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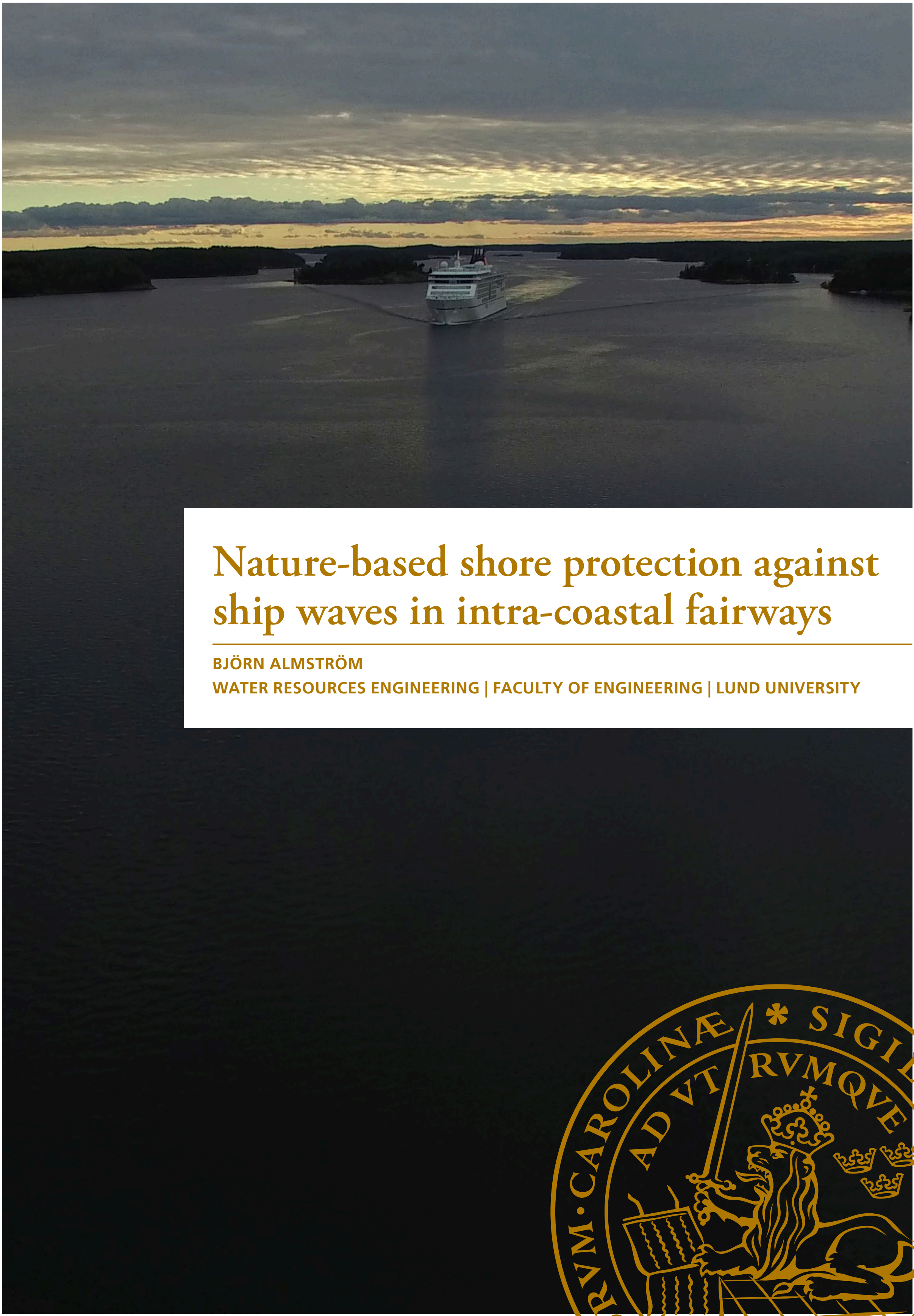

Nature-based shore protection against ship waves in intra-coastal fairways

BJÖRN ALMSTRÖM
WATER RESOURCES ENGINEERING | FACULTY OF ENGINEERING | LUND UNIVERSITY

Björn Almström is a coastal engineer with a master's degree in environmental engineering at Lund University. He has more than 10 years of experience from consultancy, focusing on climate change adaptation and numerical modelling of hydrodynamics processes in coastal and fluvial environments. During his doctoral studies, Björn has continued to advice local municipalities and governmental agencies on problem related to coastal processes. His PhD research concerns the effectiveness of nature-based solutions to mitigate ship-induced erosion in intra-coastal fairways and development of methods for predicting ship waves in such fairways.

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Björn Almström

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Nature-based shore protection against ship waves in intra-coastal fairways

Abstract

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This thesis aims at demonstrating different experimental designs of nature-based solutions for mitigating ship-induced erosion and promoting favourable hydrodynamic conditions for vegetation to establish. When designing a nature-based solution, the information about the hydrodynamic force acting upon it is imperative. However, existing methods for assessing hydrodynamic forcing from ships in intra-coastal fairways were either unable to predict the forcing, too computationally expensive or required input data not available.

Therefore, a new semi-empirical equation for predicting primary waves from ships operating in fairways with non-uniform geometry was developed and validated with field measurements. This formula was incorporated in a novel framework for a decision support tool. The framework can be applied by fairway managers for long-term assessments of ship traffic in intra-coastal fairways, identifying shores with a potential for erosion, prioritizing the identified shores in terms of probable erosion, and simulating the effects of different fairway management options to reduce erosion. Moreover, the XBeach model was evaluated for its applicability in predicting ship waves in intra-coastal fairways. Finally, field experiments with nature-based solutions for mitigating ship waves were evaluated based on their effectiveness and ability to create favourable hydrodynamic conditions for vegetation to establish. Results showed that combining a stone-based sill with vegetation successfully retained sediment and promoted vegetation to grow. In addition, the sill structure successfully dampened the water level fluctuations during the primary wave, and vegetation contributed to attenuating the secondary waves.

Key words: Nature-based solutions, ship waves, waterways, bank erosion, Furusundsleden

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Table of Contents

Abstract

Maritime shipping is vital for our society in transporting goods and people across seas. However, the hydrodynamic forces induced by maritime vessels may cause erosion of shores in fairways sheltered from wind-generated waves, resulting in the loss of land and habitats and failing structures along the fairways. The negative impact of ship traffic can be mitigated through speed restrictions, limiting ship sizes, changing navigational routes, or implementing erosion protection. Traditionally, erosion protections along fairways have consisted of stabilising shores with rock or concrete structures. In recent years, a more novel approach has emerged as an alternative, i.e., nature-based solutions. However, for nature-based solutions to be upscaled, more knowledge about various solutions' design criteria and effectiveness in different settings is required.

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Popular science summary in Swedish

Sjötrafik har alltid haft en stor betydelse för vårt samhälle genom att transportera gods och människor mellan och inom länder. Transporter till sjöss har stora fördelar associerat till relativt låga klimatutsläpp och transportkostnader. Tyvärr medför sjötrafik även en negativ påverkan på vår miljö. Den negativa påverkan kan till exempel bestå av utsläpp av luftföroreningar, tömning av ballastvatten eller utsläpp av olja. I farleder kan fartyg även inverka på de hydrodynamiska förhållandena genom att generera strömmar och vågor. Fartygsvågor kan resultera i skador på stränder och konstruktioner vid vattnet, öka grumlingen i vattnet, eller till och med innebära en fara för människor som vistas i eller på vattnet.

Särskilt stor blir påverkan från fartygsvågor i farleder som naturligt inte utsätts för vindvågor. Det gäller farleder inomskärs, i vattendrag och i sjöar. Fartygsvågor kan här utgöra ett betydande tillskott till de totala vågkrafterna som påverkar stränderna. Om vågorna är tillräckligt stora och frekventa kan de orsaka erosion av stränderna. Denna effekt kan minskas genom att sänka fartygens hastighet, ändra fartygsrutter, begränsa storleken på fartygen eller förstärka stränderna med erosionsskydd. En farled där påverkan av fartygs- och båttrafik varit påtaglig under en lång tid är Furusundsleden i Stockholms skärgård. Furusundsleden är en viktig farled med reguljär trafik av passagerarfärjor till Åland, Finland och Estland. Därutöver trafikeras farleden även av skärgårdstrafik och kryssningsfartyg under sommarhalvåret. Fartygserosionen i Furusundsleden har varit ett uppmärksammat problem ända sedan 1980-talet. Hastigheterna har begränsats för större fartyg med effekten av erosionen avtagit längs farleden. För vissa sträckor har hastighetsbegränsningen dock inte varit en tillräcklig åtgärd för att förhindra erosionen. Därför har tidigare utredningar föreslagit någon form av erosionsskydd längs med dessa stränder.

Traditionellt har erosionsskydd i farleder utgjorts av att stränderna har stabiliserats med sten eller betong. Denna metod har i många fall hindrat erosionen av stränderna, men på bekostnad av natur-, landskaps- och rekreationsvärden. De traditionella skydden kräver vanligen mer material och har en hög underhållskostnad. Därför börjar traditionella erosionsskydd alltmer ersättas av naturbaserade lösningar för att motverka erosion. Naturbaserade lösningar innebär att man tar hjälp eller inspireras av naturliga processer för att skapa erosionsskydd som bevarar eller tillskapar värden för naturen och människan. Eftersom naturbaserade lösningar är en relativt ny metodik finns det liten erfarenhet av hur de fungerar som erosionsskydd mot fartygsvågor.

Denna avhandling syftar till att undersöka effektiviteten av naturbaserade lösningar som erosionsskydd i farleder och metoder för att beräkna fartygsvågor i farleder med varierande djupförhållanden. För att undersökan effektiviteten av naturbaserade lösningar anlades olika typer av naturbaserade lösningar på tre platser i Furusundsleden, som är belägen i Stockholms skärgård. Två av platserna utgjordes av eroderande moränjord, där en flera meter hög erosionsbrant uppstått. Den tredje platsen utgjordes av ett område där vassen nästintill försvunnit på grund av fartygsvågorna. Olika varianter av naturbaserade erosionsskydd testades. Experimenten visade att en variant där en stenrevel, som löpte parallellt med stranden, kombinerades med vegetation innanför var mest framgångsrik att hindra erosionen. Innanför stenreveln skapades förutsättningar för finare sediment att ackumulera och vegetation att växa.

Utöver fältexperimenten med de naturbaserade erosionsskydden innefattar avhandlingen även en ny matematisk modell för att identifiera platser där fartygstrafik kan ge upphov till erosion längs en farled. Modellen är i första hand tänkt att fungera som ett stöd inför beslut om åtgärder i en farled. Det kan vara åtgärder som till exempel att begränsa hastigheten eller identifiera lokaler där behov av erosionsskydd behöver utredas ytterligare.

Acknowledgement

The past years of pursuing my PhD has been a long and winding journey of hope and despair, successes and setbacks, fieldwork in good weather and lousy weather. I would not have reached this far without the support, help, and encouragement from all the people I have in my life. I would, therefore, like to take this opportunity to thank everyone.

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Papers

This thesis is submitted with the support of the following papers, which are referred to by their numerals in the body of the text.

Appended Papers

I. **Almström, B**., and Larson, M. 2020. Measurements and analysis of primary ship waves in the Stockholm Archipelago, Sweden. Journal of Marine Science and Engineering 8, no. 10: 743. https://doi.org/10.3390/jmse8100743

II. **Almström, B.**, Roelvink, D., Larson, M., 2021. Predicting ship waves in sheltered waterways – An application of XBeach to the Stockholm Archipelago, Sweden. Coastal Engineering. 170: https://doi.org/10.1016/j.coastaleng.2021.104026

III. **Almström, B.**, Larson, M., Hallin, C. 2021. A decision support tool to mitigate ship-induced erosion in non-uniform sheltered intra-coastal fairways. (manuscript)

IV. **Almström, B.**, Danielsson, P., Göransson, G., Larson, M., Hallin, C. 2021. Experiences of nature-based solutions for mitigating ship-induced erosion in confined coastal waters. Ecological Engineering (in review)

The author's contribution to the appended papers

I. The author conducted the literature review, processed the water level measurements and AIS-data, and analysed the processed data. In collaboration with the supervisor, he developed the proposed semi-empirical equation. The author wrote the manuscript and revised the manuscript based on feedback in the peer-review process.

II. The author initiated, planned, and conducted the study. This included compiling and processing the input data, implementing the numerical model, and performing simulations with the model. Together with the co-authors improvements of the numerical model were identified. The results were evaluated by the author. Finally, the manuscript was written by the author and revised by him based on the peer-review process.

III. The author initiated the study. First, the author developed the script of the decision support tool. Then, in collaboration with the co-authors, the results were assessed. Finally, the author wrote the manuscript and revised it based on feedback from the co-authors.

IV. The author planned and performed the field measurements with the help of co-authors. The collected data were processed and analysed by the author. Finally, the author wrote the manuscript and revised it based on suggestions from co-authors and feedback in the peer-review process.

Conference Proceedings

Larson, L., **Almström, B.,** Göransson, G., Hanson, H., Danielsson, P., 2017, Sediment movement induced by ship-generated waves in restricted waterways, Proceedings of the 7th edition of the Coastal Dynamics Conference, Helsingör, Denmark, pp.300-311.

Almström, B., Larson, M., Granath, L. & Hanson, H., 2018, Ship generated waves over complex bathymetries, Proceedings of 32nd International Conference on Coastal Engineering. Lynett, P. Baltimore, US.

Almström, B., Roelvink, D., Larson, M., 2021, Simulating ship waves in sheltered waterways with XBeach, Proceeding of the 8th edition of the Coastal Dynamics Conference, online, Delft, Netherlands.

Other publications from the same author

Fredriksson, C., **Almström, B**., Hanson, H., Larson, M., Persson, O. 2017. Estimation of required beach nourishment volumes along the south coast of Sweden during 2017-2100, VATTEN – Journal of Water Management and Research. 73:77-84.

Hallin, C., **Almström, B**., Larson, M., Hanson, H. 2019. Longshore transport variability of beach-face grain size: implications for dune evolution. Journal of Coastal Research.

Hallin, C., **Almström, B**., Larson, M., Hanson, H. 2019. The relation between longshore variations in grain size distribution and sediment transport processes. Coastal Sediments 2019: Proceedings of the 9th International Conference.

Hallin, C., Tajvidi, N., **Almström, B**., Larson, M. & Hanson, H. 2019. Extreme value analysis of wave runup and dune erosion at Ängelholm Beach, South Sweden. VATTEN – Journal of Water Management and research. 75: 227-240.

Adell, A., Nunes De Brito Junior, A., **Almström, B**., Goodfellow, B., Bokhari Irminger, S., Hallin, C., Nyberg, J. 2021. Open-access portal with hindcast wave data for Skåne and Halland, VATTEN – Journal of Water Management and Research. 77:81-90.

Hallin, C., Hofstede, J.L.A., Martinez, G., Jensen, J., Baron, N., Heimann, T.; Kroon, A.; Arns, A.; **Almström, B**.; Sørensen, P.; Larson, M. A. 2021. Comparative study of the effects of the 1872 storm and coastal flood risk management in Denmark, Germany, and Sweden. Water, 13, 1697.

1 Introduction

Intra-coastal fairways have always been an essential infrastructure to our society, providing an efficient mode of transport that offers shelter from the open-ocean waves (Psaraftis, 2019). The development of shipping technology has led to larger and faster vessels. In sheltered fairways, this development has resulted in increasing hydrodynamic pressure on the shores of these fairways. The increased hydrodynamic pressure on the shores has a negative impact in terms of, e.g., increased erosion, reduced functions of the ecosystem, increased turbidity, safety issues, damaged structures, and habitat loss (Bilkovic et al., 2019; Osborne and Boak, 1999; Schoellhamer, 1996).

Sustainable fairway management can reduce these negative impacts (Bilkovic et al., 2019; Glamore, 2008). First, sustainable fairway management should focus on exploring operational measures to reduce the forcing on the shores, e.g., speed restrictions, limiting the size or types of ships, or adjusting the navigational route (Bilkovic et al., 2019). After that, it can be considered to implement mitigation measures that increase the resistance to erosion on the shores, e.g., rip-rap revetments, seawalls, or preferably nature-based solutions. Thus, a fundamental principle in sustainable fairway management is knowledge about the hydrodynamic forces in the fairway and how to efficiently implement erosion protection (Havinga et al., 2005).

This thesis aims to develop and test tools that can be helpful for fairway managers in investigating the hydrodynamic forces from maritime traffic. The tools include a semi-empirical equation for primary waves, a numerical model for ship wave generation and propagation, and a decision support tool for intra-coastal fairways. Moreover, the thesis demonstrates an effective design principle for nature-based solutions in sheltered fairways with large conventional ships and recreational boats.

In the past decade, there has been a shift from conventional erosion protection measures, e.g., rip-rap revetments, groins, seawalls, bulkheads, to nature-based solutions (O’Donnell, 2017; Smith et al., 2020). Nature-based solutions can be defined as using or promoting natural features and processes to create resilience while providing environmental, social, and economic benefits (European Commission, n.d.). One advantage of nature-based solutions, compared to conventional measures, are their multifunctionality (Arkema et al., 2017). The multifunctionality of nature-based solutions includes erosion protection, biodiversity gains, recreational value, and improved aesthetics. However, despite the many advantages over conventional measures, nature-based solutions are still not implemented on a large scale (IUCN, 2020). The European Commission acknowledges this and identifies the lack of evidence on nature-based solutions effectiveness as the main barrier for widespread implementation (European Commission, n.d.). In Sweden this is addressed by developing guidelines for implementing nature-based solutions in different environments (Regeringen, 2021).

