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Wake Wash
in the coast of Sjællands Odde

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"When you are face to face with a difficulty,
you are up against a discovery."

WILLIAM THOMSON

Abstract

The wake wash is a phenomenon of erosion generated by the passage of ships, this is very common in river environments or in the lagoon, sometimes it is also considered in the coast.

Besides the effects generated by the passage of ships, the wind is another relevant factor responsible for the break of the fragile balance of the coast which is constantly changing.

The aim of this paper is to analyze the waves generated by *high-speed crafts (HSC)* on the coast of the Danish peninsula *Sjaellands Odde* as to make a comparison between these waves and those generated by the characteristic wind of that area.

Chapter 1

Sommario

Il Wake wash è un fenomeno di erosione prodotto dalla scia delle navi, esso è molto comune all'interno di fiumi o in laguna, ma viene anche studiato in mare aperto, come in questo studio. Il passaggio di un natante produce sulla superficie del fluido una serie di onde che variano per forma e direzione in base alla velocità del natante stesso, inoltre si genera un'agitazione che dipende dalla profondità del fondale e che può andare a movimentare il materiale sul fondo del bacino considerato.

Questo studio tratterà un caso specifico: una zona di litorale danese soggetta alle onde generate da navi ad alta velocità di passaggio dal vicino porto. Individuate le altezze d'onda a largo generate dai venti più frequenti e da un particolare modello di nave di nuova generazione, si analizzerà la trasformazione dell'onda sulla costa confrontando gli effetti delle due cause d'onda.

Capitolo 2 Secondo la teoria di *Lord Kelvin*, le onde emesse dalla prua e dalla poppa di un'imbarcazione sono divergenti e trasversali. Le onde divergenti sono osservate nella scia di una nave come una serie di creste che si muovono esternamente rispetto alla linea di navigazione, in senso obliquo. E' possibile definire tali onde come un sistema di onde piane progressive che si propagano con direzione θ dalla linea di moto della perturbazione. La teoria di Kelvin subisce modifiche in funzione di svariati effetti come la diffrazione, la distanza dalla nave, la forma dello scafo e il pescaggio. In particolare la velocità comporta notevoli cambiamenti alla scia, infatti un aumento della velocità del natante comporta un aumento più rapido dell'altezza delle onde trasversali rispetto a quelle longitudinali. E' possibile analizzare come variano le caratteristiche delle onde di scia attraverso un numero di Froude di profondità (*depth-Froude*). Si evidenziano caratteristiche molto diverse al variare di questo parametro, infatti la teoria di Kelvin si adatta bene per numeri di Froude inferiori a 0.7 , man mano che ci si avvicina a 1 i fronti divergenti si allargano, mentre quelli trasversali assumono una forma concava rispetto alla poppa del natante. Per numeri di Froude maggiori di $1 - 1.3$ l'angolo dei fronti della scia diminuisce e spariscono i fronti d'onda trasversali. La nave considerata in questo studio è un catamarano ad alta velocità HSC (*Higth Speed Craft*), avente velocità di servizio di circa 40 nodi. Con questo valore di velocità e per profondità comprese tra 10 e 20 m del fondale si ottiene un Froude superiore a 1.3 e quindi un moto in condizioni supercritiche; si tratta di un moto in planata, ossia lo scafo non è completamente sommerso. Le onde generate dal natante, specialmente se questo viaggia a velocità sostenute, sono di carattere instabile e molto variabili in vicinanza dello scafo; per questo motivo è stata considerata un'onda sufficientemente lontana dal catamarano in modo da poter considerare le sue caratteristiche stabili. Per questo studio si è scelto di utilizzare una distanza di 700m dalla rotta e per il calcolo dell'altezza d'onda generata dalla nave si è utilizzata una legge empirica, costruita sulla base di dati sperimentali di studi precedenti. A seguito di queste considerazioni di carattere teorico e sperimentale si sono valutate le caratteristiche dell'onda di scia a largo (in acque profonde), le quali saranno utilizzate come parametri di imput nel programma di simulazione.

Capitolo 3. Caratterizzazione dell'area. Le spiagge nelle zone limitrofe al porto sono caratterizzate da una riva relativamente poco profonda e prevalentemente sabbiosa con accumuli di materiale più grossolano e ciottoli. Nel litorale più a nord la costa è più uniforme e caratterizzata da sabbia grossolana e ghiaia. In assenza di prove granulometriche realizzate, si adotta una curva granulometrica per la sabbia ed una per la ghiaia di tipo standard. Si ricavano quindi i diametri dei sedimenti in corrispondenza del 50% del peso passante. In particolare si ottiene per la sabbia $D_{50} = 0.9\ mm$ e per la ghiaia $D_{50} = 7\ mm$.

Capitolo 4. Stato del mare. Dalle misurazioni dei venti nella zona tratte dagli annuali metereologici danesi si è ricostruito il clima della zona e quindi anche le caratteristiche del mare sottoposto al vento. Per il calcolo delle onde caratteristiche si sono utilizzate le formule del SPM 84 ossia il modello presentato dallo Shore Protection Manual nel 1984, aggiornate dal CERC (Coastal Engineering Research Center). L'altezza e il periodo dell'onda sono espresse in funzione della velocità del vento, della durata dell'evento anemometrico e del fetch efficace valutato lungo la direzione media del vento. E' stato misurato il Fetch geografico con l'ausilio del programma Google Earth e calcolato successivamente quello effettivo, mentre i valori del vento sono stati forniti dagli annuali meteorologici della zona. Sono stati calcolati i valori caratteristici delle onde a largo generate dai venti provenienti da tutte le direzioni e per tutte le intensità della scala Beaufort.

Capitolo 5. Simulazioni. I valori caratteristici delle onde generate dal vento e dal natante calcolati finora sono stati inseriti come condizioni al contorno nel programma Mike 21 insieme alla batimetria dell'area di interesse. MIKE 21 è un pacchetto software ingegneristico professionale di simulazione per le correnti a pelo libero con schema bidimensionale, applicabile in ambiente fluviale e marino indistintamente. In particolare per questo studio è stato utilizzato per simulare la trasformazione dell'onda da largo a riva.

Capitolo 6. Risultati. Per il confronto e l'analisi dei dati si sono scelti tre punti posti lungo la costa tutti ad una profondità di $-3\ m$ dal SWL (sea water level). Per quanto riguarda i venti sono stati considerati solamente quelli aventi un Fetch rilevante per l'area di considerazione, infatti dal momento che il porto e il litorale sono rivolti verso ovest i venti provenienti da angoli compresi tre 0° e 180° in senso orario (con $0° = Nord$ e $180° = Sud$) sono irrilevanti perché raggiungono il litorale considerato solo attraverso i fenomeni di trasformazione. Per le onde generate dal passaggio delle navi invece, dal risultato delle simulazioni, si è scelto di considerare solamente quelle dovute alle navi in arrivo perché, avendo una direzione praticamente ortogonale alla costa, hanno effetti più gravosi.

Dal confronto delle altezze d'onda in questi tre punti si evince che l'onda generata dal natante è paragonabile a quella dei venti aventi velocità di 6.7 m/s, i quali sono anche i più frequenti. In termini di frequenze calcolando il totale degli arrivi o più in generale dei passaggi del catamarano in un anno si ottiene un valore percentuale dell'1% che è minore della frequenza dei venti che generano un'onda della stessa altezza (il vento di 6.7 m/s da Ovest ha una frequenza del 6% circa).

Velocità delle particelle: Una sostanziale differenza tra le onde generate dal vento e quelle generate dal catamarano è il periodo, infatti, mentre le onde da vento hanno periodi compresi tra $3 - 4\ s$, quelle della nave hanno un periodo di 10 s. Questo produce a parità di altezza d'onda una maggiore lunghezza d'onda e quindi una maggiore velocità massima delle particelle sul fondo. Confrontando i valori delle velocità massima delle particelle in corrispondenza dei tre punti a 3 m

di profondità si nota che le onde della scia sono paragonabili ai venti di 9.35 m/s, più gravosi dei precedenti. Per dare un'idea dell'entità dell'erosione i valori delle velocità delle particelle al fondo nei tre punti considerati sono stati messi a confronto con la velocità critica di trascinamento propria del materiale che compone il litorale. Dal confronto si evince come i punti situati in un fondale sabbioso siano soggetti ad erosione e come il catamarano sia la causa di un'erosione maggiore rispetto al vento, il quale erode in condizioni di velocità superiori ai 9.35 m/s. In termini di frequenza però i venti in grado di movimentare il materiale sul fondo fino ad una profondità di tre metri sono molto più frequenti, nell'ordine del 14%, rispetto alle onde generate dal natante.

Run-Up: Per completare l'analisi si è proceduto con il calcolo del Run-up, ossia della risalita dell'onda in seguito al frangimento a riva. Per il calcolo del run-up è necessario conoscere le caratteristiche delle onde a largo e da esse calcolare l'indice di Iribarren. I tre punti esaminati sono sollecitati da onde con le medesime caratteristiche a largo e possiedono un fondale profondo 3 metri. Rispetto alla linea di costa, il punto 1 ed il punto 3 sono posti alla medesima distanza (160 m), mentre il punto 2 è più lontano (190 m). L'altezza d'onda prodotta dal natante è circa la metà di quella generata dai venti, ma la sua lunghezza d'onda è quasi il doppio rispetto alle altre. Ciò comporta un maggiore indice di Iribarren per le onde prodotte dal natante, quindi una maggiore risalita dell'onda. In conclusione gli effetti erosivi dovuti alla risalita dell'onda generata dal catamarano non sono trascurabili e anzi sono maggiori rispetto a quelli prodotti dai venti più frequenti.

Contents

Chapter 2

Introduction

The coastline is a spatial zone where interaction of the sea and land processes occur, it is a balance of several natural elements: the weather, the wind, the geographical areas, the materials and the tides. The coast and its adjacent areas on and off shore are a significant part of a local ecosystem. The high level of biodiversity creates a high level of biological activity which has attracted human activity for thousands of years. Take a moment to realize that the first civilizations developed along the coast, and even nowadays the coasts are more populated respect to the mainland areas. Man has always sailed the sea for fishing, trade and other economic reasons and often struggled to protect or recapture those areas which could be eaten by the sea.

As a matter of fact, waves can carry sediments and cause erosion to the beaches thanks to their strength during storms. In a short time, the sea can drastically change the morphology and the ecosystem of an entire area. Waves are principally generated by the wind, but they are also generated by ships too, which in recent decades have become faster, larger and constanlty stretch the present routes.

The steady increase in water traffic produces a series of damages, direct and indirect, including:

- Damage to the shore and to the works of shore;
- Erosion of the seabed in particular in the shallow water, resulting in loss of biotopes that are of vital importance for the balance of the ecosystem;
- Threat to public safety due to the wave agitation in the seashore;
- Air and noise pollution.

New generation ships such as catamarans are different from conventional vessels because they move on the surface layer of the water producing different wave fronts, which come toward the coast and cause erosion. Wake wash is a peculiar phenomenon of erosion generated by the passage of ships it has been studied especially in ports and channels because of residual agitation; however sometimes it can be interesting to explore this phenomenon it in the open sea context as in the case of this paper.
The aim of this project is to evaluate the wave generated by a new high speed craft *catamaran* of 112 m, which will plow the waters between *Ebeltolf-Sjællands Odde* and *Aarhus-Sjællands Odde* and analyze the wave tranformation along the coasts of *Sjællands Odde*. A comparison between wind-generated waves and vessel-generated ones will be made. This study will be realized also through the help of a DHI's recognized phase-averaged spectrel wave model **Mike 21 SW**.

Chapter 3

Ship waves theory

A ship moving over the surface of undisturbed water sets up waves emanating from the bow and stern of the ship. Wave systems created by ships comprise a primary and a secondary component, where the primary wave system has its origin in the water pressure and velocity distributions which exists along a moving ship hull. Assuming schematic ship geometry, an ideal variation in both pressure and velocity will occur as the ship moves relative to the water.
By considering water as an incompressible fluid, the Bernoulli equation states that, for two arbitrary points 1 and 2 along the ship hull:

$$\left(\frac{U^2}{2} + gz + \frac{p}{\rho}\right)_1 = \left(\frac{U^2}{2} + gz + \frac{p}{\rho}\right)_2 = costant \tag{3.1}$$

Where:

- U = Ship velocity relative to water velocity $[ms^{-1}]$
- g = Acceleration due to gravity $[ms^{-2}]$
- z = Distance from reference level [m]
- p = Pressure [Pa]
- ρ = Density $[kg\ m^{-3}]$

The Bernoulli equation states that if one or several parameters change at one location, so must one or several do for the other point as well.

Ideally, this will create a single wave with a wavelength approximately equivalent to the ship length, with wave crests by the bow and stern and a wave trough midships, which correspond to the primary wave system, visualized in Figure 3.1. Subsequently, the ship is forcing a finite volume of water in front of its stern. The

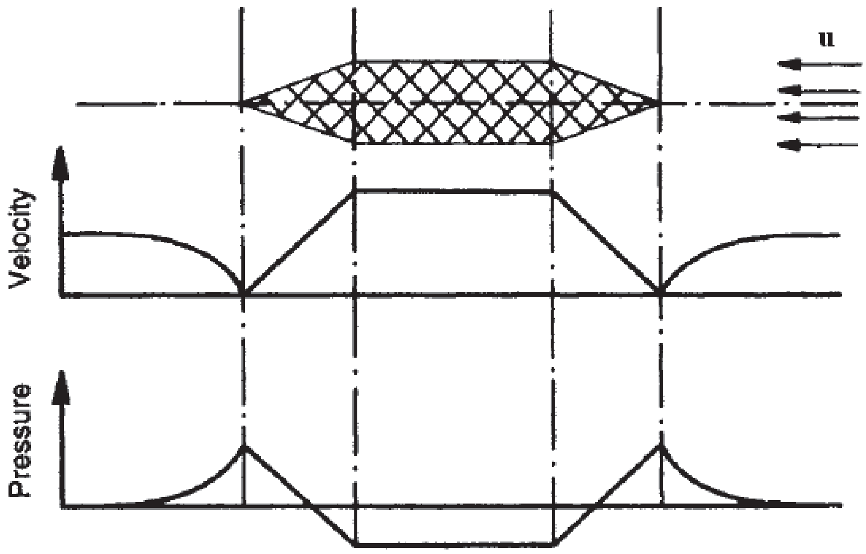

Figure 3.1: Water pressure and velocity distribution of an ideal fluid along a ship-like body, inducing the primary wave system of a ship ([1]).

primary wave system can have a long wave period, and the wave trough, which appears mid-ships, is called drawdown.

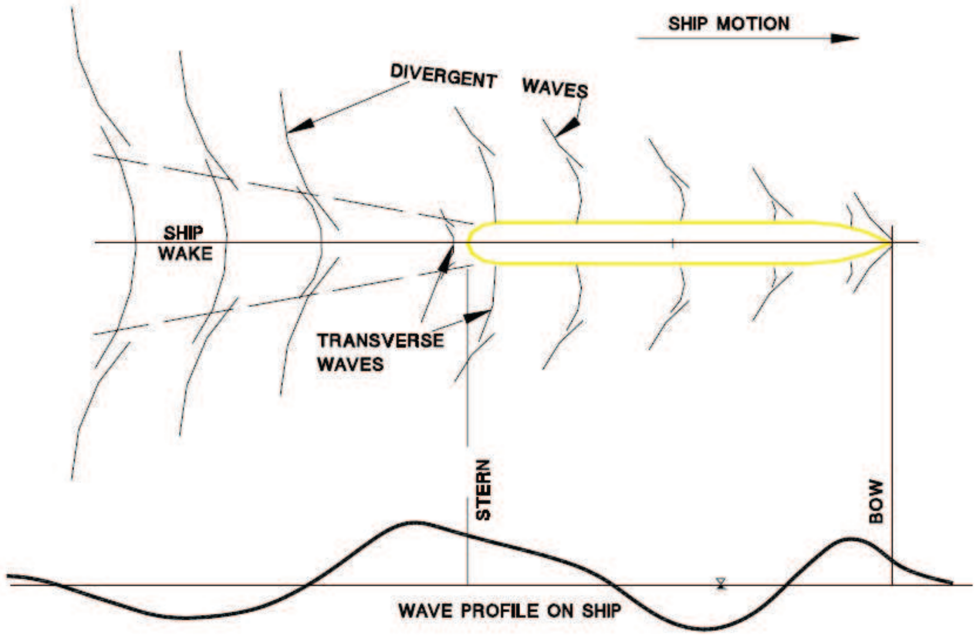

Figure 3.2: Primary and secondary wave system induced by ship activity.

There are many authors who have studied the characteristics of waves generated by ships, especially in recent decades such as *Kriebel and Seeling 2005* [7] or

Bertram 2000 [1], they have assessed the factors that depend on the waves.
The characteristics of ship-induced waves differ greatly depending on whether they are formed in deep or shallow and unrestricted or restricted waters. Other factors which affect the wave system are:

- Ship dimensions and hull design.
  This includes the overall ship length, width, and the slenderness of the ship.

- Ship draught.
  The draught of a ship is approximately linearly dependent on the total displacement of water, which affects the Bernoulli wave formation.

- Ship velocity relative to water velocity.
  The ship velocity is one parameter included in the Froude number. As stated earlier, the ship velocity relative to the water velocity affects the amplitude and period of the waves to a great extent.

- SWL depth.
  The water depth influences whether ships navigate in shallow, transitional, or deep water. These conditions influence the waves.

Lord William Thomson Kelvin has been the first who studied the continuous disturbance caused by an object crossing a liquid surface. Through his studies, he developed an exhaustive theory of this phenomenon elucidated in a paper entitled *"On Ship Waves"* presented in Edinburgh in August the 3rd 1887. By observing a disturbance of a surface pressure point that moves with velocity U on a stationary fluid surface, he noted this moving point generated a field of waves formed by the union of two systems: a system of diverging waves and a system of transverse waves. As a matter of facts, Kelvin is the father of the so-called *"Kelvin wake"* pattern in which we can observe a series of waves which propagate within an angle formed by the envelope of the waves caused by a body that proceeds at constant speed in deep water. Waves created by the bow and stern of the boat will at first be divergent and then transverse. The diverging waves are to be observed in the wake created by a ship as a series of ridges that move externally and in an oblique way with respect to the navigation course. As these phenomena have been observed by Kelvin, it is possible to define such waves as a system of progressive plane waves that propagate in the direction θ from the line of motion of the perturbation [10].

