Guidelines for the hydraulic and navigational design of approach channels

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Report SR 475
July 1996

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Contract

The work described in this report was funded by the Construction Directorate of the Department of the Environment (DoE) under research contract CI 39/5/88, "Guidelines for the hydraulic and navigational design of approach channels". The DoE nominated officer for this contract was Mr P B Woodhead and HR Wallingford's nominated officer was Dr W R White. The report is published on behalf of the DoE but any opinions expressed are not necessarily those of the funding department. The research described in this report was carried out in the Ports and Estuaries Group, managed by Dr J V Smallman. The HR job number was DAS 0049.

Prepared by .... (name) Project Engineer (Job title)

Approved by J. V. Smallman Director

Date 20th August 1996.

Summary

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This report provides guidelines for the hydraulic and navigational design of approach channels. This report also provides a practical outline of existing guidelines and advice for approach channel design. The research work described in this report concentrated on two main aspects of channel design: depth and width. In each case numerical modelling was used to test typical channel layouts with design vessels and under the influence of representative environmental conditions.

The results of this study provide sets of design curves for generic vessel groups to enable channel depth and layout to be identified from a range of wave conditions and vessel speeds. The report concludes with a series of guidelines for the design of approach channels, based on existing guidelines and the research work.

Notation

B	design vessel beam (m)
F_{nh}	froude depth number (= $v/(gh)^{0.5}$)
g	acceleration due to gravity, 9.814ms^{-2}
h	water depth (m)
H_s	significant wave height (m)
L	design vessel length (m)
r	radius of curvature through channel bend
T	design vessel draught (m)
ukc	under keel clearance (m)
v	vessel speed (ms^{-1})
W	channel width (m)
W_{bg}	width of bank clearance lane on "green" side
W_{bm}	basic manoeuvring lane width
W_{br}	width of bank clearance lane on "red" side
W_p	width of ship clearance lane
α	angle of deflection through curve
ΔW	extra channel width through curve

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1 Introduction

1.1 Background

Many ports and harbours are served by access channels which vessels must use on their final approach from the open sea. The continuous drive to reduce costs has resulted in ship owners using economies of scale, bringing on line fleets of increasingly large vessels. The manoeuvrability of these ships is restricted and they are subject to large lateral forces by wind and currents. In addition, port operators are under increasing pressure to reduce "downtime" when vessels are unable to use the port facilities, and to increase the throughput of the port either by accommodating more vessels, or larger capacity ships. This has revealed itself through an increased demand for vessels to sail in all tidal and weather conditions and in more intensive use of approach channels.

There is also a growing awareness of potential environmental risks associated with ships carrying hazardous cargoes. This calls for reassessment of the safety of operations within channels. In general, there has also been a decrease in the number of crew and their levels of skill and experience. PIANC (1985a, 1987). Port authorities have been confronted with the task of providing approach channels which may be safely navigated by such vessels whilst remaining economic to construct and maintain.

The layout and dimensions of a navigation channel will be dependent upon the expected size and characteristics of the ships and the density of traffic expected at the port. At most ports the design of an approach channel will be dominated by geographical features and commercial and economic considerations. However, the environmental conditions at the site, consisting of waves, tidal currents, wind and visibility, and operational characteristics, such as the use of pilots, tugs, navigation aids, will also make an important contribution to the final design, see PIANC (1979, 1980a, 1980b, 1983, 1985a, 1985b, 1987, 1995), Kray (1973), DTp (1982), Thoresen (1988). The factors which need to be considered in the design of approach channels are described in Chapter 2.

It can be seen from the foregoing that the design of harbour approach channels is highly site specific and is influenced by a large number of factors. It is therefore inherently difficult to produce a comprehensive set of design guidelines. However, several organisations and individuals have investigated this subject and have published recommendations. These are reviewed in detail in Chapter 3.

1.2 Terms of reference

The aim of the research study described in this report was to provide guidelines for the hydraulic and navigational design of approach channels. This research project had the following specific objectives:

- Review and summarise existing advice on the design of approach channels.

- Identify a range of limiting vessels using navigation channels.

- Use bed contact risk assessment ship movement model to investigate required channel depth under a range of wave conditions.

- Set up navigation simulation to explore required channel alignment and with.

- Produce guidelines on approach channel hydraulic and navigational design.

The first step in this research was to review the physical processes which affect ship behaviour in channels and the factors which need to be considered in the design of approach channels. These aspects are discussed in the next section and in Chapter 2.