One of these environments addressed in Sweden is fairways. This research project is a part of the knowledge-building needed for developing the Swedish guidelines for nature-based solutions in fairways.

Nature-based solutions have been implemented and researched upon in many different types of coastal environments (O'Donnell, 2017; Schoonees et al., 2019; Smith et al., 2020). However, there is little experience in how nature-based solutions can be designed to be effective in intra-coastal fairways with large ships operating. Several studies have demonstrated the effectiveness of nature-based solutions to mitigate the impact of secondary waves from recreational boats (e.g., D. Bilkovic et al., 2017; Ellis et al., 2002; Herbert et al., 2018; Safak et al., 2020). However, few studies (De Roo and Troch, 2015) have investigated nature-based solutions in fairways where primary waves are present.

Understanding the hydrodynamic forces acting upon a nature-based solution is vital for an efficient design. Hydrodynamic forces from ships in confined fairways are return currents and waves generated by the ships. These ship-generated waves can be divided into primary and secondary wave systems (Schiereck, 2001). Ship-generated waves can be a major contributor to the wave energy reaching the shore in a sheltered fairway (Soomere, 2007). The characteristics of ship-generated waves distinguish from wind-generated waves by generally having a longer period and larger wave height. There are many methods for assessing hydrodynamic forces from ships, such as water level measurements, empirical equations, and numerical models. However, few studies have investigated these methods in intra-coastal fairways with a non-uniform geometry.

This thesis and its associated papers are centred around an intra-coastal fairway, the Furusund Fairway in Sweden. The fairway is sheltered from wind-generated waves by its location inside the Stockholm Archipelago. Hence, the ship traffic significantly contributes to the wave energy reaching the shores, and the fairway has had issues with ship-induced erosion for a long time. The ship traffic consists of mainly conventional ocean-going RoRo-vessels in regular traffic. Furthermore, the heterogeneous geology creates a variation in the types of shores that are eroded, e.g., reed belts, coastal marshes, banks, pocket beaches, and bluffs. Therefore, the Furusund Fairway can be regarded as an appropriate fairway for experimental studies on ship waves and nature-based solutions in sheltered intra-coastal fairways.

Although the research was conducted within this fairway, its results can be considered generic and applicable elsewhere.

1.1 Objective

This thesis focuses on the coastal-engineering aspects of nature-based solutions in intra-coastal fairways. The specific objectives of this thesis work have been:

(i) Predicting ship waves in fairways with complex bathymetry/geometry,

(ii) developing a decision support tool for managing sheltered coastal fairways, and

(iii) implementing and evaluating experimental nature-based solution (NBS) design to mitigate ship induced erosion.

1.2 Structure of this thesis

The present thesis is a compilation thesis consisting of an extended summary of the research followed by four appended papers that the thesis is based upon. **Paper I** describes measurements of ship waves in the fairway and the development of a semi-empirical equation for predicting primary waves from ships sailing in fairways with irregular bathymetry and shoreline geometry. In **Paper II,** the method of predicting ship waves with a numerical model is explored for engineering applications. **Paper III,** a decision support tool for fairway managers is developed that incorporate findings from **Paper I** with existing methods for predicting secondary waves and wind-generated waves. Additionally, **Paper III** includes an attempt to find an erosional index suitable for assessing the potential erosion from ship waves. Finally, **Paper IV** evaluates the effectiveness of implementing nature-based solutions in a sheltered intra-coastal fairway.

The extended summary starts with a chapter describing the theoretical background for predicting ship waves, erosion mechanisms in fairways, and nature-based solutions to mitigate ship-induced erosion. Thereafter follows a description of the case-study area, the Furusund Fairway. This chapter is followed by a summary of the results from the different studies. Lastly, the research outcome from the thesis is discussed and followed by conclusions.

2 Theoretical Background

This chapter gives a theoretical background to the relevant physical processes to consider when implementing nature-based solutions in intra-coastal fairways. Moreover, the chapter also presents the results of the literature study forming the basis of the prediction of ship waves in intra-coastal fairways and evaluating the implemented nature-based solutions.

2.1 Hydrodynamic forces in intra-coastal fairways

Erosion in a fairway depends on two main factors: (i) the forcing on the banks and shore and (ii) the resistance to erosion of the banks and shore. The hydrodynamic forcing constitutes of natural processes, i.e., wind-generated waves and currents induced by the astronomical, meteorological tide, and river flows. However, where ships operate, there is an additional anthropogenic source, the ship-generated waves. The importance of these forces varies depending on the setting. For instance, wind-generated waves are normally the dominant hydrodynamic force for erosion on an open coast. In contrast, wind-generated waves are small in sheltered fairways, and ship-generated waves may become a significant driving force for shore erosion.

2.1.1 Wind-generated waves

The wind-generated wave climate is an essential driver for the morphological evolution of a fairway over time. Wind-generated waves are a function of the wind speed and duration, the fetch length, and the water depth. In sheltered coastal areas, the fetches limit the wind-generated waves, resulting in small wave heights and short periods.

Even though wind-generated waves are expected to be small in sheltered fairways, they must be considered and assessed. The morphology of the shores is often assumed to be in equilibrium with the wind-generated wave climate. Therefore, it can be assumed that any additional waves, larger than the wind-generated waves, may induce erosion. However, this assumption of equilibrium is not always valid. For example, in fairways with shores consisting of fine sediments (e.g., clay and silt), the sediment is lost as soon as eroded in contrast to shore with coarser sediment (e.g., sand or pebbles) that forms an equilibrium beach profile in response to the acting forces (Kamphuis, 1987).

Wave modelling

There are numerous methods for predicting or hindcasting wind-generated waves. For instance, different complex numerical models in two dimensions that consider many physical processes for wind-wave generation and propagation (e.g., SWAN, WAM, WAVEWATCH III, and MIKE21FM). In addition, there are also more simplistic approaches considering only the most basic wind-wave generation processes, e.g., Sverdrup-Munk-Bretschneider (SMB) formulation from the Shore Protection Manual (USACE, 1984). More simplistic approaches are motivated by their minimum input requirements, short computational time, and output being sufficiently accurate for many applications. Moreover, especially in fetch-limited environments, the more simplistic approaches may be competitive against more complex numerical models, since no swell affects the wave climate, and therefore the system wave memory is short.

Thus, in this thesis work, wind-wave generation have been hindcasted using a modified SMB formulation. The modification is described in Hanson and Larson (2008) and includes a simple memory function between time steps. This allows the wave climate to decay as the wind forcing reduces.

2.1.2 Vessel-generated waves

In fairways, the vessel-generated waves can be a significant driver of the morphological evolution of the shores. Vessel-generated waves have been the subject of scientific studies for more than a century (e.g., Gourlay, 2011; Havelock, 1908; Schijf, 1949; Soomere, 2007; Sorensen, 1997; Thiele, 1901; Thompson, 1887; Tuck, 1966). These waves are generated by the energy transferred from a vessel to the water as it moves through the water. This energy transfer creates a pressure variation along the ship hull. The pressure variation reflects the hull shape and features, trim and displacement of the vessel, vessel speed and propulsion, natural currents, and bathymetry of the fairway. The generated waves can be divided into two systems: the primary and the secondary wave system. In Figure 2-1, these wave systems are illustrated by a sketch of a generalized wave field from a ship sailing in confined waters (Figure 2-1a; after Soomere, 2007) and from measurements of the water level fluctuation during a ship passage (Figure 2-1b).

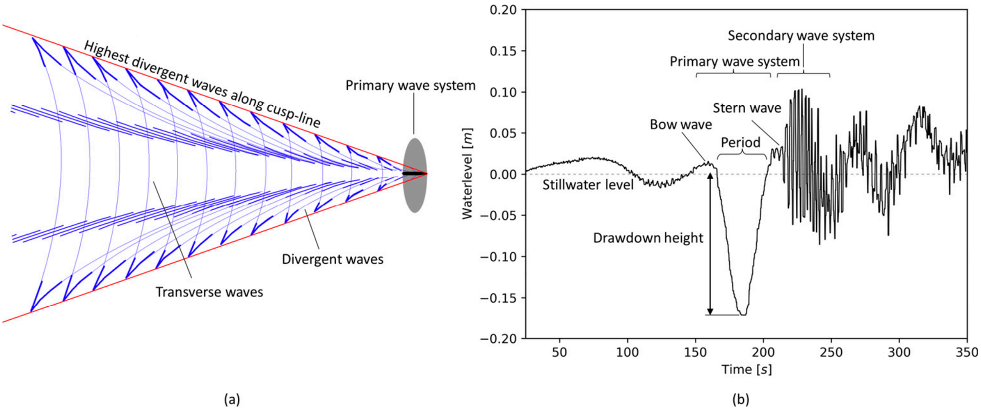

Figure 2-1.
(a) Sketch of the typical ship wave field, including both the primary and the secondary waves, after Soomere 2007. (b) Diagram illustrating a typical observation of the water level during a ship passage at the study site, including the ship wave terminology used within this thesis.

Primary waves

The primary wave system is often only noticeable in fairways with a constricted fairway cross-section. It is characterized by the drawdown wave (Figure 2-1b) and the bow and stern wave. The drawdown wave is a shallow water wave with a long period of up to 90 s in the study area (**Paper I**) and an amplitude of up to 30 cm (**Paper I**). In this thesis and appended papers, the drawdown height is defined as the distance from the still water level (during the ship passage event) and the minimum water level in the wave trough. The drawdown wave period is defined as the period between two consecutive zero up-crossings. Thus, the definition differs from the conventional definition of a wave period, defined as the time it takes for two successive wave crests to pass a given point. The drawdown wave is generated along the hull between the bow wave and the stern wave. Thus, the bow and stern waves are also components in the primary wave system.

The primary wave system is caused by water being pushed in front of the ship. This produces a return current along and under the hull. The increased velocity results in a reduced pressure field along the ship and a corresponding depression of the water surface referred to as the drawdown wave. Due to its long period, this drawdown wave can be regarded as a shallow water wave with the velocity, $c = \sqrt{gh}$, depending only on the water depth, h, and the acceleration due to gravity, g. Hence, as the drawdown wave propagates, it will change shape since the drawdown wave trough will propagate slower. The drawdown wave can develop into a bore in some bathymetric settings due to the through propagating slower than the stern wave (Parnell et al., 2015).

Secondary waves

Secondary waves are generated by the sharp pressure gradient, inducing a rapid rise and fall of the water level at the bow and stern. This initiates an oscillation of the water surface that produces the secondary waves propagating away from the vessel (Sorensen, 1997). The secondary wave system consists of transverse waves propagating in the ship's direction and diverging waves propagating in a direction oblique to the sailing line (Figure 2-1a). In deep water, the theoretical direction is $35^{o}16'$ from the sailing line. The divergent and the transverse waves interfere along a cusp-line at a theoretical angle of $19^{o}28'$ from the sailing line in deep water. This angle widens with a maximum of 90^{o} until the Froude depth number, $F_h = U/\sqrt{gh} = 1$, where U is the vessel speed (Havelock, 1908).

Wave modelling

Predicting ship waves can be done by various methods: field measurements, analytical or empirical methods, or numerical models. Each of these methods has advantages and disadvantages. For example, field measurements give accurate and detailed information about the waves from the specific ships measured and for the specific location. However, they can be time-consuming and are only valid for the ships and locations included in the measurements. Moreover, the information cannot be used for predicting ship waves at other conditions (ship type, navigational parameters, bathymetric setting) than during the measurements.

On the other hand, analytical or empirical methods have the benefit of minimum input requirements. However, they are limited to the conditions for which they were derived, and most available equations assume a uniform fairway geometry in the sailing line direction (**Paper I**). Therefore, the accuracy and detailed information from such methods can be limited. Nevertheless, they offer a rapid assessment at a small computational cost, enabling simulations of multiple scenarios and cases.

Numerical models offer the possibility of predicting ship waves for non-uniform fairways with complex bathymetries, for a wide range of ship types and can include various navigational aspects. There are different numerical models with varying complexity and computational efficiency, e.g., computational fluid dynamics (CFD) models, pressure disturbance models, and moving pressure field models. They all have different benefits and limitations. CFD models belong to an advanced type of models, extensively applied to perform detailed studies about the wave generation near the ship hull (Terziev et al., 2018) or to simulate the impact of ship waves on the shore (Fleit et al., 2019, 2016). However, CFD models are limited by their complexity, and the computational cost reduces their applicability to simulating ship wave propagation in scales of fairways (Forlini et al., 2020).

Less complex models are the moving pressure, disturbance models. Ship waves are generated by a pressure source term that needs to be calibrated for every specific ship hull geometry. Waves are propagated towards the shore by coupling with a wave propagation model, e.g., a Boussinesq-model (David et al., 2017). Several studies have demonstrated the potential of moving pressure, disturbance models (David et al., 2017; Forlini et al., 2020; Morioka et al., 2020; Shi et al., 2018). They are compared with CFD-models more computer efficient (Forlini et al., 2020). Moreover, the possibility to couple the wave generation model with any wave propagation model makes it adaptable to many specific cases. However, the drawback is that the source term needs to be calibrated. This limits the applicability of the model since additional data or information is required.

The third type of model is the moving pressure field model, e.g., Delft3D (Zhou et al., 2013), XBeach (**Paper II**), and SWASH (Kampherbeek, 2020). These types of models were originally developed for simulating low-pressure weather system responses in hydrodynamic models. The ship hull is represented in the model as a moving pressure field, where the pressure represents the draft in each computational cell. In order to represent the non-linear features of ship waves, the moving-pressure field model must include non-hydrostatic pressure. An advantage of the moving pressure field models is that any type of ship can be simulated as long as the ship hull shape is known. However, the drawback is that three-dimensional features of the hull cannot be included (Ma, 2012).

2.2 Erosion mechanisms in fairways

Erosion results from a deficit in the sediment budget because more sediment is transported away from a system than into it. Sediment transport is generated by currents that, in turn, are induced by tide, wind, waves, and gravity. In intra-coastal fairways, the drivers for currents are predominantly tide or waves. For an intra-coastal fairway with no tide, the waves are the predominant driver for sediment transport. Additionally, in non-tidal, intra-coastal fairways with confined sections, currents may also be induced by ships' return-currents.

The basic processes for sediment transport are entrainment, transportation, and deposition. Entrainment results from friction force exerted on the bottom by currents and/or waves with turbulent diffusion (i.e., the bed-shear stress), mobilizing sediment or carrying them up into suspension. When mobilized, sediment is transported in different modes depending on the magnitude of the bed-shear stress in relation to the critical bed-shear stress of the sediment. If the current induces a bed-shear stress just exceeding the critical bed-shear stress, the sediment will be sliding or rolling. Increasing the speed and saltation will occur (i.e., when the grains jump along the bottom). For very high current speeds, exceeding the fall velocity of the grains, the grains will go into suspension. Finally, sediment deposition will occur when the grains come to rest from transportation or when settling out of suspension.

The bed-shear stress is a function of the current (mean or oscillatory) and the bed roughness. The total bed-shear stress (τ_0) is made up by skin friction (τ_0') produced by the sediment grains, form drag (τ_0'') produced by the pressure field linked to the flow over bed forms, and the effective bed shear-stress responsible for sediment transport (τ_0''') caused by the momentum transfer to mobilise the grains. The bed-shear stress can be generated by currents, waves, or a combination of the two. The combined effects from currents and waves are higher than linearly adding them together. Effects from waves include the oscillatory velocity at the sea bed. This oscillatory velocity affects the bottom approximately when $h < 0.1gT^2$ or $h < 10H_s$ where T is the wave period, and H_s is the significant wave height (Soulsby, 1997). Moreover, waves with a large wave steepness have a higher capacity for transporting sediment.

2.2.1 Erosion mechanisms in reed belts

There is a negative relationship between vegetation growth and wave exposure (Coops et al., 1994; Riis and Hawes, 2003). Excessive wave forcing impacts reed belts negatively due to sediment washout from the rhizome layer and destabilization of the reed belt fringe (De Roo and Troch, 2015). Other processes to consider are the resuspension or washout of the reed belt seed bank (Foote and Kadlec, 1988) by offshore currents that the ship's primary wave can generate. The importance of seeds for the recruitment of common reeds (*Phragmatis australis*) has been shown in several studies where it was concluded that new reed stands mainly originate from seeds and, to a lesser extent, from plant fragments (Albert et al., 2015; McCormick et al., 2010). Field experiments by Foote and Kadlec (1988) showed that a stabilizing structure in front of the vegetation for reducing the washout of seeds enhanced the establishment and survival of sprouts.

2.2.2 Erosion mechanism in glacial deposit bluffs

The two dominant processes for the erosion of bluffs consisting of unsorted glacial sediments are waves attacking the bluff base, causing sequences of undercutting and collapse, and subaerial processes such as rainfall eroding the bluff surface from above (Himmelstoss et al., 2006). Bluff erosion is correlated with the base elevation relative to the still water level (Hughes et al., 2007) and the foreshore erosion rate (Kamphuis, 1987). When sandy bluffs erode, the eroded sediment that deposits in the foreshore profile eventually forms a protective beach (Kamphuis, 1987). However, a moraine bluff consisting of insufficient sand and gravel may not form a protective beach. The eroded sediment is transported offshore and does not contribute to forming a protective beach (Kamphuis, 1987). However, if the bluff consists of glacial sediment, including larger stones and boulders, the erosion rate will be reduced as a boulder lag is formed by material deposited at the bluff base (Himmelstoss et al., 2006).

