Research Project 457

A Physical Study of Fast Ferry Wash Characteristics in Shallow Water

Final Report
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1.0 INTRODUCTION

1.1 Objectives of Study

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1.3 Methodology

1.3.1 Tank Construction

1.3.2 Instrumentation and Data Acquisition (models)

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1.0 INTRODUCTION

In 1999 the Queen's University of Belfast was awarded a contract to undertake a physical study of fast ferry wash with a view to obtaining a better understanding of the physical characteristics of the long period waves which are generated. Kirk McClure Morton were engaged as sub-contractors to undertake mathematical modelling of the transformation processes which take place as the wash travels from the ship to the shore. This was essentially a "follow up" study to MCA project 420, 'Investigation of High Speed Craft on Routes Near to Land or Enclosed Estuaries'.

1.1 Objectives of Study

- Generally improve the understanding of the physical properties of the very long period waves in both critical and super critical wash by studying,
- the transverse spreading velocity of the critical wave group,
- the divergence of the leading long period waves in the super-critical wash,
  - the variation of wave height with distance from the ship,
  - the period of the various wave components and their propagation angles relative to the track of the ship,
- determine how the above is influenced by hull configuration, speed and water depth,
- provide more detailed information to improve the mathematical models of the wave transformation processes in estuaries used in research project 420 and in future would be used to produce risk assessments for fast ferry routes,
- research and demonstrate some remedial measures for reducing the surge effect on shorelines, moored ships and passing vessels in confined channels,
- determine if solitary waves can be created in estuaries due to the influence of wash induced currents and pressure fluctuations on the sea bed and on the shore line,
- undertake an initial study of the environmental impact of the wash of fast ships and initiate a longer term study,
- liaise with other groups researching fast ferry wash.

1.2 Definition of terms

The definition of ship wash can be defined in terms of 'Depth Froude Number' (Fn_h). This is defined as the ratio of ship speed to the maximum velocity a wave can travel in a given water depth. This is discussed in more detail in MCA 420(1998), Whittaker (1999), Whittaker (2000).

The main categories are as follows;

- sub-critical \( Fn_h < 1 \)
- critical \( ship\ speed = maximum\ wave\ speed \) \( Fn_h = 1 \)
- super-critical \( ship\ speed > maximum\ wave\ speed \) \( Fn_h > 1 \)
- high speed sub-critical similar to sub-critical but recognises that high speed ships in deep water can produce divergence waves with or without the transverse wave component depending on the length Froude number (the ratio of ship velocity to a function of waterline length),
- trans-critical or near-critical depth Froude numbers between 0.85 and 1.1.
The energy calculation was performed in one of two ways depending on the aspect of the wash under consideration.

1. The energy density [Joule per m²] in the wash wave time series was calculated using the surface elevation, assuming that the kinetic energy is equal to the potential energy. The integral for energy density is described as:

\[
\bar{E} = \frac{\rho g}{T_i} \int_0^T \eta^2 \, dt \quad (T_i = \text{time for complete wash})
\]

The energy density \( \bar{E} \), describes the mean total energy in one trace standardised for one square meter sea surface.

2. Alternatively when the highest wave in the wash was being considered, the wave period was measured and the wavelength was calculated from:

\[
\lambda = \frac{2\pi}{2\pi \tanh \frac{2\pi h}{\lambda}}
\]

which takes into account the angle of propagation of the waves.

In the following chapters a few parameters are used to describe the wave traces and patterns. They are as follows and are illustrated below.

Figure 1.2-1 Wave Elevation Time History

The wave height \( H \) is the height measured from a crest to the next trough after a zero crossing. The maximum wave height \( H_{\text{max}} \) is the highest wave measured in a trace.

The period \( T \) is measured from one upward zero crossing to the next positive zero crossing. The maximum period \( T_{\text{max}} \) is the period of the highest wave.
1.3 Methodology

1.3.1 Tank Construction

A shallow wide towing tank measuring 50m x 17m with a maximum water depth of 400mm was built in a warehouse provided by Belfast Harbour Commissioners. This was constructed from concrete blocks built on a level concrete floor and was sealed with a ‘brush on’ liquid membrane. A cable-way towing system with a computer controlled variable speed motor was installed to tow a variety of models with a scale of between 1:50 and 1:80 at speeds up to 4.5m/s. Loose stone beaches with a slope of 1:3 were used to minimise reflections around the tank. As the models were towed close to one side in order to maximise the measurement area, a very low reflection coefficient was essential this was achieved locally by placing variable density foam blocks in a chevron formation on top of the stone beach. The tank is shown in figures 1.3-1 and 1.3-2.

1.3.2 Instrumentation and Data Acquisition (models)

An array of 12 twin wires resistance probes were used to measure the wash wave profiles produced by the different models. These were connected via a 16 channel A to D board to a portable computer for data storage and analysis. The locations of the wave probes were adjustable to accommodate the different experiments and to measure different aspects of the wash waves produced. Other channels of information included the velocity profile of the model along the track and position relative to the time traces produced at the various wave probes.

To measure the surface elevation in the model tank, parallel wire resistance wave probes were used. The wires were fed with alternating current with a range of 0-2 mA to prevent electrolysis. An amplifier measured the drop of voltage at two resistors, which were connected in line with both wires of the probe. This signal was rectified into a pulsing direct current and smoothed by a filter. A second amplifier with a 15 volt supply, generated an output from -5.0 to +5.0 volt and an analogue/digital converter identified this signal. The package LabView® distributed by National Instruments was used for data acquisition. The values were read from the A/D-card at a frequency of 50 Hz. The user had to save each record in an asci-code spread sheet.

Before starting a new measurement task the probes had to be calibrated. The probes were positioned and the output signal of the amplifier was zeroed. The probes were then lifted 50mm and a measurement taken. These values were then used for calibration. The program provided the output in mm surface elevation.

The whole measurement program was integrated into the towing control program. Where the ship passed the first velocity logging sensor, a surface elevation measurement was taken and stopped after a user-defined time.

1.3.3 Experimental Programme

Models of both catamaran and monohull fast ferries were towed at a range of constant speeds in water depths ranging from 100 to 400mm equivalent to between 5m and 32m at full size. The various speeds resulted in wave heights and patterns being measured at depth limited Froude Numbers ranging from 0.8 to 2.6. The models included:

- a 1:50 scale model of Seacat an Incat 74m wave piercing catamaran,
• a 1:50 scale model of Superseacat, a Fincantieri MDV 1200, a 100m monohull fast ferry,
• a 1:80 scale model of a 120m SWATH catamaran of a similar generic configuration to Stena HSS 1500,
• a 1:64 scale model of the P&O Jetliner a 96m monohull fast ferry which has a round bilge hull form and a bulbous bow as in many conventional ships.

All the models could also be self propelled using either water jets or surface running propellers and radio controlled. Three of the models are shown in figure 1.3-3.

Experiments were conducted in which the models were accelerated and decelerated at different locations in the tank relative to the wave probe arrays. This was particularly important to ascertain how the super-critical wash decays after the ship has slowed down and is no longer energizing the leading long period waves.

In addition to the scale models of fast ships defined above a series of generic models were also tested. The hull shapes comprised a flat bottom in both the longitudinal and transverse directions, vertical sides, a 10mm radius curve between the sides and the bottom. In plan view the sides had a constant curvature from the stem to the point of maximum beam which in all cases was 0.5m from the stem. The hulls were lengthened by adding rectangular sections. The hulls were tested in both monohull and catamaran form and at different drafts.

Tables 1.3-1 to 1.3-6 present the full range of experiments conducted at model scale to study the sub-critical, critical and super-critical wash patterns using the range of models. The principal variables at both model and full size are also given.

Finally a qualitative assessment was made of the effect of super-critical wash produced by fast ferries on,
• other ships either approaching or travelling in the same direction,
• moored vessels at open quays in estuaries.

These tests were conducted at model scale and the observations were verified using data obtained from field measurements taken as part of other studies.
1.3.4 Instrumentation and Data Acquisition (field measurements)

For prototype data acquisition a robust measurement system, that allows one to track the wash of fast ferries, was required. As commercial wave monitoring equipment did not comply with these demands the wave power research group developed two types of measurement equipment.

An ultrasonic measurement system was used which worked on the time taken for a sound signal to be emitted by a transducer and reflected back by the air-water interface. The distance from the emitter to the water surface and back to the receiver is a linear function of the elapsed time. The ultrasonic transducer was mounted on a long pole. The signal was recorded at a frequency of 5 Hz, which provides a sufficient record of the wave amplitude.

The sea bed pressure transducer system used measured the pressure of the water overhead. The electronic equipment was housed in a watertight cylinder, which was fixed in a steel frame. The weight of the system ensured self-anchoring. An attached chain with a marker buoy located the position and allowed the deployment and retrieval of the equipment. The pressure signal was logged at a frequency of 2 Hz. Unfortunately the relationship between pressure and actual head of water is non-linear. The analysing software developed re-scaled the pressure with a complex function dependent on mean water depth and wavelength.

Both measurement systems used a data-logging card and sealed lead acid batteries supplied power. A timer was used to start data collection 45 minutes before/after the scheduled arrival/departure of a ship.

1.3.5 Mathematical Modelling – Wash Wave Transformation

The output from the physical modeling program supplemented with field measurements from other studies were used to improve the input data to the Mike 21 software which have been adapted to model the transformation of fast ferry wash in the coastal zone in MCA project 420. The refined input data included the range of wave periods used, the direction of travel of the different wash wave components and the attenuation of height with distance from the ship’s track. In addition some preliminary calculations were undertaken on sediment transport in very shallow water and at the shoreline.
1.3.6 Environmental Impact of High Speed Ship Wash

This part of the research project had an initial look at the environmental impact of high speed wash. A case study was chosen to illustrate a possible procedure for such an investigation and to show the various difficulties in accessing the impact of high speed craft. Some general conclusions on the environmental impact of HSC are presented. Though the research project MCA 457 was focused on wave generation and transformation some aspects of HSC other than wave action are discussed. However it is still difficult to predict the environmental impact, as even 5 years of operation is a short period in coastal engineering.

Figure 1.3-1 Shallow Wide Towing Tank Facility

Figure 1.3-2 Picture of Wide Tank Facility
Figure 1.3-3 Pictures of models being towed
### Table 1.3-1    HSS 1500

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>L(m)</th>
<th>Lwl(m)</th>
<th>Disp</th>
<th>B</th>
<th>T</th>
<th>Lwl/D^{HSS}</th>
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<tr>
<td>Model</td>
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<td>1.344</td>
<td>8.7kg</td>
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<tr>
<td>12</td>
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<tr>
<td>20</td>
<td>0.82 0.90 0.95 0.97 0.99 1.03 1.04 1.10 1.30 1.61 1.90 2.19</td>
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<tr>
<td>32</td>
<td>0.80 0.90 0.95 0.97 1.00 1.02 1.09 1.14 1.30 1.61</td>
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<td>48</td>
<td>0.61 0.67 0.68 0.74 0.79 0.83 0.89 0.95 0.99 1.06 1.09</td>
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### Table 1.3-2    Superseacat

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<th>Lwl/D^{HSS}</th>
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<td>15</td>
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<td>0.80 0.90 0.95 0.97 1.00 1.03 1.06 1.11 1.30 1.61 1.90 1.95</td>
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### Table 1.3-3  Jetliner

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<td>12.8</td>
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### Table 1.3-4  Seacat

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<td>Lwl(m)</td>
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<tr>
<td>12.5</td>
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14
Table 1.3-5  Generic models (Monohull)

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<th>B</th>
<th>T</th>
<th>Lwl/D°0.33</th>
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<tbody>
<tr>
<td>MA1</td>
<td>1m</td>
<td>1m</td>
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<td>MA15</td>
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<td>1.5m</td>
<td>6.65kg</td>
<td>200mm</td>
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<td>MA2</td>
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<td>9.15kg</td>
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Prototype (scale 1:50)

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<th>Disp</th>
<th>B</th>
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<th>Lwl/D°0.33</th>
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<td>519t</td>
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<tr>
<td>MA15</td>
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<td>75m</td>
<td>831t</td>
<td>10m</td>
<td>1.25m</td>
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<tr>
<td>MA2</td>
<td>100m</td>
<td>100m</td>
<td>1144t</td>
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<td>1.25m</td>
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<thead>
<tr>
<th>Depth (m) prototype</th>
<th>Depth Froude Numbers</th>
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<tr>
<td>MA1 12.5 0.90 0.97</td>
<td>1.01 1.10 1.30 1.51 1.80</td>
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<tr>
<td>MA1 20 0.90 0.97</td>
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<td>MA15 20 0.91 0.97</td>
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<tr>
<td>MA2 12.5 0.91 0.98</td>
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<table>
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<th>Model</th>
<th>L</th>
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<th>Lwl/D°0.33</th>
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<tr>
<td>MB1</td>
<td>1m</td>
<td>1m</td>
<td>5.81kg</td>
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Prototype

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<td>10m</td>
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### Table 1.3-6  Generic models (Catamaran)

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<th>Lwl (m)</th>
<th>Disp (kg)</th>
<th>B (mm)</th>
<th>T (mm)</th>
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CHAPTER 2

2.0 PHYSICAL CHARACTERISTICS OF FAST FERRY WASH

2.1 Linear Theory

2.1.1 Sub-critical Depth Froude Number
2.1.2 Critical Depth Froude Number
2.1.3 Super-Critical Depth Froude Number
2.1.4 High Speed Sub-Critical Wash
2.0 PHYSICAL CHARACTERISTICS OF FAST FERRY WASH

2.1 Linear Theory

There are several aspects of the wash of a fast ferry operating in shallow water which are fundamentally different to those of a conventional ship. The wash produced by fast ferries is classified in terms of depth Froude number and this was described by Havelock (1908) following the work of Froude (1877) and Lord Kelvin (1887). The depth Froude number ($Fn_h$) is the ratio of ship speed ($V_s$) to the maximum wave speed in a given depth of water ($h$).

$$Fn_h = \frac{V_s}{\sqrt{gh}}$$

As stated in section 1.2, the operation of a ship can then be classified as sub-critical when $Fn_h < 1$, critical when $Fn_h = 1$ and super-critical when $Fn_h > 1$. Close to the critical speed the wave induced drag and consequently the wave height increases dramatically and most ships do not have a sufficient power to weight ratio to break through into the super-critical region. Fast ferries have power to weight ratios which are an order of magnitude greater than conventional ships and due to their relatively light displacement and slender hull forms in either mono-hull or multi-hull format, can easily exceed the critical speed.

2.1.1 Sub-critical Depth Froude Number

When $Fn_h < 0.57$ the classical Kelvin wash pattern exists with a series of transverse and divergent waves meeting at the cusp locus. Figure 2.1-1a shows the Kelvin wash pattern and distinguishes the transverse and divergent wave groups. This wash pattern is clearly shown in the aerial photograph of Seacat travelling at 12 knots, figure 2.1-1b.

As $Fn_h$ increases due to either an increase in speed, a reduction in water depth or both together, the longer wave components in the wash start to ‘feel the bottom’ and the wave properties begin to change. Between $Fn_h = 0.57$ and 1 the long waves become steadily less dispersive and their energy is largely conserved in individual waves.