3.1 Translating Coordinate System

Let consider a standard fixed coordinate system (x, y, z) and a moving coordinate system which is moving in the x direction with speed U. The moving coordinate systems can be denoted in the x direction by:

$$\begin{cases} X = x + Ut \\ Y = y \\ Z = z \end{cases} \tag{3.2}$$

Let $\Phi(\mathbf{x}, t)$, be the velocity potential describing the potential flow generated by the ship relative to the earth frame. The same potential expressed relative to the ship frame is $\bar{\Phi}(\mathbf{X}, t)$. The relation between the two potentials is given by the identity

$$\Phi(x, y, z, t) = \bar{\Phi}(X, Y, Z, t) = \bar{\Phi}(x - Ut, y, z, t) \tag{3.3}$$

where the relation between the coordinates of the two coordinate systems has been introduced. Note the time dependence occurs in two places in $\bar{\Phi}$, and in one place in Φ . The governing equations are always derived relative to the earth coordinate system and time derivatives are initially taken on Φ. Therefore

$$\frac{\mathrm{d}\Phi}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\bar{\phi}(x - Ut, y, z, t) = \frac{\partial \phi}{\partial t} - U\frac{\partial \phi}{\partial x} \tag{3.4}$$

All time derivatives of the earth fixed velocity potential Φ, which appear in the free surface condition and the Bernoulli equation can be expressed in terms of derivatives of $\bar{\Phi}$, using the Galilean transformation derived above. If the flow is steady relative to the ship fixed coordinate system

$$\frac{\partial \bar{\Phi}}{\partial t} = 0 \tag{3.5}$$

but

$$\frac{\mathrm{d}\Phi}{\mathrm{d}t} = -U\frac{\partial \bar{\Phi}}{\partial x} \tag{3.6}$$

the ship wake is stationary relative to the ship but not relative to an observed on the beach.

3.2 Kelvin wake

Local view of Kelvin wake consists approximately of a plane progressive wave group propagating in direction θ. As noted above surface wave systems of general form always consist of combinations of plane progressive waves of different frequencies and directions. The same model will apply to the ship kelvin wake. Relative to the earth frame, the local plane wave in Infinite Depth takes the form

$$\Phi = \frac{\mathrm{i}gA}{\omega} e^{kz - \mathrm{i}k(x\cos\theta + y\sin\theta) + \mathrm{i}\omega t} \tag{3.7}$$

Relative to the ship frame

$$\bar{\Phi} = \frac{igA}{\omega} e^{kz - \mathrm{i}k(x\cos\theta + y\sin\theta) - \mathrm{i}(kU\cos\theta - \omega)t} \tag{3.8}$$

But relative to the ship frame waves are stationary, so we must have:

$$\begin{cases} kU\cos\theta = \omega \\ \frac{\omega}{k} = V_p = U\cos\theta \end{cases} \tag{3.9}$$

This implies the following:

- The phase velocity of the waves in the kelvin wake propagating in direction θ must be equal to $U\cos\theta$, otherwise they cannot be stationary relative to the ship.
- Relative to the earth system the frequency of a local system propagating in direction θ is given by the relation

$$\omega = kU\cos\theta \tag{3.10}$$

Relative to the earth system the *Infinite Depth Dispersion Relation for a Free Surface* states:

$$\omega^2 = gk \tag{3.11}$$

So putting together the two equations (3.10) and (3.11)

$$k^2U^2\cos^2\theta = gk \tag{3.12}$$

so that

$$k = \frac{g}{U^2\cos^2\theta} \tag{3.13}$$

$$\lambda(\theta) = \frac{2\pi U^2\cos^2\theta}{g} \tag{3.14}$$

This is the wavelength of waves in a Kelvin wake propagating in direction θ, which are stationary relative to the ship.

3.3 Application of the Group velocity

An observer sitting on an earth fixed frame observes a local wave system propagating in direction θ travelling at its group velocity $\frac{d\omega}{dK}$, by virtue of the Rayleigh device, which states that we need to focus on the speed of the energy density ($\sim$ wave amplitude) rather than the speed of wave crests.

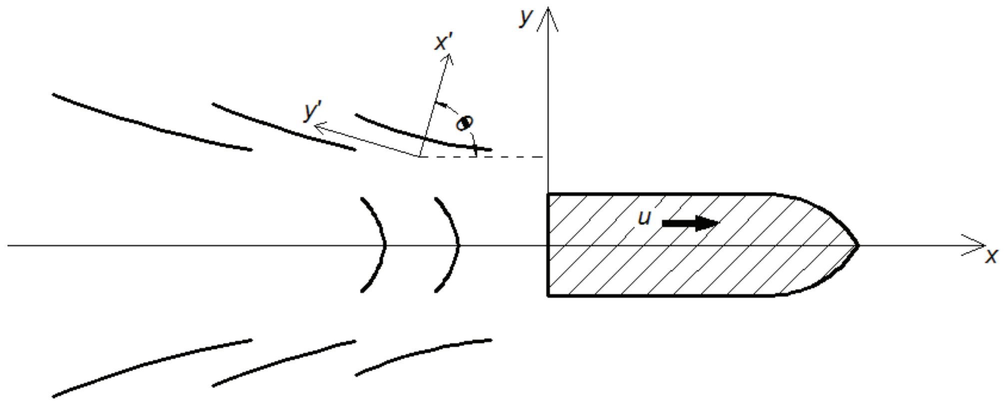

Figure 3.3: Inclined coordinate system of Kelvin wake.

So, relative to the earth fixed inclined coordinate system (X', Y'):

$$\begin{cases} V_g = \frac{d\omega}{dK} = \frac{X'}{t} \\ X' = \frac{d\omega}{dK}t = 0 \\ \frac{d}{dK}(KX' - \omega t) = 0 \end{cases} \tag{3.15}$$

Geometrically:

$$X' = [X\cos\theta + Y\sin\theta]_f ixed = [x\cos\theta + y\sin\theta + Ut\cos\theta]_{mobile} \tag{3.16}$$

So

$$KX' - \omega t = K(x\cos\theta + y\sin\theta) + (KU\cos\theta - \omega)t \tag{3.17}$$

Replacing the equation 2.17 in 2.15

$$\frac{d}{dK}(KX' - \omega t) = \frac{d}{dK}[K(x\cos\theta + y\sin\theta) + (KU\cos\theta - \omega)t] = 0 \tag{3.18}$$

However

$$(KU\cos\theta - \omega)t = 0 \tag{3.19}$$

so that the Rayleigh condition for the velocity of the group takes the form:

$$\frac{d}{dK}[K(\theta)(x\cos\theta + y\sin\theta)] = 0 \tag{3.20}$$

It follows that from the dispersion relation derived above and from the chain rule of differentiation Rayleigh's condition is:

$$\frac{d}{d\theta}\left[\frac{g}{U^2\cos^2\theta}(x\cos\theta + y\sin\theta)\right] = 0 \tag{3.21}$$

At the position of the Kelvin waves which are locally observed by an observer at the beach. So the "visible" waves in the wake of a ship are wave groups which must travel at the local group velocity, except when $\theta = 0$ and $\theta = +-\frac{\pi}{2}$, i.e. the derivatives are rispectively infinite or zero. These conditions translate into the above equation which will be solved and discussed next.

The solution of the above equation will produce a relation between $\frac{y}{x}$ and θ. So local waves in a Kelvin wake can only propagate in a certain direction θ, given $\frac{y}{x}$. Simple algebra leads to:

$$\frac{y}{x} = -\frac{\cos\theta\sin\theta}{1+sin^2\theta} = \frac{y}{x}(\theta) \tag{3.22}$$

which implies that

- $\frac{y}{x}(\theta)$ is anti-symmetric about $\theta = 0$ and each part corresponds to the Kelvin wake in the port and starboard sides of the vessel. The physics on either side is identical due to symmetry.
- $\theta = 0$: waves propagating in the same direction as the ship. These waves can only exist at $Y = 0$ as seen above.
- $\theta = \frac{\pi}{2}$: waves propagating at a 90° angle relative to the ship direction of forward translation.
- $\theta = 35°16'$ (or $35,26°$) waves propagating at an angle $\theta = 35°16'$ relative to the ship axis. These are waves seen at the caustic of the Kelvin wake.

Let the solution of $\frac{y}{x}(\theta)$ be of the form, when inverted:

$$\text{Region I}: \qquad \theta = f_1(\frac{y}{x}) \tag{3.23}$$

$$\text{Region II}: \qquad \theta = f_2(\frac{y}{x}) \tag{3.24}$$

Note that observable waves cannot exist for values of $\frac{y}{x}$ that exceed the value shown in the figure or $\frac{y}{x}\Big|_{Max} = 2^{-3/2}$. This translates into a value for the corresponding angle equal to $19°28'$ (or $19,47°$) which is the angle of the caustic for any

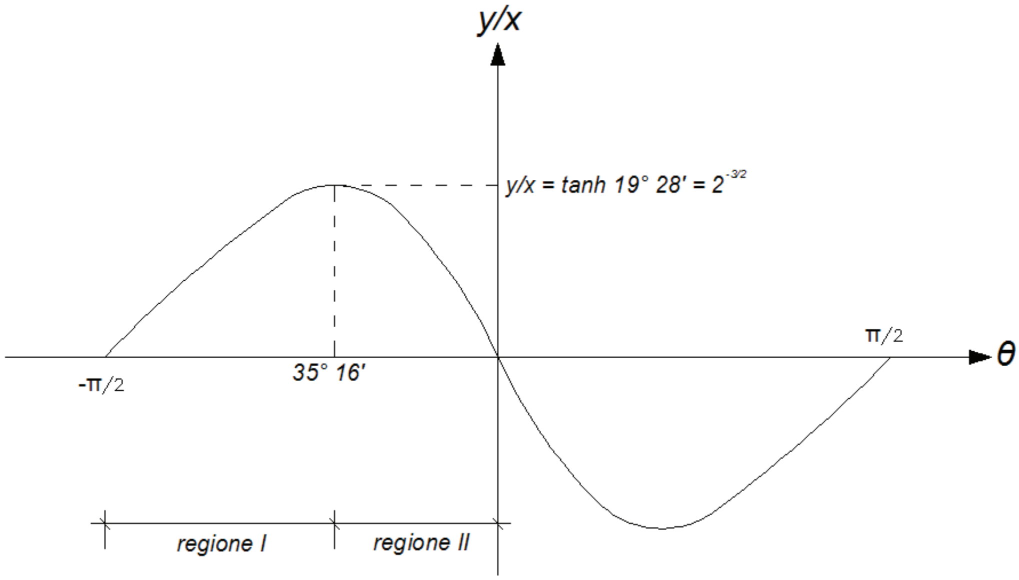

Figure 3.4: Regions of the Kelvin wake.

speed U.

The crests of the wave system trailing a ship, the Kelvin wake, are curves of constant phase of:

$$\frac{x\cos\theta + y\sin\theta}{\cos^2\theta} = \mathbf{C} \tag{3.25}$$

In Region I:

$$C = \frac{x\cos f_1(\frac{y}{x}) + y\sin f_1(\frac{y}{x})}{\cos^2 f_1(\frac{y}{x})} \equiv G_1(\frac{y}{x}) \tag{3.26}$$

In Region II:

$$C = \frac{x\cos f_2(\frac{y}{x}) + y\sin f_2(\frac{y}{x})}{\cos^2 f_2(\frac{y}{x})} \equiv G_2(\frac{y}{x}) \tag{3.27}$$

Plotting these curves we obtain a visual graph of the "transverse" and "divergent" wave systems in the Kelvin wake.

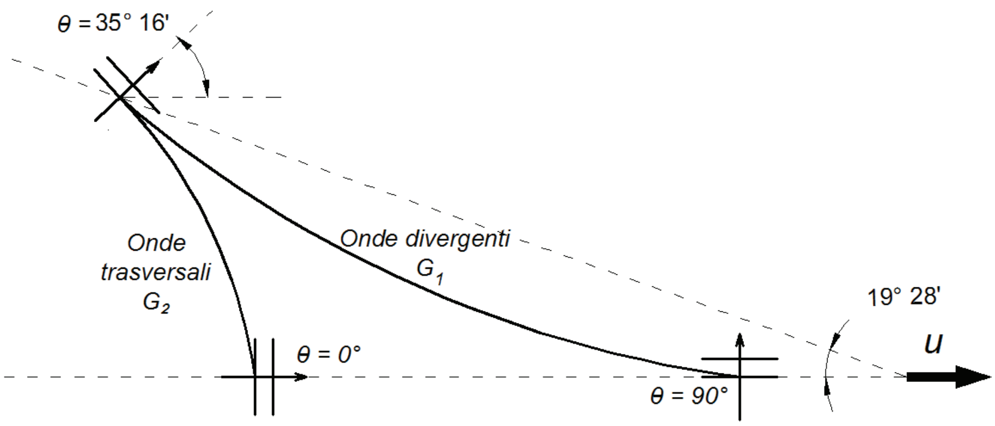

Figure 3.5: Transverse and divergent wave system in the Kelvin wake.

The theory of Kelvin undergoes changes due to several effects, for example the diffraction, the distance from the ship, the hull shape and the draft. In particular, the speed involves significant changes to the wake, in fact, an increase in the vessel's speed involves an increase of the divergent wave height and a reduction of the transverse waves. Through a *depth-Froude* number is possible to analyze how the characteristics of the wake waves change.

$$F_{nh} = \frac{V_S}{\sqrt{gh}} \tag{3.28}$$

where

- V_S is the vessel speed (m/s)
- h is the water depth (m)
- g is the gravitational constant $(9.81\ m/s^2)$

The depth Froude number can change because of two reasons, namely if the SWL depth or the ship velocity relative to water velocity changes. A decrease in Froude number means that either the ship velocity has decreased or that the SWL height has increased, i.e. the bed is declining (naturally both parameters can change at the same time). An increase in Froude number then has the opposite parametric change.

In the subcritical speed range (i.e. $F_{nh} < 0.7$), the wave system consist of diverging and transverse waves in a restricted wedge-shaped Kelvin wake, where the cusp angle is about $\pm 19.5°$ and almost independent of the ship speed. In this speed range, the wave period of the diverging waves is proportional to the ship speed ($T_s = 0.27V_s$, V_s in knots). For depth-Froude numbers beyond 1 (*supercritical speed range*), the transverse waves disappear and the wave system is characterized by a wave pattern with a convex form. This is typically the case for HSC operating in coastal water, as in this study. The divergent waves are now contained within an angle that depends on the speed of the ship. In the transcritical speed range ($F_{nh} = 0.9 \div 1.1$), transverse and divergent waves merge together into wave fronts nearly straight and perpendicular to the ships course. The figures clearly represent the three different behaviors. The waves generated by the vessel, especially if it is

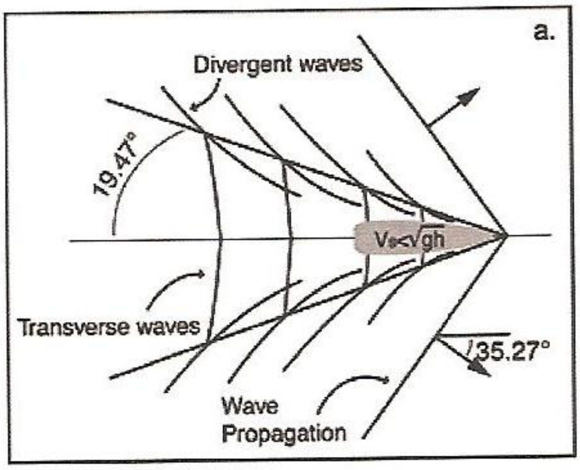

Figure 3.6: Vessel wake waves at subcritical speed $F_{nh} < 0.7$.

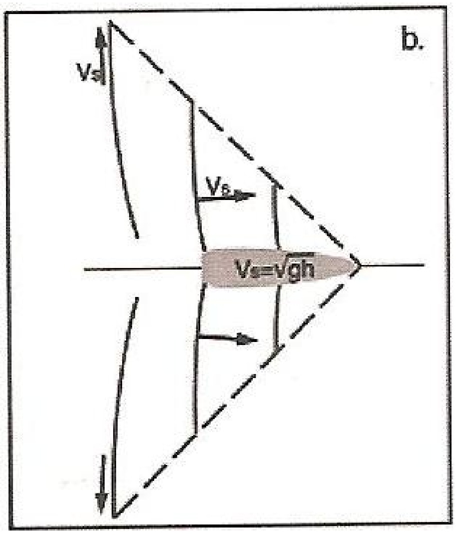

Figure 3.7: Vessel wake waves at transcritical speed, showing the wave propagating forward and the crest lengthening at vessel speed $F_{nh} = 0.9 \div 1.1$.

traveling at high speeds, are highly variable and unstable in the vicinity of the hull.

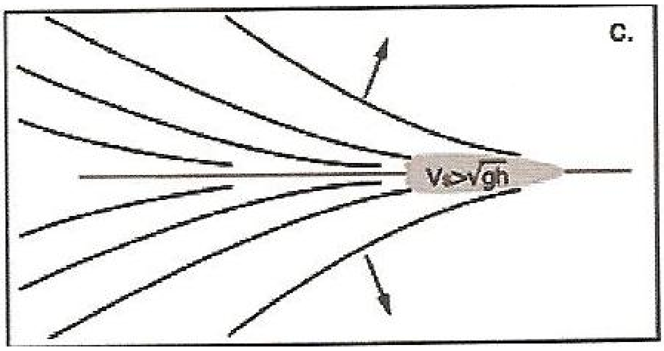

Figure 3.8: Vessel wake waves at supercritical speed $F_{nh} > 1$.

For this reason it has been considered a wave far enough away from the catamaran so the characteristics of the waves can be considered stable. In order to evaluate the ship wave height it has been chosen a distance of 700m (about 10 ship-lengths) from the navigation track and an empirical law, built on the basis of experimental data of previous studies.