2.3 Erosion management in fairways

There are several management options to mitigate erosion in fairways. These options can be categorized into measures aiming to reduce the hydrodynamic forcing on the shores or measures aiming to increase the erosional resistance of the shores.

Measures to reduce the hydrodynamic forces are mostly related to the regulation of the ship traffic. The generation of ship waves is closely dependent on the speed of the vessel. Lowering the speed can therefore decrease the energy reaching the shores considerably. Moreover, ship waves attenuate as they propagate over a distance. Therefore, if possible, the navigational route of the ships can be diverted away from sensitive shores in order to increase the distance between the ship traffic and the shores. Other management options are related to the ship traffic by limiting the size or types of ships allowed to sail in a specific fairway. Implementing management of the ship traffic should be prioritized before any other measures are considered. Alternatively, the hydrodynamic forces can be reduced by increasing the fairway cross-sectional area by dredging.

If it is not possible to reduce the hydrodynamic forces by managing the ship traffic or dredging, measures that aim at increasing the shores resistance to erosion may be implemented. Measures that increase the resistance of the shores have traditionally consisted of shoreline stabilization by hard armouring (Schoonees et al., 2019; USACE, 1984). Measures that can be categorized into hard armouring are rock revetments, bulkheads, or seawalls. Properly designed, implemented and maintained, such structures have proven successful in stabilizing the shorelines in fairways (CIRIA et al., 2007). However, the economic cost of implementing and maintaining such structures can be significant. Moreover, these structures decrease the connectivity between terrestrial and aquatic habitats (Pilkey and Wright, 1988), significantly changing the ecological functions of the shore (Gittman et al., 2016), and may increase erosion of adjacent areas. As these negative aspects of the conventional hard-armouring measures have been recognized, an alternative approach, the nature-based solutions, has emerged (Schoonees et al., 2019).

2.4 Nature-based solutions in fairways

Nature-based solutions is a term that emerged in the late 2000s to address solutions to mitigate and adapt to climate changes whilst protecting or enhancing biodiversity and sustainable livelihoods(Eggermont et al., 2015). Policymakers have adopted the term as the way forward in addressing societal challenges (e,g., climate change, disaster risk reduction, food security, water resources) while creating jobs and growth in the green economy (Eggermont et al., 2015). However, there is not a single definition of the term. One of the definitions comes from the European Commission that defines nature-based solutions as (Cardinali et al., 2021):

> “solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions. Nature-based solutions must therefore benefit biodiversity and support the delivery of a range of ecosystem services.”

In the field of shoreline management, there are several terms for nature-based solutions for mitigating coastal erosion: ‘Living shorelines’, ‘Building with nature’, ‘Engineering with nature’, ‘Nature-friendly erosion protection’, ‘Green shorelines’, ‘Nature-based shoreline protection’, ‘Ecosystem-based coastal defence’, and many more terms (D Bilkovic et al., 2017). Henceforth, we will refer to these concepts as nature-based shore protection. The purpose of nature-based shore protection in shoreline management is to protect shorelines and infrastructure while conserving, creating, or restoring natural shoreline functions (D Bilkovic et al., 2017).

What measures that are considered as nature-based shore protection varies depending on the shoreline setting. However, the protection should predominantly consist of organic technologies or materials common in the local system (D Bilkovic et al., 2017). However, engineering structures may be incorporated along shores where the hydrodynamic forces exceed the threshold for maintaining planted vegetation or habitats (O'Donnell, 2017). Engineering structures often used in nature-based shore protection are marsh sill, coir logs, revetments, or oyster reefs. A study of 46 peer-reviewed articles found that 91% of the nature-based solutions for mitigating erosion included engineering structures (Smith et al., 2020). In this study, the most common material used in the engineering structures was shell (48%), followed by rock (33%), concrete (13%), wood (9%), and coir logs (4%).

The design of nature-based shore protection is governed by many different parameters. Therefore, it is essential to understand the ecological, geological, and hydrodynamic systems at the site being considered (NOAA, 2015). The hydrodynamic conditions determine the type of engineering structure required to attenuate the hydrodynamic forces sufficiently (Table 1). For example, in a low-wave energy environment, no engineering structure is required. In contrast, a hybrid approach with a more or less intrusive engineering structure is needed in a high-wave energy environment. This continuum of green to hybrid to grey measures is described by NOAA (2015). The green measures consist of nature-based erosion protection solely based on systems without support of any engineering structures, the hybrid measures combine vegetation with a supporting engineering structure, and the grey measures consist of only an engineering structure. The grey measures are not considered as nature-based erosion protection, according to NOAA (2015).

Table 1.
Criteria ranges for appropriate conditions for four common engineering structures in nature-based solutions in sheltered coastal waters. Excerpt from Living shorelines guidelines by Miller et al. (2015).

	Marsh sill	Breakwater	Revetment	Oyster reef
Erosion rate	< 1.2 m/yr	> 0.6 m/yr	> 0.6 m/yr	< 1.2 m/yr
Tidal range	< 1.2 m	Any	Any	< 1.2 m
Wind waves	< 0.9 m	> 1.2 m	> 0.3 m	< 0.9 m
Wakes	< 0.9 m	> 1.2 m	> 0.3 m	< 0.9 m
Currents	< 2.4 m/s	< 2.4 m/s	Any	< 2.4 m/s
Ice	< 0.05 m	< 0.15 m	Any	< 0.15 m
Shoreline slope	< 1:10	Any	Any	< 1:10
Width	> 9 m	> 9 m	Any	> 9 m
Nearshore slope	< 1:10	< 1:10	Any	< 1:10
Soil bearing capacity	> 500 psf	> 1500 psf	> 500 psf	> 500 psf

Several studies exist on nature-based solutions (NBS) to mitigate erosion. However, few publication concern implemented nature-based erosion protections to mitigate ship-induced erosion (De Roo and Troch, 2015; Ellis et al., 2002; Kerckvoorde et al., 2013; Manis et al., 2015; Roo et al., 2012; Roo and Troch, 2013; Safak et al., 2021, 2020; Thuy et al., 2017). De Roo and Troch (2015) evaluated an NBS using an off-bank timber piling combined with planted reeds to reduce bank erosion induced by waves from heavy-ship traffic in the river Lys, Belgium. They concluded that the specific nature-based erosion protection configuration in their field experiment study did not sufficiently inhibit bank erosion due to the timber piling transmitting too much wave energy. Kerckvoorde et al. (2013) studied a constructed shallow water zone to favour riparian vegetation in a newly constructed canal branch in the canal Ghent-Bruges, Belgium. After eight years, the shallow water zone enabled native vegetation to cover the canal bank side, resulting in increased biodiversity.

In a wave tank experiment, dissipation of boat wake energy by a combination of oyster (*Crassostrea virginica*) reef and cordgrass (*Spartina alterniflora*) was studied, showing a 67% wave energy attenuation compared to bare sediment (Manis et al., 2015). The hybrid approach was more effective than using oyster structures and cordgrass separately. Field experiments by Safak et al. (2020) showed that boat wave transmission through a ‘breakwall’ designed with horizontal tree branches with a porosity of 70% varied between 9% to 70%. However, transmission rates increased significantly for a ‘breakwall’ with 90% porosity. Similar results were acquired in a field study of boat wave transmission through bundle brush woods in the Sacramento River (Ellis et al., 2002). The study showed that brush bundles were an effective method for reducing bank erosion from boat wakes and that the wave attenuating effect was depth-dependent.

These previous studies show the potential of using NBS to mitigate the impact of ship waves utilising a combination of stabilizing structures and vegetation. However, a majority of the nature-based erosion protections are implemented in fairways with recreational boat traffic. Since recreational boats only produce secondary waves, nature-based erosion protections have only been designed and tested against secondary waves. For example, in one study by de Roo and Troch (2015), nature-based erosion protection was investigated in a channel with large ships operating. However, it was found that the primary wave was transmitted through their nature-based erosion protection. Hence, this design was not successful in mitigating the bank erosion in the channel.

3 Study site: The Furusund Fairway

This chapter aims at giving an overview of the case study area, the Furusund Fairway. The local conditions in the fairway are essential for understanding the motivation for the investigation and the design of the nature-based erosion protection included in this study. Additionally, this chapter tries to synthesize all the previous studies conducted in the Furusund Fairway related to ship-induced erosion.

The Furusund Fairway (Furusundsleden) is the largest – in terms of ship traffic intensity – of the two fairways leading into Stockholm, the capital of Sweden. The importance of the fairway is manifested by it being classified as an infrastructure of national interests. However, the fairway is also located in an area of national interest regarding cultural environment and recreation. In addition, sensitive nature areas (Natura 2000, fish habitats, grassing meadows) are found along the fairway. Hence, the Furusund area is considered important for different national interests and natural protections. This causes conflicts and competing management strategies.

Land use consists mainly of rural residential areas (typically single houses with boat houses and jetties), forestry, and pasture. Landowners have raised awareness about shore erosion induced by ship waves along the fairway since (at least) the 1980s. The link between the erosion and the ship-generated waves is supported by several past studies (Bjärås, 2014; Daleke et al., 1989; Granath, 2015a, 2004a, 1992; Hedén and Sannel, 1992; Lars-Jörgen, 2015). As a result of the erosion, ship speed has been restricted in the fairway. In general, the speed restrictions have reduced the erosion along the fairway, but at some sites the erosion has continued, and it was proposed to implement nature-based solutions to mitigate erosion at these sites (Granath, 2015b).

3.1 General conditions

The Furusund Fairway is located in the Stockholm Archipelago, within the Baltic Sea (Figure 3-1). The region has a cold, temperate climate with a yearly mean temperature of 6.7°C. Monthly mean temperatures range from -2.2°C in February to 17.3°C in July in the reference period 1990-2020 (SMHI, 2021).

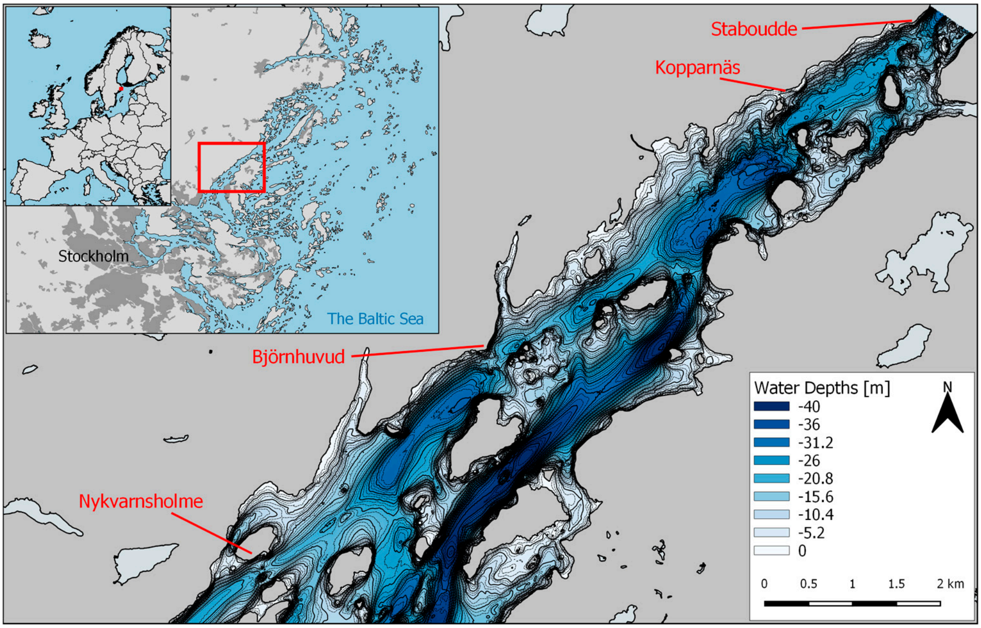

Figure 3-1.
Overview of the Furusund Fairway.

There are no tidal fluctuations in the Baltic Sea, and the meteorological forcing mainly drives the sea level changes in this area (Hellström, 1941). The nearest water level station (STOCKHOLM-2069) is located in Stockholm, about 30 km south of the Furusund Fairway, and it has been active since 1889. The maximum observed level in this time series is +1.16 m, and the minimum observed level is -0.69 m, relative to the mean sea level (Figure 3-2a).

There is a seasonal trend in the water level, with the highest water levels expected to occur from October to March (Figure 3-2a). Additionally, the 7-day rolling average of the water level during the study period of the nature-based solutions in **Paper IV** (Figure 3-2b) shows a particular phenomenon regarding the water level dynamics for this region. At times, the water level is continuously elevated for more extended periods (months). Such an event occurred between December 2019 and March 2020, when the water level exceeded +40 cm during this period (Figure 3-2b). During the period of the study in **Paper IV**, April 2018 to October 2020, the water level was above the mean water level (+0.089 m in RH2000) 68% of the time, above +0.2 m 40% of the time, above +0.4 m 13% of the time, and above +0.6 m 3% of the time.

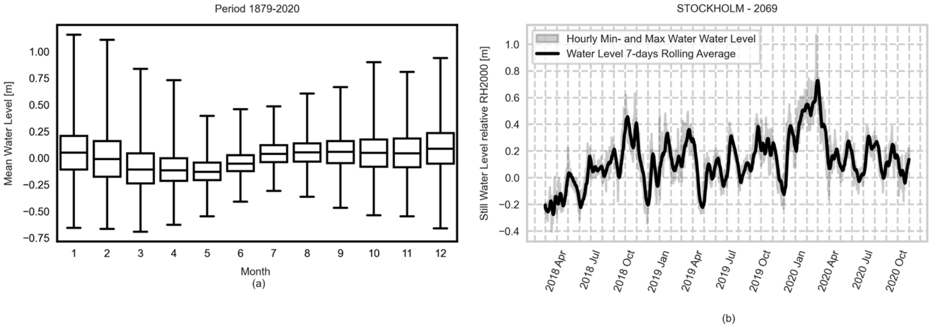

Figure 3-2.
(a) Monthly statistics of water level observations from SMHI station Stockholm-2069 for 1879-2020. The whiskers indicate the maximum and minimum observed water levels. The box indicates the 25th-, 50th-, and the 75th-percentile water levels in the Swedish national height reference system RH2000. (b) During the study period of the nature-based solutions tested in **Paper IV**, water levels are presented as seven-day rolling average (black line) and hourly minimum and maximum water levels (grey line).

SMHI (the Swedish Meteorological and Hydrological Institute) has observed wind at eight stations in the vicinity of the Furusund Fairway, of which five are presently active. From these five stations, Skarpö-98160 was chosen as representative for the Furusund Fairway due to its position in the archipelago without being as exposed as stations in the outer archipelago. Analysis of the wind data from Skarpö-98160 shows that westerly winds dominate (Figure 3-3a) and that the highest winds observed are relatively moderate in speed (Figure 3-3b).

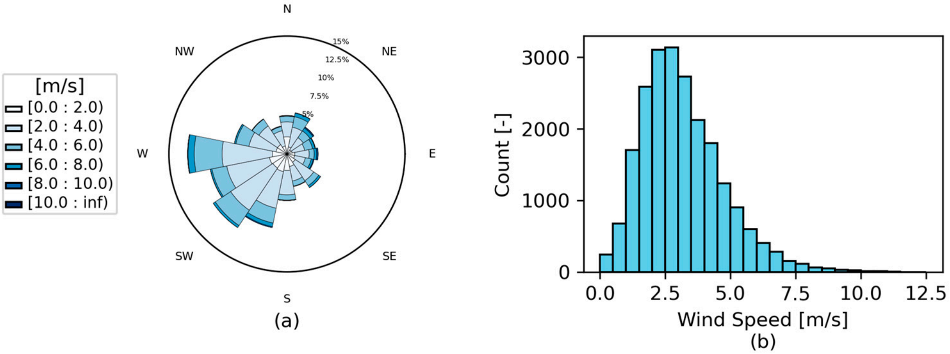

Figure 3-3.
(a) Windrose plot of wind speeds observed at Skarpö-98160 for the period 2018-05-01 to 2020-11-01. (b) Histogram of the wind speed at Skarpö-98160.

Wind-generated waves are limited in the fairway due to the moderate wind speeds and the dominant westerly winds in combination with the orientation of the fairway and the short fetches. Nevertheless, wind-generated waves were hindcasted for the period 2018-2020 (the period of the implemented nature-based solutions). Wind-generated waves are presented for the three locations selected for implementing the nature-based solutions (Figure 3-4). Wind-generated waves are dominant from the southwest. The significant wave height rarely exceeds 0.3 m, and the period is below 2 s. Hence, the hindcasted wave climate indicates that the fairway may be categorized as a 'low-energy environment' (Jackson et al., 2002).

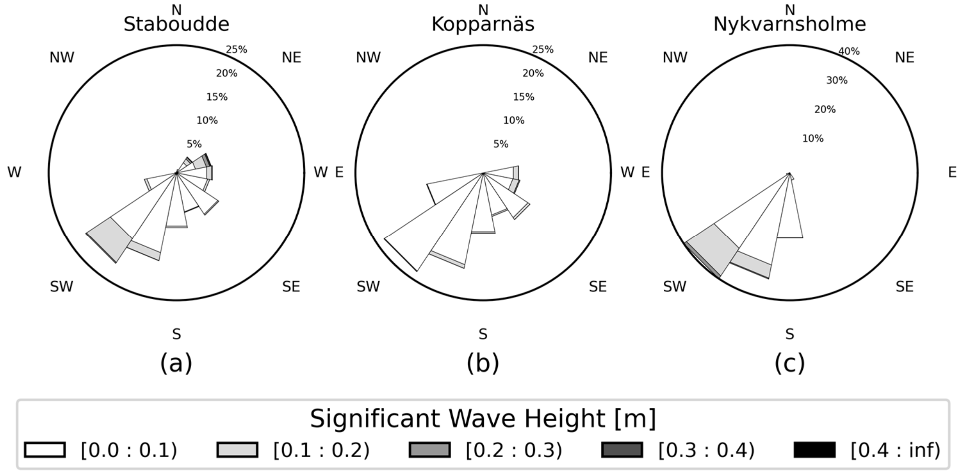

Figure 3-4.
Wave rose plots for the three locations chosen for implementing the nature-based solutions.