2.1.2 Critical Depth Froude Number

At the critical Froude number of 1, the velocity of the ship and the velocity of the waves are equal to $\sqrt{gh}$. In linear theory the energy does not disperse back along the wave train aft of the ship. Consequently a significant proportion of the propulsive power is converted into wave energy in a few waves with fronts nearly perpendicular to the track of the ship. The crest length on either side of the ship increases at a velocity of $\sqrt{gh}$, which is the same as its forward velocity. Consequently from the point where the ship reached the critical speed the wave front will be curved and will be contained within a cone of apex angle of 360°. As energy is being pumped continually into these waves, the time duration which ship speed and the shallow water wave velocity coincide must be minimised as the height of the wave can build quickly. The process is shown in figure 2.1-2a & b.

In figure 2.1-2c a wave cut through the wash produced by a fast ferry transcending the critical depth Froude number is shown. The trace was measured 500m from the track of the ship. The first group of waves has been produced when the ship was travelling through the near-critical depth Froude range. However, later in the trace the wash produced when the ship was travelling more slowly in the sub-critical range can be seen. The waves between 150s and 200s are the combination of the divergent and transverse waves at the cusp locus in the Kelvin wash. The remaining waves are the transverse waves travelling behind the ship.
2.1.3 Super-critical Depth Froude Number

In the super-critical region the long waves are non-dispersive and the wash pattern takes on a different appearance, as shown in figure 2.1-3a & b. The long waves can not travel in the direction of the ship as the water depth limits their speed. Therefore the wave fronts subtend an angle $\theta$ to the track of the ship so that $C=V_s \cos \theta$; where $C$ and $V_s$ are the wave and ship speed respectively. Consequently all the wash wave components radiate out in lines from the ship in a delta like formation. The longer faster waves are on the outside of the wash and have larger values of $\theta$ compared to the slower shorter waves with crests swept further back. The leading wave crest is straight in plan view and the subsequent wave crests are concave particularly close to the ship as where they are pulled along at a greater speed than they can physically sustain due to the limited water depth. Both the critical wave and the transverse waves, which existed before the ship entered the super-critical region, are left behind as they can not keep pace due to their velocity being restricted by water depth.

Figure 2.1-3c shows a wave cut through a wash produced by a high speed ferry at super-critical depth Froude number. This trace has been measured 2.7km from the track of the vessel. It is clearly divided into three wave frequency bands, which have been designated as zones 1, 2 and 3. The initial group of waves, shown in zone 1, do not exist in a conventional ferry wash and are peculiar to a vessel operating in the super-critical range. The first wave has a period of 40s and a height of over 0.3m, the second and third waves are the highest at 0.5m with periods of 20s and 16s respectively followed by 8 waves which steadily reduce in height and wave period to 0.2m and 8s respectively. The second zone of waves, with periods of between 5.5s and 4s, is similar to the complete wash produced by a conventional, ferry of similar displacement and are divergent sub-critical waves as described in section 4.2. The third zone has a small group of very steep waves with a period of 3s and is peculiar to fast ferries. The height and number of waves in the various frequency bands varies with distance from the track and the size and hull from of the ship. Consequently the above can only be used as a general description of a super-critical wash pattern.
2.1.4 High Speed Sub-critical Wash

In MCA 420 (1998) a further category, high speed sub-critical wash, was introduced to recognise that the largest fast ferries at full operational speed can produce a Kelvin wash pattern in deep water with both divergent and transverse waves. The wave lengths and heights are substantially greater than the sub-critical wash produced at slower speed in shallow water close to the port. In contrast, smaller fast ferries with a waterline length less than about 80m do not produce the transverse wave component in deep water. This situation is similar to the wash characteristics of speedboats, which have very short waterline lengths in relation to their speed.

Figure 2.1-4a shows a model operating at speed in deep water in the sub-critical depth Froude number range. Figure 2.1-4b shows a cut through a wash produced by an HSS 1500 on passage from Loch Ryan to Belfast Lough. The first part of the wash trace up to 1000s is super-critical. This is followed by 7 long period waves which were produced in the trans-critical zone when the ship was entering the Lough. The waves which arrive later between 1200s and 2400s are transverse waves produced when the ship was in deep water and travelling at 40 knots. The waves have a constant wave period of around 13.5 seconds. The later waves in the trace were produced when the ship was 20km away and they have followed the ship into the Lough. These waves are particularly persistent as in this case they last for 20 minutes.
Figure 2.1-1a Planview of typical Kelvin wash pattern (sub-critical)

Figure 2.1-1b Aerial photograph of catamaran with sub-critical wave pattern
Figure 2.1-2a Plan view of critical wave pattern

Figure 2.1-2b Aerial photograph of catamaran passing through critical speed

Figure 2.1-2c Wave trace produced by ship passing through critical speed
Figure 2.1-3a Plan view of super critical wave pattern

Figure 2.1-3b Aerial photograph of catamaran at super-critical speed

Figure 2.1-3c Wave trace produced by ship at supercritical speed
Figure 2.1-4a Model of catamaran at high speed sub-critical speed

Figure 2.1-4b High speed sub-critical wash
Chapter 3

3.0 WAVE WASH (VERY SHALLOW WATER)
3.1 Introduction
3.2 Non-Linear Shallow Water Wave Theory
3.3 Physical Observations
   3.3.1 Model Tests
   3.3.2 Field Measurements
3.4 Discussion of Observations
3.0 WAVE WASH (VERY SHALLOW WATER)

3.1 Introduction

*Dand, et al (1999)*, reported that during the EC-funded SPAN project (safe passage and navigation) solitary type waves were produced by a fast ferry model in a shallow wide tank. However, no measurements were taken and the only evidence of their possible existence was photographic. Subsequently the Queen’s University team have conducted an extensive range of experiments in the 50m by 17m shallow water towing tank. Models of both catamarans and monohulls were towed at a variety of speeds in very shallow water equivalent to between 5m and 8m at full size. The model tests were complimented by a series of field trials in Loch Ryan where wash waves were measured for a conventional ship and a fast ferry.

3.2 Non-Linear Shallow Water Wave Theory

A ship travelling at near critical or super-critical speed in very shallow water is capable of producing long waves which are best described by cnoidal or solitary wave theories. Cnoidal theory was originally developed by *Kortweg and De Vries (1895)*. According to this theory the wave characteristics are expressed in terms of the Jacobian elliptic function $cn$ and hence the term ‘cnoidal’ is used. The approximate range of validity for the cnoidal wave theory as determined by *Laitone (1963)* is $h/\lambda <1/8$ and $\lambda^2 H/h^3 >26$; where $h$, $\lambda$, $H$ are the water depth, wave length and wave height respectively.

The solitary wave is a limiting case of the cnoidal wave in which the wavelength becomes infinite. It is a wave of translation relative to the water mass and its surface lies entirely above the still water level. *Russell (1838)* first reported such waves in 1834 on the basis of experimental observation in a canal. It was first analysed by *Boussinesq (1872)*, prior to the development of cnoidal waves. The interesting thing about these non-linear waves is that their celerity not only depends on the water depth ($h$), but is also a function of the wave height $H$. The expression for the celerity of a cnoidal wave is $c = \sqrt{g(h+AH)}$ and $c = \sqrt{g(h+H)}$ for a solitary wave. $A = 2 m - 1 - \frac{3 E(m)}{m K(m)}$

$m$ = parameter of elliptic functions and integrals

$K(m)$ = complete elliptic integral of the first kind.

$E(m)$ = complete elliptic integral of the second kind

Theoretically a ship travelling close to the critical speed in sufficiently shallow water is capable of producing long period waves which travel faster than the ship itself. Therefore waves formed earlier in the ship’s time history will have propagated further ahead of the ship than those formed at a later stage.
3.3 Physical Observations

3.3.1 Model Tests

The first series of experiments was conducted in very shallow water with a depth of 100mm equivalent to a depth of between 5m and 8m depending on the scale of the model under test. This was to establish if solitary waves could be generated and the physical parameters which determined their creation. In figures 3.3-1, 3.3-2 and 3.3-3 the water depth was very shallow.

Figure 3.3-1 was obtained at a depth Froude number of 1.1 using the model of the 120m SWATH catamaran in a water depth equivalent to 8m. It shows the development of the leading waves at 6m intervals along the track of ship measured at a distance of one ship length. The vertical ticks show the position of the bow of the ship. Comparison of the initial part of each wave trace shows clearly a wave crest above the mean water surface travelling further ahead of the ship as time progresses. As the crest stretches, a second crest begins to form and the first crest seems to reduce in height and transfer energy rearwards. This initial wave is followed by a trough which is associated with the mid body section of the hull. Visual observation revealed that over the total operational length of the tank, (45m), when the model was at constant speed, the leading crest could travel up to 4 ship lengths ahead of the vessel. Also, more crests formed behind as the height of the leading crest reduced. Peak wave heights were observed due to the proximity to the track of the ship. However, the height of the crests decayed rapidly in the transverse direction.

Figure 3.3-2 was obtained using the model of the 100m monohull fast ferry and was measured half a ship length from the track. It shows that a solitary crest can also be generated by a monohull as well as showing how the location of the leading wave relative to the bow of the ship is transformed as the depth Froude number increases. The vertical line indicates the location of the bow of the ship. It is evident that the crest leads the bow up to a depth Froude number of 1.1 and as this increases the wave begins to lag. This is similar to the observations of Dand (1999) when testing in a narrow tank.

Figure 3.3-3 was obtained using the Jetliner model at a scale depth of 5m. Figure 3.3-3a shows the leading wave at a depth Froude number of 1.0 when the vessel is at its normal displacement of 1,500T. Figure 3.3-3b is for the same model but at double the displacement. The increase in height of the leading crest is clearly evident as is the advancement in front of the bow. This is in agreement with the theory of solitary waves, which predicts, that the speed of the wave and hence the advancement in front of the bow increases with increasing wave height. In figure 3.3-3c the model was towed backwards at normal displacement to show the effect of having a bluff bow thus increasing the local displacement of water. The increase in local wave height increases the velocity of the crest and as the wave lengthens, secondary higher frequency oscillations occur. Again this is similar to the solitary waves produced in a narrow tank.

Figure 3.3-4 is equivalent to figure 3.3-3 except that the water depth has been increased to represent 12.5m. Here the wave front does not advance in front of the bow as in the very shallow water situation. This shows that the creation of a long period wave crest travelling ahead of the vessel is restricted to very shallow water where the under keel clearance is small.
3.3.2 Field measurements

The upper part of Loch Ryan is very shallow with typical depths of 3m to 4m over much of the area south of Cairnryan. Both conventional and fast ferries operate along a dredged channel, minimum depth 5m, on route from Stranraer. As the model tests on the solitary waves indicated that the phenomenon occurred in very shallow water, an initial programme of field measurement was undertaken in Loch Ryan to ascertain if the effect could be observed in an estuary. Two sea bed pressure transducers were located off the mooring dolphins at the P&O terminal at Cairnryan. The location was roughly in line with the dredged channel from Stranraer so that any waves travelling ahead of the vessel reached the monitoring location ahead of the main wash.

Figure 3.3-5 shows the wash waves produced by Stena Voyager travelling down the channel at a speed of 6m/s at a very low spring tide. The time series clearly shows a wave crest travelling ahead of the vessel with an overall length of around 4 ship lengths and a height of 40mm. This precedes the main bow wave, the mid-body trough and the stern wave which is centred around 170s on the trace. The main body of the transverse waves in the Kelvin wash pattern with a maximum height of 560mm and a wave period of around 5s is shown centred at a time of 270s on the trace.

During a week of monitoring when there were 35 outbound passages of Stena Voyager, only three traces showed the leading wave crest. This only occurred at or close to exceptionally low tidal levels when the depth in the channel was slightly less than 6m and the depth Froude number was 0.8 A similar effect was also observed with the conventional ferries under the same operating conditions. As the tidal level rose and the depth Froude number reduced, the leading wave crest was not observed. This is in good agreement with the model test observation. It was not possible to monitor the ship at higher depth Froude numbers due to speed restrictions in the upper reaches of Loch Ryan.
3.4 Discussion of Observations

Both the model tests and field observations showed that it is possible to create a wave which travels ahead of the ship. In the model tests the wave observed often possessed both a crest followed by a trough and was capable of travelling out ahead of the ship at a slightly higher velocity, as predicted by theory. This happened at sub-critical and at trans-critical depth Froude Numbers. The leading wave was not a pure Soliton in that it could not be described purely as a wave of translation travelling entirely above the mean water surface. However, the crest and trough did seem to stretch with distance from the ship and tended to become unstable with shorter waves forming on top of the main wave. This was also observed by Dand (1999), in narrow tank experiments and this new series experiments showed that the same effect could be developed in a wide tank although to a lesser extent.

The field measurements showed that the amplitude of the waves were small in comparison to the main body of the wash following behind, and the wave was very long in period. Again figure 3.3-5 shows that the mean water level beyond a time of 180s seems to be depressed by 30mm and is effectively a long period trough which has followed the initial crest.

The model tests also showed that the amplitude of the leading waves decayed rapidly with distance from the track of the ship. The model test results presented in figures 3.3-1 to 3.3-4 were taken within a ship's length from the track.

The model tests also showed that the development of the wave was determined by the initial wave height, as was demonstrated by the bluff body experiments. Figure 3.4-1 shows a wave cut through the wash of a container vessel operating in shallow water off Cork Sands in the approaches to Harwich Haven with comparatively low under keel clearance. A long low amplitude wave travelling ahead of the vessel is evident. This supports the view that conventional ships operating above a depth Froude number of 0.8 with minimal under keel clearance would be capable of producing larger solitary waves than fast ferries due to the relatively large amount of water being pushed out of the way at the bluff bows.
Figure 3.3.1 – Development of Leading Wave Along Track
Figure 3.3.2 – Wash Wave Time Traces at Different Depth Froude Numbers
Figure 3.3.3. – Effect of Displacement and Bluff Bow
Figure 3.3.4 – Wash Wave Time Traces at Different Depth Froude Numbers
Figure 3.3.5 Wash Produced in Very Shallow Water (<6m), Depth Froude Number 0.8

Figure 3.4-1 Wash Produced by Large Container Ship
CHAPTER 4

4.0 WAVE WASH (SHALLOW AND INTERMEDIATE DEPTH)

4.1 Introduction

4.2 Leading Wave Divergence – Supercritical Wash
   4.2.1 Mathematical Model
   4.2.2 Comparison of Theory and Observation

4.3 Wave Propagation – Super-critical and Near Critical
   4.3.1 Wave Height Decay Rates
   4.3.2 The Influence of Water Depth on Wave Height and decay

4.4 Interaction between Ship Length & Depth Froude Number
   4.4.1 Influence of Water Depth
   4.4.2 Influence of ship length

4.5 Effect of Hull on Wash Waves
   4.5.1 Monohull versus Catamaran

4.6 General Discussion

4.7 Conclusions
4.0 WAVE WASH (SHALLOW AND INTERMEDIATE DEPTH)

4.1 Introduction

This section deals primarily with wash wave characteristics in shallow and intermediate depth water in contrast to the very shallow water effects described in section 3. This is the most commonly occurring situation.