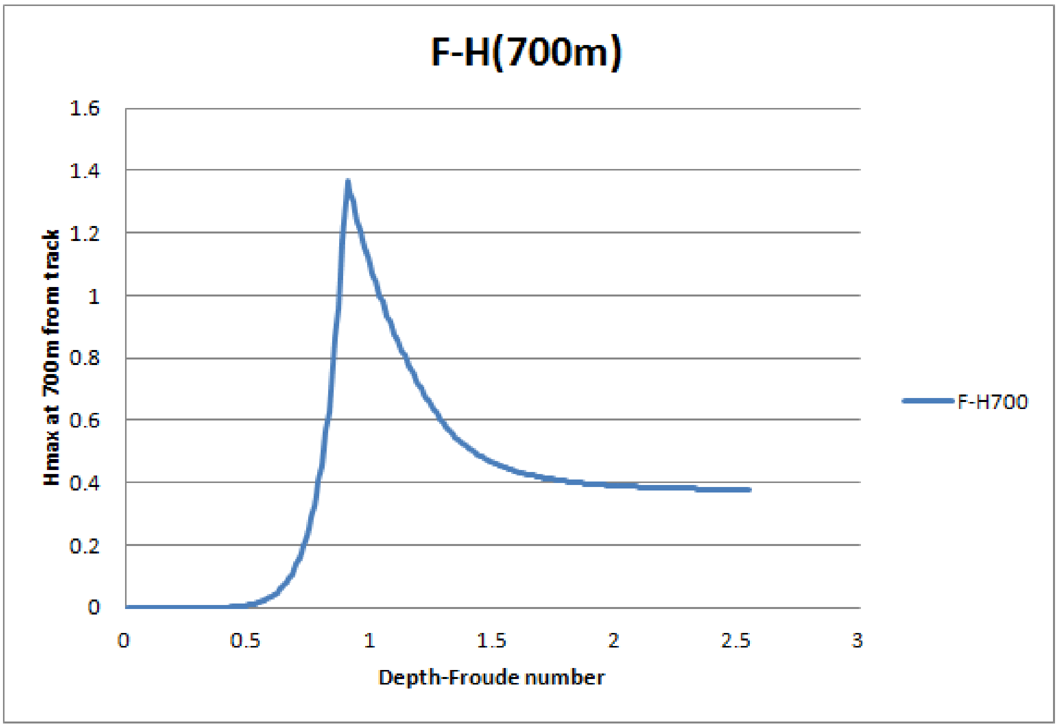

Figure 3.9: Emphirical law of decay.

$$H_{max}(700m) = \begin{cases} 1.3(F_{nh}+0.1)^{10} \ for \ F_{nh} \leq 0.9 \\ 1.3(F_{nh}+0.07)^{-2.5} \ for \ 0.9 < F_{nh} \leq 1.3 \\ 1.04(0.36+\frac{1}{F_{nh}^6}) \ for \ F_{nh} > 1.3 \end{cases} \tag{3.29}$$

3.4 Incat 112 Ferry

In 2012 he shipping company Mols-Linien has put into operation a new ship model in the ferry routes Aarhus-Sjællands Odde and Sjællands Odde-Ebeltorf. It is a 112m high-speed wave piercing catamaran veicle passenger ferry designed by Revolution Design and built in Australia by Incat Tasmania Pty Ltd. This new ferry replaces the previous model of 91m, which operated on the same route in the recent decades.

Figure 3.10: Image of the Incat 112 Ferry.

The HSC Incat 112 Hull #066, this is the full name of the ferry, has an overall length of $L_{oa} = 112.6m$. The hull is slender with a waterline length of $L_{wl} = 105.6m$, a draft of 3.5m, an individual hull beam of 5.8m and an overall beam of 30.5m. All the characteristics of the ship have been taken from the Tecnical Report [4] .

Since May 1997 the operators of high-speed craft shall provide a documentation on the wave generated by the vessel in the line parallel to the shore at 3m water depth. This wave is subjected to a limit dictated by the *Danish Maritime Authority* in order to not interfere with the small navigation along the coast and for the safety of leisure activities on the shore. The wave height criterion is:

$$H_h \leq 0.5\sqrt{\frac{4.5}{T_h}} \tag{3.30}$$

Where $H_h$is the maximum wave height [m] of the long-period wave generated by the ship and $T_h$is the corresponding period [s].

Vessel type	Incat 112 Hull #066
Overall length L_{oa}	112.6m
Waterline length L_{wl}	105.6m
Overall beam	30.5m
Draft	3.5m
Light displacement	~ 1491 tonnes
Full displacement	~ 3000 tonnes
Service speed	40

Figure 3.11: Dimensions of Incat 112.

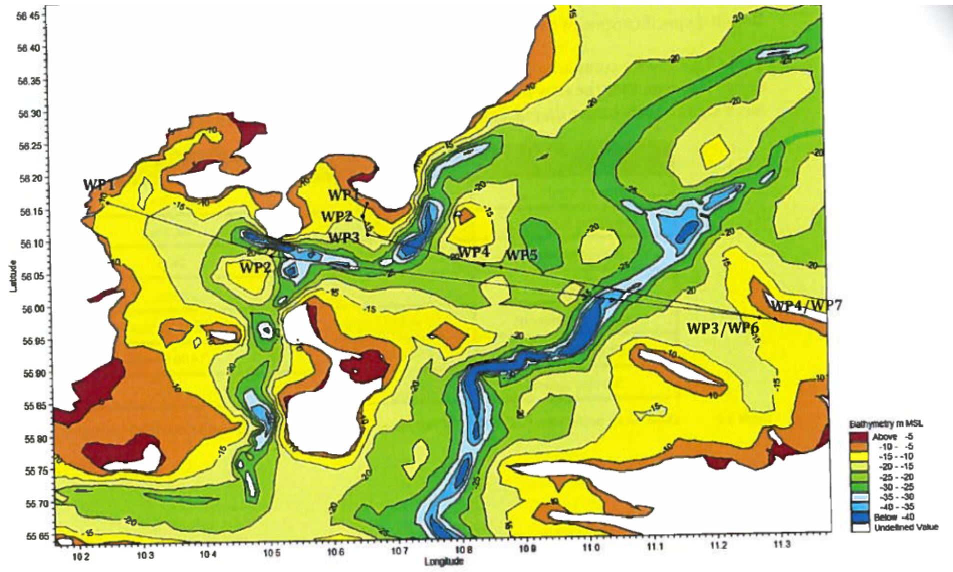

Figure 3.12: Intended routes.

In this study will be analyzed through the computerized modelling program *Mike 21* the evolution of the long-period ship-generated wave and the results will be compared with the wind-generated waves.

Wake data

To establish the initial conditions of the wave generated by the vessel along the route it has been used previous studies of wake waves close to a high-speed catamaran, treated in the Technical Report [4] and performed with laboratory tests and advanced numerical models from DHI *(Danish Hydraulic Institute)*.

The characteristics of the ship-wake wave are determined with the depth-Froude number. The speed of the ship analyzed is approximately 40 knots and with depths within 10 – 20 m so the Froude number exceeds 1.3. The motion is in *supercritical conditions*.

The maximum wave heigth is in the third part of the empirical low of dacay, this is clear also from the sperimental analysis shown in the figure (3.13).

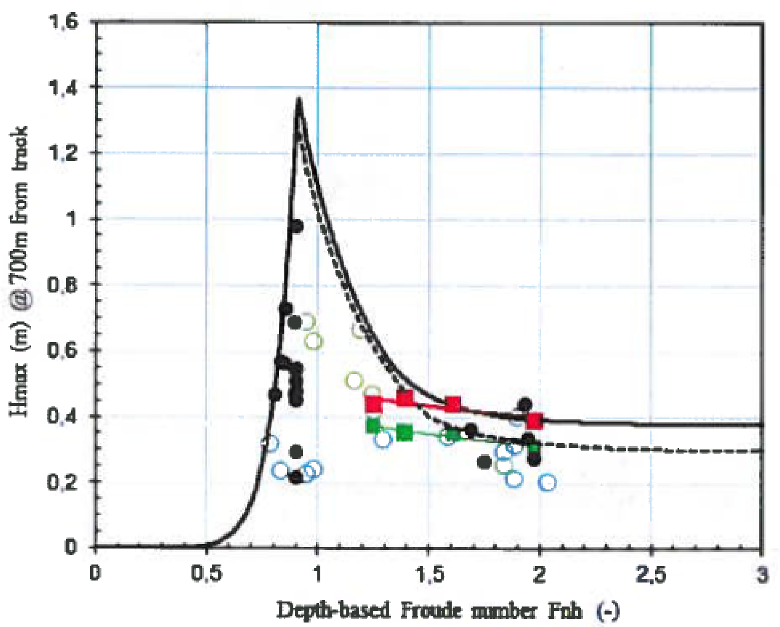

Figure 3.13: Graphical law of decay with sperimental data. The red line is the Incat 112

Concerning the wave period the Incat 112 generates a wave train that consists in groups of three or four waves. The first group contains the long-period waves (7-10s), this is followed by other groups of shorter wave period (4-5s) and (2-3). The long-period waves travel faster than the short one and they first reach the coast climbing over them. With the evolution in shallow water the long-period waves can have a significant impact on the small navigation or also in leisure activities. The wave height generated by vessels decreases moving away from the route, while the period of the same increases slightly.

Vessel Type	Vessel speed (knots)	Water depth (m)	F_{nh} (-)	H_{max} at $2L_{wc}$ (m)	Wave period (s)	Wave direction (°)	H_{max} at 700m (m)
Incat 112	38	10	1.97	0.73	8.6	60	0.39
		15	1.61	0.82	9.4	55	0.44
		20	1.39	0.86	9.7	49	0.46
		25	1.25	0.82	10.8	47	0.44

Figure 3.14: Summary of results obteined from laboratory test taken from reference [4] .

In the numerical model will be inserted a wave valued at 700 meters from the ship with the following characteristics:

$$\begin{cases} H_{Ship} = 0.43m \\ T_{ship} = 10s \end{cases} \tag{3.31}$$

Finally, it was found that for high-speed ships, thus with a depth-Froude number greater than 1 as in this case, the wavefront developed is inclined about 60° relative to the direction of the vessel (Figure 3.14). In the simulations will be used ship-generated waves from 240° for the arriving vessels and from 150° for the departing ships.

Chapter 4

Areas Background

Sjællands Odde is a peninsula 15 km long situated in the northen part of Sjælland, which is the largest island of Denmark. This area was a cluster of islands linked by the sea debris during the Stone Age, now it is a very straight hilly peninsula caracterized by cliffs and pebbly beaches. In the middle of the peninsula there is the ferry port in which the ferry company Mols-Linien operates catamaran services from the there to Aarhus and Ebeltoft ports.

Figure 4.1: Sjælland island and Sjællands Odde in the green circle.

Figure 4.2: Particular vision of the Sjællands Odde port.

The most exposed area to erosion is the east side of the peninsula because it is very exposed to the winds from west, as it will be seen later they are the most frequent. The history of the coasts of this side is characterized by violent storms, erosion and long-shore transport. In this study it will be analyzed the areas close to the harbor, on both sides, which are directly invested by the waves generated by the vessels. All the features and descriptions of the area have been taken from the Technical Report [5] Gniben, the northern part of Sj.Odde has not been considered

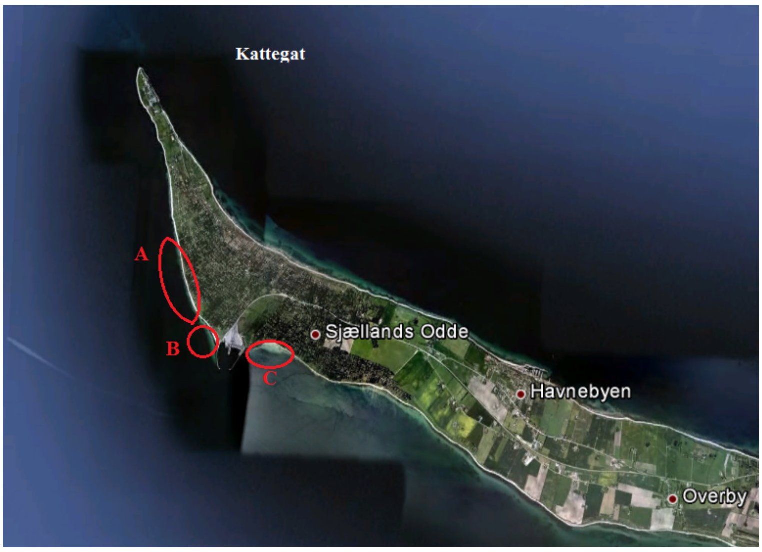

Figure 4.3: Areas considered in this study.

in this study because the shoreface and the beach are heavily covered with pebbles

and stones and in a return period of 100 years it is considered stable.
The area A (Figure 4.3) is said *Gniben-Snekkbjerg*, it has been subjected in recent decades to strong erosion and a general retreat, visible from the maps dating $1928 - 1940$ (it is a retraction in the order of 50 m). In this area there is low deposit on the sea-bottom and in addition the zone is subjected to flooding. The beach is narrow and mainly composed of pebbles and stones with bigger boulders scattered and a steep shoreline preceded inland by a low bluff (about 1 m height) composed of fine gravel. The area suffers from bluff erosion and in addition flooding in the first inland. The long-shore transport of material occurs mainly towards south, south-east and it is due to the predominance of waves from west. However it is small due to the coarse nature of the material that makes up the beach. The predominant transport is due to the cross-shore, which generates excavation of gravel during exposure to storm surges. A significant number of brushes is present along this coast, those are signs of interventions made in order to limit the material transport.
The area just north of the port (B in Figure 4.3) is characterized by accumulation of coarse and stable material since the port blocks the transport of material towards south. The beach is characterized by the presence of a pebble berm close to the harbour breakwater, while the shoreface is mostly sandy.
The C section, next to the harbour, is recessed and therefore sheltered from the strongest winds from west. The beach consists of sand, gravel and marine deposits.

Figure 4.4: Area A, signs of erosion and flooding are seen in the pebble deposited on the low hinterland.

Figure 4.5: Area B, it can be seen the pebble berm close to the brakwater.

The characteristics of the areas are summarized by the granulometric curve of the beaches. It has been used a standard particles-size distribution of sand for zone B and C, and one of gavel for zone A. The diameters of the sediment are calculated in correspondence of 90% by the passing weight. In particular, sand has $d_{50} = 0.9\ mm$ and gravel has $d_{50} = 7\ mm$.

Figure 4.6: Area C, mixed beach of sand, gravel and marine deposits.

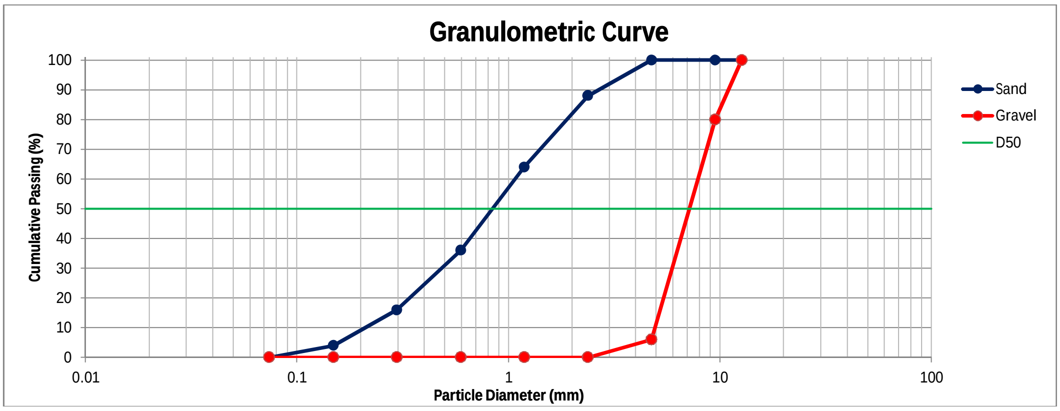

Figure 4.7: Particles-size distribution. Red is zone A, blue is zone B and C

Chapter 5

State of the sea

DANISH weather is extremely changeable. Denmark lies in the path of the westerlies, an area characterised by fronts, extratropical cyclones and unsettled weather. At the same time, the country is situated on the edge of the European Continent, where winters are cold and summers are hot. Compare to other geographical areas on the same latitude, Denmark enjoys a relatively warm climate. [2] Since the climate is extremely unpredictable, Denmark is a country ruled by the winds, which are the main cause of waves. To evaluate the state of the sea it is necessary to analyze the geography of the area. The ultimate goal is to calculate the wave height of the areas using an empirical method.

5.1 The wind

Wind is the motion that the air accomplishes almost horizontally with respect to the earth's surface. It is caused by the difference in air pressure between different areas of the earth. Among the meteorological parameters observed it is one of the most significant maritime navigation. Its strength can cause extensive damage and endanger the boats, but at the same time, has always offered a valuable contribution to human activities. The different distribution of the solar rays on the earth in the atmosphere determines areas of high and low pressure. The main mechanism is as follow: places where the heat is greater, the less and the lighter air rises vertically and a low pressure is formed below this area. The rising air cools, it becomes more dense and heavy and back heads toward the bottom, where it generates a high pressure. The atmosphere has a tendency to constantly restore the balance, for which the air moves from areas of high pressure toward the low pressure. The outcome of this motion is wind. The higher is the pressure difference between the two configurations (high and low), the greater speed of the wind will be. In reality, the wind does not move in the direction from high pressure toward the low, but in the northern hemisphere it deflects to the right, circulating around the centers of high pressure in a clockwise direction and around those of low pressure in anticlockwise, following the isobars (curves with the same pressure). This behavior is due to the rotation of the earth, it is as if the air is subjected to a force, which does not really exist and that's why it is called apparent (Coriolis force). The effects of this force is larger the higher is the air speed.