This archipelago, with its many islands, irregular coastline, and complex bathymetry, was formed during the last ice age approximately 10,000 years ago. At that time, the ice-sheet in the area moved from west to east, scraping the bedrock on the western facing shores and depositing moraine sediment on the eastern facing shores. Therefore, the geology consists of sandy moraine with small pockets of sand on the eastern facing shores of Furusund fairway and rocky outcrops on the western facing shores; thus, making the western shores more prone to erosion. The shore is dominated by moraine (39%) and clay (26%) sediment. Additionally, 12% of the shoreline consists of outcrops, 12% sand, 8% mud, 2% glacial deposits, and 1 % stones or boulders.

3.2 Ship traffic and waves

In the Furusund Fairway, ship traffic increased in the 1980s, and the operating ships became larger (Granath, 2007). Yearly, there are more than 6 900 ships (based on the year 2018) longer than 70 m that passes through the fairway in addition to many smaller vessels (inter-archipelago passenger ferries, recreational boats, military vessels, etcetera). The most frequent category of ships – 6 500 passages – are RoRo-vessels in regular ferry operation between Sweden and Åland, Finland or Estonia. The second most frequent category – 350 passages – are larger cruiser ships mainly passing the fairway in the summertime. Finally, the third most frequent category – 150 passages – is cargo ships.

Figure 3-5.
Different ship types commonly operating in the Furusund Fairway:(a) RoRo-vessel that daily operates the Furusund Fairway. (b) cruiser ships, (c) smaller fast-going intra-archipelagic ferries, and (d) cargo ships.

Ship waves have been quantified at four locations in the fairway: Staboudde, Kopparnäs, Björnhuvud, and Nykvarnsholme (Figure 3-1). In the summer of 2014, measurements of ship waves were made by Granath (2015c) as a part of a commissioned study by Trafikverket (the Swedish Transport Administration). One month of measurements per site was made using a capacitance probe at Kopparnäs, Björnhuvud, and Nykvarnsholme (**Paper I**). Additionally, measurements were also made by a pressure sensor in June 2020 at Nykvarnsholme and December 2020 at Staboudde (**Paper IV**). The data from the measurement campaigns were analysed by extracting water level fluctuations during individual ship passages by coupling these data to the ship AIS (Automatic Identification System). After that, the water level was processed by low-pass and band-pass filters. Drawdown heights and periods were extracted using a mean zero-up crossing method. Secondary waves were extracted using a the band-pass filter.

Statistics of ship waves at Björnhuvud and Nykvarnsholme for different categories of ships are presented in **Paper I**. According to the measurements, the drawdown height can be up to 0.32 m. However, it is mainly the period of the primary waves that characterize these waves. The measurement shows that the period is on average 42-57 seconds, but may be up to 81 seconds. Measurements display a clear difference between the sites in terms of drawdown height. At Nykvarnsholme, with a small fairway cross-sectional area, the drawdown height is more significant. At Björnhuvud, with a large fairway cross-sectional area, the drawdown height is lower (Figure 3-6), indicating that the impact from ship waves can vary significantly along the fairway due to its irregular bathymetry and shoreline geometry. The ship-generated waves at Nykvarnsholme are equivalent to the wind-generated waves in terms of wave height, but differ in the period by being much longer.

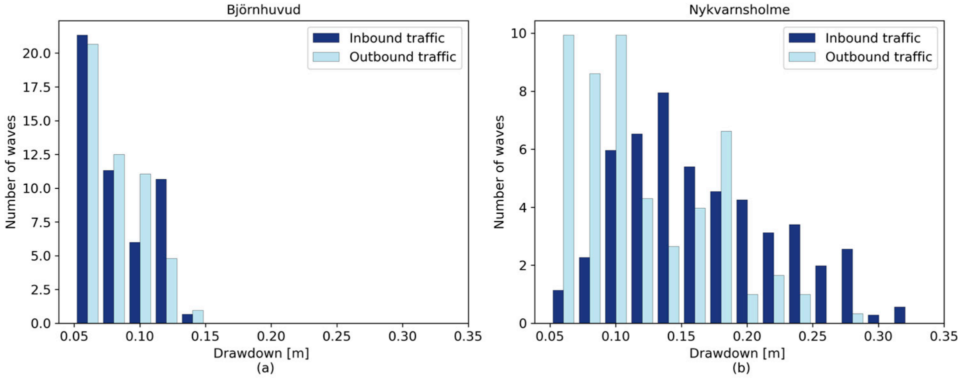

Figure 3-6.
Histogram of drawdown height for Björnhuvud (a) and Nykvarnsholme (b). (**Paper I**)

The Furusund Fairway has since the 1990s received continuous attention concerning issues related to ship-induced erosion. This has resulted in numerous studies on the subject from 1989 and onwards (Bjärås, 2014; Daleke et al., 1989; Granath, 2015b, 2015c, 2007, 2004b, 2001, 1992; Hedén and Sannel, 1992). These studies link the erosion to the ship traffic in the fairway. Erosion is claimed to mainly be a result of the primary waves from the larger ferries and cruisers, but the contribution from smaller, fast-going ferries is also somewhat acknowledged. Erosion is present along all the shores not consisting of rocks, but with a varying erosion rate. However, since sediment mainly consists of moraine material, there has been a natural armouring process at some locations along the fairway. In this process, the fine material (clay, silt and sand) is eroded, leaving coarse sediment (pebbles, boulders) on the shore (Figure 3-7a). The armouring process reduces the erosion, but in that process, the shore is transformed from a fine sediment habitat to a cobble beach; hence, changing the natural state of the shores. However, erosion can still occur during periods of elevated water levels, when the waves can attack higher up on the shore. However, this process is not present at shores with reed belts (Figure 3-7b). At other shores, the armouring process is insufficient to avoid a bluff forming (Figure 3-7c-d).

3.3 Erosion

The three typical types of shores (i.e., cobblebeaches, reed belts, and moraine bluffs) found in the Furusund Fairway are shown in Figure 3-7. In 1992, a characterization was made of the shoreline types in the Furusund Fairway (Granath, 1992). The result showed that the shoreline constituted of 6% artificial shores (e.g., jetties, seawall, revetments), 28.1% rocky shores, 2.5% boulder beaches, 6.4% cobble beaches, 16.8% mild-slope moraine shore, 9.9% steep-slope moraine shore, 2.0% sandy beaches, and 28.2% fine sediment beaches. Thus, 56.9% of the fairway's shores could be considered to be shores prone to erosion.

Figure 3-7.
Typical shorelines along the Furusund Fairway. (a) The shore in the picture consisted of reed and fine sediments in the 1990s (personal communication with the landowner, Torsten Nordstrand). Now, it is transformed to a cobble beach by armouring processes induced by waves. (b) One of the locations with a reed belt along the fairway. These reed belts have been damaged and diminished by erosion. (c) Staboudde in the north of the study area. The lighthouse was built on land in the 1970s. Since then, erosion has detached the lighthouse from land and formed a bluff. (d) Showing the pocket beach and bluff at Nykvarnsholme, south of the study area. Both the beach and the bluff have formed since the 1960s. (Photos taken in October 2016 by Björn Almström)

No detailed measurements exist that may be used to quantify the historic erosion in the fairway. However, by extracting historical shorelines, the shoreline retreat can be assessed. The historical shorelines were based on satellite images from 1960, 1975, 2005, 2008, 2011, 2013, 2015, 2017, and 2019, together with aerial images from an UAV (unmanned aerial vehicle) in 2018 and 2020. In Figure 3-8, the shoreline evolution is shown for three sites (i.e., the sites where nature-based solutions were implemented). Unfortunately, the data resolution is limiting the analysis for all shorelines except 2018 to 2020. Moreover, images taken during summertime is affected by tree foliage covering a clear view of the shoreline. Therefore, the uncertainty in the shoreline positions in Figure 3-8 should be considered when assessing the long-term evolution of the shorelines.

A general conclusion is that there has been a significant retreat of the shoreline/reed belt from 1960/1975 to 2020 at all locations. After 2005, the changes are more difficult to assess due to the quality of the satellite images and the slow erosion retreat rate. The resolution is better for the period 2018 to 2020, but changes (if they occur) are challenging to assess due to tree foliage/vegetation covering. The maximum shoreline retreat at these three locations is:

- At Staboudde (Figure 3-8a), the shoreline is retreating with about 0.2 m/year from 1960 to 1975 and with approximately 0.2-0.3 m/year from 1960 to 2020,
- at Kopparnäs (Figure 3-8b), the shoreline is retreating with about 0-0.2 m/year from 1960 to 1975 and with approximately 0.2-0.4 m/year from 1960 to 2020, and
- at Nykvarnsholme (Figure 3-8c), the shoreline is retreating with about 0.3 m/year from 1960 to 1975 and with approximately 0.4 m/year from 1960 to 2020.

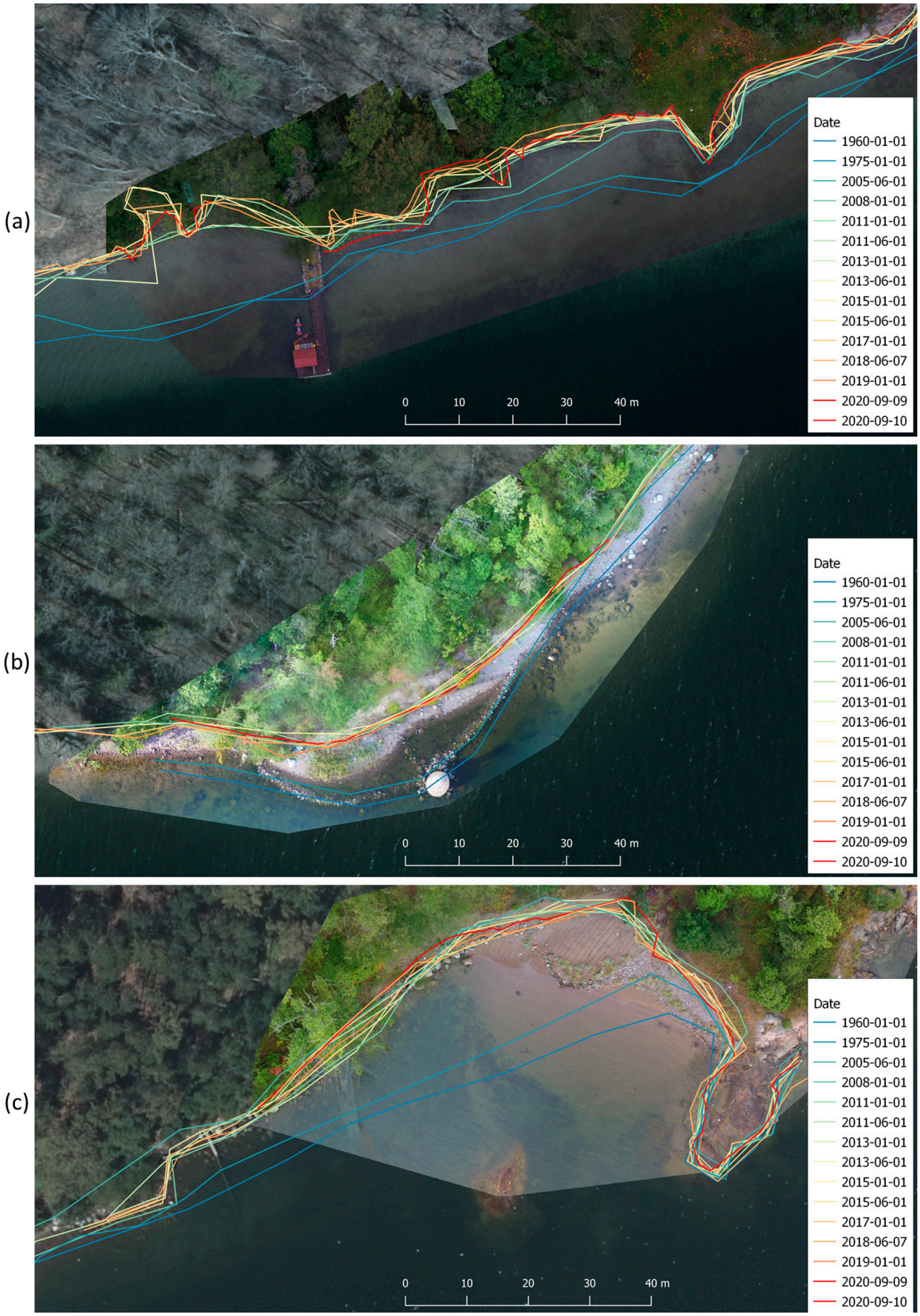

Figure 3-8.
Historic shoreline evolution at Staboudde (a), Kopparnäs (b), and Nykvarnsholme (c). At all locations, there has been a considerable shoreline retreat since the 1960s.

Landowners along the fairway have responded to the erosion through various conventional erosion mitigation measures. A typical action against erosion along the fairway has been to stabilize the shoreline by constructing a rock revetment (Figure 3-9a-b). However, most of these are poorly constructed, i.e., lacking filter layers and geotextiles, and not maintained properly. Bulkheads or sea walls have also been built to inhibit erosion, but many of them are failing (Figure 3-9c-d). The previous implemented conventional erosion protection demonstrates the difficulty in constructing such structures. Moreover, they reduce the functions of the shore by preventing a natural habitat from establishing, creating a barrier between land and water, and inhibiting recreational values.

Figure 3-9.
Examples of landowner initiative of erosion protection along the Furusund Fairway. (a) A rip-rap revetment is protecting a private road. (b) A seawall of rocks stabilizing the shoreline in front of a house. (c) A seawall that have been damaged by wave forces. (d) A rip-rap revetment protecting private property from eroding. (Photos taken in October 2016 (a-b), in August 2019 (c), and in December 2019 (d).

The fairway managers have enforced speed restrictions to reduce the hydrodynamic forcing from larger vessels sailing in the fairway. The speed has been regulated for larger ships since the mid-1990s. Currently, the speed is restricted to 10 knots for all ships, excluding three ships in regular 24-hour traffic between Stockholm and Åland. The speed restriction has mitigated the erosion along the fairway at many locations, but the erosion continues at shores with reed belts or sites close to the shore (Granath, 2015a).

4 Methodology

This chapter gives an overview of the methodology used in the appended papers. Detailed information about the methodology can be accessed in the appended papers.

4.1 Water level measurements

Field measurements of water level fluctuations during ship passages were conducted on three occasions. In the June, July, and August of 2014, in June 2020, and December 2020.

The first field campaign in 2014 was not carried out within the work of this thesis. This field campaign was part of a study on ship waves in the Furusund Fairway (Granath, 2015c). Raw data from the water level measurements and AIS data for the field campaign period were provided by courtesy of Lars Granath. In this campaign, the water level was continuously measured at three locations for about one month at each location. The locations included in the field campaign were Kopparnäs, Björnhuvud, and Nykvarnsholme. Measurements were performed with a capacitance probe that continuously registered the water level position with a frequency of 4 Hz. However, AIS data from this campaign was only available for Björnhuvud and Nykvarnsholme. Hence, these two stations were used for the analysis of ship waves in **Paper I**.

The second field campaign was conducted in June 2020 at Nykvarnsholme as a part of the work with this thesis. The measurements were conducted using a pressure sensor (RBRvirtuoso[3]). The pressure was continuously measured at a frequency of 8 Hz at a water depth of 0.7 m. The location in 2020 was about 100 metres north of the location in 2014.

The third field campaign was carried out at the end of December 2020 and the beginning of January 2021 at Staboudde. The campaign used the same device as in the second field campaign.

The water level measurements were coupled to the AIS data. This enabled the extraction of the water level fluctuations during individual ship passages. However, the quality of the water level measurements during each passage had to be inspected manually to exclude erroneous measurements; especially important was this for the measurements with the capacitance probe, which had problems with seaweed interfering with the probe.

4.2 Primary wave prediction

The primary wave is often considered as a significant hydrodynamic force on the shores in confined fairways. Therefore, to assess the ship wave impact, it is essential to quantify the primary wave. Furthermore, a method for rapidly predicting ship waves is necessary for pilot studies, feasibility studies, and long-term assessments of ship-generated wave impacts on shorelines. Hence, an empirical method can be useful for such applications. As described in the theoretical background, the primary wave is a function of the ship speed, ship geometry, and the fairway geometry. The dependence on the fairway geometry may explain why none of the existing empirical equations successfully described the drawdown height observed at Björnhuvud and Nykvarnsholme in 2014 (**Paper I**). Additionally, their inability to predict the height may also be explained by the equations being derived using datasets with a limited type of conditions prevailing in inland waterways, e.g., ship types, ship blockage ratio, and uniform fairway geometry. Hence, in an effort to predict the drawdown wave in intra-coastal waterways, a new semi-empirical equation was derived.