4.2 Leading Wave Divergence – Supercritical Wash

In the experimental test programme the characteristics of the leading long period waves in the super-critical wash was investigated in detail. Whittaker et al (1999 & 2000), MCA420 (1998) reported the observation of a very long period surge wave on the shoreline at the start of the wash produced by a fast ferry in shallow to intermediate depth water. Based on some initial experiments it was suggested that the leading wave crests in the super-critical wash had a divergence angle of between 10º and 12º at a depth Froude number of 1.1. Therefore it was necessary to establish if this observation was correct and if the angle was constant or a function of one or more variables.

It was also decided to investigate the usefulness of an existing mathematical model in predicting the super-critical wash patterns. The rational behind this was that if a mathematical model could be validated using experimental data, then this model could be used to predict the divergence angle and the wave periods at any desired water depth or distance from the ship’s track. It is important to note that the mathematical model gives no information regarding the amplitude of the waves, but only the positions of the crests and the troughs.

Figures 4.2-1 shows a plan view of the first five wash wave crests and troughs measured at model scale at three different depth Froude numbers, 1.1, 1.6 and 2.2 respectively. The direction of travel of the leading super-critical waves changes as the Froude number increases. This is given by the equation,

$$\theta = \arccos\left(\frac{\sqrt{gh}}{V_s}\right)$$

Experimentation has shown that the measured direction of travel of the first wave relative to the track of the ship agrees with theory. Figure 4.2-2 shows that the subsequent waves in the group, which are slower than the first wave, travel at a different angle. In addition the distance between the wave crests increases with distance from the track of the ship. The first crest tends to be fairly straight but the subsequent crests become steadily more curved in plan view particularly close to the ship.

Figure 4.2-2 shows three sets of wave cuts measured at different distances from the track of a 120m catamaran fast ferry operating at a depth Froude number greater than 2. Both model and field measurements have shown that at super-critical depth Froude numbers the number of waves, the height of each wave and the distribution of wave periods changes significantly with distance from the track of the ship.

In figure 4.2-2a, which is less than one ship length from the track, only two crests and one trough are discernible in the first part of the trace which is the super-critical wash. The second part of the trace is sub-critical wash components and contains much shorter waves, which are caused by the plunging plumes created by the converging water mass behind the
transom as well as the plunging water jets. The initial part of the wash is so close to the track of the ship than the different wave frequency components, each of which travel in slightly different directions, have not separated.

Figures 4.2-2(b & c) clearly show the separation of the different frequency components with time. Not only are there distinct groups of wave frequencies, as identified by Whittaker et al (1999), but there is also a spread of wave frequencies within each group. Again only the first group of waves is considered here as these represent the super-critical part of the wash and their phase and group velocity is predominately influenced by the water depth.

4.2.1 Mathematical Model

A mathematical model, derived by Yih and Zhu (1989), was used to predict the wave patterns created by a moving disturbance. According to the authors the geometric details of the ship modelled by the moving disturbance are not relevant since the wave pattern obtained will be the same, if the region under consideration is sufficiently far from the track of the ship. Formulae for the phase lines are given which depend only on the dispersion wave equation. These formulae are applied to deep water surface waves and surface waves in water of a finite depth. The parametric equations for the curves of constant phase are given for $x$, the distance from the track and $y$, the distance along the track,

\[ x = \frac{AF'}{k(F-kF')} \sqrt{(k^2 - F^2)} \]
\[ y = -\frac{A(k - FF')}{k(F-kF')} \]

where $F = kc$, $F'$ = differential of $F$ w.r.t. $k$, $k$ = wave-number, $A$ = constant of integration or scaling factor.

In dimensionless terms water depth $h$ is the length scale and ship velocity $V_s$ is the velocity scale, this becomes:

\[ F = \frac{gh}{V_s^2} \sqrt{(k \tanh k)} \]

for shallow water. The only remaining problem is to determine the constant of integration $A$ to enable a comparison of the predicted pattern with experimental data. For deep water 'A' is proportional to the wavelength on the centreline track of the ship, i.e $2\pi \frac{V_s^2}{g}$, since the wave celerity $c$ equals the ship's velocity, $V_s$. However, in shallow water the maximum wave celerity is $c = \sqrt{gh}$. Therefore the constant of integration becomes, $A = 2n\pi h$, where $n = 1,2,3,\ldots$ indicates a crest and $n = 1/2,3/2,5/2,\ldots$ indicates a trough.
4.2.2 Comparison of Theory and Observation

Using the latter scaling factor, a series of wave patterns produced by a moving disturbance at various water depths and depth Froude numbers were calculated. Figure 4.2-3 shows the calculated and measured wash patterns generated by a monohull fast ferry at model scale. The patterns are presented for a depth Froude number of 1.9 but different water depths ranging from 20m (figure 4.2-3a) to 7.5m (figure 4.2-3c) at full size.

The figures show very good agreement between theory and experiment even though the theory does not take account of the geometry of the ship such as ship length and hull configuration. However, there is in general a tendency for the mathematical model to slightly advance the leading wave crest in intermediate depth water and slightly retard the crest in very shallow water. The subsequent waves in the super-critical group are well modelled. It is also interesting to note the difference between the three wash patterns as the speed of the vessel is altered to keep the depth Froude number constant at different depths. The angle of the leading wave crest is identical in each case but the wavelengths of the first and subsequent waves are greater for the deeper water when compared to the equivalent waves at shallower depths. Also the crest line for the 5th wave in figure 4.2-3a is more curved than the same wave in figure 4.2-3c.

Figure 4.2-4 shows the relationship between the divergence of the first two wave crests and the depth Froude number. It was obtained using the four ship models operating at different speeds in a range of water depths. Knowing the speed of the models it was possible to calculate the distance of each wave crest along the time series measured from the origin. The wave angles were then calculated using values from the wave probes located at distances greater than three ship lengths from the track of the ship.

Figure 4.2-4 clearly shows that the angle between the leading wave crests is primarily a function of depth Froude number. There is also a general trend which indicates a secondary dependence on water depth. Using the mathematical model, theoretical values were also calculated for each experimental point. The correlation with the experimental data is quite good. The mathematical model predicts a definite dependence of this angle with water depth as well as depth Froude number.

Having established the correlation between the physical data and the mathematical model, this was used to predict the divergence angle of the two leading crests in the super-critical wash. This is presented as a function of water depth, distance from track and depth Froude number, (figure 4.2-5).

Table 4.2-1 shows a comparison between the measured and calculated wave periods for a 120m catamaran fast ferry. The agreement is good.
Table 4.2-1: Comparison of wave periods for theory and prototype data (in seconds)

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<td>15.7</td>
<td>12.1</td>
<td>12.3</td>
<td>9.1</td>
</tr>
</tbody>
</table>

Monohull Fast Ferry
Depth Froude Number = 1.1

Monohull Fast Ferry
Depth Froude Number = 1.6

Monohull Fast Ferry
Depth Froude Number = 2.2

Figure 4.2-1(a-c): Wash patterns at different depth Froude numbers (experimental data)
Figure 4.2-2(a-c): Wave cuts of 120m HSC (prototype) at different distances from track
Figure 4.2-3(a-c): Wash patterns at constant depth Froude numbers but different depths
Figure 4.2-4: Divergence angle for different depth Froude number

Figure 4.2-5: Divergence angle at different distances from track for several depth Froude number
4.3 Wave Propagation – Super-critical & Near-critical

4.3.1 Wave Height Decay Rates

The depth Froude number is the main characterising parameter for wake wash generation in shallow water. As discussed in section 2.1, a significant increase in wave resistance and wave height occurs at the critical depth Froude number. Figures 4.3-1(a, b) show the maximum wave height and the maximum wave energy for a ship model operating at a range of depth Froude numbers. The measurements were recorded at a distance of one ship length from the track of the ship. It is obvious from this diagram that the largest and most energetic waves are produced at approximately $F_{h} = 1$.

What is not obvious however is that the decay of the wash with distance from the sailing line differs greatly from the decay rate of the waves in the supercritical wash and hence in some cases may not be as hazardous in the far field. This point is illustrated in figures 4.3-2 and 4.3-3 where the decay of the maximum wave height and wave energy is plotted for a range of near critical and supercritical Froude numbers.

In this example, close to the track of the ship (i.e. one ship length), the maximum wave height is approximately 1.2m at the critical speed, while the corresponding value in the supercritical speed range is around 0.8m. The difference between the maximum wave energy is even more dramatic, with the critical waves having between three and four times as much energy. However if the waves in the far field are examined, the reverse situation occurs. Due to the rapid exponential decay of the leading waves at critical speed, the maximum wave height decreases to about 0.2m at a distance of five and a half ship lengths from the ship’s track. This compares with a wave height of approximately 0.5m for the supercritical waves at the same distance. The maximum wave energy in the critical waves at this distance is also much smaller, being only a fraction of the equivalent supercritical value. There is also a significant variation in the wave characteristics within the supercritical range itself. A considerable reduction in wave height and energy is achievable if a vessel operates at $F_{h} > 1.6$

The reason for the difference between the decay rates can be understood by referring back to section 2.1.2 and looking at the way in which the waves were formed. Due to the non-dispersive nature of the transverse waves at the critical speed, they will reinforce each other and grow in size so long as the ship remains at this speed. This process is illustrated in figure 4.3-4, which shows that waves formed at different instances in the ship’s time history (i.e. points ‘B’ and ‘C’) will reinforce each other at the same point, ‘A’. Once the ship accelerates into the supercritical region however, the leading waves cannot travel in the same direction as the ship because the water depth limits their speed. Therefore unlike the critical case, waves formed by the ship at different instances in its time history will not reinforce each other at the same point.

The development of the critical and supercritical waves with distance along the ship’s track can be seen in figure 4.3-5(a, b) respectively. The gauges are equally spaced approximately 4 ship lengths apart. There is clearly an increase in the wave height with time as the ship travels at critical speed. A lateral transfer of energy will also take place due to diffraction, which results in the crest length on either side of the ship increasing with time. In contrast the wave cuts taken at different positions along the track for the ship travelling at supercritical speed are practically identical. This is because the wave energy is dispersed uniformly away from the ship, increasing the area of the wash pattern with time, but not effecting the individual wave heights.
It is interesting to note that although the distances between the wave probes in figure 4.3-5a are identical, the increase in the wave height between gauges 10 and 3 (figure 1.3-1) is much more significant than the corresponding increase between gauges 3 and 11. This suggests that at critical speed there is an upper limit on the wave height that a vessel can produce. Common sense also tells one that the wave height cannot increase indefinitely. This means that at some point the energy input to the wave system will be equal to the amount of energy being transferred laterally along the crests, and an equilibrium situation similar to the supercritical case exists. Therefore in this situation, a wave decay rate similar to the supercritical one, would not be an unreasonable expectation. If this is so, then the decay rate of the critical waves depends on the time spent at the critical speed.

To investigate if this is indeed the case, some experiments were conducted using the Superseacat model. This model was run at critical speed for different time intervals. Figure 4.3-6 shows the decay of the maximum wave height and energy for two different scenarios. All measurements have been converted to full scale values using a scaling factor of 1:50. In the first instance the ship has travelled for 1200m at the critical speed before reaching the measurement point. In the second instance, it has only travelled for 500m. The difference between the two different operational strategies is significant. Not only is the maximum wave height and wave energy greater for the 1200m run, but the decay rate of the waves is also substantially different with the waves generated during the shorter run decaying much faster. It was not possible to determine whether the decay rate would eventually approach a decay rate similar to a supercritical one since the time needed to establish such a steady state was too great for the limitations of the towing tank. However the example above clearly illustrates that the decay of the waves at critical speed is dependent on the time.

The patterns of the leading waves in both instances were also plotted in figure 4.3-7. The most notable difference between the two patterns is the shape of the leading wave crests when viewed from above. As the ship remains at the critical speed, the wave crests tend to move forward and propagate in a direction almost parallel to the track of the ship and the leading wave crest tends to straighten. This is further evidence of the unsteady nature of the critical waves.

The decay of the waves with distance from the ship’s track for a ship operating at supercritical speed was also investigated. Havelock (1908) predicted that in sub-critical wash the transverse wave components decay in proportion to $1/x^{0.5}$ while the divergent waves decay at a rate of $1/x^{0.33}$. Note that Havelock used the distance $\sigma$ from the travelling impulse to the wave to calculate the decay. In this case $x$ is the distance perpendicular to the ship’s track. This approach is more practical for coastal engineering purposes and results only in an additional constant in the equation. Figure 4.3-8 shows an example of the decay rates measured for a 120m catamaran operating at a depth Froude number of 2. In the figure the maximum wave height for the first group of waves in the super-critical wash is plotted against distance from the track of the ship. Data from field measurements and model tests has been included. In both cases a decay rate of $1/x^{0.25}$ has been fitted to the data. In this data set the water depth was between 10 and 13m. The difference between the wave heights in both series is due to the fact that the model (when scaled using a factor of 1/80) had a greater displacement (4500tons), than the actual prototype (4000tons). During the model tests with shallower water, decay rates as low as $1/x^{0.2}$ were observed.

The significance of this finding is that the leading waves in the super-critical wash are much more persistent than sub-critical waves in this instance. Consequently the wave height is greater at a given distance from the ship compared to an equivalent height of wave in a sub-critical wash. However it was also found that the decay rate varied considerably
with the h/L ratio (water depth/ship length – see next section) and to a lesser extent with hull configuration. The low height decay rate in the leading super-critical wash for small h/L ratios, is attributable to the highest waves being largely non-dispersive in that energy is conserved in individual waves.

However, the crests diverge with distance from the ship spreading the energy over a larger area hence reducing the wave height. Also there is some dispersion of energy into the subsequent waves.
Figure 4.3-1 Variation of wave height and energy with depth Froude number
Figure 4.3-2  Decay of maximum wave height with distance from track
Figure 4.3-3  Decay of maximum wave energy with distance from track

(a) – Sub-critical to critical

(b) – Super-critical
Figure 4.3-4 Development of critical and super-critical wash patterns
Figure 4.3–5(a) Wave development along track (near critical)
Figure 4.3–5(b) Wave development along track (super-critical).
Figure 4.3-6 Decay of maximum wave energy and height with distance from track.
Figure 4.3–7 Wash patterns at critical depth Froude number

(a) – 500m

(b) – 1200m
Figure 4.3-8: Decay of maximum wave height of first group with distance from track
4.3.2 The Influence of Water Depth on Wave Height and decay

Dand et al. (1999) showed that the effect of the depth/length ratio with regard to wash height is negligible for vessels operating in the supercritical speed range. However, no information regarding the maximum wave energy or the decay of the waves with distance from the sailing line was given. The depth/length ratio’s were also quite small, the largest being $h/L = 0.125$. To ascertain whether this ratio does indeed effect these variables it was decided to run a series of experiments using the $1/50^{th}$ scale monohull Superseacat model with an overall length of 100m. The tests were conducted at various water depths giving $h/L$ ratios as follows:

<table>
<thead>
<tr>
<th>depth/length ratio ($h/L$)</th>
<th>water depth (h) m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>20</td>
</tr>
<tr>
<td>0.15</td>
<td>15</td>
</tr>
<tr>
<td>0.125</td>
<td>12.5</td>
</tr>
<tr>
<td>0.1</td>
<td>10</td>
</tr>
<tr>
<td>0.075</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Figure 4.3-9(a–e) shows longitudinal wave cuts taken at a distance of one ship length from the ship’s track, for a range of different water depths. What is immediately obvious from the figure is the change in the profile of the wave cut as the vessel travels in different water depths ranging from 7.5m to 20m. Particularly noticeable is the change in the position of the highest wave in the group and the varying wave height distribution throughout each group.