5.1.1 Wind directions

The movement of air on the surface of the earth and the means to give an indication of it were studied since ancient times, as the *Tower of the Winds* evidences in Athens, it is an octagonal building architected by Andronicus (between the second and first centuries BC). Each of its eight sides represent a direction of the wind. In origin on the top of the tower there was a triton swivel with a rod in his hand which was directing, according to the wind direction, on one of the sides of the octagon. The motion of the air, in this construction, is personified with the representation, on each side, of the gods that, for the appearance and for garments, give an idea of the time associated with each type of wind. The Tower of Andronicus already represents the completion of an ancient rose, formed of four directions.
Even today, the wind direction is understood as the original direction of the air flow and may be indicated by the compass, in which each quadrant, determined by the points of the compass is divided into four equal parts. Therefore, there are sixteen different directions, numbering starts from the north in a clockwise direction. In meteorology the division azimuth ranging from 0° to 360°, so for example a south wind is a wind of 180°. To determine the direction you look at the trend of smoking, which makes visible air currents also very weak, or the direction in which you move the shadow of the low clouds, the position of the flags, the direction in which the waves are pushed.

5.1.2 Wind speed

The force of the wind, the speed of the movement of the air mass is measured in meters per second (m/s). However, in meteorology, for reasons related to aviation and shipping, knot (kt) is being used as official unit, which corresponds to one nautical mile/hour. Next to these two units, using the kilometer/hour (km/h) and the mile/hour are used. The approximate measure of the strength of the wind can be determined by observing the effect it produces on the things and objects that are located outdoors. The Beaufort scale is an example of this, a practical measure of the wind speed, which takes its name from its inventor Francis Beaufort (1774-1857), British admiral and hydrographer. Using his experience as a sailor, he spotted 12 degrees of intensity defined from the effects of wind on the sea. The tools to measure the wind are anemometers or anemographs (from the greek $anemos = wind$ and $metron = measure$ or $grapho = write$). In meteorology, because the wind is constantly changing close to the ground, in order to compare wind data provided by the various weather stations, it was agreed that the transmitters are placed on a pole at a height of 10 meters above the ground, on a flat free of obstacles. Regarding Sjællands Odde the wind data from the Technical Report 99-13 of Danish Meteorological Institute [2] were used, in which the wind roses of 63 Danish stations and the explanation of the Danish weather. In addition the frequency data were taken from Danske Meteorologiske Institut [3]. The wind data were taken form the wind roses of Røsnæs Fyr and Gniben because they are the nearest stations to Sjaellands Odde.

Figure 5.1: Anemometer.

TABLE A

Beauforts table for wind force and wind speed equivalents

Beaufort number	Description	Velocity equivalent at a standard height of 10 metres above open flat ground: Knots	Metres per second	Kilometres per hour	Specifications for estimating speed over land
0	Calm	< 1	0 – 0.2	< 1	Smoke rises vertically.
1	Light air	1 – 3	0.3 – 1.5	1 – 5	Direction of wind shown by smoke-drift but not by wind vanes.
2	Light breeze	4 – 6	1.6 – 3.3	6 – 11	Wind felt on face; leaves rustle; ordinary vanes moved by wind.
3	Gentle breeze	7 – 10	3.4 – 5.4	12 – 19	Leaves and small twigs in constant motion; wind extends light flag.
4	Moderate breeze	11 – 16	5.5 – 7.9	20 – 28	Raises dust and loose paper; small branches are moved.
5	Fresh breeze	17 – 21	8.0 – 10.7	29 – 38	Small trees in leaf begin to sway, crested wavelets form on inland waters.
6	Strong breeze	22 – 27	10.8 – 13.8	39 – 49	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.
7	Near gale	28 – 33	13.9 – 17.1	50 – 61	Whole trees in motion; inconvenience felt when walking against the wind.
8	Gale	34 – 40	17.2 – 20.7	62 – 74	Breaks twigs off trees; generally impedes progress.
9	Strong gale	41 – 47	20.8 – 24.4	75 – 88	Slight structural damage occurs (chimney-pots and slates removed).
10	Storm	48 – 55	24.5 – 28.4	89 – 102	Seldom experienced inland; trees uprooted; considerable structural damage occurs.
11	Violent storm	56 – 63	28.5 – 32.6	103 – 117	Very rarely experienced; accompanied by widespread damage.
12	Hurricane	64 and over	32.7 and over	118 and over	

Figure 5.2: Beaufort scale.

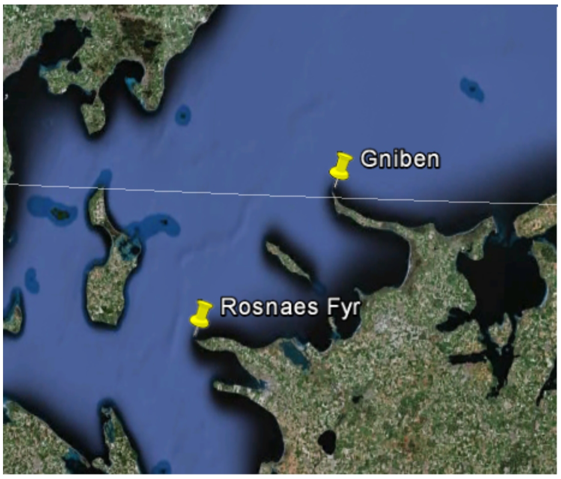

Figure 5.3: Map with the two station Røsnæs Fyr and Gniben.

The wind data were analyzed taking into consideration the geographical position of Sjællands Odde, the resulting data relating to the frequencies are the following:

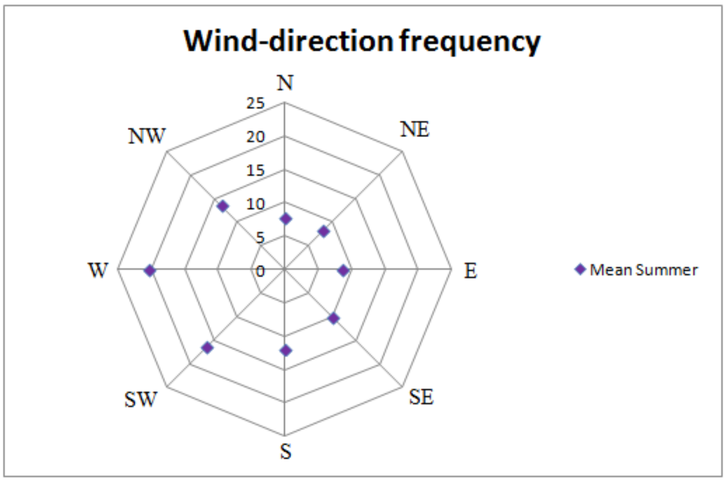

Figure 5.4: Wind direction frequencies.

Beaufort	1	2	3	4	5	6	7	8	9	10	11	12
frequencies %												
N	1.35	1.75	1.925	1.375	0.75	0.3	0.1375	0.0375	0.0125	0	0	0
NE	1.6	2.375	2.3	1.175	0.525	0.0875	0.0375	0.025	0.0125	0	0	0
E	1.575	2.325	2.95	1.275	0.375	0.05	0.0125	0	0	0	0	0
SE	1.375	2.825	3.575	1.825	0.525	0.05	0.0125	0	0	0	0	0
S	1.35	2.425	3.625	2.625	1.275	0.425	0.15	0.0625	0	0	0	0
SW	0.875	1.925	3.775	4.75	3.125	1.475	0.425	0.1125	0.0125	0	0	0
W	0.9	1.925	4.4	5.925	4.5	1.9	0.75	0.1	0.0375	0	0	0
NW	0.925	1.825	3.275	3.725	2.35	0.85	0.35	0.0875	0.025	0	0	0

Figure 5.5: Frequencies in detail of the wind.

5.2 The wave

When the wind blows on the sea, it has as a consequence of deforming its surface, not only in the area where it is blowing, but also in areas hundreds of kilometers away. In fact it is possible to observe the rough sea even in areas without wind, because the deformation does not dampens at the same time where it ceases, but fades slowly. The surface of the sea, beyond the state of stillness, under the beating wind, presents elevations and depressions that are followed on a regular basis, so much that their movement can be traced back to the physical concept of a wave. The breaking wave is characterized by several elements: the *height*, defined as the vertical distance between the second peak and trough, that is, between the highest and lowest wave, the *length*, ie the distance horizontally between two crests or two successive troughs; the *speed* of propagation, ie the space traveled per unit of time from the ridge. The *period*, ie the time interval between two consecutive passages of a ridge for the same fixed point. The *slpoe*, given by the ratio between the height and length of the wave, the *direction* of origin and finally the *age*is defined as the ratio between the speed of the wave and the speed of the wind. As soon as the wind begins to blow, the sea ripples by the effect of friction of the air flowing over the surface of the water. The waves that are formed are called capillaries and are small *ripples* of the sea surface. After the *ripples* are formed, the wind does not exert only a simple friction, but a real pressure that causes a lowering in the point in which it is mostly exerted, and a compensatory elevation in correspondence of the point where it is less. Thus forming the waves of gravity, ie the normal waves, which move precisely under the action of gravity. The capillary waves are shorter and fast and they smooth out as soon as the wind ceases. Waves that arises from gravity are longer, faster and continue to propagate long after the end of the wind. For example, a wind of 1 or 2 nodes is sufficient to produce the capillary waves, while a more intense wind turns the waves in gravitational waves. In the waves of gravity, due to the pressure caused by the wind on the sea, the mass of surface water fluctuates and assumes a circular motion which is transmitted to adjacent areas, creating a profile wave that propagates in the direction of the wind. The visual effect resulting from this process is the sea surface moves meanwhile the wave profile is moving without water displacement. Therefore, the motion of the water is apparent, its particles only run almost in circular trajectories, which become smaller and smaller towards the bottom. At a depth equivalent to about half the length of the wave, the circular movement turns into very small movements in a plane almost horizontal, to run out soon after. For shallow water or transition water the orbits of the particles have an elliptical shape and with the depth they keep unchanged the major axis and decrease the minor axis.

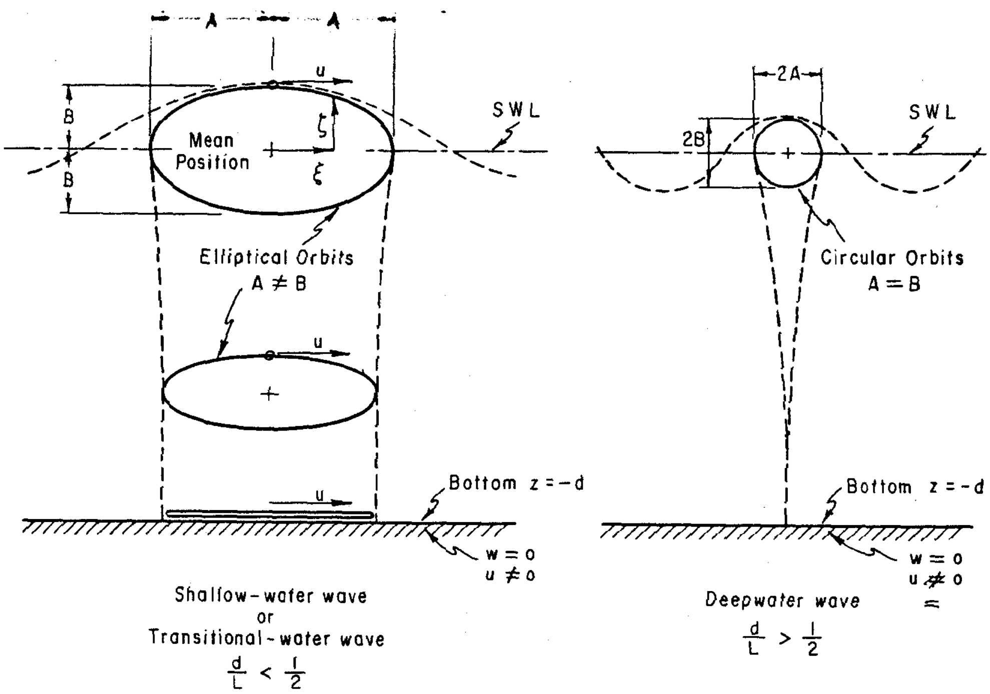

Figure 5.6: Movements of a water particle.

A wave has certain unique characteristics:

- the phase $\omega = \frac{2\pi}{T}$
- the frequency $f = \frac{1}{T}$
- the celerity $c = \frac{L}{T} = \frac{2\pi}{T}$
- the wavelength L is defined as the distance between two points of the same phase
- the period T is defined as the interval of time between two points of equal phase.

The behavior of the waves is studied by means of the linear theory. It assumes that the fluid is a perfect fluid, which is incompressible and affected by geopotential, thus leading to the definition of a field of irrotational flow. This theory leads to the fundamental dispersion relation:

$$\omega^2 = gk \tanh(kh) \tag{5.1}$$

Where k is defined as "*wave number*" $= \frac{2\pi}{L}$ and ω is the pulsation. The dispersion relation is fundamental to tie the behavior of waves from deeper waters to shallower. The two scenarios that occur by analyzing the previous expression are, in fact, shallow and deep water and allow to derive the value of the celerity of the wave and the group celerity, which is calculated with the formula $c_g = \frac{\Delta\omega}{\Delta k}$.

Deep water In deep water that is $\tanh(kh) \to 1$ then $c_o = \frac{\omega}{k} = \frac{gT}{2\pi} = 1.56T$

Where is c_o represents the "offshore celerity". The concequence of this formula is that in deep water the speed does not depend on the height of the bottom but from the period.

The "group celerity" is: $c_g = \frac{g}{2\omega}$ it means that the single wave travels faster than a group of waves. Thanks to simplifications that can be made about the Hyperbolics functions it is possible to write a connection between the magnitude of the bottom and the wavelength; in the case of deep water this behavior is valid when:

$$\frac{h}{L} > \frac{1}{2} \tag{5.2}$$

Shallow water In shallow water it is $\tanh(kh) = kh$ then it follows that $c = c_g = \frac{\omega}{k} = \sqrt{gh}$ it means that single waves and group waves move together at the same speed.

This behavior is valid when:

$$\frac{h}{L} < \frac{1}{20} \tag{5.3}$$

Between the two limits $\frac{1}{20}$ and $\frac{1}{2}$ there is the field of intermediate water. The height of the waves increases when the wind provides enough energy. When you exceed 10 knots of wind speed, not only increases the height of the waves, but also their length and speed. These increases are not unlimited, but it has a maximum. To achieve this maximum the sea need unchanged and persistent action of the wind for a long time. Only after a few days the wave velocity becomes equal to that of the wind and its dimensions do not increase more. To estimate the wave height for a given wind speed, it must be taken into account both the duration of the wind and the fetch.

5.3 Fetch

Fetch is the area of sea or lake on which blows a wind of constant direction, which generates waves. To be more specific, fetch is the distance traveled by the wind without encountering obstacles along which waves of increasing height are formed, so from it as well as from wind intensity depends the sea state at a given point. For example sailing near the center of a depression, where the isobars are very curved and the wind cannot expire with constant direction for a considerable distance, you could find a sea less developed than you would meet away from the depression where the fetch is greater, even if the wind has less intensity. In the generation of waves, the sea state has characteristics of "living sea", ie the area where the wavy oscillations are present in evolution. It can be assumed that, in addition to the waves that have accumulated more energy transferred from the wind, and therefore have the maximum height and the longer period waves are much younger, shorter and lower them overlapping. Between the waves younger some increase in height so quickly to break forming the so-called white caps. When the waves come from the area of generation, those little steeper and crest are muffled, while those who had reached the maximum height and then the maximum development spread outside the storm (swell). Long waves are then the final stage of the evolution of the sea in the area of generation. The state of development of the wave, also known as "wave age" can be evaluated with the $\beta = \frac{c}{v}$ between the celerity of the wave and the wind speed that generates it. This ratio increases until the wave remains under the action of the wind, until reaching its limit value equal to $\beta = 1.37$, ie the condition of "sea fully developed". From here it follows that another very important parameter for determining the development of the wave "t" is the duration of the disruption, it is closely related to fetch, it is referred to as "minimum wind t_{min}" The minimum amount of time because all wind energy is transferred to the sea or because the sea is fully developed. If the duration of the disturbance is less than the minimum not all the energy of the wind can move to the sea, but if the duration is greater than the minimum do not have the possibility to transfer other energy, for which the wave does not increment more to how large "t". Similarly minimum Fetch is indicated as the length of the stretch of water to which, with a wind speed and a duration assigned, the sea is fully developed. For each pair of values (u; F) it is possible to identify the minimum duration and vice versa for each pair of values $(u; t)$ can be identified a minimum fetch.

The identification of fetch is performed by measuring the geographical distance between the point of interest and the nearest land in each directions. It is easily obtainable with GoogleEarth. This is called *geographical fetch*.

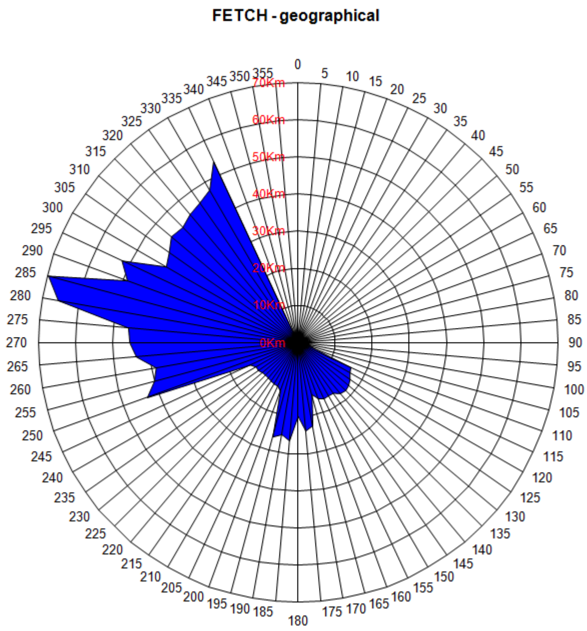

Figure 5.7: Geographical Fetch.

The wind is not constant in magnitude and direction, it varies in a causal way (*bursts*, turbulence). It transmits energy to the surface of the sea along a bundle of directions around a prevailing direction. The characteristics of the waves at a given point therefore depend on the state of the wind evaluated along a beam directions. Therefore, for the purpose of prediction of the characteristics of the wave, it is important not only the length of fetch according to the average direction of the wind, but also the fetch along directions close to this. It uses a weighted average of the geographical fetch, this weighted average is called "fetch effective". The procedure for construction of the fetch effective is the following.