The new semi-empirical equation was derived based on non-dimensional quantities emerging from a simple analytical solution that considered the main governing physical processes. The analytical solution (not yet published) was derived from the continuity and energy equations assuming specific functional shapes for the water surface and return velocity across the fairway. The functional shape was taken from a closed-form solution for the flow around a cylinder presented by Matviyenko et al. (2013), but adapted to a passing ship. In the process of deriving the analytical solution, a number of non-dimensional groups related to the generation of primary waves were identified. These groups were the ratio between the distance to the shore and the ship width (x/B), the ratio between the ship width and the fairway top width (B/T), the ratio between the draught and the hydraulic depth (d_s/D), and the depth-based Froude number ($u/\sqrt{gD}$). Additionally, the correlation analysis between parameters and drawdown height indicated a strong relationship between the drawdown height and the ship length (**Paper I**). Hence, a final dimensional group was identified as the ratio between the ship length and the draught (L/d_s).

The dimensionless groups were combined into a power relationship. A multiple regression analysis determined the coefficients of the dimensionless groups. The multiple regression analysis utilized a data set derived by coupling the water level measurements in 2014 with the corresponding AIS-data. This data set contained 466 single ship passages with relevant ship-related parameters (e.g., ship speed, route, length, width, heading, draught) associated with corresponding drawdown height and period. The optimum coefficient values were determined by randomly splitting the data set into one calibration and one validation data set of equal size. In the multiple linear regression process, it was found that the randomized splitting influenced the results. Therefore, the optimum coefficients in the proposed equation were found by randomly generating 100 calibration and validation sets, for which coefficients values were determined. The coefficient values for specific dimensionless groups converged to an average value. These average coefficient values cannot be used directly as the optimum coefficient values for the proposed equation since the coefficients in the equation relate to each other. Therefore, the set of coefficients with values nearest to the averaged coefficients values was chosen as the optimum coefficient values for the equation. Thus, the following equation for drawdown height was proposed:

$$\frac{S_D 2g}{u^2} = 0.2\left(\frac{u}{\sqrt{gh}}\right)^{0.39}\left(\frac{B}{x}\right)^{0.86}\left(\frac{B}{T}\right)^{0.51}\left(\frac{d_s}{h}\right)^{0.93}\left(\frac{L}{ds}\right)^{0.71} \tag{1}$$

where S_D is the drawdown height, g is the gravitational acceleration, u is the ship speed, D is the hydraulic depth, B is the ship width, T is the top width, d_s is the draught of the ship, and L is the length of the ship.

In **Paper I**, it was shown that there was a correlation between the drawdown height and period. Therefore, an identical approach and dimensionless groups were applied for deriving a semi-empirical equation for the drawdown period, except for the period which is normalized by the ship length and speed. This is motivated by the length and speed of the ship being essential parameters for the period of the primary wave in narrow channels. The proposed equation for the drawdown period was:

$$\frac{T_p L}{u} = 4.6\left(\frac{u}{\sqrt{gh}}\right)^{-0.28}\left(\frac{B}{x}\right)^{0.09}\left(\frac{B}{T}\right)^{-0.22}\left(\frac{d_s}{h}\right)^{-0.62}\left(\frac{L}{ds}\right)^{-0.64} \tag{2}$$

where T_p is the drawdown period.

4.3 Numerical modelling of ship waves with XBeach

XBeach is an open-source code initially developed for modelling waves, mean flows, sediment transport, and morphological changes during a storm in the nearshore area, beaches, and dunes (Roelvink et al., 2009). It is a widely applied model within the coastal community, and the model capability has been extended to various applications related to coastal hydrodynamics and morphology. One such application is the capability to calculate ship waves. This is made possible by the non-hydrostatic module (Roelvink et al., 2018; Smit et al., 2010) and the implemented routine for representing a ship hull geometry as a moving pressure field (Ma, 2012). The principle for the moving pressure field method is to update the water pressure head in each grid cell as the ship moves through the computational domain. This method can represent important forces associated with ship wave generation, such as the vertical pressure from the ship, the ship pushing water ahead of itself, and the suction force behind the stern (Ma, 2012). However, this method cannot include the force or the disturbance originating from the ship propulsion. Additionally, the moving pressure field method cannot include three-dimensional features of the ship hull (i.e., the bulbous bow).

A few publications demonstrate that the numerical model XBeach is capable of simulating the primary wave generation from ships (Jong et al., 2013a; Ma, 2012; Ming-gui et al., 2015; Zhou et al., 2014). However, the ability of XBeach to produce secondary waves from ships is not presented in these studies. The exclusion of the secondary waves in these studies may be explained by the upper limit of XBeach corresponding to relative depths (kh) of 2.5. This upper limit affects the propagation of short-crested waves in deep water. Thereby, XBeach cannot represent the secondary waves since they can be considered as short-crested waves propagating over large relative depths. A recent development of XBeach enables solving the non-hydrostatic pressure with an additional horizontal layer without much extra computational effort. It was demonstrated by de Ridder et al. (2020) that this approach was consistent with linear wave theory up to relative depths of 4. The higher limit of the relative depths for XBeach would imply a greater potential to represent the generation and propagation of secondary waves in XBeach.

The XBeach capability of modeling ship waves was evaluated in **Paper II** by simulating the M/S Baltic Princess passages during the measurements at Björnhuvud and Nykvarnsholme in 2014. The M/S Baltic Princess was selected since it is one of the four ferries that operate the Furusund Fairway twice a day year-round. In conjunction with that, technical drawings of its ship hull were provided by AS Tallink Grupp, operating the M/S Baltic Princess. However, technical drawings of ship hulls can be difficult to attain. Therefore, simulations were carried out using a generic hull for RoRo-vessels obtained from the DEFLTship open-access database. The generic hull was adjusted to correctly represent the geometric parameters specified in the AIS-data (i.e., ship length, width, and draught). The hull grid from the technical drawings and the open-access database were assigned to a two-dimensional grid of 0.5x0.5 m. The model domain was represented by a computational grid of 2x2 m. Input to the XBeach model for simulating ship waves were:

- **Bathymetry**: Retrieved by the Swedish Maritime Administration Agency (swe: Sjöfartsverket) as 10x10 m grid. This data was acquired by a multibeam survey of the Furusund Fairway.
- **Still water level**: The still water level in the Furusund Fairway was retrieved as hourly measurements from the SMHI nearby water level station, Stockholm-2069.
- **Ship track**: Based on AIS-data with a resolution of approximately 10 s. AIS data was processed and was interpolated using a spline method to avoid instabilities due to noise in the AIS data.
- **Ship heading**: The heading of the ship was extracted from the AIS data. This information was interpolated using spline in the same way as for the ship track.
- **Ship speed**: Extracted from the AIS data and interpolated using spline. Additionally, to avoid instabilities, a spin-up period of 360 s. was applied in which the ship was slowly accelerated from still-standing to actual speed.

Simulations were compared with water level measurements from 2014 of the M/S Baltic Princess passing Nykvarnsholme and Björnhuvud in the Furusund Fairway. In total, 42 in- and outbound passages were included in the simulations. The comparison with measurements included the ability of XBeach to reproduce the wave height and period for the primary and the secondary waves. In addition, a qualitative assessment was made of the wave field produced by XBeach and the shape of the primary wave.

The applicability of a model to an end-user depends on the skill needed to operate the model, the computational cost for the simulation, and the required input. **Paper II** shows that the XBeach model requires input data readily available for most end-users, except for the ship hull geometry. Technical drawings of the ship hull geometry are often the property of the shipowner or the shipbuilder. Acquiring these drawings may not be possible or very difficult. However, open-access databases (e.g., the DELFTship database) contain generic hull shapes for various categories of marine vessels. If generic hull shapes could be used as input for XBeach, it would significantly increase model applicability. Therefore, comparisons were made between simulations using the actual hull shape (derived from the technical drawings) and the generic hull shape (derived from the DELFTship database). The generic hull shape was geometrically adjusted according to information in the AIS data, i.e., adjusting the ship length, beam, and draught parameters.

4.4 Decision support tool

Numerical models presently require too much computational effort and input data for long-term assessment of ship wave impact on a large regional scale. For such applications, a more simplistic approach to predict ship waves is needed. Hence, a decision support tool was developed in **Paper III** to assess the potential erosion along a fairway with complex geometry, e.g., an intra-coastal waterway such as the Furusund Fairway. The objective with this decision support tool was to assess the potential ship-induced erosion, relate it to the wind-generated waves at the location, and assess different fairway management solutions (e.g., increasing shore resistance to erosion, ship speed regulations, changing ship routes, or limiting the ship size). Similar models have previously been developed for fairways with uniform geometry, but only for secondary waves from smaller vessels (Fonseca and Malhotra, 2012; Glamore, 2008; Hartman and Styles, 2020; Macfarlane et al., 2014). Therefore, none of these tools would be applicable to a fairway with a non-uniform geometry operated by large ships.

The decision support tool is constructed as a framework with minimum input requirements where modules can be exchanged. The possibility to exchange modules enables the tool to be easily adapted to specific cases, e.g., using site or ship specific modules for primary or secondary wave prediction. A schematization of the decision support tool is presented in Figure 4-1.

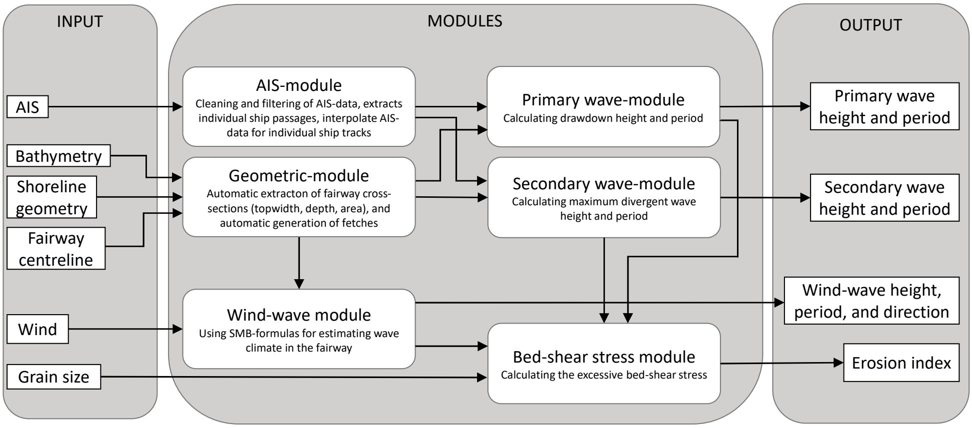

Figure 4-1.
The schematization of the decision support tool.

Input data for the decision support tool are AIS, bathymetry, shoreline geometry, wind, and grain size along the fairway. The modules enable the automatic processing of the input data without any additional input from the user. AIS data is processed in the AIS-module by applying cleaning and filtering algorithms to exclude erroneous data points, extracting and interpolating ship tracks for individual ship passages. The fairway is represented in the model as cross sections at an equidistance along the fairway centreline. These cross sections are extracted in the Geometric-module. Outputs from the AIS- and the Geometric-modules are used as input in the modules calculating the primary and secondary waves. Wind-generated waves are calculated in the Wind-wave module that uses wind and fetches as input. The fetches are automatically extracted for every output point along the fairway in the Geometric-module. In the bed-shear stress module, the excess bed-shear stress is calculated for primary, secondary, and wind-generated waves using input from each module and the grain size along the fairway. Finally, output from the model includes an erosion index, wave height, and period along the fairway for primary, secondary, and wind-generated waves. Additionally, for wind-generated waves, the output includes the direction of the waves. The format of the output is text- and shape-files that can be processed by commonly available software.

The primary waves are predicted using the modified version (Eq. 1) of the semi-empirical equation in **Paper I**. Additionally, an important insight from **Paper I** was that the water level response at the shore as a result of the primary wave generated at the ship is not instantaneous. Therefore, any change in the parameters relevant to the water level response at the shore is delayed. This delay is assumed to be equal to the time it takes for a shallow-water wave to travel the distance from the ship to the shore. Hence, the response of the water level fluctuation from the primary wave is governed by conditions occurring before the ship passes a given point in the fairway. This is illustrated in Figure 4-2 for a fairway with non-uniform geometry.

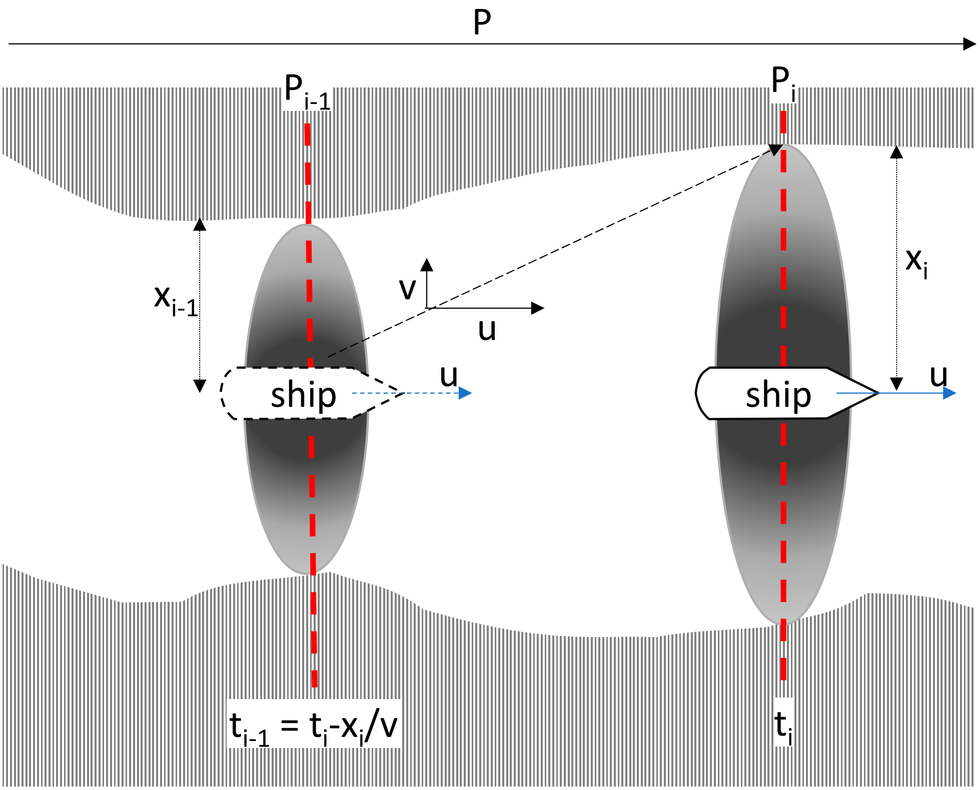

Figure 4-2.
Illustration of the concept of the primary wave generation. A grey area indicates the surface water depression area, the white box indicates the ship, and the red line indicates the cross-section of the fairway. *P* is a location along the fairway, *x* the distance from the ship to the shore, u is the ship speed, v is the shallow water wave celerity ($\sqrt{gh}$), t is the time, and the subscript *i* denotes the step where the primary wave is observed and *i-1* denotes the step when the primary wave is generated.

Secondary waves are predicted using equations from the literature. However, no equation in the literature was valid for all speed regimes (i.e., subcritical, trans-critical, and supercritical speed). Therefore, two equations are used to predict the secondary waves from a wide range of ship types operating at different speeds. For the Furusund Fairway, the PIANC (1987) formulation of secondary waves is applied to ships operating at subcritical speed. In addition, this formulation was modified with an attenuation factor, γ, included to decrease the wave height as a function of the distance to the ship (Eq. 3).

$$H_{2nd} = A_p h \left(\frac{L}{h}\right)^{-0.33} \left(\frac{u}{\sqrt{gh}}\right)^4 \gamma \qquad (3)$$

where H_{2nd} is the maximum secondary wave height, A_p value of unity and γ is the wave attenuating factor equivalent to the distance raised to the power of -1/3 (Cox, 2020; Glamore, 2008). An equation from Bhowmik *et al.* (1991) is applied For ships operating at super-critical speed (Eq. 4).

$$\frac{H_{2nd}g}{u^2} = e^{4.996}\left(\frac{L}{x}\right)^{0.56}\left(\frac{gx}{u^2}\right)^{0.215}\left(\frac{g\nu}{u^3}\right)^{0.402}\left(\frac{gd_s}{u^2}\right)^{0.355} \qquad (4)$$

where ν is the kinematic viscosity.

Wind-generated waves in the decision support tool are hindcasted using a modified SMB-formulation to preserve wave energy between time-steps (Hanson and Larson, 2008). Fetches are automatically derived from the input data and extracted for every output point for a user-specified directional bin.

The erosional index is based on the assumption that there is a potential for erosion to occur if the sediment is mobilized by the waves. The potential of mobilizing sediment is calculated by normalizing the excess bed-shear stress, τ_{exc} (Van Rijn, 1990).

4.5 Field experiments of nature-based solutions

In **Paper IV,** field experiments of nature-based solutions to mitigate ship-induced erosion are evaluated. Three locations within the Furusund Fairway were selected for the field experiments. The selection was based on the following aspects or requirements: known history of ship-induced erosion, permission from landowners to implement the nature-based solutions, terms in environmental permit from authorities, the type of erosion, and the funding available for implementing the nature-based solutions. Moreover, these three sites represent various hydrodynamic forcing, geological conditions, and erosional processes. Hence, the selected sites reflect the broad range of conditions found in the Furusund Fairway. The type of sites is likely to be found in many fairways having problems with ship-induced erosion.

The objectives of the experimental designs tested in **Paper IV** were to stop erosion and create favourable conditions for promoting vegetation. The design should be able to dissipate the hydrodynamic forces sufficiently from the primary and secondary waves. It should also be durable to withstand the climatic and hydrodynamic conditions in the fairway without excessive maintenance. Moreover, the installation of the nature-based solutions should be doable with a minimum number of people to be economically feasible as well as the installation should be scalable. The morphological change was used to evaluate the implemented nature-based solutions. Additionally, photographs were used to document how the nature-based solutions evolved during the studied period (e.g., vegetation growth, the structural durability, indications of shore erosion).