1.3 Physical processes which affect ship behaviour in channels

There are several physical phenomena which affect the handling of ships in channels and these may be grouped as hydrodynamic and environmental effects. Hydrodynamic effects are caused by the interaction of the pressure field, which surrounds a vessel underway, and the channel structure or another vessel. Environmental effects are associated with wave conditions, tidal currents, the impact of tidal depths, and wind conditions on ship motion, see PIANC (1979, 1983, 1985a, 1987, 1995), Kray (1973), DTp (1980, 1982), NPC (1975)

The principal physical processes which affect ship behaviour are briefly described in this section, and are represented in Figure 1. These physical phenomena interact with each other in a highly complex manner which can result in unpredictable ship behaviour.

(i) Directional instability

Most vessels underway exhibit a degree of directional instability, and as a result, they tend to weave about a chosen track. The amplitude of the deviation depends upon the handling characteristics of the ship and the skill of the ship handler. In the approaches to a port, a high level of directional stability can be both advantageous, for example along a straight channel, and problematic, for example, where the vessel must navigate around sharp bends. PIANC (1995)

(ii) Speed/depth factor

There is a relationship between a ship's maximum obtainable speed and the water depth. In shallow water, resistance from the channel bottom and water resistance may restrict the vessel's transit speed. A useful measure of resistance to motion is the Froude Depth Number, $F_{nh} = v/(gh)^{0.5}$, where v is the vessel speed and h is the water depth. The value of F_{nh} increases the level of resistance increases. In practice few ships are able to attain values of F_{nh} greater than 0.6 to 0.7, see PIANC (1995)

(iii) Squat

Whilst underway a vessel tends to settle bodily into the water. This is caused by a drop in pressure as the water displaced by the ship flows down the sides and under the keel. The ship may also experience a change in trim depending on the shape of the hull. This sinkage is referred to as squat. As the speed of the vessel increases, the amount of squat increases.

In recent years many researchers have investigated this phenomenon and have produced a large number of empirical and semi-empirical formulations to predict ship squat. A comprehensive review of squat prediction formulations can be found in PIANC (1985b).

(iv) Blockage

In dredged channels the interaction of the pressure field around a moving vessel with the channel causes additional squat. Also the resistance to the ship's motion is increased due to the presence of the channel banks.

(v) Channel bank interaction

When a ship sails close to and parallel to a channel bank some additional squat is observed, as well as a tendency to yaw unpredictably. These effects increase as the vessel speed increases and the depth of water and the distance between the bank and the ship decreases. A shallow bank angle will produces less effect than a steep bank.

(vi) Ship to ship interaction

As two ships pass close to one another, either during overtaking or whilst sailing in opposite directions, the pressure field of each ship reacts on the other. This results in a set of fluctuating forces which affect the behaviour of both vessels. Some additional sinkage can also occur.

(vii) Wave effects

The vertical motion of the vessel can be significantly affected by wave action. The degree of movement depends upon the characteristics of the vessel, the vessel speed relative to the wave (wave encounter frequency), the water depth and the wave characteristics.

The response of a moving ship to wave agitation is dominated by the wave encounter frequency and the wave length. The response of large ships is negligible for waves with very short wave lengths or with high wave encounter frequencies at small wave heights. In general, as the wave length increases and the wave encounter frequency becomes low, the vertical movement of the ship increases. At very long wave lengths, or where the ship is travelling at a similar speed to the waves, the vertical movements tend to approach the wave height. In addition, if a vessel encounters waves with a period close to one of the natural periods of the ship motions, the response of the ship will be large. This response is also very sensitive to the angle of wave approach to the ship and the wave encounter frequency.

In situations where a ship has a very small underkeel clearance, the vertical response tends to be small. This occurs as the gap between the keel and the channel bed becomes small and viscous effects become increasingly important. At very small underkeel clearances, there is significant energy dissipation as water is squeezed out of the gap, which results in a corresponding attenuation of the vessel response.

(viii) Wind effects

Wind forces on a ship can cause sideways drift and in many circumstances, a turning moment. The impact of these effects depend upon the direction and speed of the wind relative to the ship, the windage of the hull and superstructure, and the underkeel clearance. Generally, vessels have to make course corrections to counteract the drift, resulting in a 'zigzag' or 'crabbing' motion along the intended course. However, in some circumstances the turning effect of the wind can assist a vessel to negotiate a bend. The maximum drift will occur when the wind is at right angles to the ship (beam winds), however, variations in wind strength and direction can cause the ship handler most difficulty. Drift resulting from wind forces is reduced as the underkeel clearance decreases.