For instance, in figure 4.3-9a (water depth 7.5m), the first wave is the highest in the group whereas in figure 4.3-9e (water depth 20m), the third wave is the highest. The corresponding wave periods are 12.5 and 5 seconds respectively. This means that in shallow water most of the wave energy is contained in a single wave whereas in deeper water the energy is distributed between several different waves. This point is illustrated in figure 4.3-10, which shows the energy of the highest wave as a percentage of the total wave energy in the group, for different depth to ship length ratios. Clearly the most energetic wave contains a much larger portion of the total wave energy in the wash when the ship is travelling in relatively shallow water. This is a significant result because it is often a single wave which can cause wash related accidents.

Figure 4.3-11a shows the decay of the maximum wave energy with distance from the ship’s track. A considerable increase in the magnitude of the maximum wave energy is evident, as the water becomes relatively shallower. The decay rates, which are in the same order as the data series, also decrease with decreasing $h/L$ ratio, from $x^{-0.68}$ to $x^{-0.29}$. The unusual ‘hump’ in the $h/L=0.075$ data series, (water depth 7.5m), is due to a focusing of the waves as a result of refraction. This was caused by slight variations in the surface level of the tank floor, which were more significant for very shallow water tests. As a result, some of data points were artificially high, while the outermost data point was lower than expected. However, a decay rate was also calculated using the values from the first four wave probes which were not subject to any refraction effects. The decay rate was then found to be $x^{-0.30}$, which is only slightly different. Therefore it was felt that overall the refraction effect balanced itself out in this particular case.

Figure 4.3-11b shows the decay of the maximum wave height with distance from the sailing line. Close to the ship's track there does not seem to be any particular relationship between the wave height and the depth/length ratio, which supports the findings of Dand et al. (1999). However, the calculated decay rates indicate that the waves produced in
shallower water will decay more slowly with distance and hence will probably be the highest waves in the far field. The decay rates range from $x^{-0.27}$ to $x^{-0.41}$, for h/L ratios of 0.075, (water depth 7.5m), and 0.2, (water depth 20m), respectively.
Figure 4.3 - 9 Longitudinal wave cuts at a range of different water depths
Figure 4.3 -10 Maximum wave energy as a percentage of the total wave energy.

(a)

Figure 4.3 –11 Decay of the maximum wave height and energy with distance from the track for different water depths.

(b)
4.4 Interaction between Ship length & Depth Froude number

4.4.1 Influence of Water Depth

The behaviour and resistance of a ship travelling in shallow water is different from deep water. The wave resistance in particular changes, as the energy contained in the waves is less dispersive and conserved in a smaller number of waves near to the ship. The wave resistance of a ship in shallow water is equal to the wave resistance in deep water when the length of the transverse wave in deep and shallow water is the same.

This leads to the following equation

\[ V_{SS} = V_{SD} \sqrt{\frac{1}{\tanh \frac{1}{F_{n_h}^2}}} \]

where the equivalent ship velocities \( V_{SS} \) for shallow water can be related to the deep water velocity \( V_{SD} \) with the same wave resistance.

This statement is only valid if the ship stays in the sub-critical speed range. When the ship reaches critical speed the energy transferred by the ship into the wave system reaches a maximum, as does the wave resistance. If the ship travels at super-critical speeds there is no transverse wave, because the wave is not able to travel at the ship's speed. From this it follows, that there is no wave “along” the hull. It has to be concluded that the wave resistance is therefore no longer only dependant on the ship speed or Ship length Froude number, but also on the water depth or respectively the depth Froude number.

In figure 4.4-1 the energy density is plotted for tests with a 1:50 scale model of a 100m long mono hull fast ferry at a distance of 2 ship lengths. This high speed craft has a water line length of 87.7m and a draft of 2.6m and the tests were undertaken with water depths of between 5 & 20m. The energy density is a common parameter used in coastal engineering, as it is the energy per unit surface area. From the energy density in combination with the frequency spectrum the wave attack on the shoreline can be calculated.

Figure 4.4-1a clearly shows a peak for each water depth at different ship length Froude numbers \( F_{n_l} \). In this case the highest energy content occurs at a length Froude Number of 0.39 for a water depth of 12.5m. This coincides with a depth Froude number of 1.0, as shown in figure 4.4-1b. This is not surprising as the ship is operating in a power intensive range close to the hump speed and at the critical depth Froude number speed. Curves have also been plotted for different water depths. As the water becomes deeper the peak energy density moves to a higher value of length Froude number. Often the peak wave resistance would occur at a length Froude number of around 0.55 and this data is tending towards that value. Shallower water reduces the length Froude number associated with the peak wave energy. This is caused by the reduced water depth, which results in the critical wash waves being produced at lower ship velocities.

The data also illustrates another important point when fast ships are operated in shallow water. For example consider a ship operating at \( F_{n_l} = 0.44 \) at a speed of 25knots in a water depth of 20m and cannot reach higher speeds due to power restriction, the ship will slow due to an increase in wave energy while travelling into shallower water. This is due to the operational point being on the left-hand side of the wave energy curve. Therefore for constant energy output from the ships propulsion system, an increase in wave energy will result in a reduction of speed.
On the other hand, if the ship operates at a length Froude Number of $F_{nl} = 0.6$ at a speed of 35knots in water depth of 20m and keeps the engine power constant, the wave resistance will decrease with decreasing water depth because the operational point is on the right-hand side of the curve. Consequently the ship will speed up. This effect has been observed with real ships although there might be other forms of resistance either increasing or limiting the gain in wave resistance.

In figure 4.4-1b wave energy density is plotted against depth Froude number. All the peaks occur in a band of depth Froude number of between 0.85 to 1.1 depending on water depth. In deeper water (20m) the maximum energy occurs at a depth Froude number of 0.95 where for very shallow water (5m and 7.5m) the maximum is reached at $F_{nh} = 1.1$. Other data obtained for other ship models in the test series has shown that the peak wave energy can occur at depth Froude numbers of 0.85 in a water depth of 48m.

In conclusion it has been observed that the peak in wash wave energy density does not necessarily occur at a depth Froude number of 1 but varies between 0.85 and 1.1 depending on the water depth. Deeper water results in a lower value of depth Froude number. The situation is complicated further by the length Froude number. In the example illustrated above with a 100m vessel, the critical ranges of length and depth Froude number coincided. However, the situation with a 50m vessel would be different with the ship transcending the 'hump' speed range prior to reaching the critical depth range. At the 'hump' speed it is observed that the trim of the vessel increases as the stern drops into the trough of the bow wave. This increases the wave resistance and hence the energy density of the wake. Consequently observations of wash waves produced by small high speed vessels can not be directly scaled to provide an indication of the wash produced by larger ships. It seems that the depth Froude number is the predominant parameter. However, length Froude number does influence the maximum wash wave energy generated in shallow water. The worst combination is when the critical length and depth Froude number coincide. Unfortunately this occurs with vessels of 100m length or more when they are accelerating in water depths of around 15m, which is typical of many estuaries.

Obviously ferry operators try to avoid the trans-critical depth Froude number range during a passage. However, there are situations when this region can not be avoided. For example vessels operating at between 35 and 40 knots in the North Sea where the typical water depth is between 40 and 50m are in the upper end of the trans-critical range. Also, vessels entering an estuary, which are down on peak power, carrying a heavy payload and possibly with the added factor of hull fouling can drop into the critical range and produce a large wash travelling in the same direction as the ship. This will run into the estuary and possibly into the port.
Figure 4.4-1: Energy density

(calculated at a distance of 1.99 L_{WL} from centreline of towing rig. The energy is plotted in relation to the maximum energy measured at that particular distance).
4.4.2 Influence of Ship Length

In order to examine the influence of hull length on the interaction between the length and depth Froude numbers, a series of generic hull forms were used, as described in section 1.3.3. The generic mono hull form tested was assigned a scale of 1:50. This enabled the hull length to be varied from 50 to 100m in 25m increments by attaching rectangular sections to the stern. In all cases the draft was kept constant as was the transom immersion depth and the cross sectional profile.

Figure 4.4-2(a-c) and figure 4.4-3(a-c) shows the maximum wave energy density plotted against the length and depth Froude numbers for three hull lengths and for two different water depths. The measurements were recorded at a distance of 100m from the track of the ship for the shortest ship, and 250m for the other two.

It is evident from figure 4.4-2(a-c) that the position of the peak wave energy density varies between Fnh = 0.9 and Fnh = 1.00, depending on the ship length to water depth ratio. This feature was also observed in section 4.4.1. However, what is even more interesting in this case, is the variation between the peak wave energy density values, for a given vessel, travelling in different water depths.

Referring firstly to the shortest model, (length 50m), figure 4.4-2a, it is evident that the maximum wave energy density occurs when the ship is travelling in the 12.5m water depth. The corresponding value for the 20m water depth is some 10% less. As the ship increases speed into the supercritical region (i.e. Fn > 1.1), there is a predictable drop in the wave energy density, but this time without the noticeable difference between the respective wave energy densities.

A similar trend is observed for the longer vessels (75m and 100m respectively) in figure 4.4-2(b-c), although in both these instances the maximum wave energy density occurs when the vessels are travelling in the deeper water. Therefore it seems that there is an additional parameter which influences the generation of wake wash at critical speed.

The answer to the problem can be found by examining figure 4.4-3(a-c), which shows the corresponding length Froude no. for each depth Froude no. in figure 4.4-2(a-c) respectively. On doing this it becomes apparent that whenever a depth Froude number close to one coincides with a length Froude number of approximately 0.5, then a worst case scenario in terms of wash generation occurs. This is because the ship is now operating at the ‘hump speed’ (typically between 0.4 and 0.6), and the critical depth Froude number simultaneously.

As noted earlier when the ship accelerated into the supercritical range, no such relationship between length and depth Froude number exists. This is because the length Froude number is based on the ratio between the ship’s waterline length and the wave length of the transverse waves on the centreline, which are an increasing function of the ship’s velocity. However, as mentioned in section 2.1, if a ship travel at supercritical speeds the transverse wave system disappears and the wavelength of the leading waves becomes a function of the water depth.

This does not mean that the length of the ship will not influence the supercritical wave pattern, since the depth/length ratio is an important parameter as discussed earlier. However, it does mean that the use of length Froude no. to describe the interaction between
the wave pattern and the hull is not valid in the *supercritical* situation and that the depth Froude number should be used instead.
Hull Length – 50m

Hull Length – 75m

Hull Length – 100m

Figure 4.4–2(a-c) Maximum Wave Energy Vs Depth Froude Number.
Figure 4.4 – 3(a-c) Maximum Wave Energy Vs Length Froude Number.
4.5 Effect of Hull Form on Wash Waves

4.5.1 Monohull versus Catamaran

Docters (1999) stated that from a theoretical point of view a catamaran will always experience less wave resistance than an equivalent monohull, when operating at high Froude numbers. Recently however, Macfarlane and Renilson (2000) have concluded that although monohulls generate larger wave heights for a given speed, displacement and waterline length, the overall difference in the wave energy produced by monohulls and multihulls is not very great. This is due to the fact that the monohulls were found to produce lower wave periods than the equivalent multihull. Their results were based on the analysis of experimental data for over eighty different hull configurations, involving over six thousand individual wave cuts. All the experiments were conducted in deep water. Hence, the authors suggest that in order for a vessel to display ‘low wash’ characteristics, it does not necessarily have to be a multihull.

Based on these findings it was decided to conduct a series of experiments using a generic monohull and catamaran to compare the wash waves produced by the vessels while operating in shallow water at critical and supercritical speeds. Generic models were constructed so that identical hull forms could be used. Figures 4.5-1a & b, show two longitudinal wave cuts recorded at a depth Froude number of unity for the catamaran and monohull respectively. The wave probes are located at a distance of three and a half ship lengths from the track of the ship and all measurements have been converted to full scale using a scaling factor of 1:50.

The first two waves in each trace have similar wave heights and periods, with the maximum wave heights being 1320mm and 1350mm for the catamaran and monohull respectively. The maximum wave energies are also similar, 186kJ/m for the catamaran and 195kJ/m for the monohull. One obvious difference between the two traces is the relatively calm region in figure 4.5-1a between two distinct wave groups. This feature is commonly observed in catamaran far field waves, and it is generally accepted that the small wave region is a result of wave interference between the wave systems of the two component hulls (Gadd, 1999).

Figures 4.5-2a & b, give comparisons between the wash generated by the two vessels operating at supercritical Froude numbers of 1.8 and 1.9. Again the distance is 3½ ship lengths from the navigation route. In this case, the difference between the two wash patterns is much more noticeable. The monohull produces a range of wave frequencies, which increase gradually in the downstream direction. The wave periods vary from a maximum of 10 seconds for the leading wave to about 3 seconds for the shorter trailing waves. The catamaran on the other hand, produces discreet wave frequency groups with regions of comparative calm in between. The second wave group contains waves which are higher than any of those produced by the monohull. This leads to the conclusion that the wave interference between the wave systems of the two component hulls can be either constructive interference or destructive interference, depending on the wave frequency. The maximum wave height and maximum wave energy for the monohull is 820mm and 30.4kJ/m respectively. The corresponding values for the catamaran are 1015mm and 27.7kJ/m. In this case although the maximum wave height for the catamaran is 25% greater, the maximum wave energy is 10% smaller.

Figure 4.5-3a & b shows the wash waves measured at a distance of eleven ship lengths from the navigation route. As expected, the number of waves in the trace and the total time taken for all the waves to pass a particular point has increased due to dispersion.
The maximum wave heights are now almost identical, 490mm for the monohull and 485mm for the catamaran. The maximum wave energies are however much different, with the catamaran value being less than half that of the monohull (8 and 17.5kJ/m respectively). It seems therefore (based on the measurements taken \(3^{1/2}\) ship lengths from the track), that equivalent catamarans and monohulls produce similar waves in terms of maximum wave energy, and that for a given speed neither vessel could be considered as generating significantly lower wash than the other. However, when the wash from each vessel is compared at greater distances from the track of the ship (figure 4.5-3), the maximum wave heights are similar but the energy is substantially different due to the difference in frequency. These results raised some important questions concerning the decay rates of the wash with distance from the sailing line and so it was decided to investigate the matter further.