4.5.1 Case study sites

The first site, Staboudde, is a headland with severe erosion that has formed an eroding bluff. The headland consists of unconsolidated glacial sediment (sandy moraine) where the finer sediments are eroded, leaving boulders and large pebbles that armour the beach. The armouring response has slowed the erosion rate at the site. However, the erosion is still active at the site resulting in a loss of the oak habitat with a high ecological value existing inland of the bluff. The erosion is most likely a result of the ship waves and is accelerated during elevated water levels. The secondary waves dominate the hydrodynamic forcing due to the proximity to the fairway area (approximately 50 m).

At the second site, Kopparnäs, the erosion has resulted in the retreat of the reed belt. The site is characterized by having a shallow foreshore with silty sand on top of the clay. The reed belt has continuously eroded since the 1960s, and only a patchy reed belt fringing the shore remains today. The erosional process is likely an effect of the secondary waves mobilizing the sediment and the suction force of the primary wave transporting the sediment offshore.

The third site, Nykvarnsholme, is similar to Staboudde in terms of the erosion that has created a bluff escarpment. The geology at the site consists of mainly sandy moraine with smaller fractions of boulders and pebbles compared to Staboudde. Therefore, no armouring layer has been created. Instead, the bluff is feeding the sandy beach in front of the bluff with sediment. The erosion has been notable since the 1960s, creating a small embayment due to the erosion. In this embayment, the primary waves are the dominant forcing.

4.5.2 Nature-based erosion protection

The principle of the nature-based erosion protection design was to dampen the water level fluctuation of the primary wave and dissipate the secondary waves. By dampening the water level fluctuations, the outward current that enables sediment transport and seed removal is reduced. This is expected to create favourable conditions for vegetation to establish along the fairway shores. When established, the vegetation will become a part of the nature-based protection by attenuating incoming ship and wind-generated waves.

Different designs of nature-based erosion protection from the literature were assessed. The long period of the primary wave makes it difficult to dissipate the wave energy by breaking. A solid sheet pile sea wall is neither an option due to the wave reflection and due to that it would impact the connectivity between land and sea. Additionally, it was assessed that using only vegetation would not be sufficient. Therefore, a design combining a stabilizing structure and vegetation was proposed. The purpose of the stabilizing structure was to dissipate the short crested secondary waves. The primary wave, with its long period, will not be dissipated by the stabilizing structure. However, the stabilizing structure will inhibit the lowering of the water level inside the structure during the primary wave, and no outward current will be generated. Additionally, the vegetation will further dissipate the wave energy. This function is essential during high tide events when the dissipative ability of the stabilizing structure is diminished.

The different designs included in the field experiment at Staboudde and Kopparnäs are illustrated in Figure 4-6. The initial design of the stone-based sill at Staboudde (Figure 4-1 and Figure 4-6a-b) was based on cobbles with a diameter of 50-100 mm. However, this design could not resist the hydrodynamic forces at the site resulting in a dispersion of the sill. The sill was therefore reinforced with larger cobbles (100-400 mm) after 1.5 years. The experiments at Staboudde included two different designs, with a backshore (Figure 4-1 and Figure 4-6a) and without a backshore fill with topsoil combined with vegetation (Figure 4-1 and Figure 4-6b). The objectives for testing this was whether (i) the sill in combination with the vegetation is able to retain the topsoil (i.e., effective in reducing erosion), (ii) it is needed to include a backshore with vegetation in the nature-based solution, and (iii) sediment accumulates onshore the sill when no fill is made.

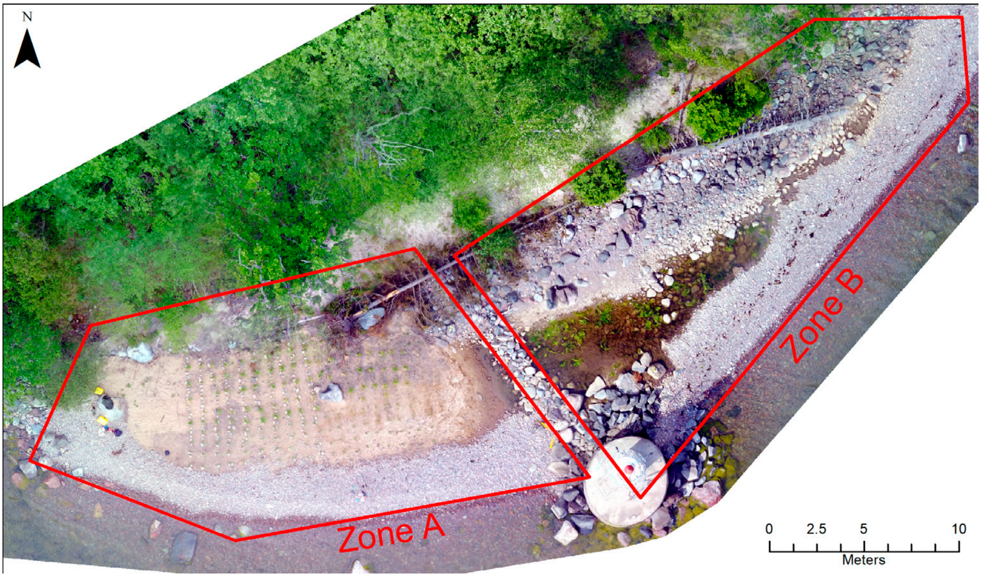

Figure 4-3.
Aerial photograph of Staboudde taken one month (June 2016) after completion of the nature-based erosion protection. Zone A shows the zone with a backshore landward of the sill. Zone B is the zone without a backshore. (Photo by Mats Öberg, SGI)

The site Kopparnäs was divided into three zones: Zone A, Zone B, and Zone C. In Zone A, a small nourishment of silty sand was used as a reference zone for erosion without any intervention (Figure 4-6c). Coir logs were used as a sill (i.e., stabilizing structure) in Zone B and Zone C. In Zone B, coir logs were placed in a pyramid shape with a crest level corresponding to the mean sea level and at a distance of approximately 10 m from the shoreline (Figure 4-6d). A fill was made of top-soil onshore of the coir logs and in half of the zone reed was planted. The purpose of the fill was to assess if the nature-based solution was able to retain this sediment. In Zone C, two coir logs were placed parallel to each other at a distance of 5 m from the shoreline (Figure 4-6e). The crest level of the coir logs was at -0.10 m relative to the mean sea level. Similar to Zone B, a fill was made of topsoil onshore of the sill and half of the onshore area was planted with vegetation.

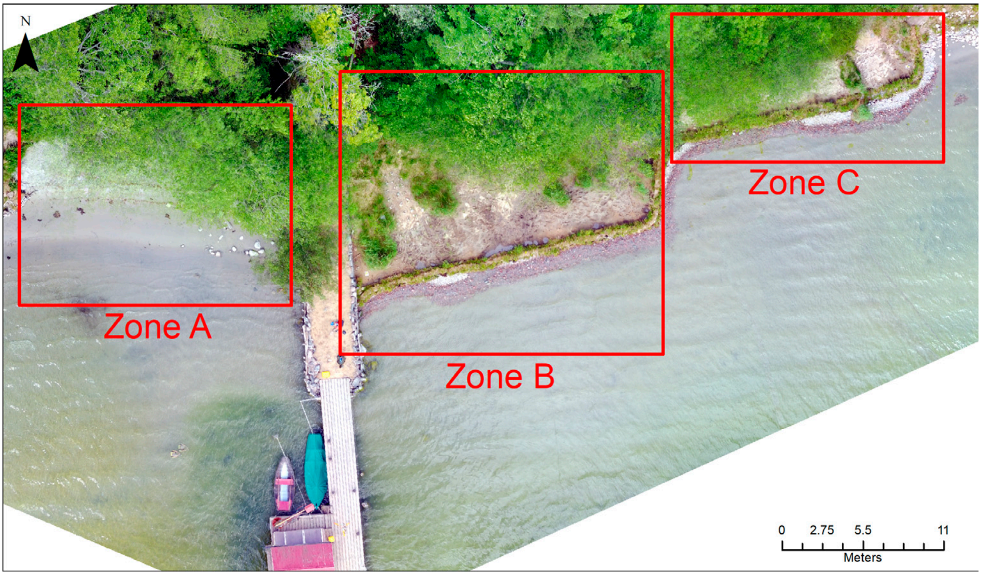

Figure 4-4.

Aerial photograph of Kopparnäs taken one month (June 2016) after completion of the nature-based erosion protection. In Zone A a small nourishment of silty sand was placed, in Zone B a sill of three coir logs was used, and in Zone C a sill consisting of two coir logs was used.

At Nykvarnsholme, the design of the nature-based erosion protection needed to consider that the eroding bluff supplies the beach in front of the bluff with sediment (Figure 4-5). Hence, inhibiting the erosion could result in the beach eroding. Therefore, the bluff was nourished with sand (0-4 mm). The objective of the nourishment was to stop the bluff from retreating without disrupting the supply of sand to the beach.

Figure 4-5.
Aerial photograph of the embayment at Nykvarnsholme. The photo was taken one month after nourishing the bluff (red area). (Photo by Mats Öberg, SGI)

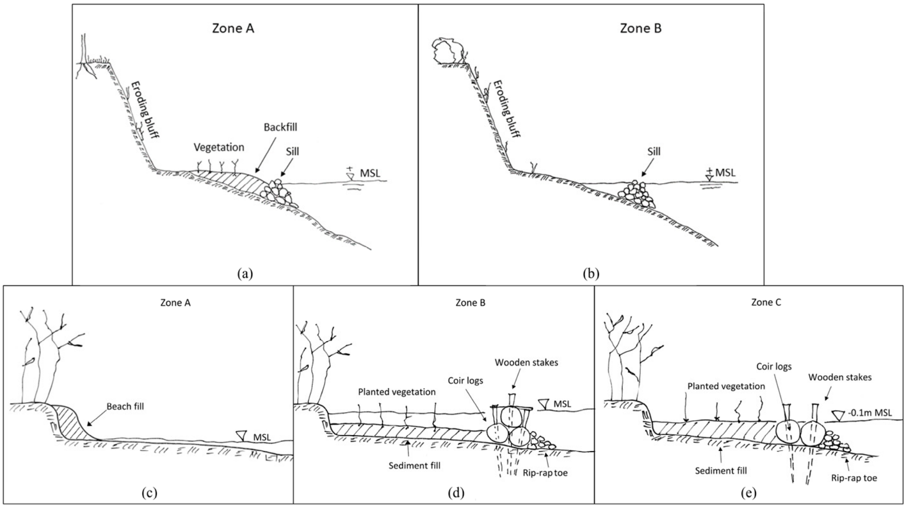

Figure 4-6.
Illustrations of the different nature-based erosion protection designs included in the field experiment. (a-b) shows the stone-based sill structure implemented in Staboudde. In (a), the sill is accompanied by a backshore fill with vegetation. In (b), a test is made with only the sill structure. (c-e) shows the designs in Kopparnäs. (c) was utilized as a reference site for the response without any intervention. In (d) and (e), the stabilizing structure was constructed by coir logs and planting of reed vegetation.

5 Results and discussion

The key results of the appended publications are presented and discussed in this chapter. Additional results and more detailed discussions are found in the appended papers.

5.1 Predicting primary wave

In **Paper I**, it is shown that existing formulas (Bhowmik et al., 1981; CIRIA et al., 2007; Dand and White, 1978; Hochstein, 1967; Kriebel et al., 2003; Maynord, 1996; Schijf, 1949) for estimating primary waves are unable to accurately predict the drawdown in Furusund. Hence, a new equation was proposed in **Paper I** based on the conditions in the Furusund Fairway. In **Paper III,** this equation was modified to describe cases when a ship is not sailing in the middle of the fairway cross-section. Applying the modified proposed equation for the drawdown height and the equation for the period shows good agreement with the field measurement conducted in 2014 (Figure 5-1). The coefficient of determination (R^2) was 0.65 for the drawdown height and 0.64 for the period, demonstrating that the modified proposed equation performed better than the existing equations in the literature. The corresponding R^2-value for the existing equations ranged from 0.48 to 0 when applied to the 2014-dataset. Their poor agreement can be explained by the equations being developed for conditions other than the conditions present in the Furusund Fairway; that is, most of them were developed for rivers or channels and for specific types of ships. The different behaviours of the equations imply that care should be taken in selecting an equation suitable for the type of fairway and ships being assessed.

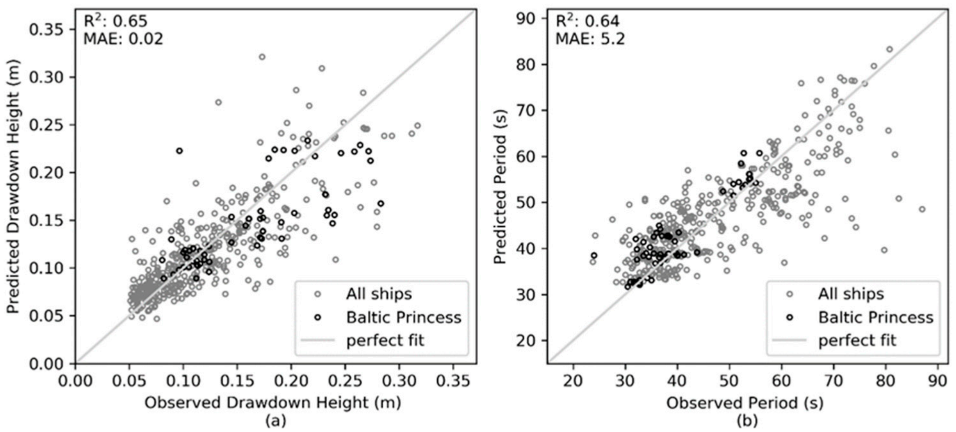

Figure 5-1.
Results from the calibration of the proposed equations for drawdown height (a) and period (b) using measurements from the 2014 field campaign. The grey markers indicate all ships, the black markers indicate values for a single ship, and the grey line indicates the perfect fit between observed and predicted values.

In **Paper III**, the modified equation was validated using water level measurements at Nykvarnsholme in June 2020 and at Staboudde from the end of December 2020 to the beginning of January 2021 (Figure 5-2). The results were encouraging, with a coefficient of determination (R^2) of 0.86 for the drawdown height and an R^2-value of 0.66 for the wave period; especially considering that the data sets are independent of the calibration data sets. However, the modified proposed equation requires further validation in other fairways than the Furusund Fairway and for other types of ships.

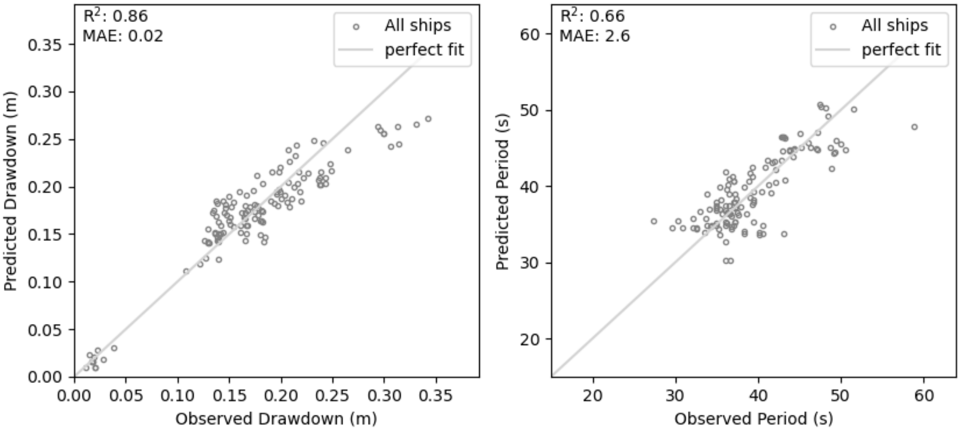

Figure 5-2.
Results from validating the semi-empirical equation developed in **Paper I** and modified in **Paper III** for the data sets collected at Nykvarnsholme in June 2020 and at Staboudde from the end of December 2020 to the beginning of January 2021.

5.2 Numerical modelling of ship waves

The main objective in **Paper II** was to validate the XBeach capability of simulating primary and secondary waves for a real-world application. Combined with the already known ability of XBeach to simulate the sediment transport induced by waves, the model would be most useful for assessing the impact from ship waves in fairways and finding effective designs of mitigation measures.

In total, 42 individual ship passages were simulated for the M/S Baltic Princess. From each simulation, the water level fluctuation was compared with the measured water level, the ship wave field was assessed, and statistics were derived (i.e., primary and secondary wave height and period). The main features of a ship wave field are represented in the XBeach model, as shown in Figure 5-3. The ship is pushing the water in front of itself, resulting in an elevated water level that precedes the ship. The primary wave is seen as a depression area in the vicinity of the ship. The secondary waves are present, with divergent waves originating from the bow. However, the stern waves have a much smaller period than expected.