(ix) Current effects

Tidal currents can have a significant impact on vessel behaviour. A strong cross current will necessitate a course correction similar to that used to counteract drift due to wind. However, currents may be variable in both strength and direction which can result in the need for continual changes to the ship's heading. A longitudinal current may affect the squat, trim and manoeuvrability of a vessel, caused by its modified speed over the ground.

(x) Changes in salinity

A vessel of the same mass will displace more fresh water than salt water, as fresh water is less dense than salt water. Therefore a vessel in fresh water will draw more than when it is in salt water. If the salinity of the water through which the vessel is passing alters, a corresponding change in its draught will occur.

1.4 Outline of the report

The remainder of this report is divided into six chapters. Chapter 2 describes the factors which need to be considered in the design of approach channels and Chapter 3 summarises existing guidelines and advice. A more detailed description of factors affecting the design of channel depth is presented in Chapter 4, along with a description of the numerical modelling which was carried out. Similarly, Chapter 5 describes the design of channel width and the navigation simulation study. Chapter 6 summaries the guidelines for the hydraulic and navigational design of approach channels, and Chapter 7 provides recommendations for further work to consolidate and extend the research described in this report.

2 Approach channel design considerations

2.1 Design methodology

In general, approach channels may be divided into three main groups as discussed by Thoresen (1988) and shown in Figure 2. These are:

- channels surrounded by deep water where no dredging is required
- partially dredged channels in shallow water
- channels where the entire channel area is dredged.

For channel design, the influence of wave action, tidal currents, tidal height, wind and reduced visibility must be considered for all types of channel, along with the expected traffic density and patterns.

At present there are many techniques available to port engineers for the design of approach channels, and generally a combination of design methods will be used in any design project, as described in PIANC (1980, 1984, 1985a, 1985b, 1987), DTp (1982), Turner (1984), Strating (1982) and Schilperoort (1985). These may be divided into four groups as follows:

(i) Experience

- Recording of vessel manoeuvres on routine sailings.
- Analysis of existing successful approach channels and common practice at other ports with similar traffic.

This type of method has a high probability of safety but can lead to excessively costly and unnecessarily conservative designs.

(ii) Computation

- Predict the individual ship behaviour factors and set the dimension allowances with no account for interrelation.
- Predict the resultant ship motion relative to an intended path including the effects of environmental and hydrodynamic interaction.
- Use computer simulation of the ship manoeuvres using automatic pilots.

The main disadvantage of this type of approach is that the results of the calculations and model simulations are only as good as the understanding of the physics on which the predictions were made. At present many of the phenomena observed and their interactions are not well understood. However, these techniques provide and important first stage analysis, in the design process, which can lead to the use of experimental techniques to refine and provide design data.

(iii) Experimentation, including real-time navigation simulation

- Undertake a program of ship manoeuvring trials to record the ship behaviour.
- Use physical models with self-propelled or towed model ships to investigate aspects of the design.
- Use computer simulation of the ship manoeuvres using human pilots.

The design process often involves several iterations around the design parameters before a suitable solution is reached. A safety factor must be applied to each dimension, however, it is very difficult to assign with confidence a safety factor that will not be an over or under-compensation. Experimentation techniques enable many design options to be considered and provide detailed and reliable design data for determination of safety factors.

(iv) Risk assessment

- Develop a formulation to compute the probability of exceedance of a vessel for each dimension of the channel. This can be based on ship simulator or full scale ship manoeuvring results.

This type of method has been recently developed which is being used increasingly for design purposes. Unfortunately, accurate statistical descriptions of the factors determining the ship controllability are not currently available due to a scarcity of test results. However, this type of probabilistic approach will enable flexibility in the design procedure.

2.2 Limits of channel operation

The need for most new or altered channels will have been initially identified by commercial and economic considerations. However, before work on the design of the channel can begin, an careful examination of the limitations on its use must be established. One typical design concept begins with the identification of a design vessel and acceptable operational/environmental windows. In many cases these limits are optimised throughout the design process.