The decay of the wave height and wave energy is plotted in figures 4.5-4a & b and 4.5-5a & b for both ships travelling at critical and supercritical speeds respectively. The decay rates have been calculated from ‘best fit’ lines drawn through each data series. The wash produced by both vessels travelling at critical speed is quite similar with the monohull creating slightly higher and more energetic waves on average. The decay rates are also similar, and being exponential, the waves reduce rapidly in height and energy with distance from the sailing line. In the critical case an exponential decay function provides a better fit to the data.

In the supercritical case, figure 4.5-5, however, a completely different scenario is observed. Two different data series have been plotted for the catamaran because of its tendency to produce distinct wave frequency groups. These series have been labeled ‘short period’ and ‘long period’ waves. ‘Long period’ refers to the leading group of waves while ‘short period’ refers to the steeper second group of waves. A single series has been plotted for the monohull since there is only a single group of waves in this case.

The maximum wave height decays at a rate of \(x^{-0.4}\) for the catamaran long period waves, \(x^{-0.51}\) for the monohull and \(x^{-0.57}\) for the catamaran short period waves. The corresponding decay rates for the maximum wave energy are \(x^{-0.60}\), \(x^{-0.59}\), and \(x^{-0.93}\) respectively. It is evident from these graphs that the decay rates associated with each wave group are very important when trying to determine the potential impact of the wash in the far field. For instance, the maximum wave energy produced by both vessels are similar at distances close to the ship’s track. (i.e. within three ship lengths). However due to the rapid decay of the catamaran ‘short period’ waves, this is no longer the case in the far field. Therefore, because the monohull produces higher ‘long period’ waves than the catamaran, it’s wash will present more of a hazard at the wave breaking point in shallow water. The graphs also illustrate the usefulness of the maximum wave energy as a parameter for describing the wake wash. Clearly if the maximum wave height alone was used, valuable information regarding the distribution of wave height and period is lost. This is because the maximum wave height does not distinguish between short and long period waves.

To see if ‘real’ ships also display this behaviour, it was decided to compare the wash of the Jetliner and Seacat models. Because both models have a very similar displacement and length at model scale, it was necessary to use the same scaling factor (i.e. 1:50) to enable a fair comparison. It is important to note that although these two ships have different hull forms (i.e. round bilge and ‘V’ shaped), this will not affect the relative comparison between the wash produced in the critical and supercritical speed ranges.
**Figure 4.5-6a & b** shows a similar trend to that observed with the generic models. Although the maximum wave energy is reasonably similar when the vessels are travelling at critical speed, a significant difference occurs when operating in the supercritical regime. However, in contrast with the generic catamaran, the Seacat ‘long period’ waves are much more energetic than its ‘short period’ waves, in the far field. This is because the generic catamaran produces high short period waves due to the shape and immersion of its stern which is not realistic for a properly designed ship.

In conclusion, based on these experiments catamarans operating at supercritical speeds produce significantly lower wash than a monohull of similar length and displacement. The reduction in wash generation by catamarans in the supercritical speed range is probably due to the interaction between the long period diverging waves produced by each demi-hull. However, more research is needed to confirm that this will be the case with a wide range of hull forms.
Figure 4.5-1  Wave cuts at critical depth Froude number

Figure 4.5-2  Wave cuts at super-critical depth Froude number
Figure 4.5-3  Wave cuts 11 ship lengths from track
Figure 4.5-4  Decay of wave energy / height – critical depth Froude number

(a)

(b)

y = 596e^{-0.0079x}  \quad y = 540e^{-0.0068x}

y = 2151e^{-0.0034x}  \quad y = 1931e^{-0.0026x}
Figure 4.5-5  Decay of wave energy / height – super-critical depth Froude number
Figure 4.5-6  Wave energy decay with distance from track
4.6 General Discussion

If a ferry operates at super-critical speed in a confined estuary, the inherent characteristics of the initial waves are unavoidable, affecting substantial lengths of coastline. A typical observation of the characteristics of super-critical waves on reaching the shoreline, as shown in figure 2.1-3c, is that the water level rises about 0.2m over the first 25 seconds and is followed by a 15 second draw down of about 0.2m. The next wave is the most dangerous being the largest in the complete wash pattern with a height sometimes in excess of 0.7m having built in shoaling water before it breaks and either surges up the beach or impacts directly on to sea walls and promenades at high tide. The remaining waves in the initial super-critical group will follow reducing in height and period. The super-critical wave group is over in about five minutes. In many locations the wash waves reach the shoreline ten minutes or more after the ship has passed. It is this, which is particularly dangerous, as the general public does not expect the wash to arrive so late and may think that any potential danger is over. Consequently public warning notices need to inform about both the presence of wash waves and their delay after the passage of the ship. Also it is recommended that fast ferry operators optimise their courses and speeds in order to ensure that they do not create excessive and unacceptable wash at critical locations. However, the quantification of acceptable wash heights and periods is a matter of debate.
4.7 Conclusions

The pattern of the wash wave system has been measured for different depth and length Froude numbers and compared with theoretical predictions. The following has been concluded,

(a) linear theory provides a good prediction of wave patterns, the angle of each wave in the leading group of waves in super-critical wash, divergence of wave crests and wave periods in the far field,

(b) In the supercritical wash, the decay rate of the maximum wave height with distance from the track of the ship was found to vary significantly depending on the h/L (water depth/ship length) ratio. For large ships travelling in relatively shallow water, decay rates as low as \(x^{-0.2}\) have been observed, making super critical wash waves much more persistent than sub critical wash in these situations. However for h/L ratios of 0.15 or greater, the decay rate of the leading waves was greater than \(x^{-0.33}\).

(c) The rate of decay of the maximum wave height at the critical speed was substantially different to the supercritical decay rates. This was attributable to a non-linear process, which occurs in this situation and causes the wave heights to increase dramatically around the ship’s hull. As a result the waves were found to decay much faster with distance from the ship’s track.
- An exponential function was found to provide the best representation of the decay process. It was also shown that the decay rate of the critical waves was dependent on the time spent at critical speed and that the shape of the wave pattern also changes with time and therefore it is not steady.

(d) Both length and depth Froude numbers are important parameters and neither can be considered in isolation.
- The peak wash wave energy does not necessarily occur at a depth Froude number of one but is influenced by the length Froude number,
- The occurrence of peak wash will be different for different sizes of vessels. For example in a 15m deep estuary a 50m vessel would transcend the critical or hump speed range of length Froude numbers before hitting the critical depth Froude number range. In contrast a 100m vessel would transcend the critical length and depth Froude number regions simultaneously.

(e) A comparison of the wash generated by catamarans and equivalent monohulls provided some unexpected results for the models tested. It was found that although the vessels produced similar wash in terms of wave height and energy at the critical speed, the long period waves generated by the catamaran at supercritical speeds were approximately half as energetic as those produced by the equivalent monohull.

(f) In super-critical wash in very shallow water often the first wave in the group is the highest. As the water depth increases either the second on third wave is the highest. Consequently in calm weather these waves are the most dangerous as coastal users are caught unawares as the largest wave comes first and breaks or surges on the shore without a gradual build up to act as a warning.

(g) All wave groups in the wash will create risk for different users of the coastal zone.
- Long period waves surge on beaches and shallow banks.
- Short steep waves are particular dangerous to small craft in open water.
• Steep trans-critical waves are significant to all sizes of craft particularly when overtaking.
CHAPTER 5

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5.0 ENVIRONMENTAL IMPACT

5.1 Introduction

While the wave generation of high speed craft has been the subject of several publications in mathematics, physics, naval architecture and coastal engineering, the environmental impact is still the least investigated issue. One of the aspects of this research project was to have an initial look at the environmental impact of fast ferry wash and set up monitoring programmes, which would monitor changes over a longer period. As a parallel programme of work was ongoing to study the environmental impact of ferry wash in Loch Ryan (Scotland) it was decided to concentrate effort there rather than diversify into Belfast Lough as originally planned. The investigation into the coastal processes in Loch Ryan shows one possible procedure for an Environmental Impact Study of high speed craft. Some general conclusions on the environmental impact of HSC will be presented. Though the research project MCA 457 was focused on wave generation and transformation, some aspects of HSC other than wave action will be discussed. However, it is still difficult to predict the environmental impact, as even 5 years of operation is a short period in coastal engineering. Future work and long term monitoring is suggested.

5.2 The Coastal Processes in Loch Ryan

In summer 2000 the Loch Ryan Advisory Management Forum commissioned Kirk McClure Morton (2001) in collaboration with QUB to investigate the coastal process in the Loch. The Forum is a group of local authorities, users of the loch and institutions concerned with environmental issues within the Loch. The Loch is a designated Marine Consultation Area (MCA25) for its important habitat (biological and ornithological). The Loch Ryan Study involved a combination of mathematical modelling, physical modelling and field measurement. The scope of the study was as follows,

- provide data on natural coastal processes such as wind waves, tidal movements, sediment transport pathways (littoral and nearshore) and shoreline changes,
- identify and quantify the effects of man-made disturbances such as wash waves produced by both conventional and fast ferries with particular emphasis on sediment transport and the effect of different propulsion systems, gravel removal and sewage discharge
- study the effect of coastal defence and other structures on the natural movement of sediments,
- provide guidance on future management of the area.

Loch Ryan is an ideal location for this type of study for several reasons. These are as follows:

- there is good historical data over 100 years on the movement of shorelines due to both natural processes and human activities
- there is a wide variety of types of shoreline and sea bed material,
- parts of the loch are sheltered from the prevailing wind seas and are only subject to waves from ferries,
- the northern part of the loch is subject to naturally occurring long period swells,
- the loch is fairly shallow ranging in depth from 20m near the entrance to 3 and 4m in the upper reaches.
- up to 3 fast ferries and 5 conventional ferries operate in the area and there is no other shipping.
5.3 The Site

Loch Ryan, shown in figure 5.3-1, is 13km long and between 1.5 and 4km wide. It is open to the North and exposed to swell waves from the North Atlantic in a general direction of $340^\circ$. With a maximum depth of 15m at the inner part and a mean depth of around 5m the Loch is very shallow. The entrance is flanked by rocky cliffs rising in the north east to over 300m above sea level. A 700m wide muddy inter-tidal zone stretches at the south or inner end of the loch in the vicinity of Stranraer. The western coast from Stranraer to Kirkcolm mainly comprises sand and gravel beaches with finer deposits resulting from the sheltered position. The tide ranges between +0.2m at MLWS and +3.0 at MHWS.

5.4 Ferry Operations in Loch Ryan

5.4.1 Current and Historical ferry operation in Loch Ryan

The ferry service from Loch Ryan to Northern Ireland is one of the most established and historical routes in the Irish Sea. The first regular service commenced in 1861. At present Stenaline and P&O operate from Stranraer and Cairnryan respectively.

Stenaline operates one fast ferry and two conventional ferries. The fast ferry, Stena Voyager, is an HSS 1500, a 120m long semi-swath catamaran. This is the largest fast ferry operating in the area. P&O also operate one fast ferry and three conventional ferries. Their fast ferry Super Star Express is an Austal Auto Express 84, which is an 84m long catamaran. Until the year 2000 they operated a 96m long fast monohull, Jetliner. Recently a new modern conventional ship has been taken into operation, which is capable of speeds up to 23 knots. Seacontainers operated Seacat Scotland, a 74M Incat wave piercing catamaran, on the Belfast to Stranraer route between 1992 and 1999.

5.5 Methodology

5.5.1 Wash Monitoring

A number of physical measurements with seabed pressure transducers were taken to quantify the size and characteristics of the wash produced by both fast and conventional ferries. The positions of the monitoring units are shown in figure 5.3-1. Results of these monitoring sessions were used for the numerical modelling.

5.5.2 Field Observations

During this study an investigation of the shoreline was carried out. Several sediment samples were taken from the beaches mainly in the inter-tidal zone to derive the erosion characteristics. On banks and beaches, where the particle size was excessive for normal sedimentary sample analysis, the grading of the material was determined using a line count analysis method. As well, the shoreline morphodynamics was investigated and the main structures like ridges, bars, gravel cusps and overtopped beaches determined. Beach profiles along the shores all around Loch Ryan were surveyed to get an overview of the current state.

5.5.3 Historical Data review

In order to establish the earlier coastal processes available, historic data was reviewed for the key areas. The sections of the shoreline, which are prone to changes due to storm attack or deposition due to their sheltered position, were selected. The available data mainly consisted of different hydrographic surveys and aerial photographs of the area.
5.5.4 Mathematical Modelling

5.5.4.1 Numerical Simulation of Wind and Wash Waves

To obtain an overview of the wave climate in Loch Ryan, representative wave data from outside the Loch was used as well as wave generation within the Loch itself. The annual wave climate for waves approaching from 270° to 60° from the North included the effect of waves generated outside Loch Ryan. For other directions only waves generated in the Loch itself were considered. The wind wave characteristics were calculated from wind data for the area and data on swell waves in the North Atlantic produced by the Meteorological Office.

Having established the various wave characteristics for both wind seas and ferry wash the MIKE 21 suite of software was used to model the transformation processes taking place within the loch. Two types of mathematical model were used in order to produce information on different parts of the transformation process. A spectral wind wave model based on conservation of the energy density function was used to produce wave characteristics throughout the loch for the natural wave climate. Finally a breaking wave model was used to calculate the wave transformation processes which take place in very shallow water off beaches due to shoaling, refraction and bed friction.

With respect to ferry wash, the same software was used. The time series were broken down into a series of characteristic frequencies to represent different parts of the wave train. The variation of direction of travel and height of the wash wave components was calculated along the track of the ship and this provided the input to the two models. This also provided input to the sediment transport model.

5.5.4.2 Numerical simulation of longshore sediment transport

Numerical modelling was undertaken using LITPACK/MIKE21, a integrated modelling system for littoral processes and coastline kinetics. This model uses data from the wave and tidal models together with bathymetry and sediment grading of the nearshore area. The model contains modules which enable the simulation of littoral currents, longshore sediment transport and coastline development.

Data derived from both the field measurements and the mathematical model were used as input for calculating the sediment transport at a range of sections across the shoreline around the loch. The simulation was carried out on an annual basis. The natural wave attack and the wave attack caused by the ferries on the inbound and outbound trips were distributed over five different tidal levels during flood and ebb tide cycles.

5.6 Morphology of the Study Area

Two areas have been selected for detailed discussion, Kirkcolm Bay and the manoeuvring area at Stranraer.

To the north of Kirkcolm Bay (called Clachan Heughs) benches of red sandstone and coves form cliffs with 3-6m wide beaches towards the sea. In some coves the sandstone is hollowed out creating overhanging sections of soil fixed by roots. Near Corsewall the beaches are smoothly embanked with fine glacial sediments in the intertidal zone. Gravel banks (up to 300 mm diameter) form a storm beach on the upper end. At Kirkcolm Bay gravel is partially thrown in tong like formations into the adjacent fields. Around the Scar, brick and concrete slabs have been dumped along the foreshore forming an embankment to protect the low laying land beyond. The beach shows no significant vegetation.
On the seabed the bed-rocks break in some places through the sediment layer. Near the shoreline the seabed is characterised by sands, gravel and pebbles. Towards the mouth of the Loch, gravel and coarse sandstone are prevalent. At The Wig and south west of the Spit the substrata comprises fine sands with muddy spots and shells.