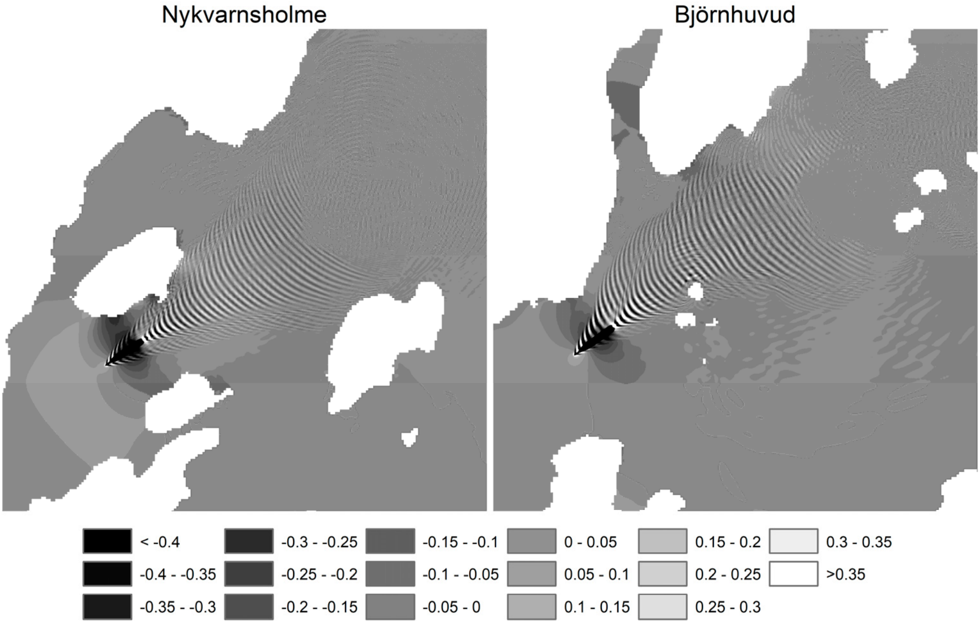

Figure 5-3.
The ship wavefield generated by XBeach is exemplified by simulations at Nykvarnsholme and Björnhuvud. Darker colours indicate water level depression.

The water level fluctuation during a ship passage is presented as the best and worst fit between simulation and observation at Nykvarnsholme and Björnhuvud to indicate the range of performance from the model (Figure 5-4). A low-pass filter was applied to the observed and simulated water level to exclude secondary and wind-generated waves. In general, XBeach is able to capture the shape of the low-frequency component of the ship waves very well. The bow wave is represented in the model, as is the shape of the drawdown wave. The exception is at the location Björnhuvud where XBeach cannot quite replicate the shape of the drawdown wave, even though the amplitude of the drawdown is accurately reproduced. The stern wave is, in general, overestimated in XBeach. Moreover, the oscillation after the ship has passed is also not correctly represented.

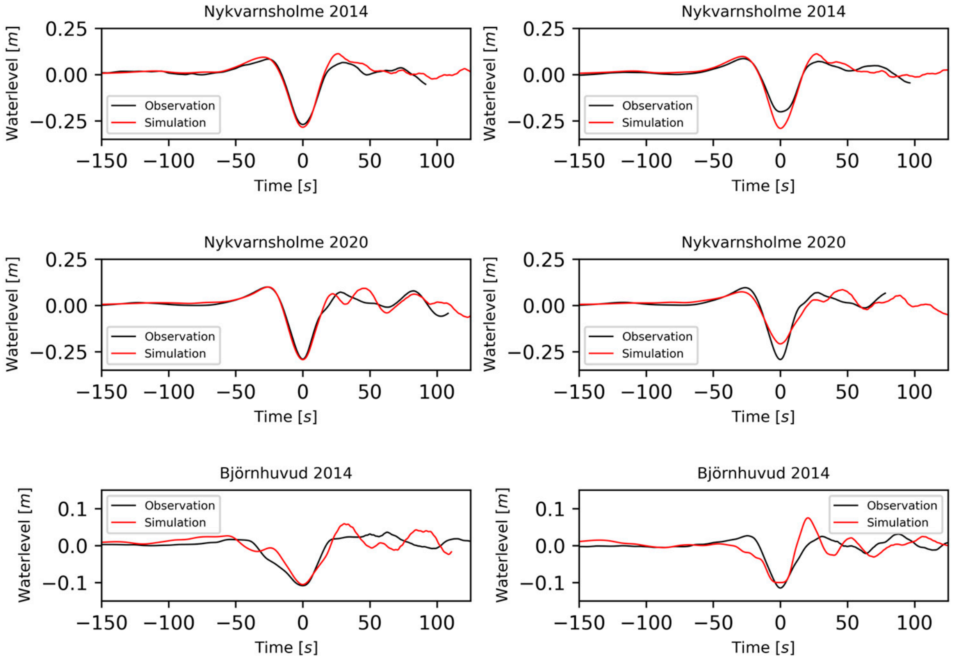

Figure 5-4.
Results from applying a low-pass filter to the observed and simulated water levels in XBeach. The left panels show the simulation for each site and measurement campaign with the best performance. The right panels show the simulations with the worst performance in terms of predicting the primary wave.

The XBeach capability of simulating secondary waves is exemplified in Figure 5-5 by applying a band-pass filter to exclude the low-frequency primary wave and any high-frequency wind-generated waves. The increased capacity of simulating wave propagating over larger relative depths has improved the capability of XBeach to simulate secondary waves compared to results presented in previous studies (Jong et al., 2013b; Ma, 2012; Ming-gui et al., 2015; Zhou et al., 2014, 2013). The secondary wave height and period are in the right order of magnitude compared to observations, but XBeach is not yet able to fully represent the generation and propagation of the secondary waves.

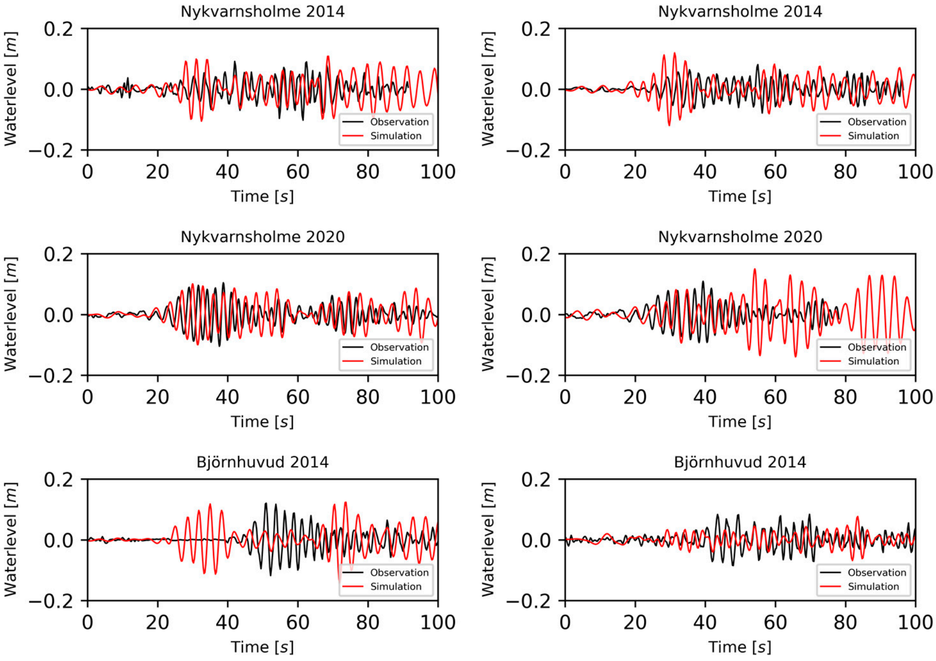

Figure 5-5.
Results from applying a band-pass filter to the simulated and observed water levels during ship passages.

Summarizing all the simulations (Figure 5-6), it can be concluded that XBeach performs satisfactorily in predicting the drawdown height and the drawdown period at Nykvarnsholme, but less well regarding the period at Björnhuvud.

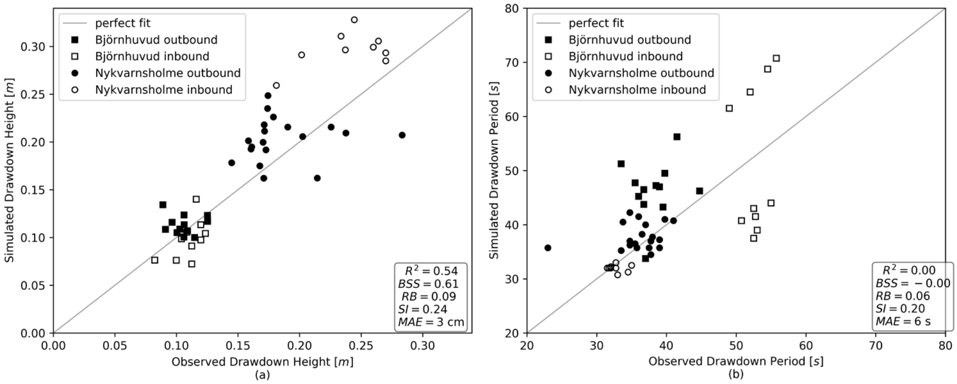

Figure 5-6.
Summary of all simulations compared to measurements from 2014. The left panel presents the drawdown height, and the right panel shows the drawdown period. (**Paper II**)

The XBeach performance in simulating secondary waves are shown in Figure 5-7. For the highest secondary waves, there is no correlation between the simulated and observed wave height (Figure 5-7a). However, the simulated and the observed wave heights are centred upon 0.20 m, and the range in the data sets are similar (approximately 0.10 – 0.32 m). Furthermore, the simulated wave period of the highest secondary waves does not correlate with observations (Figure 5-7b). Therefore, the simulated wave periods tend to be overestimated compared to observed periods. This is also reflected in the timing of the arrival of the secondary waves (Figure 5-7c). The simulated secondary waves have a higher celerity due to having a longer wave period. Hence, the simulated waves arrive earlier than observed.

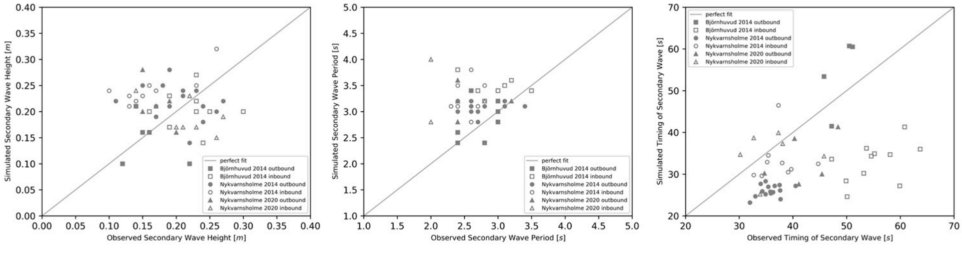

Figure 5-7.
Results for the secondary wave height (left panel), the period (mid panel), and the timing of arrival of the highest wave (right panel) from all simulations compared to measurements in 2014 and 2020.

Results from **Paper II** show that almost identical results were achieved for the generic hull compared to the simulations with the actual hull for the primary waves (Figure 5-8). However, for the secondary waves, the correlation for wave heights between the generic hull and the actual hull is weaker than for the primary waves. This can be explained by the hull shape having a large influence on the generation of the secondary waves than the primary waves.

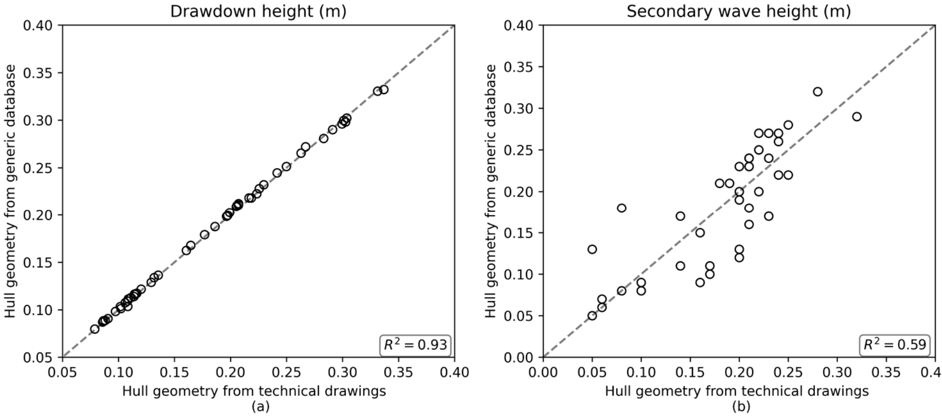

Figure 5-8.
Comparison between simulations using the real hull geometry derived from technical drawings and the generic hull attained from the DELFTship database. (a) Results for the primary waves, and (b) results for the secondary waves.

It is demonstrated in **Paper II** that XBeach shows potential to be used for simulating ship waves in real-world applications. Thereby, it would be possible to simulate the morphological response in fairway banks from ships. Moreover, the morphological and hydrodynamic impact from various erosion protection measures may also be simulated to find the optimum design. However, the computational efficiency comes with the drawback that secondary waves are not fully represented. Hence, future development of the XBeach ship simulating capability should focus on resolving the secondary waves better.

5.3 Decision Support Tool / Framework

In **Paper III,** a decision support tool was developed and tested by applying it to the Furusund Fairway by simulating the ship traffic during 2019. It was demonstrated that it was possible to identify many of the known erosional hot spots in the Furusund Fairway. Results can be seen in Figure 5-9, where the cumulated excessive bed shear-stress (EBSS) during 2019 is presented for primary, secondary, wind-generated waves. For primary waves, only Staboudde in the north, and

Nykvarnsholme in the south are indicated as potential erosional sites (Figure 5-9a). More locations are indicated as potential erosional sites when the secondary waves are considered (Figure 5-9b). Moreover, the analysis of the wind waves shows that only at a few locations do large wind-generated waves coincide with the erosional hot spots. Indicating that the ship traffic may be associated with most of the observed erosion, but not with all.

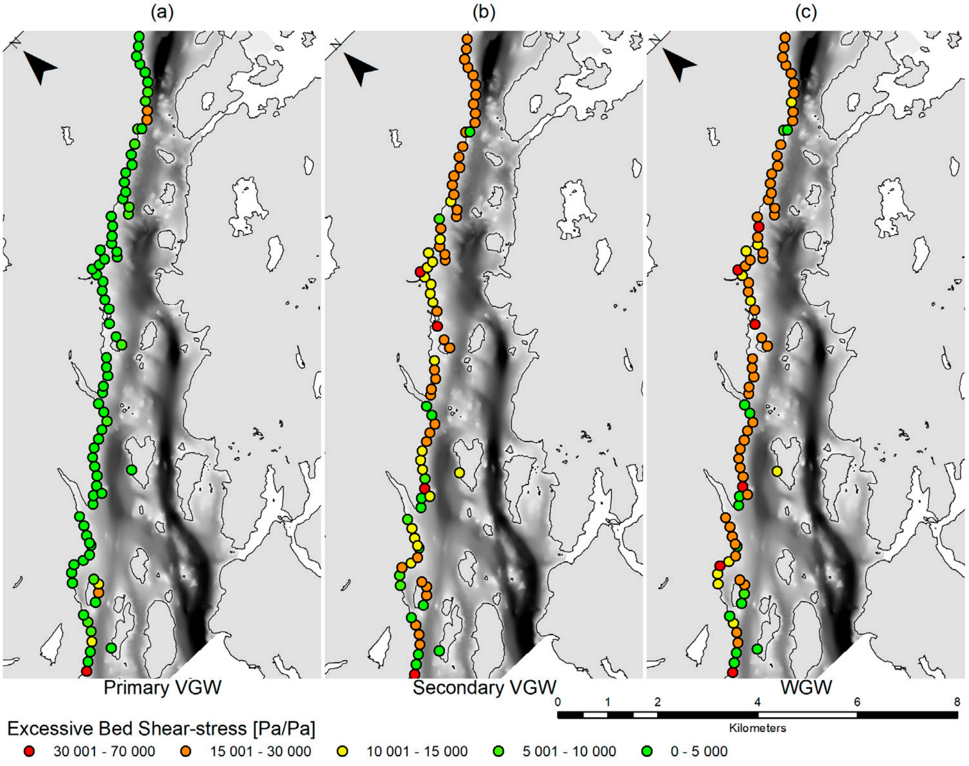

Figure 5-9.
Excessive bed shear stress for (a) primary waves, (b) secondary waves, and (c) wind-generated waves (**Paper III**).

The decision support tool can be used to simulate different fairway management strategies. To demonstrate its capability, four scenarios with different speed restrictions were simulated. Figure 5-10 illustrate how the excessive bed shear stress changes using different speed restrictions compared to scenario 0 (i.e., speed limited to 12 knots). If the speed is increased, the histogram shifts to the right (Figure 5-10a). Hence, the potential erosion along the fairway is increased. Reducing the speed limit from 12 to 10 knots (Scenario 2) will reduce the locations along the fairway with potential erosion (Figure 5-10b). However, even if the speed is lowered to 8 knots, there are still some locations where primary waves may mobilize sediment (Figure 5-10d).