The total sector is divided in n sub-sectors of equal angular opening $\Delta\alpha$, for example equal to 5°, then it is assumed that:

1) The wind transfers energy to the surface of the sea according to all the directions i that form an angle $\alpha_i = \pm 90°$ with the direction of the wind.

2) The rates of energy transmitted by the wind according to the different directions are proportional to the square of the cosine of the angles α_i that the same form with the directions of the wind.

If F_i is the geographical fetch along the direction i, the corresponding length of the effective fetch F_{eff} is given by:

$$F_{eff} = \frac{\sum F_i \cos^2 \alpha_i}{\sum \cos^2 \alpha_i} \tag{5.4}$$

The angles α_i should run from $-90°$ to $-90°$ and therefore the summations go from $i + L$ to $i - L$ with $L = \frac{90}{\Delta\alpha}$.

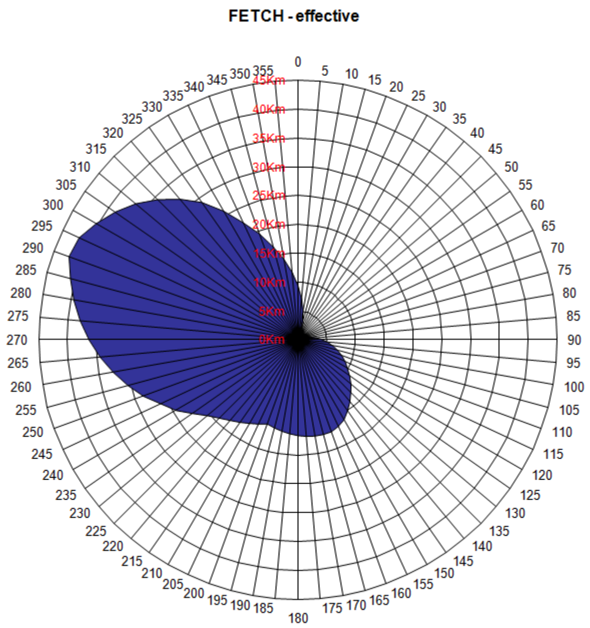

Figure 5.8: Effective fetch.

Finally it was mean the data in 30-degrees sectors in order to obtain the fetch for the main directions.

5.4 Indirect models for wave calculation

The available models provide the characteristics of a state of sea generated by a wind field having constant speed and direction for the entire duration of the event and on the whole area of generation. This simplification of the transfer of energy from the wind to the sea surface allows the reconstruction of storms once known the speed, direction, duration of the wind and the extension of the generation area. Between the direction of the wind and the storms there is a deviation that sometimes is significant. This is because the different length of fetch determines a dissymmetry in the transfer of energy and therefore a different direction of propagation of the wave. In models of indirect reconstruction it is therefore necessary to evaluate a procedure for calculating the deviation between wind direction and storm surges.The reconstruction models are classified into four categories:

- Spectral models: they solve the differential equation of energy transport calculating the energy spectrum of all the grid points with which it is discretized by the area of generation;
- Parametric models: They speculate a constant distribution of the wave energy representable as a function of a limited number of parameters;
- Statistical models: Are based on the technique of multiple regression, they evaluate the relationship between the wave and the wind field;
- Empirical models: The most widely used in engineering practice, which are based on experimental relations between the wind and the characteristics of the wave motion.

The SMP method (Shore Protection Manual 1984) is used in that case where there are not direct wave measurements. It determines the wave characteristics such as the significant wave height (H_{m0})and the peak period (T_P)from the wind field.

5.4.1 SMP method

The SPM model, presented by the Shore Protection Manual in 1984, was derived from the CERC (Coastal Engineering Research Center) as an evolution of the traditional method of Sverdrup, Munk and Bretshneider, introducing the concept of significant spectral wave height introduced by Hasselman. [9]. The wave-height and wave-period are expressed as a function of the wind speed, the duration of event and the effective fetch evaluated along the mean wind direction. The characteristics of the sea state depend on the development of the wave motion. The model distinguishes between fully-arisen sea and sea restricted by fetch and duration of the wind.
If the development of the wave is limited by the wind duration or fetch-limited in deep water ($\frac{h}{L} > \frac{1}{2}$) it used the following formulas:

$$\frac{gt_{min}}{U_A} = 68.8 \cdot \left(\frac{gF}{U_A^2}\right)^{2/3} \tag{5.5}$$

$$\frac{gH_{m0}}{U_A^2} = 0.0016 \cdot \left(\frac{gF}{U_A^2}\right)^{1/3} \tag{5.6}$$

$$\frac{gT_P}{U_A} = 0.2857 \cdot \left(\frac{gF}{U_A^2}\right)^{1/3} \tag{5.7}$$

However, if the sea is fully arisen it means that the waves get as much energy as they lose so their characteristics depend only on the wind speed:

$$\frac{gF}{U_A^2} \geq 23123 \tag{5.8}$$

$$\frac{gH_{m0}}{U_A^2} = 0.243 \tag{5.9}$$

$$\frac{gT_P}{U_A} = 8.134 \tag{5.10}$$

The characteristics of the wave in the SPM model depend on of the force factor of the wind U_A (wind stress), this correction factor has been introduced to take into account the transfer of energy from the wind to the sea surface, it is defined as:

$$U_A = 0.71 U_{10}^{1.23} \tag{5.11}$$

where $U_{10}$is the wind speed at the height of 10m over mean water level, which has to be corrected according to the air-sea temperature and duration with the following formulas:

$$\frac{U_t}{U_{t=3600}} = 1.277 + 0.296 \tanh\left(0.9 \log_{10}(\frac{45}{t})\right) \tag{5.12}$$

for $1s < t < 3600s$. This is the duration-averaged wind speed,t is the time in witch the wind treads a mile ($1mile = 1609m$).
Using the SPM method and the fech data the wave heights were calculated for the each wind-speed on the Beaufort scale, as can be seen from the following tables. $H_0 = wave\ height$, $T_P = period$, $L = lenght$ calculated for each wind-speed and for esch direction with the SPM method are present in the Appendex.

B (Beaufort)	v m/s	N	45	E	135	S	225	O	315
0	0.1	0.002	0.001	0.001	0.002	0.003	0.003	0.004	0.004
1	0.9	0.030	0.009	0.021	0.035	0.040	0.045	0.060	0.056
2	2.45	0.099	0.029	0.069	0.116	0.133	0.148	0.196	0.185
3	4.4	0.197	0.058	0.137	0.230	0.263	0.294	0.389	0.367
4	6.7	0.319	0.094	0.223	0.373	0.426	0.476	0.631	0.596
5	9.35	0.466	0.138	0.326	0.546	0.623	0.696	0.922	0.871
6	12.3	0.635	0.188	0.444	0.744	0.849	0.949	1.257	1.187
7	15.5	0.824	0.244	0.576	0.965	1.101	1.230	1.630	1.539
8	18.95	1.032	0.305	0.722	1.208	1.379	1.541	2.041	1.928
9	22.6	1.257	0.372	0.879	1.471	1.679	1.877	2.485	2.348
10	26.45	1.498	0.443	1.047	1.754	2.002	2.237	2.963	2.799
11	30.55	1.760	0.521	1.230	2.060	2.351	2.628	3.481	3.288
12	34.8	2.036	0.602	1.423	2.383	2.720	3.040	4.026	3.803

Table 5.1: H0 corresponding to the wind speed and the fetch from each direction.

Chapter 6

The numerical model

MIKE 21 is a professional engineering software simulation package for the flowing free surface with two-dimensional scheme, developed by the Danish Hydraulic Institute DHI and applicable both in fluvial and marine environment. MIKE 21 is usable for the two-dimensional simulation of hydraulics phenomena such as rivers, lakes, estuaries, bays, coastal areas and seas including transport solid, water quality, wave propagation, eutrophication, oil spills, cohesive sediment transport and more. The system Mike 21 consists of four main groups of numeric models: hydrodynamic, sedimentary process, and wave models hydrodynamic environment. In this case it is used the SW model specific for applications involving the assessment of wave climates in offshore and coastal areas. [8].
First, the mesh was created with version Mike Zero. There were created two meshes with different mesh-sizes, triangulating the chosen domain and interpolating the geometry created with data from the bathymetry. The result is two "boxes" to put as domain in Mike 21 SW.

Create a good mesh is important because this will be the basis for all the subsequent calculations, so it is better to spend more time on it than having to go back later in case of errors.

6.1 Model settings

In order to perform the simulation is necessary to set the file ".sw", i.e. put the data into a format which can be understood by the numerical model [8]. First of all it must be entered the domain, ie the mesh previously created, and the baundaries, that the program automatically recognizes from the mesh, have to be named. Then

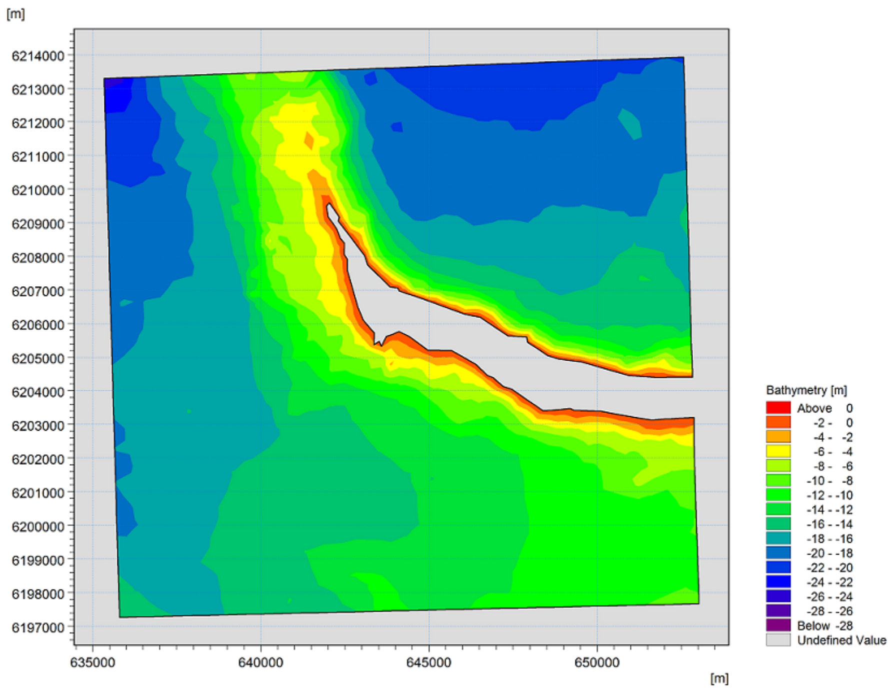

Figure 6.1: Mesh of the area for the calculation of the wind conditions.

it need to enter the period to be covered by the simulation, ie the number of steps and the time step interval of the simulation. Finally a list of parameters has to be set, this section is *spectral wave module* that simulates the growth, decay and transformation of the waves.

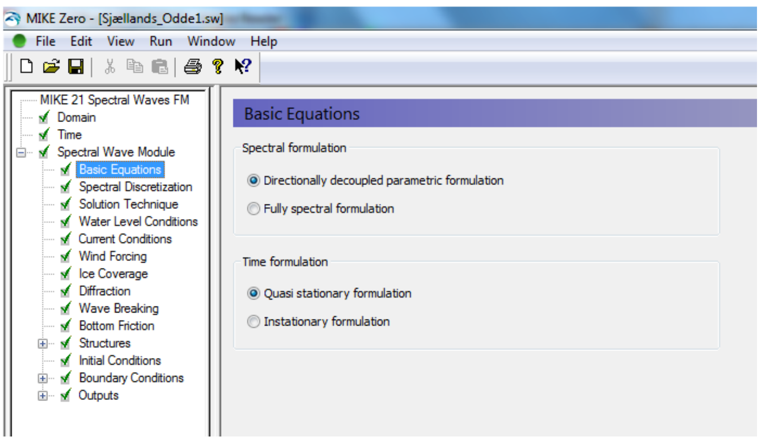

Figure 6.3: Screenshot of setting.

It is very important to choose the equations on which the calculation will be based, for this case it was chosen the "directionally decoupled parametric formulation" (Figure 6.3), which is based on the parameterization of the wave action conservation equation. This configuration is done in the frequency domain

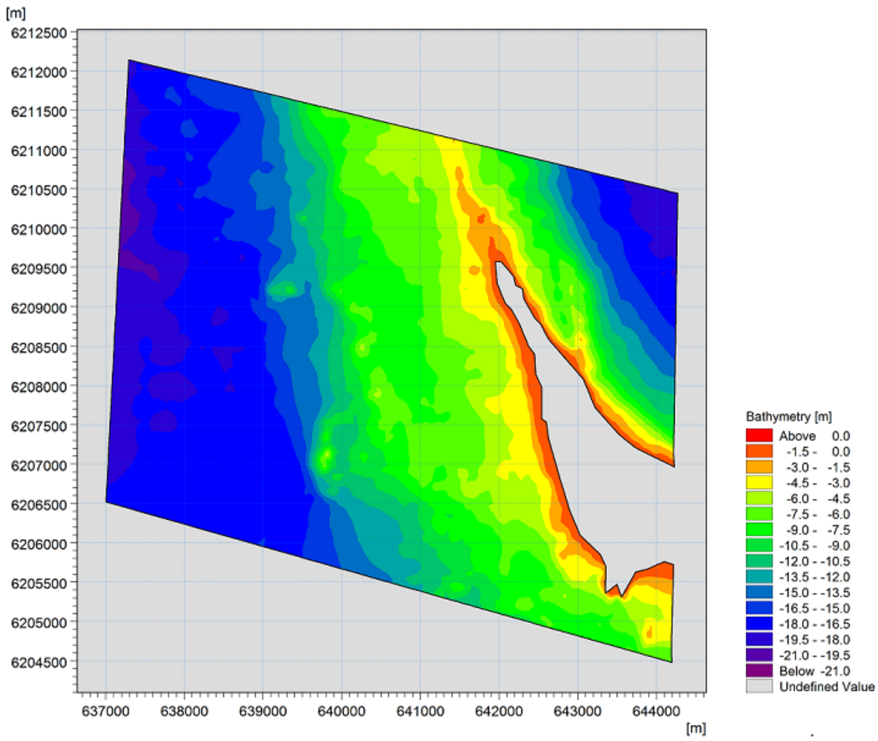

Figure 6.2: Mesh of the ship-wave simulation, the south boundary is the line 700m from the ferry route.

through the introduction of the zeroth and placing the first moment of the wave action spectrum as a dependent variable, following Holthuijsen et al. (1989). Moreover, it was chosen the "quasi-stationary" mode, in which the time is removed as an independent variable and a steady state solution is calculated at each time step. The default parameters were used for the other items except the wind, the waves and the boundary conditions that will be seen later.

6.1.1 Wind-waves

In order to obtain the characteristics of the wind-waves, data about wind speed and boundary conditions have been inserted in the interface of simulation. It has been done eight different simulations, one for each direction of the wind rose.
Under the item *Wind Forcing* the data of wind were entered, i.e. the direction and the wind speed taken from the Beaufort scale and transformed into m/s. In "Boundary Conditions" for each simulation it was entered the wave height in deep water H_0 and the corresponding wave period T_P in one outline, while the other outlines were considered as closed or lateral contours.

The program, after running, gave as output an image from which it was possible to extrapolate the data to compare.

6.1.2 Ship-waves

To simulate the passing vessel were left the default parameters and it was only inserted the boundary conditions for the south outline. The south contour of the domain represents the line parallel at 700m to the ship's route. This represents the line from which the long period waves starts. The wave is the one that was calculated previously.

The two cases of arriving and departing ship were simulated with the following data as input on the southern boundary:

$$\begin{cases} H_{ship} = 0.43m \\ T_{ship} = 10s \\ Direction = 240° \end{cases} \quad \begin{cases} H_{ship} = 0.43m \\ T_{ship} = 10s \\ Direction = 150° \end{cases} \tag{6.1}$$

The program gave the following file as results.

Figure 6.4: Representation of the boundary conditions for the principal directions (N, E, S, W), on the left, and the diagonal directions (NE, SE, SW, NW), on the right, as they appear in the program.

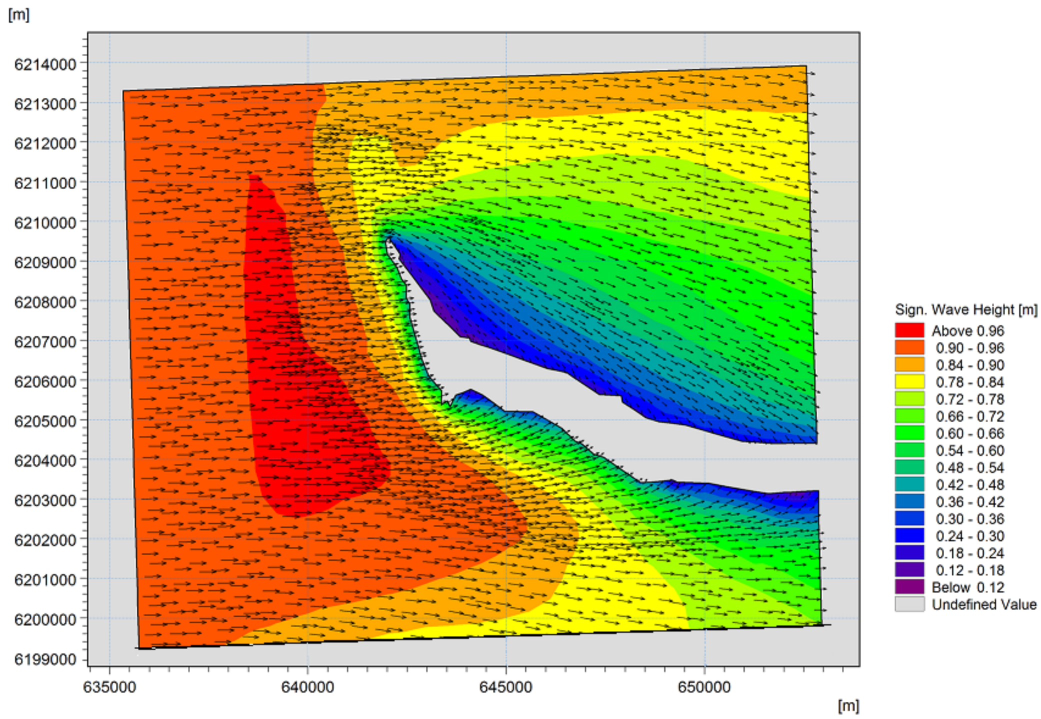

Figure 6.5: File output of a west wind 9.35m/s speed, with the vectors it is possible to see the shoaling and the refraction of the wave on the coast.