2.2.1 Design ship

The design ship is the vessel for which the main channel dimensions are determined, and is usually the ship which will constitute the greatest risk of incident in the channel. The vessel may be particularly large, display poor manoeuvrability or carry an hazardous cargo. Therefore, for design purposes, a real vessel from the current or future fleet using the port, or a hybrid encapsulating the worst features of a range of vessels is often used.

To assist in the selection of a design ship, PIANC (1995) have produced the following approximate guide to classification of manoeuvrability of vessels:

1. In general, long slender ships are more directionally stable than short beamy ones. The latter will be able to manoeuvre around tight bends more easily.

2. In shallow water, where the water depth to draught ratio is less than or equal to 1.5, all ships will turn less readily.

3. Low speed manoeuvrability may be quite different from that of the service speed for which the ship is designed.

4. Single-screw/single-rudder ships will manoeuvre quite well, but will experience screw bias (an offset due to lateral movement of the stern induced by the propeller necessitating counter rudder).

5. Ships with single controllable-pitch screws may experience screw bias, even when the propeller pitch is set for low or zero thrust.

6. Twin-screw/twin-rudder ships generally have good manoeuvrability and control at all speeds.

7. Twin-screw/single-rudder ships generally have good manoeuvrability at service speed, but poor manoeuvrability at low speeds.

8. Ships fitted with adequate bow- or other thrusters may have very good low-speed manoeuvrability. Ships with omni-directional thrusters will generally have excellent low speed manoeuvrability.

In addition, PIANC (1995) advises that the hazard due to the cargo being carried by the vessel must be taken into account. Clearly, larger margins of safety are required for vessels carrying highly hazardous cargo than more benign materials. PIANC (1995) suggests that cargoes are assessed in terms of their toxicity and the potential for explosion, pollution, combustion and corrosion. In general, the cargo type should be described as low hazard, for example, passengers, containers, general cargo; medium hazard, such as bulk oil; and high hazard, for example, chemicals, LPG, LNG. Subsequently, the selection of an appropriate design vessel and safety factors in the channel design must take account of the level of the expected hazard. For example, a channel to be used by LPG carriers will require a larger underkeel clearance than those for general cargo vessels, and hence one of the design vessels may need to be the LPG carrier with the deepest draught.

2.2.2 Ship operational windows

The operational windows of the channel identify the conditions during which it is safe for vessels to use the channel. They are highly site specific and must take account of the environmental conditions at the site, for example, tidal levels, wave and wind conditions, current strength and orientation, visibility. These are described in PIANC (1979, 1980a, 1980b, 1987, 1995) and DTp (1982). For example, it is usually desirable that all vessels which use the port have access in all weather conditions. However, this is often uneconomic, due to the additional capital and maintenance dredging which would be required to ensure access at all times for very large, less frequent ships. Therefore, to avoid additional dredging it may be more economic to dredge for the most frequent large vessel, and apply tidal windows when there will be sufficient depth for larger ships with less frequent arrival patterns. In addition, weather windows are also specified which indicate wind/wave conditions when it is not safe to use the channel.

2.3 Principal design parameters

The principal design parameters for an approach channel are width, depth and alignment. Each of these are described in this section.

2.3.1 Channel width

The total channel width is often sub-divided into zones as indicated PIANC (1980b, 1987), Kray (1973), DTp (1982), Thoresen (1988), USACE (1983), DPWC (1969) and presented in Figure 3. These are:

- One or more manoeuvring lanes which form the envelope within which the all vessels should remain during transit. This should be wide enough to accommodate the drift of any vessel due to directional instability, cross winds and currents.

- A zone along each edge of the channel to allow adequate bank clearance. This should be wide enough to ensure a vessel sailing at the edge of the manoeuvring lane is not significantly affected by channel bank interaction.

- In channels where vessels are permitted to pass each other, a ship clearance lane is required separating the manoeuvring lanes. This should be wide enough to prevent excessive ship to ship interaction.

2.3.2 Channel depth

The design channel depth will be governed by a large number of factors including:

- the draught of the design vessel
- the water level throughout the tidal cycle
- the design operational windows
- vessel speed, which influences squat and resistance
- the local wave climate
- the seabed material
- the local rate of sediment accretion in the channel

The design of the channel depth is discussed in more detail in Chapter 4.