At the southern basin of the Loch a mix of shells on mud and fine to silty sands is predominant. A thick layer of shells and small stones with medium sand distinguishes the dredged channel.

The water depth in the body of the Loch (south of The Wig and south of Beacon No.1) is generally less than 5m. Around the navigation channel there are areas where the depth exceeds 5m. A deep area occurs stretching from Cairnryan Harbour to Old House Point with average depth of 12 m and a deeper spot of 15.5 m at Old House Point. North of Garry Point the bathymetry reaches 15 m deepening towards the Northern Channel with a gentle slope. sands with gravel and broken shells.

5.7 Ship Operational Procedures

The course and locations of deceleration and acceleration of the various ships entering and leaving Loch Ryan are shown in figure 5.3-1. All ships approaching Loch Ryan pass to the north of the cardinal buoy off Milleur Point and head into the Loch until passing Cairn Point. The ships bound for Stranraer alter their course passing Cairnryan and follow the navigation channel from Spit buoy via beacons 1, 3 & 5. Information on the operational procedures of conventional and fast ferries was obtained from all operators. This data was used for the numerical modelling of the wave wash together with the number of occurrence as given in table 5.1

Table 5.1 Overview of the number of ferry sailing's during the past 20 years in Loch Ryan.

<table>
<thead>
<tr>
<th>Period</th>
<th>Departures per week</th>
<th>Departures per year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional</td>
<td>HSC</td>
</tr>
<tr>
<td>1980-1992</td>
<td>94</td>
<td>-</td>
</tr>
<tr>
<td>1992-1996</td>
<td>94</td>
<td>28</td>
</tr>
<tr>
<td>1996-1999</td>
<td>89</td>
<td>97</td>
</tr>
<tr>
<td>1999-2000</td>
<td>89</td>
<td>69</td>
</tr>
</tbody>
</table>

5.7.1 Conventional Ferries

The majority of the conventional ferries of both P&O and Stenaline arrive at the entrance to the loch at a speed of between 15 and 17knots. The ships slow to either enter or pass the port at Cairnryan. To the south of Cairnryan on route to Stranraer, the ships travel along the navigation channel at a maximum speed of 10 knots. The reverse process takes place on the outbound journey. During 2000 P&O have introduced a new conventional ferry capable of operating at 23 knots. The impact of this ship is not been taken into account in the study.

5.7.2 Fast Ferries

The Super Star Express arrives at a maximum speed of 37 knots (19m/s) and slows down near and to the south of Cairn Point. The vessel turns in front of the northern basin of Cairnryan ferry terminal and reverses into the harbour, mooring stern onto the link-span. On the outbound course Super Star Express accelerates immediately after turning to the north after leaving the harbour basin. The previous ship, Jetliner, had a similar operational procedure although the maximum speed was only 33 knots.
On the inbound passage, Stena Voyager slows from 40 knots to 17 knots off Old House Point. She slows to 12 knots before the ferry terminal at Cairnryan and maintains this speed to Stranraer. On the outbound passage the reverse procedure is used with acceleration taking place off Cairn point. At high tide during the tern breeding season Voyager slows at the Forbes Shoal Buoys to avoid the wash over topping the low banks which form the Scar.

When Seacat Scotland was operating on the Belfast Stranraer route, on both the inbound and outbound passages, the ship slowed in the vicinity of the Cairnryan ferry terminal but travelled at 36 knots both in the northern part of the loch and between Cairnryan and Stranraer.

### 5.8 Wash Wave Characteristics

All the fast ferries operating in the northern part of Loch Ryan generate wash waves in the super-critical depth Froude number range as a consequence of the limited water depth of between 20m and 8m. During deceleration from and acceleration to super-critical speeds either on inbound or outbound passages, the vessels transcend the trans-critical speed range. This is where they produce the maximum wave heights. These locations are highlighted as hatched areas in *figure 5.3-1*.

Leaving Loch Ryan, HSS generates trans-critical waves after passing Cairn Point, which is their designated acceleration location. The waves approach the shoreline mainly along the cliffs at Clachan Heughs and the beaches at Old House Point.

The conventional ferries currently operating in Loch Ryan can reach a maximum speed of either 17 knots or 23 knots in open water. However when approaching shallow water the ships slow due to increased wave drag resulting from the reducing under keel clearance.

### 5.9 Historical Records of Coastal Changes

The admiralty charts surveyed in 1898/99 and 1972 were used to determine the natural changes in the coastline along Kirkcolm Bay. *Figure 5.9-1* shows the simplified charts with the older contour lines as dotted lines and the survey of 1972 as shaded areas. The reference datum on both charts is similar as well as the tidal levels. Any sediment transport processes occurring along this part of the shore are nourished by the local sediment supply, as major sediment transport from the northern directions is not possible.

It was found that for example the promontory at (2) has moved and a new promontory has formed further south (3). The datum and 2m contour have moved out in zone (5) & (6) by about 150m to 300m within 75 years. The former shoals are a continuous area above the chart datum ending in a 80m wide and 275m long ridge. It is known that gravel removal took place around The Scar during the 1960’s. Unfortunately the quantity is not known, therefore the change at Kirkcolm Point itself is both natural and created by human activity.

The aerial photographs taken in 1940, 1989 and 1999 of Kirkcolm Bay and The Wig were used to establish the most recent developments along the coast. Although the photographs of 1940 and 1989 were not rectified and information about the distortion was not available, the landmarks within the area of interest fitted very well. In this study the waterline was taken as a measure of the change in the coastline. As the tide level effects the waterline and precise tide levels were not available, only major changes could be identified. The outcome was in consensus with the chart data. A specific change, which could be linked to fast ferry operation in particular however, was not found.
5.10 Wave Effects Kirkcolm Bay

5.10.1 Wind Seas

Only the eastern and the western coastlines of the northern half of the loch are subject to long period swell waves. These primarily originate in the North Atlantic and in the North Channel between Scotland and Ireland. Swell waves with a period of 12s to 15s are common and these are supplemented by shorter waves generated in the Firth of Clyde and the North Channel. There is also some local wind seas from south-easterly winds with a typical period of 4 to 5 seconds. Figure 5.10-1 shows the relative heights and directions of the swell waves entering the loch from the north. Similar calculations were carried out for all wind directions. Using the refraction model the wave height and direction of propagation was derived under consideration of local wind sea effects. In conjunction with the occurrence and duration of the related wind situation the wave climate was calculated for seven typical locations in the Loch. Two results are shown in Figure 5.10-2. The wave roses are divided in wedges of 15 degrees showing the different wave heights in different colours. The centre indicates the occurrence of waves below 0.15 m (calm). This wave climate was used as input to the sediment transport calculations, which provided an insight into the natural processes taking place.

5.10.2 Ferry Wash

During a five day monitoring period wash was monitored for both conventional and fast ferries. This included inbound and outbound passages. Figure 5.10-3 shows two typical wash wave traces of two fast ferries inbound measured off Kirkcolm Bay at location RNS. The first trace is for Stena Voyager and the second is the P&O Jetliner. Each wash trace was categorised in terms of frequency bands, typical heights within each band and number of waves resulting from each passage. The total number of passages per year for each vessel was also calculated. As well, wave propagation modelling was carried out to predict the direction of propagation and the increase in wave height due to refraction, as shown in figure 5.10-4. The wave angle can be derived from the monitoring of ferry wash and other mathematical models, however the bathymetry changes these angles and wave heights as demonstrated in MCA 420 (1998).

5.11 Numerical Simulation of Longshore Drift

A range of particle sizes was used in the sediment transport calculations. Figures 5.11-1 a to d show the output from the longshore drift calculations using a particle size of 5mm. The figures show the longshore drift resulting from the naturally occurring swell waves, the combined effect of conventional ferry wash waves, the combined effect of the wash from fast ferries and the total effect of all three combined.

The values calculated are only potential transport rates and provide a relative measure of the longshore drift caused by the three different sources. The total process taking place in the field is very difficult to model as the particle size grading ranges from gravel to very fine sand. The fine material is eroded first leaving a top layer of gravel and pebbles. This top layer armours the sediment and even though a potential transport rate exists only a small amount of material is actually transported.

The results of the calculation are shown in figure 5.11-1 for cross section 3 at Kirkcolm Bay (the location of cross section 3 is shown in figure 5.3-1). Natural sediment transport shown in figure 5.11-1 a occurs only in the southern direction as the natural swell approaches with a period of about 13 seconds from the mouth of Loch Ryan. A lower level
of wave attack occurs further out with another peak at a depth of 1.3 meters 600m off the coast. The largest transport rate appears in the inter-tidal zone and just below the chart datum in a zone 50m wide from the beach seaward. This is due to the waves breaking at this water depth.

The mass transport rate due to conventional ferries, shown in figure 5.11-1 b, is much smaller than the natural rate due to wind seas. The fundamental difference is that the ferry wash causes a reversal of the transport direction depending on whether the vessels are inbound or outbound. Due to this cancellation effect the net movement of material in one direction is very small.

The fast ferries also produce a variation in mass transport direction depending on the direction of travel of the vessel. This is shown in figure 5.11-1 c. However, the mass transport rate in the southern direction is about twice that in the northern direction. This is due to the super-critical wash being more developed in the inbound passage with a larger number of longer period waves compared to the outbound passage. On the outbound passage the near-critical wash, which is the largest, dissipates very quickly with distance from the sailing line. This is because the ships accelerate quickly and energy is pumped into these waves for a very short time. When both these effects are added together, the net mass transport in a southern direction is similar to that caused by the wind seas.

**Figure 5.11-1 d** shows the combined effect of both wind seas and all ferry wash. This shows that the peak sediment transport in a southern direction close to the shoreline is similar for both the ferry wash and the wind seas. However, the transport of material further offshore is greater for the wind seas.

A similar set of calculations were performed for a 1mm particle size at the same location. This produced a different effect with the sediment transport due to wind seas being substantially greater than that produced by the ferry wash. This demonstrates that any conclusions reached about the relative environmental impact of ferry wash compared to natural processes is highly dependant on the particle size of the sea bed materials. The result indicates as well that the current grain size of the top layer is just above the critical size, armouring the sediment underneath.

In summary to the computational modelling, the following can be stated. There are insufficient long term measurements available to confirm the effect of the high-speed wash on the shoreline. The leading long period waves in fast ferry wash tend to move larger sized material than the shorter wind seas, in particular those further from the shore. The daily attack by high-speed wash is higher than the normal non-storm wind waves. There are therefore two potential scenarios to be considered:

a) The fast ferry wash improves the armouring, the top layer of stones will be heavier as well as the size will be bigger. This enforced armouring goes along with an initial increase in erosion and cross-shore transport. After this process has settled the shoreline is more stable against severe storms, than it was before. Meanwhile the finer sediments eroded during the initial phase will nourish beaches and sections of the shore that are more sheltered.

b) The ship wash changes the overall wave climate and accelerates the natural coastal processes already taking place. This means that more material is eroded at the cliffs, feeding the longshore transport of sediments further south. At the same time the longshore
transport will be accelerated causing a loss of shore at certain points (this is the natural process and has taken place for many years before any ferries were operating).

5.12 The Environmental Impact in Harbours and Channels

5.12.1 Sea Bed in the Harbours

Figure 5.12-1 shows a schematic view of Stranraer Harbour, the adjacent sea bed contours, the extent of the dredged area which forms the start of the channel, the turning area and three shaded areas where there is scour. In the harbour between the Mail Quay and Ross Pier, two scour areas can be found. One is created by the conventional RoRo-ferries, which berth with their bows too the link span. The port operators have indicated that this situation has not changed in many years.

The SWATH Ferry berths stern to the link span next to the Mail Quay. The local scour area in front of the link span can be attributed to the action of the water jets. The port operators have indicated that this has occurred since the introduction of Voyager in 1996. It is interesting to note that a similar situation has occurred at Harwich where another HSS 1500 berths. Here the seabed has been eroded in two parallel tracks in line with both hulls. It is thought that the water jets are particularly prone to cause sea bed erosion when the reversing buckets are down and the flow is being directed forward and down at an angle of about 40°.

The above observations show that both conventional ferries and fast ferries with water jet propulsion generate local bed scour. Ideally the seabed should be paved in order to prevent the problem and this has been done in some ports.

5.12.2 Manoeuvring areas

In front of the harbour basin is a dredged area, which is maintained to a minimum depth of 5m to provide space for ships to manoeuvre, as also shown in figure 5.12-1. Within the basin there is evidence of a scoured area which coincides with the turning location for both the high speed and conventional ferries. The SWATH ferry enters the area bow first and reverses into the berth. There is a high degree of control with four steerable water jets and in conjunction with the computer controlled navigation system there is very little deviation in the location of the turning point. Consequently the scour area tends to be fairly concentrated.

The situation is partially redressed by the conventional ferry, which reverses from its berth and turns to travel along the channel. This manoeuvre is not as precise as with the high speed ferry and consequently the scouring action tends to be more distributed. It is thought that a dynamic equilibrium has been reached in the area. This means, that the fast and conventional ferries are eroding material due to the locally very high water velocities while turning but this material is deposed in the near field super-elevating the edge slopes, which causes slides and partially refills the scour area. The very low tidal currents contribute very little to this process, as the velocities are too low.

5.12.3 Seabed Scouring under Normal Operation

High-speed craft with jet propulsion operating at sub-critical speed in a navigation channel or shallow water have very little effect on the seabed. There are several explanations for this: Firstly the flow through the jets is very little, the HSS for example pumps only 4% of the water through the jets at 12 knots compared to full speed. The highest velocities are reached at the water surface, where the jets plunge into the water. The main disturbance is caused by the
flow around the hull. The under keel clearance and the shape of the hull are the determining
factors for this. In contrast to this, a conventional propeller has a much higher secondary flow
radial to the shaft due to the added mass effects and the flow around the propeller tips.

There have been discussions about the effect of jet propulsion on the seabed under high
speed operation. To start with, the general perception of jet propulsion units sucking in
water underneath the ship is incorrect. The intake of a water-jet is designed to pressurise
water under normal operation. This means that the velocity in the intake is lower than the
ship speed and only water very near to the hull gets pushed into the jet because of the
intake duct shape. This agrees both with cavitation tunnel measurements and numerical
simulations of Allison et al. (2001) and Verbeek & Bulten (2001). Under the current
operating procedure the disturbance generated by Stena Voyager on the seabed due to their
hull and jet plumes is minimal. HSS causes less flow around the hull than any conventional
ferry of similar transport capacity. Furthermore the jet plumes are likely to increase the oxygen
concentration in the shallow areas on warm, calm summer days and therefore improve the
overall water quality.

5.13 Conclusions on Environmental Impact

The general conclusions from this study are as follows:

- The vulnerability of a coastal zone to wave attack is dependant on the typical particle
  size and the grading of the material. If fine sediments are interspersed with gravel and
  small stones, then armouring takes place and the mass transport rate is significantly
  reduced.

- On beaches with fine to medium size sediment the long period wave wash of high speed
  operation will always cause an initial increase in sediment transport. The long term
development however depends very much on the magnitude of attack and the
composition of the sediment.

