Navigating ships generate a specific pattern of bank-directed surface waves, resulting in maximum hydraulic forces on the upper half of the bank protection, around the still water level. Its characteristics, such as propagation directions, wave heights, and wave periods alter with ship design (different types, draught, speed) and navigation orientation and interact with topographic boundaries and local hydraulic conditions. As a result, theoretical calculations of the ship-induced loads on a specific embankment are not straightforward. Accordingly, field measurements provide a welcome alternative for the determination of these forces and the response of the bank protection to the ship-generated wave actions.

This paper focuses on the data handling for the determination of the ship wave characteristics. The practical methodology for (pre)-processing and analysis of the recorded ship wave data will be described in detail. At the end, the first results of the measurement campaign will briefly be presented.

Location

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 as a provisional measure, in anticipation of a further deepening of the profile in order 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 categorised as a waterway subject to dense shipping traffic.

Furthermore, the river has a fixed water level which is maintained during normal weather conditions and a small cross-sectional width (50.2 m on the free water surface) and depth (3.5 m), 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 in a straight section of the waterway where the technical-biological method of bank protection is applied in order to maximize the ship-induced forcing on the revetment. Limit (maximum) speed for displacement ships, and cruising ship speed in case of planing ships, are the best approached in this configuration.

**Measurement technique**

Since July 2009, ship wave characteristics are being registered using pressure sensors (Druck PTX 1830, GE Sensing & Inspection Technologies), which continuously record the subsurface water pressure fluctuations at a sampling frequency of 10 Hz. The data is transferred to an on-site data logger where it is stored in a binary file on a memory card. More detailed information regarding the technical specifications of the measurement device and the layout of the monitoring system can be found in De Roo et al. (2010).

**SHIP WAVE BASICS**

Ship-generated waves have their distinct characteristics in comparison with wind-generated waves. Navigating ships generate a specific pattern 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 characterized 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. 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. Transverse and diverging secondary waves, propagating under an oblique angle to the sailing line of the ship, are caused by the pressure pattern due to discontinuities in the hull profile. The secondary wave train usually consists of two higher waves followed by 10 to 15 smaller waves.

The primary wave and secondary waves generate a constant wave pattern with interference cusps formed on a line with an angle of 19°28' to the sailing line of the ship in deep water (Figure 1). These wave patterns were first investigated by Lord Kelvin in 1887. The direction of propagation of the interference cusps is then at an angle of about 35° with the sailing line, hence the angle of approach for a bank parallel to the sailing line is 55° (in deep water conditions).

Figure 1 depicts the primary and the secondary ship wave system. All observable parameters of the ship wave pattern for a ship navigating at subcritical speed are illustrated in Figure 2. The magnitude and thus, relevance of these parameters varies with the characteristics of the navigating ship and the local geometry of the waterway.

**Figure 1** Primary and secondary wave system around a navigating ship (adapted from Schiereck, 2001)

**Figure 2** Parameters of the ship wave pattern for a ship navigating at subcritical speed
DATA PROCESSING

General considerations

The data (pre-) processing as well as the data analysis are carried out using a self-designed program implemented in Labview (National Instruments). The routine comprises several steps and subroutines running both semi- and full-automatic.

Signal analysis of ship waves is handled using the generally adopted method for wave analysis, which combines processing steps in the time and frequency domain. However, various ways of conducting this generally adopted method on ship waves are found in literature; mainly, a classification can be made into methods interpreting the ship wave pattern in itself (e.g. Chwang et al., 2003; Hofmann et al., 2008) and methods separating the ship wave pattern into a primary and secondary wave system (e.g. Verney et al., 2007; Teschke et al., 2008). Since the contribution of each ship wave system is to be estimated in its dynamic interaction with the bank protection as well as the response of the protecting structure on every wave component, a method in accordance with the latter approach is opted for the ship wave characterization.

The methodology of the data processing consists of the sequential execution of following steps: first, a ship wave event is detected and selected in the water pressure time series; second, correction and filtering of the signal takes place in the frequency domain; third, the wave parameters are determined after retransformation of the data to a water elevation time series. These steps are more in-depth discussed in the following subsections. Figure 3 illustrates the analysis methodology including the processing steps for a certain ship wave event.

Identification and selection of a ship wave event

The identification of a ship wave event is done by stipulating a minimum water level fluctuation of $0.06 \text{ m}$ and an interval time of $100 \text{ s}$ between two peaks as conditions to be met in the raw data set upon selection as ship wave event. Additionally, the peak detection algorithm is carried out on the reverse water pressure time series in order to minimize the multiple selection of an individual ship wave event by additional detection of its stern wave. The amplitude of the peak, i.e. the maximum drawdown, and the location of the peak, i.e. the occurrence time of the maximum drawdown, are both identified and collected in the ship wave event database.