2.3.3 Channel layout

The basic layout and alignment of an approach channel will be dictated mostly by the local bathymetry and topography. In general, approach channels are located in the deepest water available, in the approaches to the port or harbour, as capital and maintenance dredging is expensive. If possible the channel should be aligned such that the influence of cross-currents, winds and waves are minimised, as these will increase the required channel width, and hence the amount of dredging required. This is described in PIANC (1980b, 1987), Kray (1973), DTp (1982), Thoresen (1988), USACE (1983), DPWC (1969) and Morihira et al (1984).

It is widely accepted that the channel should be as straight as possible, as bends are more difficult for many vessels to negotiate. However, if it is necessary to introduce a bend, the angle of deflection and number of curves should be kept to a minimum. It is also generally accepted that the channel should be wider through bends because ships will have a wider swept path in the bend than along the straight section. Turner (1984), Thevenot (1992) and Duncan (1968) suggest several methods of widening the channel at bends and discuss their various merits and drawbacks. Some of the more popular methods have been illustrated in Figure 4.

The method of widening becomes increasingly important as the depth of the channel becomes large, compared to the depth in the local area. It must be noted that widening the channel at a bend can affect the alignment and nature of the tidal flows, which in turn can make it dangerous for a vessel to attempt the bend in some current conditions. It may also lead to changes in the sediment regime causing further uncertainty in channel depth determination.

2.4 Other design considerations

2.4.1 Aids to navigation

It is important that vessels using the channel are confident of their position relative to the channel. Therefore, consideration must be given to the navigation aids available to the ship handler. In recent years, a wide variety of navigation aids have been developed and installed in the approaches to ports, as discussed in IALA (1993).

2.4.2 Traffic flow

If the channel is intensely used an assessment of traffic flow may be required. This should identify whether multiple lanes of traffic are required or areas where a smooth flow of vessels could be interrupted. If necessary, a traffic control system should be developed to prevent a reduction in navigational safety.

2.4.3 Use of pilots and tugs

It may also prove cost effective to make use of trained pilots and tugs to escort vessels in the approach channel. In many cases, tugs will be required to control the stopping manoeuvre and to assist large or unwieldy vessels onto their berths, and in some ports the use of pilots and/or tugs is compulsory. Therefore it may not be difficult to increase their role and standby at channel bends and other areas where manoeuvring difficulties occur. There will, of course, be a cost implication in making tugs available in this way.

2.4.4 Environmental impact

Dredging a new channel or extending an existing one may have a significant impact on the surrounding area:

- Current flows are likely to be concentrated in the deep channel, which has two effects:

  a) Current velocities in the surrounding shallow water will be reduced altering rates of sediment transport and possibly increasing rates of accretion.

  b) Increased current velocities in the deep channel may alter rates of sediment transport and erosion within the channel.

  Both of these factors can led to uncertainties in the determination of channel depth.

- Wave refraction and reflections resulting from a dredged channel may have a large impact on the wave climate in the area. For example, wave energy reflected from the approach channel to Port Qasim, Pakistan has resulted in severe erosion along vulnerable low-lying islands north of the site.

- Deep water channels constructed in estuaries could cause saline intrusion further upstream than with the natural bed. This may have serious implications for fresh water extraction for nearby farmland and other local industries which use fresh water.

- In the approaches to many ports seabed material is highly contaminated with heavy metals and other pollutants, due to previous industrial activity. Considerable care must be taken during dredging of such material and suitable investigations and treatment systems must be employed.

- Any increase in traffic transporting hazardous cargo carries an associated increase in the risk of an incident.

2.4.5 Design uncertainties

There are several uncertainties associated with the use of approach channels which must be considered in a final design. These are described in PIANC (1979, 1980a, 1980b, 1983, 1985b, 1987), Kray (1973), DTp (1982), and may be summarised as follows:

- It is difficult to accurately predict the environmental factors which can have a significant impact on ship behaviour. Tides and currents may be predicted with some confidence, but the wind and wave conditions can only be predicted from studies using long term wind and wave information from the site. The density and rate of siltation in dredged sections of a channel are also very difficult to determine with confidence and may be subject to seasonal variations.

- The actual level of the channel bed will be difficult to maintain at a given level due to the tolerance and accuracy of the dredging procedure.

- Unpredictable or unforseen circumstances may occur even with careful consideration of the operational limits of the channel.

- There will always be a degree of variability in ship handling due to different levels of skill and experience.

2.5 Design compromises

Ultimately, it is unlikely that an initial design for an approach channel will satisfy all of the financial, commercial, environmental, navigational and safety criteria for the site. Therefore, in most situations some sort of design compromise must be found.