- Each shoreline needs to be modelled individually. It is essential to obtain up to date
  information on the beach morphology and sediment grading to predict the sediment
transport generated by fast ferries as well as an overall picture of the natural littoral
paths.

- The leading long period waves in fast ferry wash tend to move larger material than the
shorter wind seas particularly further from the shore. In comparison the short steep
waves produced by conventional ferries tend to move material closer to the shoreline.

- In sheltered locations the daily wave attack by high speed wash is likely to be higher
than the normal non-storm wind waves.

- Numerical models of longshore drift have shown that the erosion produced by fast
  ferries is greater than conventional ferries.

- The impact of high speed wash depends very much on the morphological state and
situation of the shoreline. The wave wash has less impact on a beach that is naturally
well balanced (only transport but no erosion or transport with little erosion) than on a
beach where the natural equilibrium is already disturbed or destroyed due to coastal
works or sediment removal.

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• Temporary speed restrictions placed to protect for example small islands and banks with bird colonies during the nesting season appeared to be applicable and efficient.

• The increased wave attack on less erodable cliffs due to fast ferry operation can be a benefit to the coastal system, as the additional eroded material could nourish other locations, depending on the local bathymetry and wave climate.

• Compared to conventional ferries, fast ferries with water jet propulsion tend to produce more sea bed scour in harbours and manoeuvring areas but do so in a more localised position.

• Fast ferries operating at comparable speeds to conventional ferries in very shallow water tend to disturb less sediment due to their lower displacement and more streamlined hulls. The disturbance caused by the hull of a high speed craft itself is in general less than compared with the transport capacity of conventional ships.

• The intake of water jets is fed by water near to the hull and under normal operation the water is not sucked into the units by the water pumps. The impact of high speed craft on the seabed in channel is mainly due to the pressure wave and the flow around the hull than the water jets themselves.

• The plumes of jet propulsion systems are likely to increase the oxygen concentration in the shallow areas on warm, calm summer days and therefore improve the overall water quality.
Figure 5.3-1: Loch Ryan – Bathymetry and navigation routes
Figure 5.9-1: Bathymetric changes from 1898 until 1972 along Kirkcolm Bay and the Spit
Figure 5.10-1: The natural wave heights and the refraction of waves penetrating into Loch Ryan from the Irish Sea

Figure 5.10-2: Natural wave climate at location I and II
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Figure 5.10-4: Numerical model of fast ferry wash
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Chapter 6

6.0 THE EXCITATION OF SHIPS BY WAVE WASH GENERATED BY HIGH SPEED CRAFT

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6.0 THE EXCITATION OF SHIPS BY WAVE WASH GENERATED BY HIGH SPEED CRAFT

6.1 Introduction

In the following chapter the impact on other vessels of waves generated by fast ships at super critical and near critical depth Froude numbers is discussed. Three situations are included,

- a fast ship overtaking another vessel,
- a fast ship approaching an on-coming vessel,
- the effect of fast ship wash on moored vessels.

In general the excitation processes caused by high speed ship wash are similar to any other gravity wave excitation as considered in sea keeping predictions. The reactions of a ship in regular waves are often described as a damped spring mass system. In the following paragraph some parameters, definitions and expressions used by naval architects will be explained. The six equations for ship motions in regular waves are given in Appendix 6.1. For more details see the naval architecture literature (e.g. Lloyd (1998)).

A series of experiments were conducted in the wide shallow tank to observe the behaviour of vessels under the conditions outlined above. Video was taken of the experiments to enable observation of both the fast ship and the other vessel. It was not possible to make any other form of measurement within the scope of this contract.

6.2 Ship Motions

The definition of the three linear and angular motions of a ship is shown in figure 6.2-1.

\[
\begin{align*}
x_1 & \text{ surge} & x_4 & \text{ roll} \\
x_2 & \text{ sway} & x_5 & \text{ pitch} \\
x_3 & \text{ heave} & x_6 & \text{ yaw}
\end{align*}
\]

**Figure 6.2-1: Ship motions and their definition in space**

The waves generated by high speed craft are small in amplitude compared to either their wavelength or the typical length of ship operating in shallow estuaries. Unlike wind seas, the initial wave group in super-critical ship wash is composed of regular sequences of waves which progressively vary with time in terms of wave period and wave height. Although the direction of the initial waves changes with both wave period and distance from the ship, wave refraction aligns the wave crests with the sea bed contours. Consequently at the shoreline the wash looks like a train of parallel crested waves steadily varying in height and period. In many cases the linearised equations for small amplitude ship motions in regular waves are applicable. However it has to be pointed out that most sea keeping theories are
limited in their application to high speed super-critical wave wash because of the following two reasons:

- In most sea keeping calculations the waves are assumed to be sinusoidal. As shown in section (2), linear wave theory represents and predicts the properties of the wave pattern well. Therefore linear wave theory and in particular the assumption of the wash consisting of sinusoidal waves seems to be practical.

- The waves in most sea keeping calculations are assumed to be deep water waves. One needs to prove that the equations take the general functions for wave and group velocities \( c \) and \( c_g \) for any water depth into account.

Before applying any general prediction methods for ship motions in high speed wash one needs to prove the validity.

### 6.2.1 Encounter Frequency

The wave frequency \( v \) has direct influence on the motion of a floating object with no speed through water. However if the ship is moving the excitation is more dependent on the frequency at which the ship encounters the waves.

![Figure 6.2-2: Definition of heading angle of a ship in regular waves](image)

The encounter frequency is a function of the heading angle. The heading angle \( \mu \) is defined as the angle between the ship’s course and the direction of wave propagation. The corresponding encounter frequency can be calculated using the following equation

\[
\omega_e = \omega - kV_S \cos \mu
\]

Furthermore for a high speed craft approaching another ship from any direction in constant water depth at a depth Froude number above 1 the heading angle can be estimated for the first wave using the following equation.

\[
\mu = \gamma - \arccos \frac{\sqrt{gH}}{V_{HSC}}
\]

with \( \gamma = \text{course}_{\text{ship}} - \text{course}_{\text{HSC}} \),
\( H = \text{mean water depth} \),
\( V_{HSC} = \text{speed of the HSC} \).
For the following waves the divergence in angle can be taken from the graphs in figure (4.2-5) or calculated using the mathematical model described in section (4.2.1).

Transfer functions (or response amplitude operators) are graphs of the excitation or response of one particular ship at a range of encounter frequencies. The response function is made dimensionless by dividing by the wave amplitude (for linear motions) or wave slope (for angular motions). In deep water the wave amplitude is equal to half of the horizontal and vertical maximum displacement of a particle at the water surface. In shallow water however the orbital motions become elliptic, the horizontal displacement is greater than the vertical displacement.

The horizontal amplitude (half of the displacement) of a particle at the water surface can be calculated using the following equation:

\[ \eta_{x_{\text{max}}} = \eta_0 \cdot \text{coth}(kH) \]

with \( \eta_0 \) = wave amplitude, \( H \) = water depth, \( k \) = wave number.

The natural frequencies, which can be obtained in many cases more easily than the transfer functions, can be used to estimate the point of harmonic response of a vessel in regular waves with small amplitude, but not the amplitude of the response.

In the following sections some general characteristics of conventional monohull ships will be used to describe the motions of the ship's centre of gravity in high speed wash. Absolute motions will be discussed in a later section of this chapter.

However in many cases the wave pattern generated by a high speed craft in a coastal area consists of several groups of waves and a range of frequencies, as shown in figure 6.2-3. As a result a wide range of ships is effected by these waves, each by a different group in the wave pattern.

**Figure 6.2-3: Typical wave trace of HSC measured near navigation channel, the HSC has slowed down ~5NM from monitoring location and passed with sub critical speed at a distance of less than 1NM**
6.2.2 Coupling of motions

If a ship is free to move (no moorings, anchorage or towing/trawling gear deployed) surge is uncoupled from all other motions. In general heave and pitch are coupled. Sway, roll and yaw are also coupled motions.
6.3 Ships Encountering Wash from High Speed Craft

6.3.1 Ships Passing and Overtaking

Motions in following or head waves ($\theta=180^\circ$ or $0^\circ$)

In Figure 6.3-1 one example is shown of a ship encountering high speed wash from the stern. The ship navigates in the same direction as the wave travels. If the wave celerity is substantially greater than the ship speed, it will experience similar motions to a particle of water at the surface. The maximum surge will occur in the wave crests and troughs and will reach the same value as the horizontal particle amplitude ($h_{\text{max}}$).

\[
\text{Super-critical speed} \quad Fr = 1.5
\]

\[
\text{V_{vessel}} \quad \text{Wave propagation} \quad \text{V_{HSC}} \\
\text{1. wave crest} \quad \text{2. wave crest}
\]

\[c_{\text{wave}} = V_{\text{HSC}} = \sqrt{gH} \]

Figure 6.3-1: Wave pattern (crest lines) of HSC at supercritical speed and smaller vessel encountered by wash

The encounter frequency is always positive for a high speed craft, (HSC), overtaking the vessel. In following waves (caused by a passing HSC) the heave amplitude is not bigger than the wave amplitude ($h_0$). In head seas (caused by an overtaking HSC) this is in general the same case. However, at higher speeds some vessels tend to a heave / wave amplitude value bigger than 1 for encounter frequencies between 1 and 1.5. This is the case of a HSC passing another HSC either during or shortly after one of them has passed through the critical speed range. The high speed craft will hit a critical wave which will most likely be a head wave.

The heave transfer function for a slender long monohull is shown in Figure 6.3-2. For higher speeds (above 20 knots) the ratio of heave to wave amplitude is bigger than 1 with a slight negative phase shift. It is possible that the ship speeding into the critical wash wave will partially emerge from the water at the bow and slam into the following wave. This has been observed in Belfast Lough and Loch Ryan and was accommodated by the masters of HSC warning each other about the existence of a critical wave. Therefore the master of a HSC has to be vigilant when passing through other high speed wash while operating at high speeds.
Figure 6.3-2: Transfer functions of a long slender monohull in regular head waves at different speeds

Table 6.1: General relationships between wavelength, ship length and heave amplitude in following or head waves

<table>
<thead>
<tr>
<th>Wavelength / ship length</th>
<th>Heave / wave amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 5</td>
<td>~1</td>
</tr>
<tr>
<td>between 5 &amp; 1</td>
<td>depending on ship speed</td>
</tr>
<tr>
<td>&lt; ¾</td>
<td>Small to zero</td>
</tr>
</tbody>
</table>

The pitch transfer functions of many ships are similar to the heave transfer functions at following or head waves.

Considering the buoyancy forces along the hull a simple illustration for the motions can be given:

- For long waves the maximum heave will occur at the troughs (max. negative heave at the crest). The maximum pitch is reached after one quarter of the encounter period from the trough (max. negative pitch occurs ¼ period before the crest).

- For a wave being as long as the ship the buoyancy forces induce a moment causing pitch. Dynamic effects and the coupling of motions alter the simple relationship for longer encounter periods.

- If the wavelength is short compared to the ship length the different buoyancy forces in the crests and troughs of the waves eliminate each other.
6.3.2 Motions in beam waves (m=90°)

A ship travelling towards or away from the track of the HSC as shown in figure 6.3-3 will be excited by beam waves. Similar to the motions in head or following waves a ship with a beam smaller than the wavelength will follow the orbital motions of a particle at the surface. As a consequence the heave amplitude is in a first approximation equal to the amplitude of the wave. For a small craft (e.g. a leisure craft) the supercritical waves are not very important, the passenger will hardly experience any motion, as the acceleration is very small. However for a draft limited ship operating in a channel with small bottom clearance the large but slow motions can be vital. The maximum ratio of heave to wave amplitude is reached at this course for a VLCC. This increases the risk of a grounding situation. The sway is again equal to the horizontal particle motions or the horizontal wave amplitude ($h_x$). The maximum heave will be experienced at the crest and trough and maximum sway at the wave zero crossing points.

Roll motions are particularly strong in beam waves and at zero vessel speed. With a higher forward speed, the roll damping increases. The maximum roll amplitude (maximum harmonic response) occurs at slightly lower wave frequencies (natural frequency). Again the natural frequencies can be used to predict the frequency of harmonic response of the ship. The amplitude of the roll motions is very much dependant on the metacentric height of a ship, meaning that for one ship encountered by the same wave but with different loading situations the roll amplitude will be different.

![Figure 6.3-3: Wave pattern (crest lines) of HSC at supercritical speed and larger vessel encountered by wash](image)

A report prepared by SSPA (1998) states that the wash from high speed ships is only a potential problem for VLCC’s if the distance between the ships is less than 0.1 to 0.3NM. However, beyond this distance there may be a problem as a result of shoaling and wash concentration.
6.3.3 Motion in oblique waves - overtaking

When passing in channels or fairways, the course of the overtaking ship and the HSC are parallel. In *figure 6.3-4* a situation is shown, where a vessel is being overtaken by a fast craft at super-critical speed. The ship will experience motions caused by oblique waves. The curved line in the diagram illustrates the lateral displacement due to the orbital motions of a particle at the water surface. Small craft (ship length < 1/4) behave like a particle on the water surface. The dominant motions will be surge, sway and heave, depending on the encounter angle and the ratio of wave amplitude to horizontal wave amplitude. Roll and pitch are small because of the wave slope being small.

A ship with a length of between 1/4 and 4 1 will alter its course significantly. When the first wave reaches the ship the stern will be lifted and shifted away from the High Speed Craft. This results in a turn of the ship towards the overtaking vessel at the first zero crossing point of the wave. The maximum yaw will occur when the centre of gravity is at the crest of the wave. As the wave progresses underneath the moving ship this will be reversed. Approaching the first trough the ship will yaw to the other side. The stern is moved towards the overtaking ship while the bow is displaced away from it.

Due to these course alterations there is the possibility of collision if the ships have almost the same speed and are very close to each other. It has to be stated that a good helmsman or autopilot will adjust these course changes and minimize them. If the ship length is longer than one wavelength the motions become small compared to the wave amplitude and wave slope.

*Figure 6.3-4: Wave pattern (crest lines) of HSC at supercritical speed and vessel encountered by oblique wash*

*Figure 6.3-4* illustrates the problem of defining one particular type of ship, that is effected by high speed wash. At the 4th wave the wavelength has reduced to half the length, consequently a range of vessel sizes is effected by different parts of the wave train.
The oblique angle of the waves advancing underneath the ship causes rolling due to the asymmetry of the forces resulting from the wave elevation. Hull shapes with a high overall beam to length ratio, like catamarans, are more effected than other conventional ships. Again it depends on the response of a particular hull design and their roll damping (catamarans have a high rate of roll damping, which results in the vessel following the water surface without motion amplification.)

However the strongest effect on larger vessels can be expected from the first waves of the supercritical wash, as these waves are the biggest in the wave pattern. However, small boats are more effected by the tail waves, which are generated by the jet plumes, plunging into the water at the rear of the high speed craft or the sub critical wash near the ship.

