, and the event selection routine of the software is not able to separate two overtaking or closely following ships from each other.

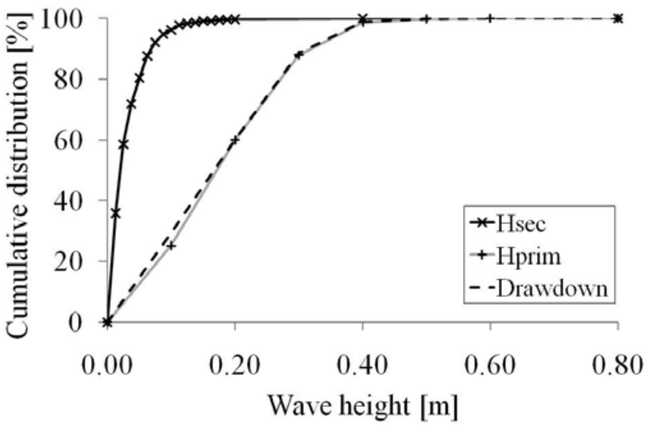

Figure 7 Cumulative distribution of the drawdown, primary and secondary wave height. Averaged values of all measured ship wave events.

Erratic data or non-recording of a ship wave event by one of the pressure sensors led to the exclusion of 339 events from further processing.

Figure 5 and Figure 6 exemplify the separation into the primary and secondary ship wave system by the analysis software. Here, the maximum drawdown is 0.35 m and the suction lasts for 18.34 s. The stern wave has a height of 0.35 m and a wave period of 7.86 s. The maximum secondary wave height is determined to be 0.21 m. These short wave heights decay rapidly from 0.21 m to 0.0044 m in a few minutes. The primary wave system shows a period of 24.78 s while the secondary wave has a 7.42 s period.

In general, a ship passage affected the technical-biological bank protection on the measurement location for, on average, 516 s. The largest observed drawdown was analysed at 0.59 m, the highest recorded primary wave and secondary wave were respectively 0.60 m and 0.32 m.

Figure 7 illustrates the prevailing wave climate by indicating the cumulative distribution of the drawdown, the primary and the secondary wave heights. Given the significant higher values for the primary wave height and drawdown, the graph clearly points out the predominance of the primary wave system in a restricted, non-tidal waterway such as the river Lys. The probabilities of the drawdown and stern wave obviously exhibit similar characteristics; the secondary wave demonstrates a deviating behaviour.

5.2 *Energy dissipation through timber piles*

The variances observed between the incident and transmitted waves of the primary and secondary wave system are compared in Figure 8 and Figure 9 respectively. Quasi no reduction in wave height is found for the primary wave system. The slope of the linear correlation line plotted through the secondary wave data indicates a decrease in

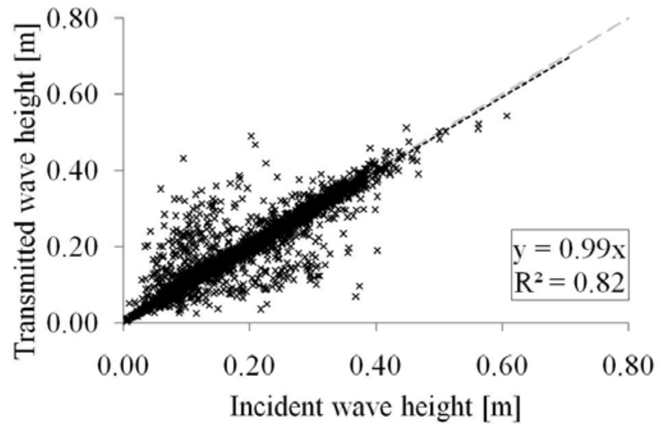

Figure 8 Variance between the incident and transmitted wave height for the primary wave system. Linear regression analysis indicates no clear difference between the wave heights.

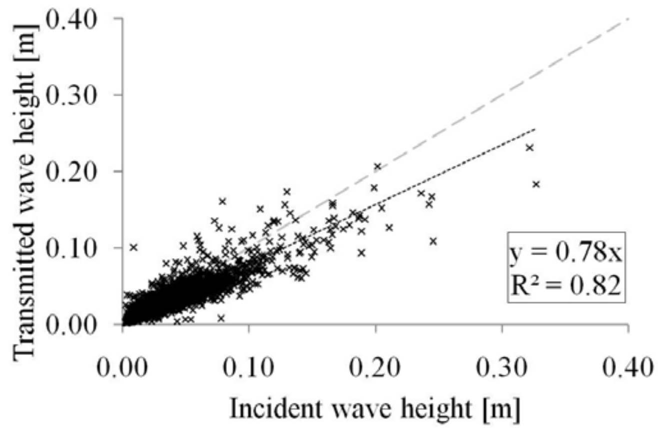

Figure 9 Variance between the incident and transmitted wave height for the secondary wave system. Linear regression analysis indicates a reduction in wave height of roughly 20% for the transmitted waves.

wave height for the transmitted waves with 20%. Given the predominance of the primary wave system, questions arise whether the timber piles properly act as wave reductor for the prevailing wave climate.

These doubts are confirmed in the calculated wave transmission coefficients, using Equation (1), and energy densities for the incident and transmitted waves, using Equation (2). Table 1 summarizes the values of these variables. Both transmission coefficients, close to unity, indicate the failure of the timber piles regarding load reduction. The large standard deviation shows the high variability in absorption between the waves. The difference in magnitude by a factor 10 between the primary and secondary wave energy density once more recognises its superiority to the secondary wave system.

Table 1. Determination of the transmission coefficient (C_T) and ratio between energy density of incident (E_I) and transmitted (E_T) waves for the primary and secondary ship wave system.

	C_T		E_T/E_I	
	PW *	SW	PW	SW
Mean	1.05	0.98	1.24	1.21
Stand.dev	0.36	0.50	1.63	3.86

* PW: Primary wave; SW: Secondary wave

6 CONCLUSIONS AND OUTLOOK

Objective of the present study was to analyse the energy dissipation of ship waves through a single row of off-bank timber piles, designed to act as wave reductor in a technical-biological bank protection type.

Taking into account the specific patterns of bank-directed surface waves which interact with local conditions, an experimental test setup was designed along the river Lys, a restricted non-tidal waterway subject to heavy shipping traffic. The resulting time series of subsurface water pressures was converted into water elevation series per ship passage. Primary and secondary wave systems were characterized separately, using a self-designed program implemented in Labview.

Analysis of the ship wave characteristics indicated that the prevailing wave climate in a restricted, non-tidal waterway is dominated by the primary ship wave system. Energy dissipation through the timber piling was quantified using (1) linear regression analysis between the incident and transmitted wave heights, (2) the determination of the wave transmission coefficient, and (3) the difference in energy density between incident and transmitted waves. Only the secondary wave system seems to experience significant wave height reduction. Hence, the effectiveness of the wave reducing piling appears to be insufficient for the preponderant wave climate.

This alternative bank protection type however consists of a twofold load reduction, i.e. a first reduction by an off-bank timber piling, followed by a further wave absorption through a (reed) vegetation belt. In order to quantify the complete response of this technical-biological bank protection method to the heavy ship wave climate, a more extensive prototype monitoring system has been designed and brought into operation at the same measurement site. The layout of the new monitoring system is presented in De Roo et al. (2010b). Improvements in the test setup include (1) the use of additional pressure sensors to be able to determine the incident and transmitted wave climate and (2) the application of suspended solids and water velocity measurement devices.

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