Frequently a cost-benefit review is used to identify the optimum design based on a variety of options as discussed in PIANC (1995). For example, if the original channel design calls for an excessive amount of dredging, the tidal window for the channel could be reduced. This would require less channel depth and therefore reduce the volume of material to be removed. However, the penalty will be a further restriction on channel access. However, in some cases significant improvements in the navigation aids for the channel can reduce the required channel width, due to the increase in accurate information which these aids provide to pilots/mariners.

3 Existing design guidelines for approach channel design

It has already been established that the design of approach channels is highly site specific, and hence, it is difficult to derive or apply a set of general guidelines. Despite this, various guidelines and recommendations have been produced in recent years aimed at improving safety within the channels and reducing the cost of construction and maintenance to a safe minimum.

This chapter examines the existing recommendations on channel depth and layout. Definitions of channel parameters are illustrated in Figure 5.

3.1 Channel depth recommendations

A set of recommendations were produced by PIANC (1980b). These suggested channel depths given in terms of gross underkeel clearance, which is defined as the distance between the keel of a stationary vessel and the channel bed. The main recommendation was that the gross underkeel clearance (ukc) should always be greater than 0.5m. In addition, the following characteristics were recommended:

- In open sea areas where ships will be moving at speed and may be exposed to large swell, it was recommended that the ukc should be approximately 20% of the draught.

- Areas where stationary ships are exposed to large swell, or where ships are sailing in partially protected waters the ukc should be approximately 15% of the draught.

- Channel sections sheltered from swell should allow for ukc between 10% and 15% of the vessel draught.

PIANC (1985b) outlined a comprehensive guide to design procedures suitable for channels with hard seabeds and methods for evaluation of ship behaviour factors. In a separate report PIANC (1985a) discussed the problems associated with navigation in muddy areas where depth determination may be difficult.

In their most recent report on the subject PIANC (1995) have produced a set of preliminary design recommendations representative of modern practice. This document suggests a minimum ukc of 0.6m and a value of Froude depth ratio, $F_{nh} = v/(gh)^{0.5}$, of less than 0.7. It also gives the following rough guide on acceptable channel depths, but recommends that in areas where significant wave action is expected a more detailed examination of wave induced ship motions should be made. This guidance is provided in term of the vessel draught to water depth ratio, T/h, and significant wave height, H_s:

- $T/h \geq 1.1$ in sheltered waters
- $T/h \geq 1.3$ in waves $H_s \leq 1.0$m
- $T/h \geq 1.5$ in waves $H_s \geq 1.0$m and with unfavourable periods and directions

In DTp (1982) the UK Department of Transport produced a guide on the design of navigation channels based on the results of a UK research programme, which was initiated by the National Ports Council and the Department of the Environment. The guidelines take the form of a series of prediction tables for various aspects of ship behaviour and a table of interactions. These tables may be used to carry out an iterative design procedure. Tables predicting speed/depth factors, squat and additional squat due to blockage, ship to ship interaction and ship to bank interaction are presented. However, wave and swell effects have not been accounted for and therefore no recommendation is made on the additional channel depth required in areas exposed to waves.

The US Army Corps of Engineers produced a manual for approach channel design USACE (1983). This recommends that to avoid damage to the propeller from timber and other debris and to prevent excessive disturbance of silty bed material a minimum clearance of 0.6m or 0.9m should be allowed for soft and hard beds respectively. In addition, it suggests that a 1.5m clearance should be maintained between any water intake in the vessel hull and a silty channel bottom to prevent fouling of equipment such as pumps or condensers. An 'efficiency' clearance is also recommended to ensure the vessel can maintain design speed without a significant increase in fuel consumption. Finally, it recommends that 0.3m to 0.9m extra clearance is allowed to account for the tolerance in dredged bed level. However, this manual does not include any guidance on channel depths in areas which are exposed to waves.

A series of graphs presenting the tolerance that should be applied to channels where there are likely to be significant levels of wave activity can be found in DPWC (1969), the Port Design manual produced by the Canadian government. This document was produced in 1969, and therefore may have been superseded by later publications.

A summary of the recommendations on channel depths found in the current guidelines can be found in Table 1.

3.2 Channel width recommendations

Most of the published recommendations evaluate channel width in terms of design vessel beam, B. Many of these divide the channel width into manoeuvring and clearance lanes, which are dealt with separately.