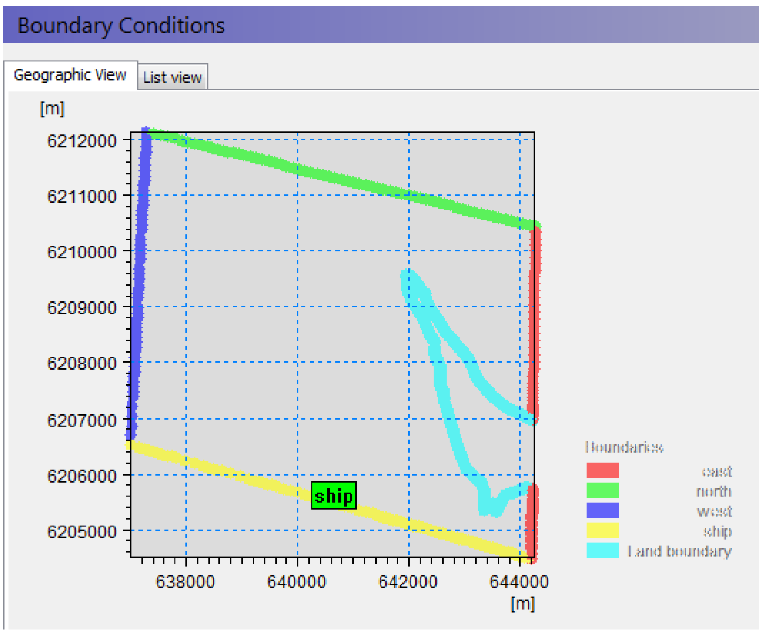

Figure 6.6: Boundary conditions, the south outline is 700m from the ship's route.

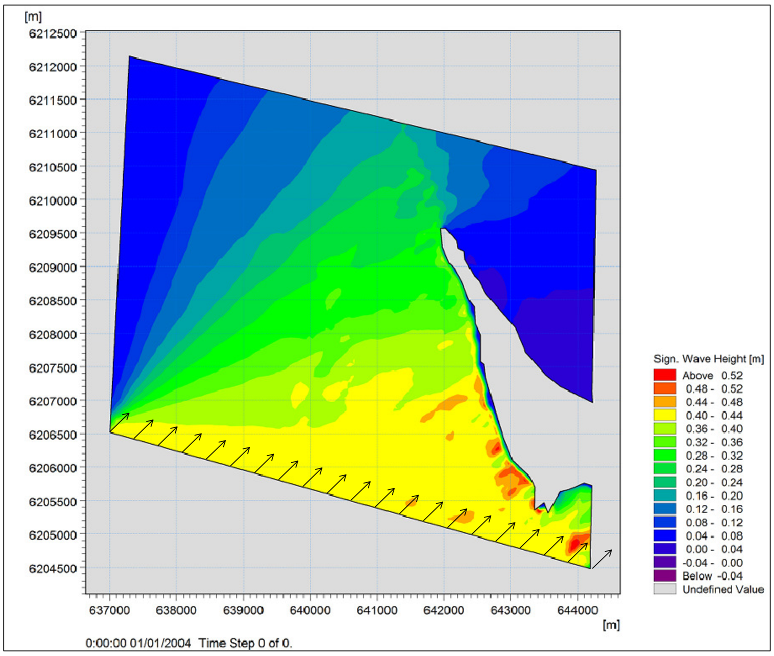

Figure 6.7: Wave height generated by the **arriving** ships. The waves proceed with an angle of 60° from the direction of the ship's route.

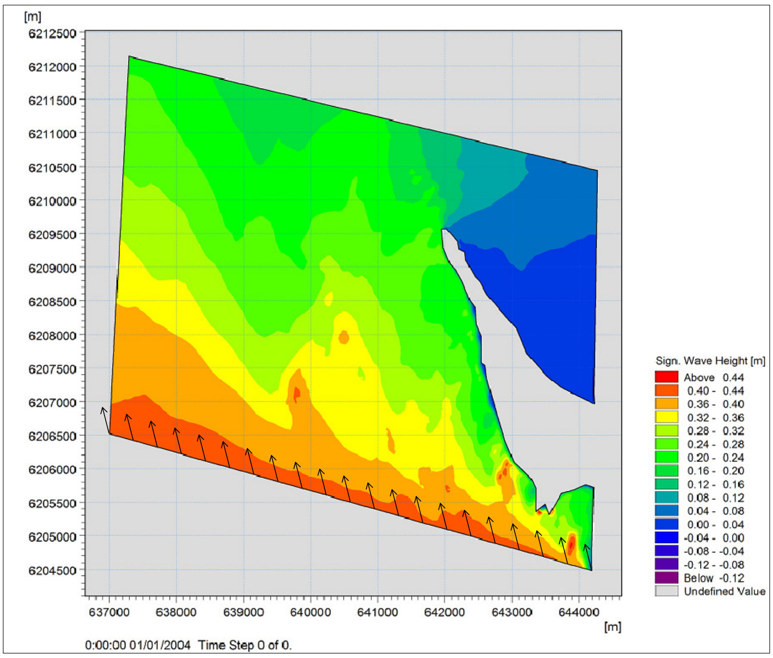

Figure 6.8: Wave height generated by the **departing** ships. The waves proceed with an angle of 60° from the direction of the ship's route.

Chapter 7

Results

In order to compare the results there were chosen three different point in the area under the influence of the harbor. This three points are situated at $-3m$ depth.

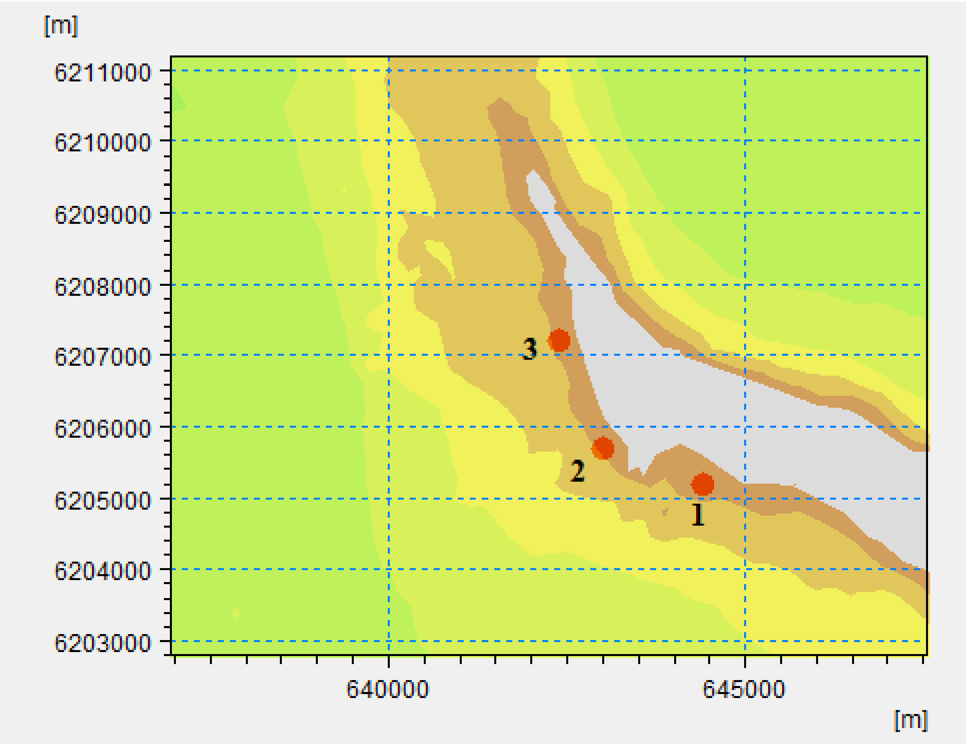

Figure 7.1: The three point chosen from the three areas descripted at the biginning.

7.1 Significant wave height

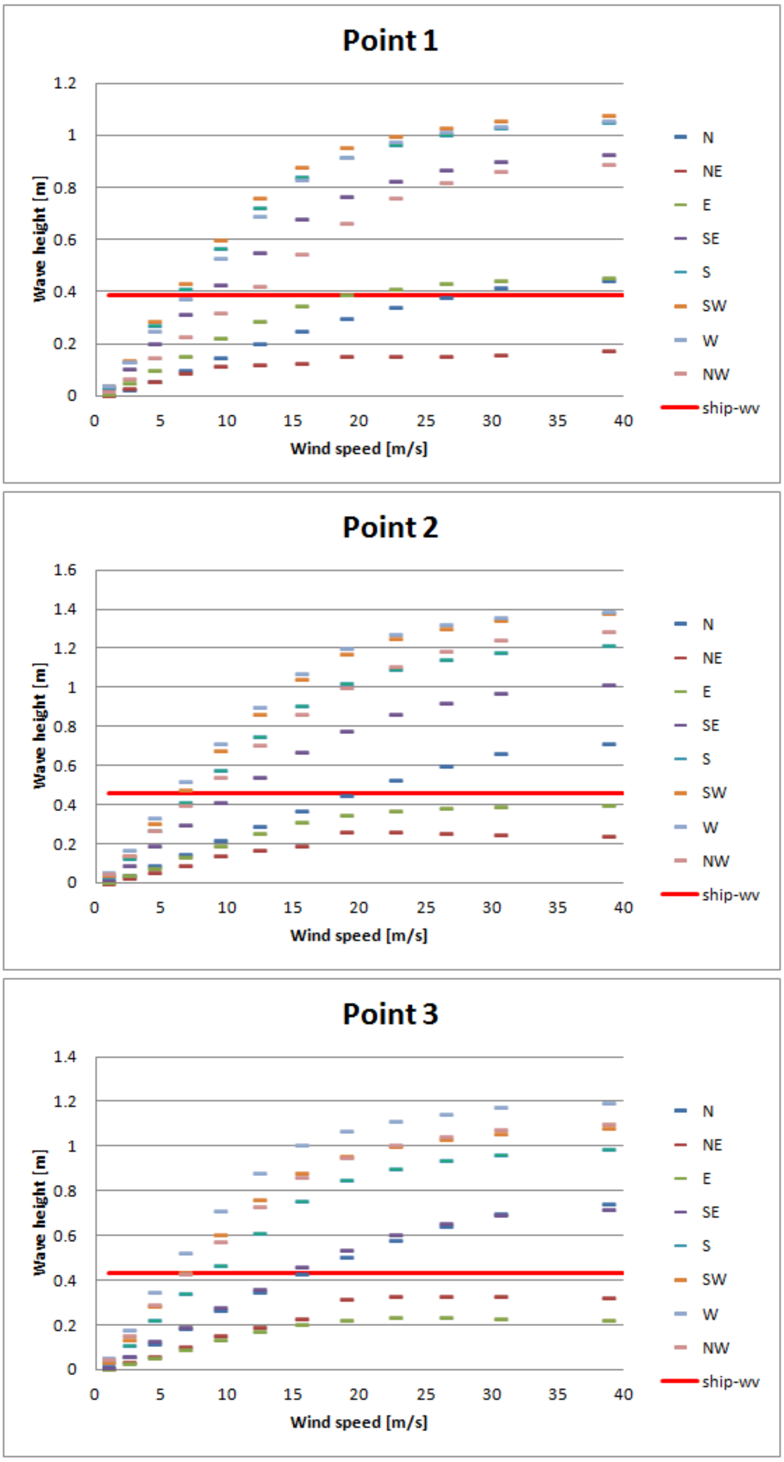

Figure 7.2: Wave height corresponding to each direction and wind speed and the line is the wave height generated by the vessel.

The wave height generated by the ship is comparable with the waves produced by winds from south-west, south and west with 6.7 m/s speed. These winds are the most frequent in this area, as it can be seen in figure 7.3. In the comparison

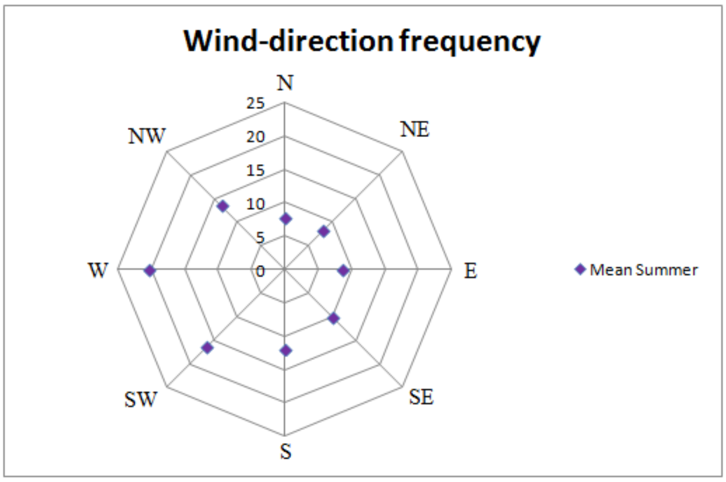

Figure 7.3: Annual wind frequencies in percentage; the winds that characterize the state of the sea in that area come mostly from west, south, south-west and north-west, so as a result the waves of greater height are those coming from these directions (this is due also to the fetch).

between ship-waves and wind-waves it is necessary to talk in terms of frequencies. From the Sjællands Odde's wind-rose it can be seen that the most frequent winds are those from west, south, south-west and north-west. In detail, the table 7.1 represents the highest frequencies and their respective speeds and wave heights (the wave heights are only a mean, because for each direction and wind speed there is a different wave height corresponding). The frequency of a wind coming from west with the same wave height of a ship-generated wave is about 6%.

v	Ho	S	SW	W	NW
2.45	0.17	2.425	1.925	1.925	1.825
4.4	0.33	3.625	3.775	4.4	3.275
6.7	0.53	2.625	4.75	5.925	3.725
9.35	0.78	1.275	3.125	4.5	2.35
12.3	1.06	0.425	1.475	1.9	0.85

Table 7.1: Particolar of the frequency for the most common wind at Sjællands Odde.

Regarding ship-generate-waves frequency the results of the simulations show that the most significant waves are those caused by ships arriving, because they come from south-west (in particular from 240°) and they impact the coast orthogonally without any refraction since they are straight. Mols-Linien provides about ten arrivals a day with some reductions during the winter season. The data from the Technical Note [6] states a number of 3240 arrivals in one year. It is assumed that an event of waves generated by the ship arrival is represented by a wave train with 10 waves with a wave period of 10 s, so in one arrival the duration time is 100 s and in one year are totally 324000 s, i.e. 4 days. In term of percentages it is the 1%. This seemingly small value deserves a more thorough analysis indeed the characteristics of the wave generated by the vessel are completely different from those from wind.

The wave heights and their corresponding wave periods in the line at 3m depth are just below the limit imposed by the Danish Maritime Authority.

7.2 Wave-period

Comparing the period it can be noted that at equal wave height, the waves generated by ships have a longer period than those generated by wind. Even if they change approaching to the shore, due to refraction and shoaling, the wave period of the ferry remains between $7 - 10$ s against the $3.8 - 4.2$ s of the waves by the wind. The long-period waves move faster than a short-period waves and they also have a longer wave length. This means that they are able to lift more material on the bottom and for a longer stretch.

7.3 Sediment transport

To assess the potential risk on the coast due to transport solid generated by the waves is necessary to calculate the speed of the particles at the bottom Umax. Behind this there is a linear theory given by the following expression.

$$U_{max} = \pi \frac{H_{max}}{T} \frac{1}{\sinh kh} \tag{7.1}$$

where

- H_{max} is the maximum wave height
- T is the associated wave period
- K is the associated wave number (remember that $k = \frac{2\pi}{L}$, with $L = wavelenght$)

- h is the water depth (in meters).

The speed of the particles obtained from the simulation of the passing ferry must be compared with those of waves generated by wind, this for the three points previously considered. Because of the vessel generates waves of long period and, as mentioned earlier, these waves move a deeper portion of the sea, the particles velocity is greater than that of waves generated by wind. This means that there will be a greater shift of sediments and thus a consequent erosion. In the following graphs it will be represented only the data from north-west, west, south-west and south directions, because of they are the most frequent.

While the wave height of the ship was similar to that of a 6.7 m/s speed wind, the speed of the particles is corresponding to a higher speed of the wind (9.35 m/s) a degree more in the Beaufort scale. In order to understand the amount of erosion the maximum particles velocity at the seabed has been compared with the critical velocity of initiation of motion, calculated with the formula from SPM manual [9].

$$V_c = \sqrt{8g\frac{d_{50}}{1000}\frac{\gamma_s - \gamma_w}{\gamma_w}} \tag{7.2}$$

where

- γ_s is the specific weight of sand or gravel
- γ_w is the specific weight of water
- d_{50} is taken from the granulometric curve; it is 0.9 mm for sand and 7 mm for gravel.

In point 1 and 2 (Figure 7.5 and 7.6) ship-waves cause motion of the particles untill 3 m depth, in point 3 (Figure 7.7) there is no motion because of the bigger size of the gravel. In term of frequences the west wind moves material on the seabed when wind spped is over 6.7 m/s, i.e. 14%; this value is greater than the 1% of the passing ship.