The connection of an identified ship wave event to an actual ship is partly facilitated by the ship data provided by the Flemish Administration of Waterways and the Sea Canal which operates the lock at Sint-Baafs-Vijve, located 8 km upstream of the measurement site. Based on the pictures taken at the measurement site during every ship passage, a ship wave event can be attributed to a record of the lock’s ship data base. In this way, the number of recorded ship wave events and the actual number of ship passages can be checked and the percentage of missed or erratic ship passages can be evaluated. This holds just a rough estimation of the accuracy of detected ship passages because recreational boat traffic can bypass the lock.

The length of an identified and isolated ship wave event includes the water pressure time series from two minutes before until ten minutes after the occurrence time of the maximum drawdown. However, shipping traffic is dense on the river Lys, and regularly ships must follow each other closely or pass each other with very little clearance. This hampers the correct selection of an identified ship wave event in two ways. On the one hand, dense shipping traffic results in the interference of several ship wave patterns, and hence a selected ship wave event consists of the superposition of various wave signals, giving a misrepresentation of a single ship’s loading. By dynamically adapting the length of a particular ship wave event to the interval time between the present and both the preceding and next events, it is tried to attach only the predominant, its own, wave pattern to a particular ship wave event. On the other hand, the stipulated criteria of the peak detection algorithm occasionally result in the non-identification of two events following each other more closely than the interval criterion of 100s.
Figure 3 Ship passages at the prototype monitoring system on the river Lys: A. Time series of water level fluctuations; B. Zoom on one ship wave event; C. Primary wave system of the ship; D. Secondary wave system of the ship.
DATA FILTERING

The time series of the selected ship wave event is detrended by subtracting the hourly mean water pressure. The series then consists of water pressure fluctuations due to wind- and ship-generated waves. The contribution of each one of these phenomena can be separated out of the wave event because wind- and ship generated waves are characterized by different wave periods, i.e. below and above 2 s respectively. The primary and secondary wave system are further distinguished 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. As separation is carried out based on distinct wave frequencies, a fast Fourier transform with a 10% cosine tapered window is applied, converting the pressure time series into the frequency domain. After correction of the pressure signal for depth attenuation using the linear wave theory (Ellis et al., 2006), band pass filters are applied for the identification of the ship wave patterns. A low band pass filter preserves the events with a frequency $f < 0.1$ Hz (excluding the low frequency components up to 0.0083 Hz) and hence, determines the primary ship wave system. A band pass filter ranging from 0.1 Hz to 0.5 Hz is used for the identification of the secondary ship wave system.

DATA ANALYSIS

Once the primary and secondary wave signals are extracted, the inverse Fourier transform provides the water elevation time series for both wave systems in the ship wave event. Their relevant wave parameters are processed making use of the zero downcrossing method. Within each event, the maximum and minimum water elevation, together with the wave period, are calculated separately for each interval between two consecutive zero downcrossings. Because of the transient nature of ship waves, the calculation of the significant wave height and period of the wave event is of little importance. Conversely, the application of a sorting algorithm selecting the maximum wave height and corresponding period out of all the zero-downcrossing intervals per wave event results in, respectively, the identification of the stern wave and primary wave period, and the characteristic wave height and period of the secondary wave system. With regard to the primary wave system, the duration of the drawdown as well as the ascent of the water level and the magnitude of the water level depression are analysed in addition.

Subfigure 3C and 3D exemplify the separation into the primary and secondary wave system. 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.

RESULTS

The principal aim of the designed data processing and analysis software is the development of a data base including all identified ship events. Per ship event, the duration of the event, the occurrence time of the maximum drawdown and all the relevant wave parameters of the primary and secondary wave system are listed together with the essential ship information obtained from the Flemish Administration of Waterways and the Sea Canal.

During the first six months of the measurement campaign (July – December 2009), 7802 ship events were identified and put in the data base. In general, a ship passage affected the technical-biological bank protection at 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. Because of the large variability in ship speed, a remarkable difference is observed between the primary wave periods of passing ships.

Figure 4 illustrates the prevailing wave climate by indicating the shortfall probabilities of the drawdown, the primary and the secondary wave heights. The graph demonstrates the predominance of the primary wave system in a restricted, narrow 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.
CONCLUSIONS AND OUTLOOK

Since July 2009, a monitoring system provides time series of subsurface water pressures at a measurement site along the river Lys. In order to develop a database with relevant ship characteristics, a data (pre)-processing and analysis tool is designed and implemented in Labview. Ship passages are identified and selected in the pressure time series using an event selection routine based on a minimum water level fluctuation of 6s and an inter-event time of 100s as pre-defined criteria to be met. Subsequently, filtering extracts the primary and secondary wave system separately out of the original wave signal, consisting of the superimposition of these different components. At the end, the software processes the relevant wave parameters and puts them in a database. Additionally, ship information obtained from the local waterway authority is attached to this ship event list.

The software shows that dense shipping traffic on the restricted, non-tidal river Lys changes the local hydrodynamics by generating a specific pattern of bank-directed surface waves of which the primary wave system is predominant. An extensive amount of 7802 ship events is already detected during the six months of continuous data acquisition and put in the database. The objective is to use this software to further quantify and assess the effect of ship waves on a more nature friendly, technical-biological bank protection type.

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