6.3.4 Motions in oblique waves - Passing

The effect of the high speed wash on an oncoming ship is similar to the response during overtaking. The wave pattern will be the same at similar speeds and water depths and so the wavelength, but the encounter frequency is higher. The risk of collision is less, as the ship will yaw away from the high speed craft at the first wave while abeam.
6.4 Motions of Moored Ships

The movements of moored ships are different to the motions of a free moving ship. The motions are constrained by the mooring, which is a flexible system. This adds another spring to the spring mass system. The eccentric mooring couples heave, surge and roll and introduces additional roll motions. The strength of the coupling depends on the eccentricity of the mooring and the angle of the mooring lines.

The wave pattern reaching the moored ship is usually more complicated compared to open waters due to the influence of coastal structures and the local bathymetry. The angle of propagation is due to wave reflection and wave refraction around solid obstacles and, unless the berth is open to the incoming waves, these changes need to be considered. The wavelength can be shorter due to diffraction, which can increase the height at the same time. For illustration purposes a wave reaching a quay and the resulting wave crest bending is shown in figure 6.4-1.

![Figure 6.4-1: Moored ship encountered by stern waves on a pier](image)

If the ship shown in figure 6.4-1 were alongside the pier with no moorings the movements would be surge and heave. Due to the mooring the ship will perceive additional rolling motions due to the coupling effect. Moorings consist of a set of different ropes with varying length and elasticity. It is important that the mooring lines facing in one direction are of similar length, similar elasticity and similar tension. Otherwise one rope could take excessive strain and can eventually fail. Short transverse lines are not recommended at a berth, which is subject to long period waves from the wash of high speed ships. If loading or discharge processes are taking place, which are sensitive to ship movements, it is recommended to interrupt these processes. It is good practice for the master of the HSC to notify the personnel in charge of the loading process via VHF prior to the approach.

6.4.1 Other Wash Induced Effects

Apart from the effect on moored ships discussed in MCA 420 (1998) there are other problems such as surge in marinas and small craft harbours due to the leading long period waves in the super-critical wash. However, during the course of this study other phenomena have either been observed or reported by users of the coastal zone. These fall into two categories:

- the dynamic response of floating structures such as link-spans and pontoons in harbours and marinas,
- relative motion of supply ships or pilot boats and another ship.

These are summarised in table 6.4-1.
Table 6.4-1 Wash induced effects at moorings

<table>
<thead>
<tr>
<th>Ship type/mooring situation</th>
<th>Effected by</th>
<th>Counter measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cruise liners, large ships at freight and ferry terminals</td>
<td>Long period swell, dislocation of link span, ramp or gangway</td>
<td></td>
</tr>
<tr>
<td>Small boats in yacht harbours</td>
<td>Steep crested tail waves</td>
<td>Floating breakwater</td>
</tr>
<tr>
<td>Working ships, pilot embarkation</td>
<td>Huge relative motions due to different behaviour in waves</td>
<td>Cease work process, secure equipment</td>
</tr>
<tr>
<td>Freight discharge and loading at anchorage, Replenishment at anchorage</td>
<td></td>
<td>Awareness and knowledge about existence of the problem</td>
</tr>
</tbody>
</table>

6.5 Absolute Ship Motions

The six motions so far discussed were the movements of the centre of gravity of a ship in regular waves. In many cases the motions of the ship at a particular location within the ship is more important, like movements in the restaurant of a passenger ferry, or of the ejector of a conveyor discharging from a coal ship or the minimum bottom clearance of a large cargo ship.

While the three angular motions are the same at any point of the ship the linear displacements depend on these angular motions. However the linear displacements can be easily calculated for any point of the ship with co-ordinates in respect to the centre of gravity. The minimal bottom clearance for example at the port shoulder at $\frac{LWL}{2}$ of the ship is composed of the clearance with no motions less the heave as well as the lever arms of pitch and roll. The angular motions are in phase with the linear movements for intermediate encounter frequencies. For head waves, pitch and heave are synchronised for many ships. This causes large absolute motions, which are significantly greater than the wave amplitude.

![Diagram](image.png)

**Figure 6.6-1 Super-critical depth Froude number**
### 6.6 Summary
(Wave zones shown in figure 6.6-1)

<table>
<thead>
<tr>
<th>Type of marine vehicle</th>
<th>Effected by group of pattern</th>
<th>Risks</th>
</tr>
</thead>
</table>
| Leisure craft / small boat / tug         | Surging long waves in harbour entrances  
                                       | Short tail waves near craft                                                                | Grounding  
                                       |                                                                 | Capsizing/broaching (only very small craft) |
| Pilot boat / small fast craft            | Short tail waves and medium waves (zones 2 & 3) if boat effected boat is travelling at high speed | Emergence / slamming / propeller emergence / propeller racing       |
| Coastal and river cargo ship & bulk carrier | Head waves (zone 1)       
                                       | Beam waves (zones 1 & 2) Group  
                                       | Oblique waves (zone 1)                                                                  | Distinct pitch and heave causing deck wetness or freeboard exceedance  
                                       |                                                                 | Distinct roll                                                                  |
| Ocean going container vessel / tanker    | Beam waves (zone 1)                                                                   | Roll and heave cause grounding  
                                       |                                                                                       |                                                                 |
| High speed craft / Fast ferry            | Head waves at high speed / in particular critical wave                                    | Critical encounter frequency emergence/ slamming/ air ingestion in water jet unit  
                                       | Oblique waves (zone 1)                                                                  | Distinct roll in particular for wide beam ships passenger experience unexpected motion  
                                       |                                                                                       |                                                                 |
| Working barge / jag up rig / platform / pontoon | Short period tail waves       
                                       | Surging long waves in very shallow water                                                  | Unexpected freeboard exceedance at calm day  
                                       | Any long period wave 1. & 2. group                                                       | grounding in shallow water  
                                       |                                                                                       | Shifting of equipment or building material due to unexpected movement of working platform  


Appendix 6.1: Ship Motions

Motions in regular waves
For a given hull shape at a particular speed and heading in waves of a particular length the forces and moments $F_i$ can be assumed to be functions of the displacement, velocity and acceleration of the surface depression and the six possible motions. Six generalised equations can be found.

$$\sum_{j=1}^{6} (A_{ij}\ddot{x}_j + b_{ij}\dot{x}_j + c_{ij}x_j) = F_{wi} \quad (i = 1..6)$$

where $\ddot{x}_j$, $\dot{x}_j$ and $x_j$ are the three rotational and three translatory displacements, velocities and accelerations (see fig XX for definition)

$$A_{ij} = a_{ij} \quad \text{for } i = 1..6; j = 1..6 \text{ and } j \neq i$$

and the virtual masses and moments of inertia

$$A_{ij} = m + a_{ij} \quad \text{for } i = 1..3; j = 1..3 \text{ and } j = i$$
$$A_{ij} = I_{ij} + a_{ij} \quad \text{for } i = 4..6; j = 4..6 \text{ and } j = I$$

and the exciting forces and moments due to the waves are

$$F_{wi} = a_{i}\eta + b_{i}\dot{\eta} + c_{i}\ddot{\eta} \quad (i = 1..6)$$

Assuming transverse symmetry and small motion these equations can be simplified and contain 36 coefficients. These coefficients are again functions of hull shape, ship speed, heading and wavelength. As a result the actual motions are different for every type of ship, ship length, heading etc.
Chapter 7

7.0 CONCLUSIONS
7.0 CONCLUSIONS

Based on a combination of physical model tests in a shallow wide towing tank and an extensive range of field measurements, the following has been concluded;

1) **Solitary waves:** Both conventional ships and fast ferries can produce solitary type waves, which are of very long period and can travel several ship lengths ahead in very shallow open water. Large displacement ships operating in shallow water are particularly prone to generating this type of wave. However, with respect to fast ferries the following should be noted:

   (a) These waves are only generated at sub-critical and near-critical depth Froude numbers when the water is very shallow with a small under keel clearance of 1m to 2m. Consequently they occur when there is a high 'blockage'.

   (b) The height is small compared to the main body of the wash and trials with HSS in Loch Ryan at a depth Froude number of 0.8 and an under keel clearance of 1.5m has produced a solitary wave height of less than 50mm.

   (c) Solitary waves were not observed at higher tidal levels when the under keel clearance exceeded 2m and the depth Froude number was less than 0.8.

   (d) The height of the solitary wave increases as the critical depth Froude number is approached and subsequently disappears beyond a value of 1.1.

   (e) Vessels operating in the 'hump' speed range at a Froude length number of between 0.4 and 0.6 when operating at depth Froude numbers of between 0.8 and 1.1 are most capable of producing solitary waves.

   (f) Bluff bodies which displace more water at the bow produce larger solitary wave heights and there is a greater tendency to 'bulldoze' the water out of the way.

2) **Super-critical and Critical Wash Waves:** As solitary waves are only generated in very specific circumstances and are very small in height, it is the leading waves produced at super-critical and trans-critical depth Froude numbers in conjunction with the transverse high speed sub-critical waves which are the most significant to users of the coastal environment.

   (a) **Mathematical model:** A mathematical model has been compared to and validated by experimental data. It was found that the model provided a good prediction of the wave patterns, the angle of each wave in the leading group of waves, and the divergence of the wave crests. As a result it was possible to predict the period of the leading waves in the far field and also to calculate the divergence angle between these waves. This angle was shown to be a function of depth Froude number (Fn) and the x/h (transverse distance/water depth) ratio. A graph was constructed to enable the divergence angle to be calculated at various distances from the ship’s track, for a range of depth Froude numbers. It was observed that as the depth Froude number increases beyond 1.9, the divergence angle is practically constant for a given x/h ratio. The divergence angle is significant as it increases the period of the leading waves with increasing distance from the track of the ship.

   (b) **Decay:** In sub-critical wash the decay of the height of the divergent waves is a function of distance $x^{-0.33}$ and for the transverse waves $x^{-0.5}$. In super-critical wash the rates of decay can be substantially less with the lowest decay rate measured being $x^{-0.2}$. However it was found that the decay rate varied significantly with water depth/ship length ratio and to a lesser extent with hull configuration. The low height
decay rate in the leading super-critical wash is attributable to the waves being largely non-dispersive in that energy is conserved in individual waves. However, the crests diverge with distance from the ship spreading the energy over a larger area hence reducing the wave height. Also there is some dispersion of energy into the subsequent waves.

The rate of decay of the maximum wave height at the critical speed was substantially different to the supercritical decay rates. It was observed that the wave heights were significantly greater around the ship’s hull, but were found to decay much faster with distance from the ship’s track. However, both the wave height and the decay rate were dependent on the length of time that the vessel spent at the critical speed.

(c) **Length Froude number:** The length Froude number is an important parameter in intermediate as well as deep water as it influences the point at which a vessel produces its maximum wash when travelling in the critical speed range. A worst case scenario in terms of wash generation occurs when a ship operates at the ‘hump speed’ (typically between \( F_{nl} = 0.4 \) and 0.6) and the critical depth Froude number simultaneously.

(d) **Hull configuration:** Catamarans tend to produce wash with distinct wave frequency groups due to phase cancellation of some waves from each hull. This varies with hull length and spacing. In comparison monohulls generally produce a continuous spread of wave frequencies from the long initial waves to the short tail waves. It was observed that catamarans operating in the supercritical regime produce less energetic waves than monohulls of similar length and displacement.

(e) **Wash persistence:** As the crests of the initial waves in the super-critical wash are continuous the height of the waves already produced will reduce when the ship slows to sub-critical speed. This is due to the lateral spread of energy along the wave as the crest length increases without further input of energy from the ship.

3) **Conventional ships:** Wash problems are not solely associated with fast craft. All craft capable of exceeding a depth Froude number of 0.85 enter the trans-critical range. Several new ferries are capable of operating at speeds up to 30 knots. In general they are much larger and heavier than the largest fast ferries and are capable of creating wash problems.

4) **High Speed Vessels Passing Other Ships:** The effect of the wash of high-speed craft on other moving vessels is dependent on size, displacement and hull form. Consequently the risk to each vessel must be assessed individually. However, there are a number of general observations which have been made:

(a) All vessels are effected by some part of the super- or trans-critical wash due to the spread of wave periods.

(b) Small craft are particularly at risk from the steep sometimes near breaking waves produced by fast craft in the trans-critical zone. They are particularly at risk of broaching and capsizing when being overtaken.

(c) Long period wash waves cause large vessels to yaw and alter course, which can be problematical in a confined channel posing the risk of grounding, or when passing other ships in close proximity posing the risk of collision.

(d) Vessels operating at high speed are more affected by high speed wash than at low speed.
(e) Maximum pitch motions are expected for most craft, when the super-critical wash encounter the ship as head or following waves.

(f) Maximum heave motions are expected for bigger craft, when the super-critical wash encounter the ship as beam waves.

(g) Wash induced roll of deep draft wide beam ships such as container vessels operating in confined channels run the risk of grounding at the turn of the bilge.

(h) Compared to normal sea-keeping calculations it is important to consider, that the orbital motions are elliptic in shallow water, therefore the horizontal motions are much bigger, than the vertical.

5) **Moored Ships and Super-critical Wash:** Moored ships will surge on the long period super-critical or near-critical waves. As with any damped mass spring system, the response of the ship will depend on size, displacement and the elastic constraint of the mooring system. Large ships will respond to the long period waves while small vessels will respond to the shorter wave components. Consequently each ship and mooring configuration has to be analysed individually to assess the problems caused by fast ferry wash. A range of general observations can be made:

(a) It is important that the mooring lines facing in one direction are of similar length, similar elasticity and similar tension to avoid individual ropes taking excessive strain and breaking.

(b) The fact that mooring lines are attached to one side of a vessel results in induced roll when the vessel surges. However the motions are usually very complex.

(c) Field observations have shown that incidence of mooring rope breakage can be reduced if the crew of the moored vessels is aware of the imminent arrival of high speed craft.

(d) If loading or discharge processes are taking place, which are sensitive to ship movements, it is recommended to interrupt these processes. It is good practice for the master of the HSC to notify the personnel in charge of the loading process via VHF prior to the approach.
6) **Environmental Impact:** Initial studies were completed and longer term monitoring programmes instigated to determine the environmental impact of wash from fast craft and to make a comparison with other ships.

The following initial general conclusions have been reached:

(a) The vulnerability of a coastal zone to wave attack is dependant on the typical particle size and the grading of the material. If fine sediments are interspersed with gravel and small stones, then armouring takes place and the mass transport rate is significantly reduced.

(b) On beaches with fine to medium size sediment the long period wave wash of high speed operation will always cause an initial increase in sediment transport. The long term development, however, depends very much on the magnitude of attack and the composition of the sediment.

(c) The leading long period waves in fast ferry wash tend to move larger material than the shorter wind seas particularly further from the shore. In comparison the short steep waves produced by conventional ferries tend to move material closer to the shoreline.

(d) Temporary speed restrictions placed to protect for example small islands and banks with bird colonies during the nesting season appeared to be applicable and efficient.

(e) The initial studies have not indicated that water jets cause more scour of the sea bed in a channel compared to conventional ships with propellers. It is thought that the pressure field around a large ship with low under keel clearance is more likely to scour the channel. However, in the manoeuvring area at the berth where the ship is moving astern with the reversing buckets diverting the flow from the jets down under the hull, bed scour can be more severe compared to an equivalent sized ship with propellers.
Chapter 8

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