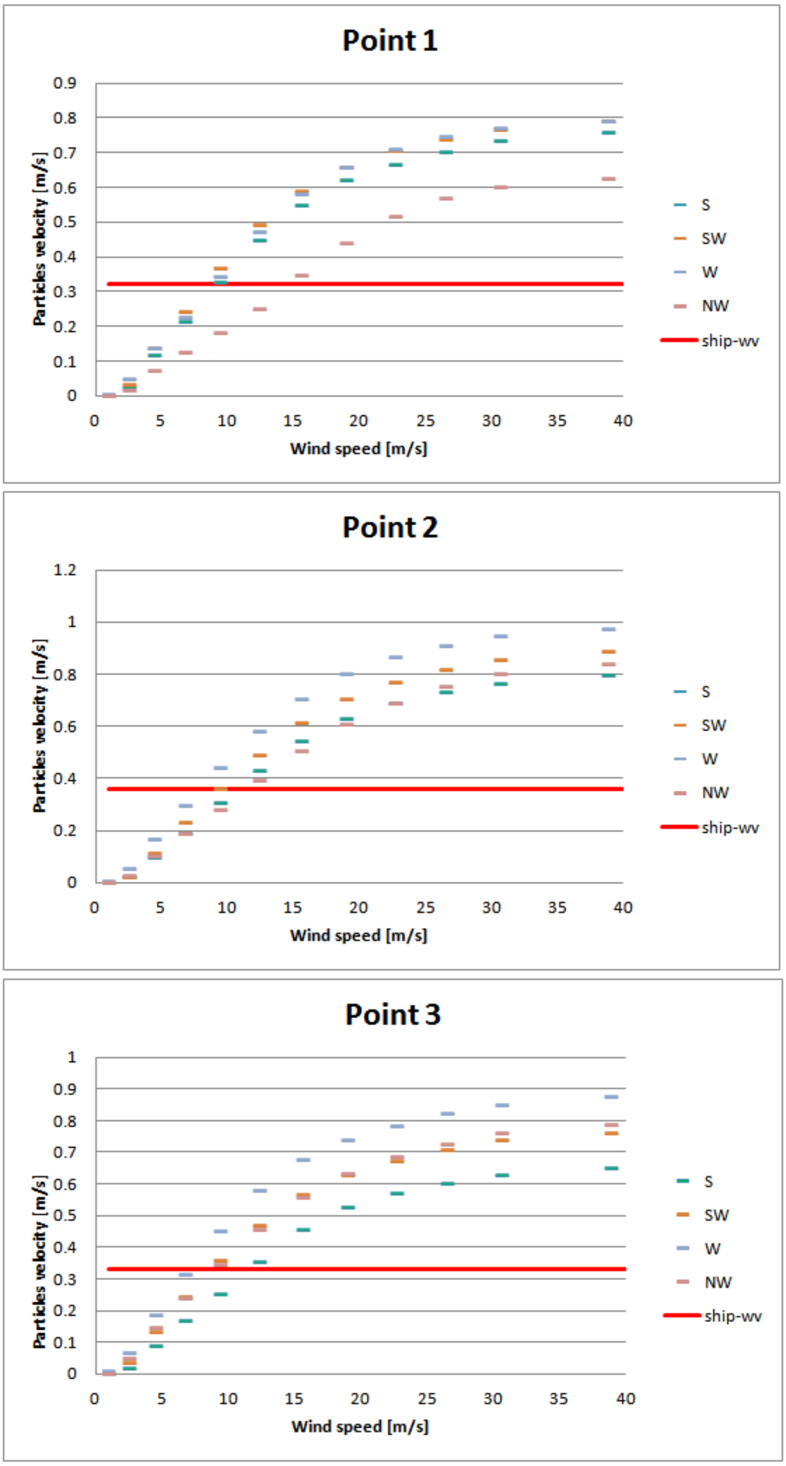

Figure 7.4: The speed of the particles due to the passage of the ship is comparable with that of most frequent winds.

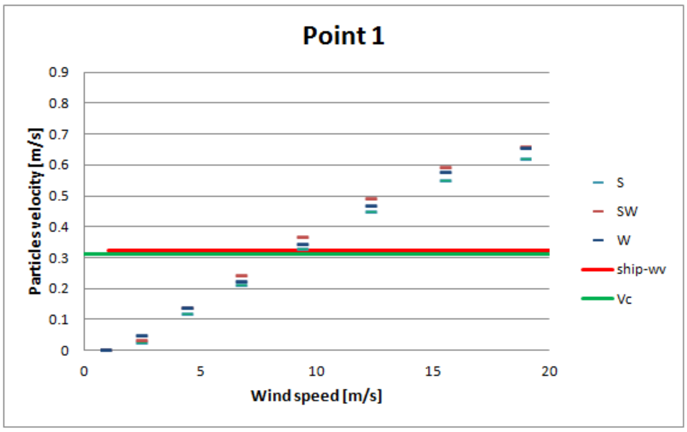

Figure 7.5: Comparison between maximum velocity at the seabed and critical velocity of initiation of motion. Point 1.

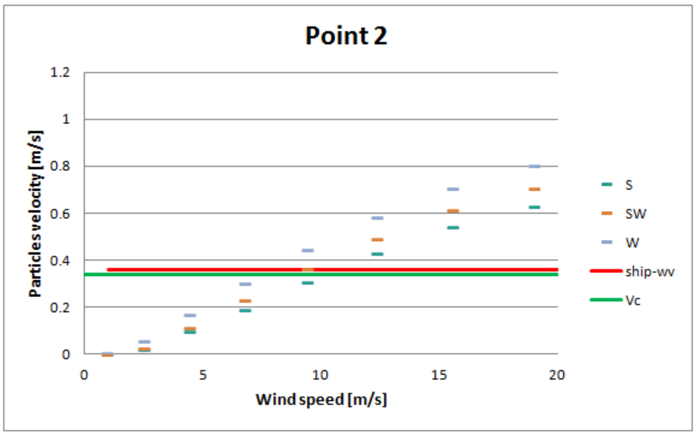

Figure 7.6: Comparison between maximum velocity at the seabed and critical velocity of initiation of motion. Point 2.

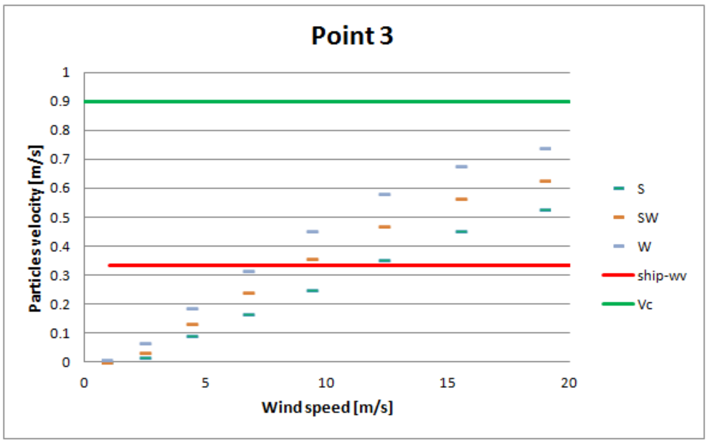

Figure 7.7: Comparison between maximum velocity at the seabed and critical velocity of initiation of motion. Point 3.

7.4 Run up

Wave run-up is the maximum vertical extent of wave uprush on a beach, run-up is due to the breaking waves on the shore.

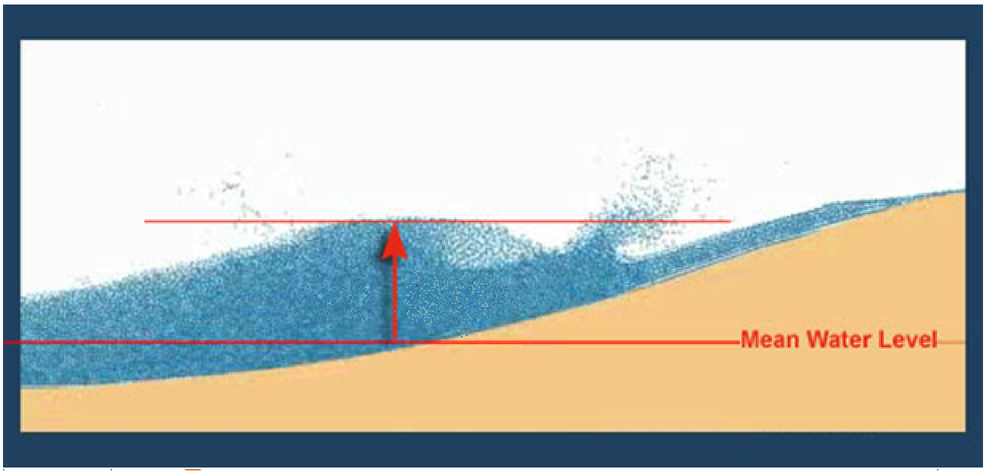

Figure 7.8: Run-up due to breaking waves

Wave runup is an important process in causing and or promoting bluff erosion. Wave runup may cause erosion by directly impacting the bluff, dislodging material, and redistributing it to the foreshore and nearshore. Wave runup promotes bluff erosion by carrying failed bluff material away from the toe of the bluff, regardless of what caused failure and erosion of the bluff. The two percent wave run-up (R_2%) is the run-up that only two percent of the wave run-up values observed will reach or exceed, this value is investigate in this study using the formula in the SPM manual [9].

$$R_{2\%} = 1.86\xi^{0.71} H_0 \tag{7.3}$$

- ξ is the Iribarren number, it is used to describe breaking wave types on beaches.

$$\xi = \frac{\tan \alpha}{\sqrt{H_0/L_0}} \tag{7.4}$$

- H_0 is the wave height in deep water
- L_0 is the wave lenght in deep water.

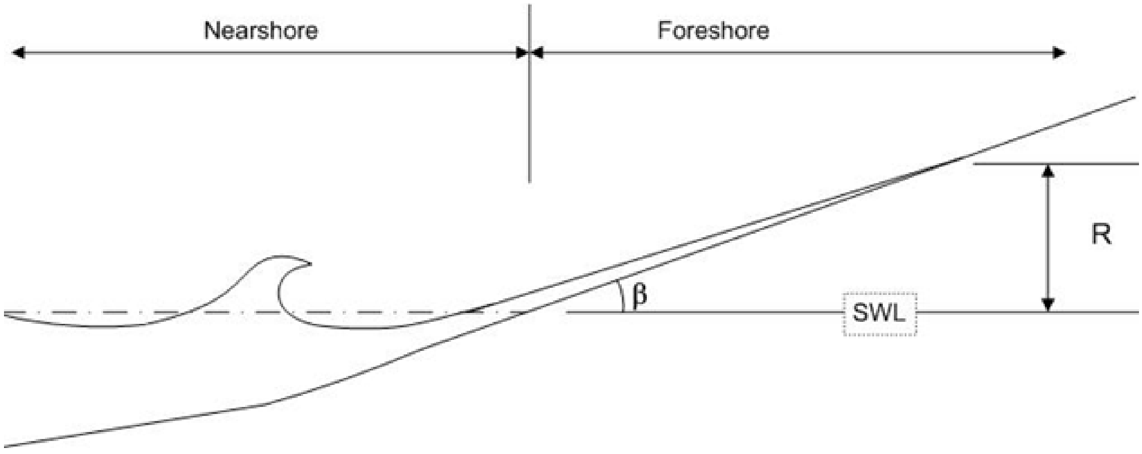

Figure 7.9: Run-up.

Run-up: POINT 1 tan b = 0.01875		
Wind from W 1 (6.70 m/s)	Wind from W 2 (9.35 m/s)	Vessel
x = 0.1133	x = 0.1065	x = 0.3572
R 2% (m)		
0.2497	0.3490	0.3851
Lenght R 2% (m)		
13.315	18.613	20.538

Figure 7.10: Run-up in point 1.

It has been compared the run-up of the ship waves with the most frequent wind waves run-up. Compared to the coast line, point 1 and point 3 are placed at the same distance (160 m), while point 2 is further away (190 m). The height of the wave produced by the vessel is about half of that generated by the winds, but its wavelength is almost double compared to the others. This implies a greater index of Iribarren for waves produced by the vessel, then a greater run-up of the wave. In conclusion the effects of erosion caused by the rising of the wave generated by the catamaran are not negligible, in fact they are greater than those produced by the most frequent winds.

Run-up: POINT 2 tan b = 0.01580		
Wind from W 1 (6.70 m/s)	**Wind from W 2 (9.35 m/s)**	**Vessel**
x = 0.0954	x = 0.0897	x = 0.3008
R 2% (m)		
0.2210	0.3089	0.3409
Lenght R 2% (m)		
13.995	19.564	21.587

Figure 7.11: Run-up in point 2.

Run-up: POINT 3 tan b = 0.01875		
Wind from W 1 (6.70 m/s)	**Wind from W 2 (9.35 m/s)**	**Vessel**
x = 0.1133	x = 0.1065	x = 0.3572
R 2% (m)		
0.2497	0.3490	0.3851
Lenght R 2% (m)		
13.315	18.613	20.538

Figure 7.12: Run-up in point 3.

Chapter 8

Conclusion

As already mentioned, the biggest problem in Sjællands Odde is the erosion of cliffs due to the impact of combined wind waves and storm surge. The waves have a local impact on the cliff in those situations where the water level is high enough for the waves strike the slope, ie during storm events. The waves caused by passing ships are added to the natural raising of the level (run-up) and go to aggravate the situation. This, however, because of the low frequency of ship-waves becomes a problem only in cases where the two situations (passing ship and strong wind) coexist.

Cross-shore transport The waves coming from high-speed ships are different from those of natural origin, since they carry a greater power in the same wave height. This is due to the longer period of the wake waves. These furter undergo to the effect of shoaling, so grow rapidly in height and have a more violent impact on the coast (usually with plunging wave breaking type). The run-up that is expected is greater than a wind wave of the same height. In this case the wave produced by the wake will typically be less than 0.5m (locally may be larger due to non-linear effects of shoaling), this means that most of the times it will go beyond any possible bar present on the coast without wave breaking and arrive undisturbed in inland areas. The waves of the wake, in the impact with the coast line, will cause high particles speed in the run-up phase and a long period run-down with low velocities. This will cause a big cross-shore transport, predominantly of large size material from the bottom (pebbles and stones) and a steepen of the highest part of the profile (formation of a berm) with a resulted flattening of the lower part. The main impact will be on the foreshore mainly due to an additional movement of bottom material in and out from the coast (the opposite to the long-shore movement due to the natural climate). This indicates that the erosion produced by high-speed vessels will generate only small changes in the beaches formed by pebbles, then only a potential redistribution in the cross-shore direction. For reasons of time, this phenomenon is not analyzed in this study.

Through numerical modeling programs such as Mike 21 it is possible to recreate and predict the effects of storm surges and ship-waves with a good approximation. However, erosion is determined by the time and there is always a degree of uncertainty due to unpredictable factors, such as increases in the frequency of storms, or changes in the amount of these climatic variations over time. So it is useful to assist the use of computer programs with the constant monitor of the area over time in order to see how the coast evolves and how much it differs from the predictions. In this way it is possible to better evaluate the right means to face the continuing change in the balance of the coast.

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Appendix A

Wave heights with SPM method

Data about H_0 = *wave height*, T_P = *period*, L = *lenght* calculated for each wind-speed and for esch direction with the SPM method.

Direct	Uo	t (*)	U3600	UA	Fetch (Km)	Fetch (m)	tmin	Hmo deep	Tp deep	L
N	0.9	1787.778	0.888877	0.614234	9.220	9219.91716	16624.13	0.030	1.111	1.926
30	0.9	1787.778	0.888877	0.614234	0.782	782.499521	3210.532	0.009	0.488	0.372
60	0.9	1787.778	0.888877	0.614234	0.832	831.896641	3344.264	0.009	0.498	0.388
E	0.9	1787.778	0.888877	0.614234	4.506	4506.17831	10314.78	0.021	0.875	1.195
120	0.9	1787.778	0.888877	0.614234	10.073	10073.4622	17634.92	0.031	1.145	2.044
150	0.9	1787.778	0.888877	0.614234	15.477	15476.8316	23480.59	0.039	1.321	2.721
S	0.9	1787.778	0.888877	0.614234	16.454	16454.34	24459.14	0.040	1.348	2.834
210	0.9	1787.778	0.888877	0.614234	16.960	16960.0274	24957.74	0.041	1.362	2.892
240	0.9	1787.778	0.888877	0.614234	24.491	24490.6285	31885.08	0.049	1.539	3.695
O	0.9	1787.778	0.888877	0.614234	36.057	36057.4086	41265.2	0.060	1.751	4.782
300	0.9	1787.778	0.888877	0.614234	39.376	39376.2639	43760	0.062	1.803	5.071
330	0.9	1787.778	0.888877	0.614234	25.696	25696.2382	32923.09	0.050	1.564	3.815

Direz	Uo	t (*)	U3600	UA	Fetch (Km)	Fetch (m)	tmin	Hmo deep	Tp deep	L
N	2.45	656.7347	2.342607	2.022966	9.220	9219.91716	11173.45	0.099	1.653	4.264
30	2.45	656.7347	2.342607	2.022966	0.782	782.499521	2157.87	0.029	0.727	0.824
60	2.45	656.7347	2.342607	2.022966	0.832	831.896641	2247.754	0.030	0.742	0.858
E	2.45	656.7347	2.342607	2.022966	4.506	4506.17831	6932.792	0.069	1.302	2.646
120	2.45	656.7347	2.342607	2.022966	10.073	10073.4622	11852.82	0.104	1.703	4.524
150	2.45	656.7347	2.342607	2.022966	15.477	15476.8316	15781.83	0.129	1.965	6.023
S	2.45	656.7347	2.342607	2.022966	16.454	16454.34	16439.54	0.133	2.005	6.274
210	2.45	656.7347	2.342607	2.022966	16.960	16960.0274	16774.66	0.135	2.026	6.402
240	2.45	656.7347	2.342607	2.022966	24.491	24490.6285	21430.68	0.162	2.290	8.179
O	2.45	656.7347	2.342607	2.022966	36.057	36057.4086	27735.26	0.196	2.605	10.585
300	2.45	656.7347	2.342607	2.022966	39.376	39376.2639	29412.07	0.205	2.682	11.225
330	2.45	656.7347	2.342607	2.022966	25.696	25696.2382	22128.35	0.166	2.327	8.445