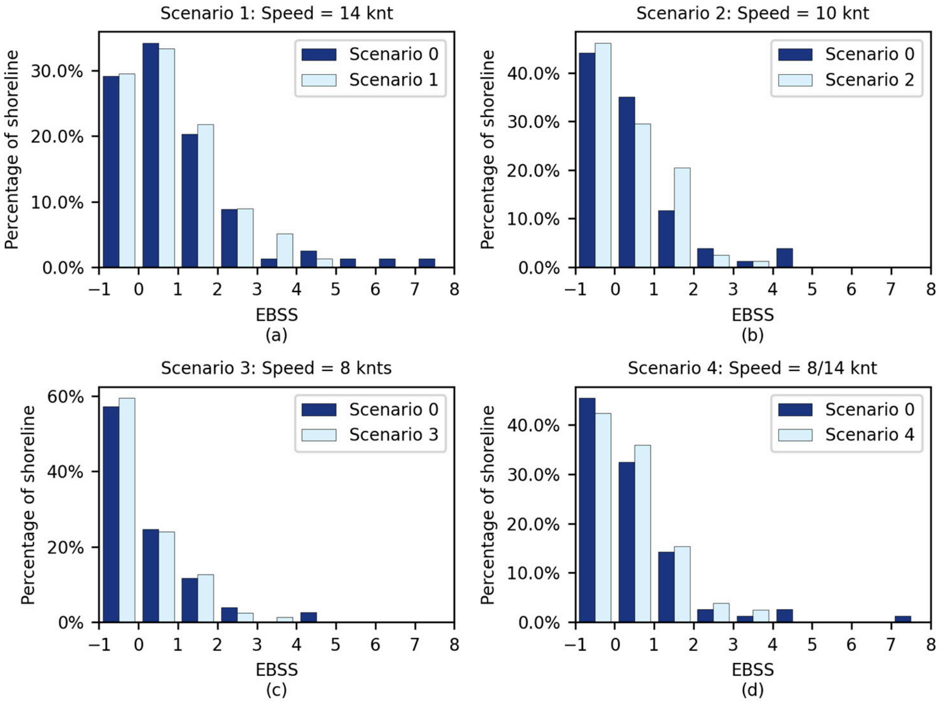

Figure 5-10.
Histogram presenting the excessive bed shear stress (EBSS) along the fairway for primary waves for different simulated scenarios. Positive EBSS indicates that the waves can mobilize sediment. (**Paper III**).

Speed is also a governing factor for determining the secondary wave height (Figure 5-11). Even though a speed of 14 knots would not change the number of locations with potential erosion, the excessive bed shear-stress would significantly increase at those sites (Figure 5-11a) and potentially increase the erosion. On the other hand, lowering the speed to 10 knots reduces the number of locations with the potential of erosion (Figure 5-11a). Lowering the speed from 12 to 8 knots would (except for a small portion of the fairway) diminish the potential for the shore to erode.

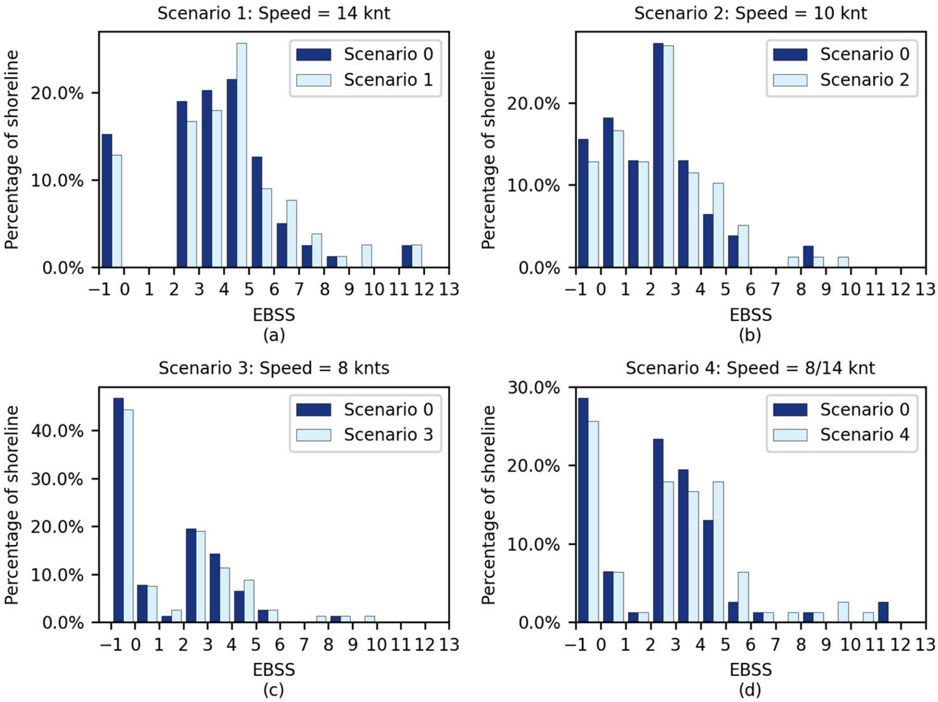

Figure 5-11.
Histogram presenting the excessive bed shear stress (EBSS) along the fairway for secondary waves for different simulated scenarios. Positive EBSS indicates that the waves can mobilize sediment. (**Paper III**)

The decision support tool developed in **Paper III** should be regarded as a tool to identify areas where ship waves may pose a problem. It can also be used for initial studies on optimal management options in a fairway. Preferably, the identified areas or the optimal managements options should thereafter be studied using a more complex model (e.g., the XBeach model presented in **Paper II**) or by initiating monitoring of the ship waves.

There are potential for further development of the decision support tool. For example, a new equation or algorithm valid for all the speed regimes and different types of vessels would improve the model. Moreover, adding the capability of estimating the sediment transport would significantly improve the usability of the model. However, this requires information about the sediment transport during single event ship passages for different sediments. In addition, the interaction between primary, secondary, and wind-generated waves in relation to sediment transport needs to be established.

5.4 Effectiveness of nature-based solutions against ship waves

The 2.5-year field study of the nature-based solutions demonstrated that the proposed design effectively dampened the water level fluctuations induced by the primary waves. Secondary waves were dissipated through breaking over the sill structure. Except during high-water events, it was observed that waves did not dissipate over the sill structure. However, during such events, the vegetation attenuated the incoming wave energy. The wave-energy dissipation was not quantified in **Paper IV**, but the wave-energy dissipation in vegetation has been verified through field and laboratory experiments in numerous studies (Gabel et al., 2017; Shepard et al., 2011).

The initial design of the nature-based solutions at Staboudde (i.e., the stone-based sill) and Kopparnäs (i.e., the coir logs) were not able to withstand the hydrodynamic forces upon them (**Paper IV**). The incoming waves, therefore, reshaped the sill and the sill dispersed throughout the beach profile. Neither was the planted vegetation in Staboudde able to stabilise the backshore without support from the sill; thus, resulting in erosion of the backshore. Therefore, in October 2019, a new sill was constructed with larger cobbles (100-400 mm). This new sill was resistant to the incoming waves, and the backshore was stabilised (**Paper IV**).

The coir logs used at Kopparnäs was not successful in resisting the conditions present at the site, resulting in deterioration and failure of the coir logs. However, this result should not be interpreted that coir logs are generally unsuitable for use in fairways. Instead, the outcome was a result of the specific coir log product used and how the installation of the coir logs was made (**Paper IV**). Eventually, the coir logs were replaced in October 2019 with a stone-based sill made of 100-400 mm in diameter stones. This sill remained stable throughout the remainder of the study.

It was concluded in **Paper IV** that the nature-based solutions with a stone-based sill were successful in retaining the erodible sediment onshore of the sills. This conclusion is motivated by that the nourished sediment at Kopparnäs was quickly eroded without any intervention (Zone A at Kopparnäs, **Paper IV**), and that the backshore retreated without the support of the sill in Staboudde.

Qualitative observations were also made about the vegetation at the case study sites. It was observed that the vegetation at Staboudde thrived behind the sill structure that had a crest-level comparable to the mean sea level. The planted reed in this zone survived, but the reed also expanded into the area not planted. This could be explained by the seeds not being washed out from the shallow zone by the ship waves due to the sill structure. At Staboudde, the planted vegetation was established. In addition, other species than those originally planted were established on the backshore (Lemel and Karlsson, 2020). This indicated that the sill structure in combination with the fill of the backshore created favourable conditions for vegetation. The fact that vegetation was not established in the zone without a backshore at Staboudde demonstrates the importance of a backshore.

Another observation about the backshore and the vegetation was their function during a high-water event from December 2019 to March 2020. During this event, the still water level was constantly above +40 cm. As a result, the wave dampening function of the sill was reduced since the sill crest is at approximately the mean sea level. Therefore, waves were able to attack the bluff base, resulting in slumping and notching of the bluff. However, the vegetated backshore reduced the incoming waves sufficiently to avoid slumping and notching on the bluff in the zone with the backshore. This can be explained by the vegetation dissipating the wave energy and that the bluff base becomes elevated due to the backshore fill.

At the third case study site, Nykvarnsholme, the bluff erosion was mitigated using a small nourishment of mixed sand material (0-4 mm). The purpose was to inhibit the retreat of the bluff without limiting the supply of sand to the adjacent beach. Expectations were that the nourished sediment would allow the erosion processes to continue without resulting in loss of land. The experiment demonstrated that the erosion of sediment was eroded without the bluff retreating. The nourished sediment was eroded entirely in the part of the bluff with a lower bluff base. In the section with a higher bluff base, the nourished sand remained during the entire study. Moreover, the adjacent beach did not erode or accumulate. In conclusion, the short lifespan of the nourishment in the lower part should be related to the small cost (i.e., monetary, sediment used, and work required) of the nourishment. In some locations, such a solution could be found feasible.

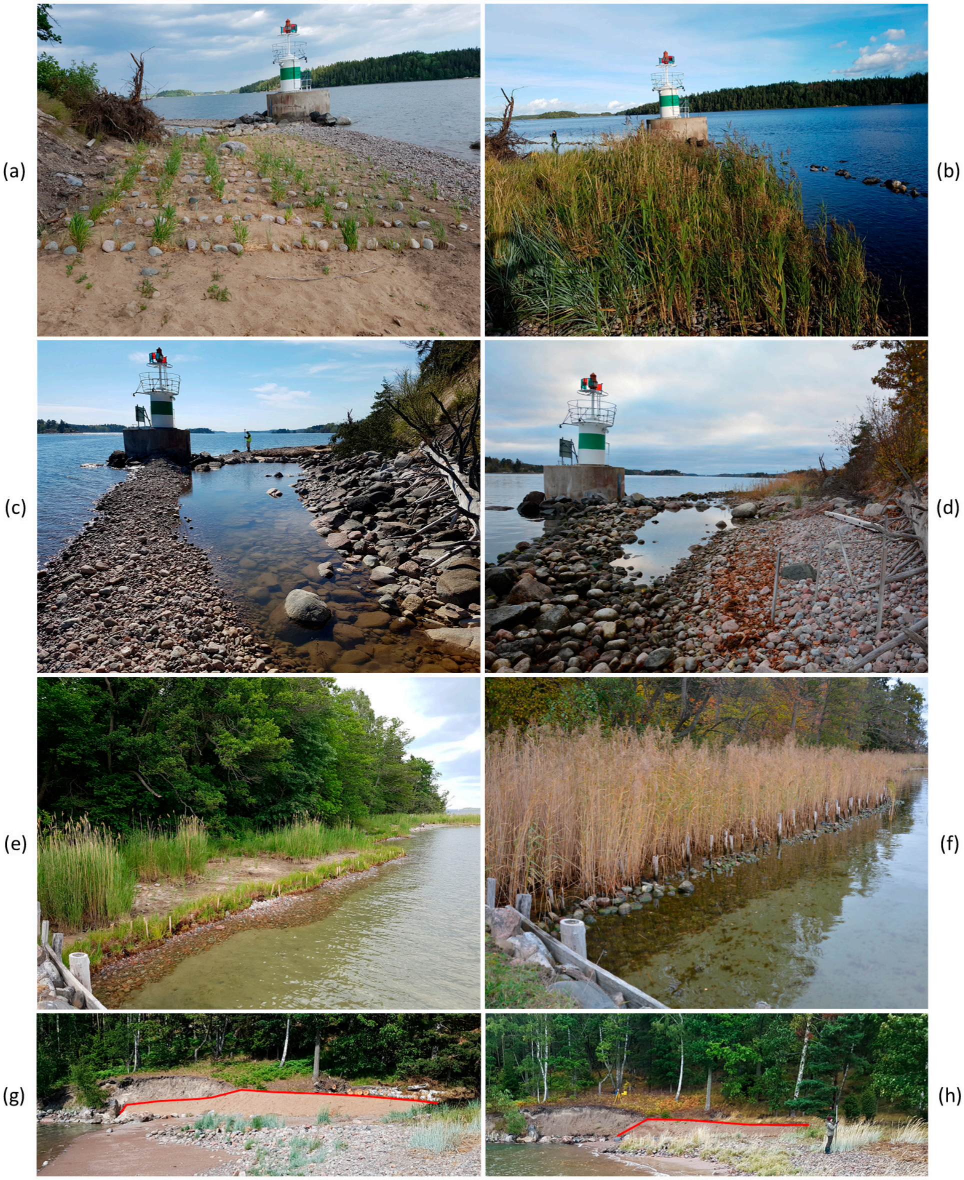

Figure 5-12.
Pictures taken of the experiment nature-based solutions just after they were implemented and just recently. (a) Staboudde - Zone A, 2018-06-08 (photo by: Björn Almström). (b) Staboudde – Zone A, 2020-09-10 (photo by: Björn Almström). (c) Staboudde – Zone B, 2018-05-08 (photo by: Björn Almsröm). (d) Staboudde – Zone B, 2021-10-12 (photo by: Anette Björlin). (e) Kopparnäs – Zone B, 2018-06-08 (photo by: Björn Almsröm). (f): Kopparnäs - Zone B, 2021-10-12 (photo by: Anette Björlin). (g) Nykvarnsholme, the red line outline the nourished sediment, 2018-06-08 (photo by: Björn Almström). (h) Nykvarnsholme, the red line outline the nourished sediment, 2020-09-10 (photo by: Björn Almström).

6 Conclusion and future work

In this thesis work, methods for achieving sustainable management of intra-coastal fairways have been developed and evaluated. Sustainable fairway management should be able to permit maritime traffic without interfering with the ecosystem services along the shores. This requires methods for predicting the hydrodynamic forces from ship waves and methods for protecting the shores from ship waves by promoting nature-based solutions.

The first three papers focused on different methods for predicting ship waves in intra-coastal fairways. In **Paper I**, measurements of ship waves were assessed, and existing equations for primary waves were evaluated. Unfortunately, none of the tested equations from the literature showed good agreement with the measurements. Therefore, a new formula was proposed based on parameters essential for the primary wave generation and on parameters available in open data sources, i.e., data from AIS and sea charts. In **Paper III**, this proposed equation was modified to include cases where the ship deviates from sailing in the mid-section of the fairway. Power coefficients in this equation were calibrated using a dataset from 2014, and it was validated based on a different dataset from 2020. The validation showed encouraging results with R^2-values of 0.86 for the drawdown height and R^2-values of 0.66 for the wave period. However, the equation needs to be further validated with independent datasets to ensure its validity in other types of fairways.

In **Paper II**, the numerical model XBeach was evaluated based on its capability to predict ship waves in intra-coastal fairways. XBeach is a hydrodynamic and morphological numerical model offering a one-tool solution for simulating ship waves from the ship to the shore. The evaluation of XBeach was based on field measurements from 2014 and included one ship that operates daily in the Furusund Fairway. In total, 42 passages were simulated, and the results showed that XBeach was able to generate and propagate primary and secondary waves. The primary waves were better represented by XBeach than the secondary waves. Though, the secondary waves were in the right order of magnitude. However, further research is required to improve how XBeach reproduces the secondary waves.

Additionally, the evaluation of XBeach included an assessment of its applicability to real-world cases. It was found that technical drawings of the ship hull are challenging to attain and cumbersome to digitize. Tests were therefore conducted using a generic hull from an open-access database. Results showed similar results, enabling reliable simulations without access to detailed information from technical drawings.

A decision support tool for fairway management in intra-coastal fairways was developed in **Paper III**. The basic principle of the tool is that it should be a model easy to apply and require little computational effort. Therefore, the model is based on input data readily available and based upon simplistic formulas for ship wave prediction. The model consists of modules for processing AIS data, fairway geometrics, ship- and wind-wave predictions, and calculating an erosion index. These modules operate independently and can easily be replaced by other modules to adopt the decision support tool to a specific case. Moreover, the module for the erosion index uses the relation between the bed shear-stress induced by waves and the critical bed-shear stress of the sediment. This approach indicates potential erosion and ranks them according to how much the bed shear stress exceeds the critical bed shear-stress.

Applying the decision support tool to the Furusund Fairway demonstrated that the tool can be used for long-term simulations (one year) and identify the areas previously reported being prone to erosion. Moreover, scenarios of different speed regulations were simulated in the decisions support tool. The results from the simulations showed that the number of locations could be decreased by reducing the speed. However, although the speed was reduced to eight knots, some areas still showed potential to erode in the Furusund Fairway. Therefore, future work should focus on the understanding of sediment transport processes in an intra-coastal fairway. For example, how do the primary, secondary, and wind waves contribute to sediment transport, and how do these waves interact in terms of sediment transport.

In **Paper IV**, different nature-based erosion protection designs were implemented to inhibit erosion and create favourable conditions for vegetation to establish. The different nature-based erosion protections targeted three types of eroding shores found in the fairway: eroding reed belts, eroding bluffs, and eroding bluffs supplying the adjacent beach with sediment. The field experiments demonstrated that a stabilizing structure (i.e., a sill) combined with vegetation can mitigate erosion and simultaneously promote vegetational growth.

The experiment showed that the hydrodynamic forces were too large for using vegetation without support. Moreover, high-water periods demonstrated that the sills wave attenuating function was diminished but that waves were attenuated by the vegetation during these events. Therefore, the conclusion from Paper IV was that the best design included a stabilizing structure (e.g., a sill) and vegetation. Additionally, nourishment of a bluff escarpment was demonstrated to be effective for reducing the retreat of the bluff without interfering with the local sediment transport system. However, this solution requires regularly occurring nourishment of the bluff base. In the future, monitoring the implemented nature-based erosion protection should continue to monitor the long-term effectiveness of the solutions. Moreover, the monitoring should be extended to include biological metrics (e.g., biodiversity, biomass).

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