Direz	Uo	t (*)	U3600	UA	Fetch (Km)	Fetch (m)	tmin	Hmo deep	Tp deep	L
N	4.4	365.6818	4.084071	4.007773	9.220	9219.91716	8896.43	0.197	2.077	6.727
30	4.4	365.6818	4.084071	4.007773	0.782	782.499521	1718.121	0.057	0.913	1.299
60	4.4	365.6818	4.084071	4.007773	0.832	831.896641	1789.688	0.059	0.931	1.353
E	4.4	365.6818	4.084071	4.007773	4.506	4506.17831	5519.969	0.137	1.636	4.174
120	4.4	365.6818	4.084071	4.007773	10.073	10073.4622	9437.354	0.205	2.139	7.136
150	4.4	365.6818	4.084071	4.007773	15.477	15476.8316	12565.67	0.255	2.468	9.501
S	4.4	365.6818	4.084071	4.007773	16.454	16454.34	13089.35	0.263	2.519	9.897
210	4.4	365.6818	4.084071	4.007773	16.960	16960.0274	13356.18	0.267	2.544	10.099
240	4.4	365.6818	4.084071	4.007773	24.491	24490.6285	17063.35	0.320	2.876	12.902
O	4.4	365.6818	4.084071	4.007773	36.057	36057.4086	22083.14	0.389	3.272	16.698
300	4.4	365.6818	4.084071	4.007773	39.376	39376.2639	23418.23	0.406	3.369	17.707
330	4.4	365.6818	4.084071	4.007773	25.696	25696.2382	17618.85	0.328	2.922	13.322

Direz	Uo	t (*)	U3600	UA	Fetch (Km)	Fetch (m)	tmin	Hmo deep	Tp deep	L
N	6.7	240.1493	6.053034	6.502573	9.220	9219.91716	7571.031	0.319	2.440	9.288
30	6.7	240.1493	6.053034	6.502573	0.782	782.499521	1462.154	0.093	1.072	1.794
60	6.7	240.1493	6.053034	6.502573	0.832	831.896641	1523.059	0.096	1.094	1.868
E	6.7	240.1493	6.053034	6.502573	4.506	4506.17831	4697.599	0.223	1.922	5.763
120	6.7	240.1493	6.053034	6.502573	10.073	10073.4622	8031.368	0.333	2.513	9.853
150	6.7	240.1493	6.053034	6.502573	15.477	15476.8316	10693.63	0.413	2.900	13.119
S	6.7	240.1493	6.053034	6.502573	16.454	16454.34	11139.29	0.426	2.960	13.666
210	6.7	240.1493	6.053034	6.502573	16.960	16960.0274	11366.36	0.433	2.990	13.944
240	6.7	240.1493	6.053034	6.502573	24.491	24490.6285	14521.24	0.520	3.379	17.815
O	6.7	240.1493	6.053034	6.502573	36.057	36057.4086	18793.17	0.631	3.844	23.055
300	6.7	240.1493	6.053034	6.502573	39.376	39376.2639	19929.36	0.659	3.959	24.449
330	6.7	240.1493	6.053034	6.502573	25.696	25696.2382	14993.97	0.532	3.434	18.395

Direz	Uo	t (*)	U3600	UA	Fetch (Km)	Fetch (m)	tmin	Hmo deep	Tp deep	L
N	9.35	172.0856	8.240606	9.503599	9.220	9219.91716	6671.458	0.466	2.769	11.962
30	9.35	172.0856	8.240606	9.503599	0.782	782.499521	1288.424	0.136	1.217	2.310
60	9.35	172.0856	8.240606	9.503599	0.832	831.896641	1342.092	0.140	1.242	2.406
E	9.35	172.0856	8.240606	9.503599	4.506	4506.17831	4139.441	0.326	2.181	7.422
120	9.35	172.0856	8.240606	9.503599	10.073	10073.4622	7077.099	0.487	2.852	12.689
150	9.35	172.0856	8.240606	9.503599	15.477	15476.8316	9423.034	0.604	3.291	16.895
S	9.35	172.0856	8.240606	9.503599	16.454	16454.34	9815.74	0.623	3.359	17.599
210	9.35	172.0856	8.240606	9.503599	16.960	16960.0274	10015.83	0.632	3.393	17.958
240	9.35	172.0856	8.240606	9.503599	24.491	24490.6285	12795.86	0.760	3.835	22.943
O	9.35	172.0856	8.240606	9.503599	36.057	36057.4086	16560.21	0.922	4.363	29.692
300	9.35	172.0856	8.240606	9.503599	39.376	39376.2639	17561.4	0.963	4.493	31.487
330	9.35	172.0856	8.240606	9.503599	25.696	25696.2382	13212.42	0.778	3.897	23.690

Direz	Uo	t (*)	U3600	UA	Fetch (Km)	Fetch (m)	tmin	Hmo deep	Tp deep	L
N	12.3	130.813	10.60131	12.95539	9.220	9219.91716	6016.814	0.635	3.070	14.706
30	12.3	130.813	10.60131	12.95539	0.782	782.499521	1161.996	0.185	1.349	2.840
60	12.3	130.813	10.60131	12.95539	0.832	831.896641	1210.398	0.191	1.377	2.958
E	12.3	130.813	10.60131	12.95539	4.506	4506.17831	3733.254	0.444	2.419	9.125
120	12.3	130.813	10.60131	12.95539	10.073	10073.4622	6382.651	0.664	3.162	15.601
150	12.3	130.813	10.60131	12.95539	15.477	15476.8316	8498.389	0.823	3.649	20.772
S	12.3	130.813	10.60131	12.95539	16.454	16454.34	8852.56	0.849	3.724	21.638
210	12.3	130.813	10.60131	12.95539	16.960	16960.0274	9033.019	0.862	3.762	22.079
240	12.3	130.813	10.60131	12.95539	24.491	24490.6285	11540.25	1.036	4.252	28.207
O	12.3	130.813	10.60131	12.95539	36.057	36057.4086	14935.22	1.257	4.837	36.505
300	12.3	130.813	10.60131	12.95539	39.376	39376.2639	15838.17	1.313	4.981	38.712
330	12.3	130.813	10.60131	12.95539	25.696	25696.2382	11915.94	1.061	4.321	29.125

Direz	Uo	t (*)	U3600	UA	Fetch (Km)	Fetch (m)	tmin	Hmo deep	Tp deep	L
N	15.5	103.8065	13.09571	16.80069	9.220	9219.91716	5517.484	0.824	3.348	17.489
30	15.5	103.8065	13.09571	16.80069	0.782	782.499521	1065.563	0.240	1.471	3.377
60	15.5	103.8065	13.09571	16.80069	0.832	831.896641	1109.948	0.248	1.502	3.518
E	15.5	103.8065	13.09571	16.80069	4.506	4506.17831	3423.434	0.576	2.637	10.851
120	15.5	103.8065	13.09571	16.80069	10.073	10073.4622	5852.96	0.861	3.449	18.552
150	15.5	103.8065	13.09571	16.80069	15.477	15476.8316	7793.115	1.068	3.979	24.702
S	15.5	103.8065	13.09571	16.80069	16.454	16454.34	8117.894	1.101	4.061	25.731
210	15.5	103.8065	13.09571	16.80069	16.960	16960.0274	8283.377	1.118	4.103	26.256
240	15.5	103.8065	13.09571	16.80069	24.491	24490.6285	10582.53	1.343	4.637	33.543
O	15.5	103.8065	13.09571	16.80069	36.057	36057.4086	13695.76	1.630	5.275	43.411
300	15.5	103.8065	13.09571	16.80069	39.376	39376.2639	14523.77	1.703	5.432	46.036
330	15.5	103.8065	13.09571	16.80069	25.696	25696.2382	10927.05	1.376	4.712	34.635

Direz	Uo	t (*)	U3600	UA	Fetch (Km)	Fetch (m)	tmin	Hmo deep	Tp deep	L
N	18.95	84.90765	15.72593	21.04246	9.220	9219.91716	5118.601	1.032	3.609	20.321
30	18.95	84.90765	15.72593	21.04246	0.782	782.499521	988.5288	0.301	1.586	3.924
60	18.95	84.90765	15.72593	21.04246	0.832	831.896641	1029.705	0.310	1.619	4.088
E	18.95	84.90765	15.72593	21.04246	4.506	4506.17831	3175.939	0.722	2.843	12.608
120	18.95	84.90765	15.72593	21.04246	10.073	10073.4622	5429.824	1.079	3.717	21.556
150	18.95	84.90765	15.72593	21.04246	15.477	15476.8316	7229.717	1.337	4.289	28.702
S	18.95	84.90765	15.72593	21.04246	16.454	16454.34	7531.016	1.379	4.378	29.898
210	18.95	84.90765	15.72593	21.04246	16.960	16960.0274	7684.536	1.400	4.422	30.507
240	18.95	84.90765	15.72593	21.04246	24.491	24490.6285	9817.477	1.682	4.998	38.975
O	18.95	84.90765	15.72593	21.04246	36.057	36057.4086	12705.63	2.041	5.686	50.441
300	18.95	84.90765	15.72593	21.04246	39.376	39376.2639	13473.78	2.133	5.856	53.490
330	18.95	84.90765	15.72593	21.04246	25.696	25696.2382	10137.08	1.723	5.079	40.244

Direz	Uo	t (*)	U3600	UA	Fetch (Km)	Fetch (m)	tmin	Hmo deep	Tp deep	L
N	22.6	71.19469	18.45673	25.62293	9.220	9219.91716	4793.365	1.257	3.854	23.172
30	22.6	71.19469	18.45673	25.62293	0.782	782.499521	925.7177	0.366	1.694	4.475
60	22.6	71.19469	18.45673	25.62293	0.832	831.896641	964.2776	0.378	1.729	4.661
E	22.6	71.19469	18.45673	25.62293	4.506	4506.17831	2974.14	0.879	3.036	14.377
120	22.6	71.19469	18.45673	25.62293	10.073	10073.4622	5084.813	1.314	3.969	24.581
150	22.6	71.19469	18.45673	25.62293	15.477	15476.8316	6770.341	1.628	4.580	32.729
S	22.6	71.19469	18.45673	25.62293	16.454	16454.34	7052.495	1.679	4.675	34.093
210	22.6	71.19469	18.45673	25.62293	16.960	16960.0274	7196.26	1.705	4.722	34.788
240	22.6	71.19469	18.45673	25.62293	24.491	24490.6285	9193.675	2.048	5.338	44.443
O	22.6	71.19469	18.45673	25.62293	36.057	36057.4086	11898.32	2.485	6.072	57.518
300	22.6	71.19469	18.45673	25.62293	39.376	39376.2639	12617.66	2.597	6.253	60.995
330	22.6	71.19469	18.45673	25.62293	25.696	25696.2382	9492.972	2.098	5.424	45.890

Direz	Uo	t (*)	U3600	UA	Fetch (Km)	Fetch (m)	tmin	Hmo deep	Tp deep	L
N	26.45	60.83176	21.29143	30.54571	9.220	9219.91716	4520.641	1.498	4.087	26.052
30	26.45	60.83176	21.29143	30.54571	0.782	782.499521	873.0479	0.436	1.796	5.031
60	26.45	60.83176	21.29143	30.54571	0.832	831.896641	909.4139	0.450	1.833	5.241
E	26.45	60.83176	21.29143	30.54571	4.506	4506.17831	2804.923	1.047	3.219	16.164
120	26.45	60.83176	21.29143	30.54571	10.073	10073.4622	4795.507	1.566	4.209	27.636
150	26.45	60.83176	21.29143	30.54571	15.477	15476.8316	6385.135	1.941	4.857	36.797
S	26.45	60.83176	21.29143	30.54571	16.454	16454.34	6651.236	2.002	4.957	38.330
210	26.45	60.83176	21.29143	30.54571	16.960	16960.0274	6786.821	2.032	5.007	39.111
240	26.45	60.83176	21.29143	30.54571	24.491	24490.6285	8670.59	2.442	5.660	49.967
O	26.45	60.83176	21.29143	30.54571	36.057	36057.4086	11221.35	2.963	6.438	64.667
300	26.45	60.83176	21.29143	30.54571	39.376	39376.2639	11899.76	3.096	6.630	68.577
330	26.45	60.83176	21.29143	30.54571	25.696	25696.2382	8952.859	2.501	5.751	51.594

Direz	Uo	t (*)	U3600	UA	Fetch (Km)	Fetch (m)	tmin	Hmo deep	Tp deep	L
N	30.55	52.66776	24.26878	35.88122	9.220	9219.91716	4284.443	1.760	4.312	29.003
30	30.55	52.66776	24.26878	35.88122	0.782	782.499521	827.4322	0.513	1.895	5.601
60	30.55	52.66776	24.26878	35.88122	0.832	831.896641	861.8981	0.529	1.934	5.835
E	30.55	52.66776	24.26878	35.88122	4.506	4506.17831	2658.369	1.230	3.396	17.996
120	30.55	52.66776	24.26878	35.88122	10.073	10073.4622	4544.947	1.840	4.441	30.767
150	30.55	52.66776	24.26878	35.88122	15.477	15476.8316	6051.519	2.280	5.124	40.966
S	30.55	52.66776	24.26878	35.88122	16.454	16454.34	6303.717	2.351	5.230	42.673
210	30.55	52.66776	24.26878	35.88122	16.960	16960.0274	6432.218	2.387	5.283	43.543
240	30.55	52.66776	24.26878	35.88122	24.491	24490.6285	8217.562	2.868	5.972	55.629
O	30.55	52.66776	24.26878	35.88122	36.057	36057.4086	10635.05	3.481	6.793	71.994
300	30.55	52.66776	24.26878	35.88122	39.376	39376.2639	11278.02	3.637	6.996	76.346
330	30.55	52.66776	24.26878	35.88122	25.696	25696.2382	8485.082	2.938	6.068	57.440

Direz	Uo	t (*)	U3600	UA	Fetch (Km)	Fetch (m)	tmin	Hmo deep	Tp deep	L
N	34.8	46.23563	27.31841	41.50482	9.220	9219.91716	4081.476	2.036	4.526	31.960
30	34.8	46.23563	27.31841	41.50482	0.782	782.499521	788.2342	0.593	1.989	6.172
60	34.8	46.23563	27.31841	41.50482	0.832	831.896641	821.0674	0.612	2.030	6.429
E	34.8	46.23563	27.31841	41.50482	4.506	4506.17831	2532.434	1.423	3.565	19.830
120	34.8	46.23563	27.31841	41.50482	10.073	10073.4622	4329.64	2.128	4.662	33.903
150	34.8	46.23563	27.31841	41.50482	15.477	15476.8316	5764.84	2.638	5.379	45.141
S	34.8	46.23563	27.31841	41.50482	16.454	16454.34	6005.091	2.720	5.490	47.023
210	34.8	46.23563	27.31841	41.50482	16.960	16960.0274	6127.504	2.761	5.546	47.981
240	34.8	46.23563	27.31841	41.50482	24.491	24490.6285	7828.271	3.318	6.269	61.299
O	34.8	46.23563	27.31841	41.50482	36.057	36057.4086	10131.23	4.026	7.131	79.332
300	34.8	46.23563	27.31841	41.50482	39.376	39376.2639	10743.74	4.207	7.344	84.128
330	34.8	46.23563	27.31841	41.50482	25.696	25696.2382	8083.119	3.399	6.370	63.294

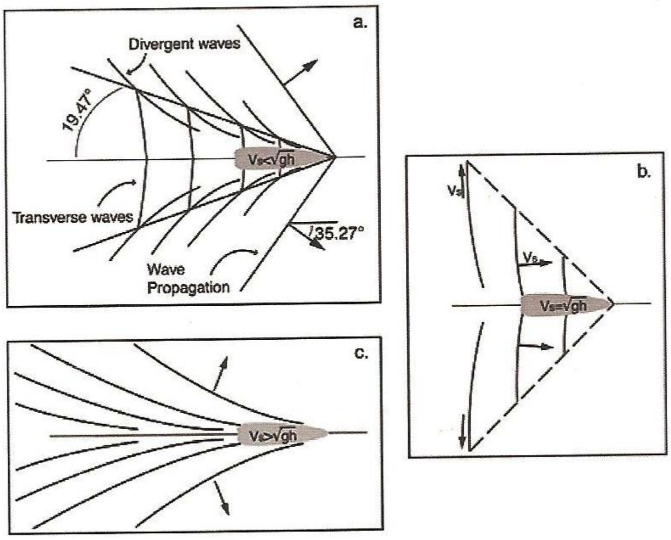
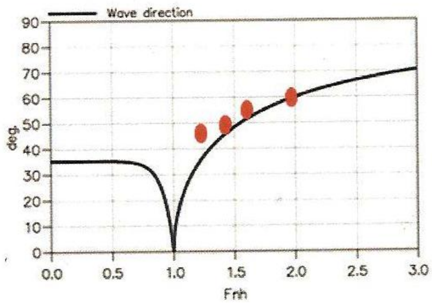


Figure 4.2 Vessel wake waves at (a) subcritical speed (F_{nh} < 0,7), (b) critical speed (showing the wave propagating forward and the crest lengthening at vessel speed (F_{nh} ~ 1) and (c) supercritical speed (F_{nh} > ~1). From [6].



$$\theta = 35{,}267(1-\exp(12(F_{nh}-1))) \text{ for } F_{nh} \leq 1$$

$$\theta = arccos(\frac{1}{F_{nh}}) \qquad \text{for } F_{nh} > 1$$

Figure 4.3 Wave propagation direction of diverging waves versus depth-Froude number. From [4]. The red marks are the results derived from the CFD calculation for Incat 112, [2].

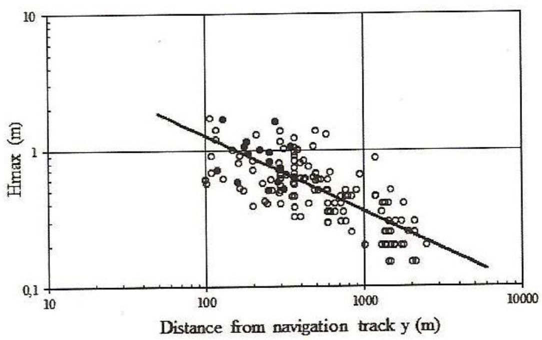


Figure 4.4 Maximum wave height of the long-period ship-generated waves versus the distance from the navigation track. The measured data (∘∘∘) are from various field campaigns involving catamarans (from [6]) and (•) are results for Incat 91 Max Mols, [3]. The trend line (–) is given by $H_{max}=16y^{-0.55}$, where y (in meters) denotes the distance from the track.

Figure A.1: Angle of divergent waves from [4], page 15.

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