PIANC (1980b) recommends that the following criteria should be used:

- For single lane traffic the channel width should be greater than or equal to 5B.

- There should be a safety margin of approximately 1B to 2B each side of the manoeuvring lane.

- If strong variations in currents are expected, an additional width of 1B to 2B should be provided in each manoeuvring lane.

- For two way traffic the single lane channel width should be increased by 3B to 5B, with additional allowance for vessel drift.

- The separation distance between passing ships should be greater than 2B.

As previously mentioned, PIANC (1995) contains the most recently produced comprehensive guidelines. Although it is recognised that in many cases further more detailed design will be necessary, it recommends an initial design should be based on the following:

- Width of the basic manoeuvring lane should be 1.3 to 1.8B, depending upon the manoeuvrability of the vessel.

- Width of the bank clearance lane should be 0.3 to 1.3B, depending upon vessel speed and the type of the bank.

- Width of the ship clearance lane should be between 1B and 2.5B, depending on the vessel speed and traffic density.

In addition PIANC (1995) have provided a set of look-up tables which include additional width allowance on the basic manoeuvring lane width, which takes account of:

- vessel speed
- drift due to wind
- drift due to currents
- wave effects
- aids to navigation
- visibility
- seabed material
- channel depth
- cargo hazard level

Thoresen (1988) makes the following recommendations for approach channel widths:

- A manoeuvring lane of width of 1.6 to 2.0B

- An additional width of 1.0 to 2.0B on each side to allow for bank clearance with single lane traffic.

- A yaw allowance of 5 to 10° should be included.

This results in a single lane channel width of 3.6B to 6B. For two way traffic, a passing ship clearance width greater than 30m or 1B should be provided. This generates a two ship channel width of 6.2B to 9B.

The USACE (1983) manual suggests that:

- The minimum width of the manoeuvring lane should be 1.6B in favourable conditions (no cross currents or winds and in wave conditions which do not induce significant ship yaw). However, this should be increased to 2.0B if the vessel has poor manoeuvrability, or the conditions are unfavourable.

- The width of any ship clearance lane should be at least 0.8B.

- An allowance of 0.6B should be made for bank clearance, however, if the bed material is hard, or the vessel has poor controllability it is recommended that this allowance is increased to up to 1.5B.

Similarly the Canadian guidelines, DPWC (1969), advise that a single lane traffic manoeuvring lane width should be no less than 1.4B, increasing to 1.6 to 2.0B for two-way or multi-lane traffic. The ship clearance should be at least 1B. This document also identifies that the bank clearance margin should be between 0.7B and 1.4B, depending upon the conditions and whether the vessel has a pilot or not.

The DTp (1982) guidelines are based on the concept of evaluating a required channel width by taking into account the ship's available rudder angle. Each lateral force and moment experienced by a vessel transitting the channel is accounted for by allocating a rudder angle that would be needed to ensure the vessel remains on course. Prediction tables for some suggested rudder angles for ship to bank interaction and wind effects, and a table giving safe ship separations are presented. In this way, the operational limitations of the ship can be established and the necessary width of the channel calculated. It also recommends that a single lane manoeuvring channel should be greater than 1.6B.

Unlike the guidelines already mentioned in this section a Japanese reference, Morihira et al (1983), defines channel widths in terms of vessel length, L. This reference suggests that in a relatively quiet channel, with one-way traffic only, the channel width should be greater than 0.5L. As the density of traffic increases, so should the number of lanes in the channel, and as the overall channel length increases, the channel width should be increased up to 2.0L.

The recommendations on channel widths discussed above are summarised in Table 2.

3.3 Channel layout recommendations

PIANC (1980b) recommends that the vessel drift angle due to wind and currents should not be greater than 10° to 15°. Channel bends should be designed to permit radial steering, implying that one long, well marked bend is preferable to several shorter bends in close succession. The following recommendations are also included, in terms of radius of channel bend curvature, r, and ship length, L:

- A bend curvature of $r > 10L$ is preferred, but r must be $\geq 5L$.

- Straight sections of greater than 10L should link consecutive bends.

- The channel width through the bend should be larger than in the straight sections, to correspond with the extra width required by the ship. The extra channel width trough the bend should be $L^2/8r$. Additional allowance should also be made for any expected increase in manoeuvring difficulty.

- Changes in channel width should not exceed 10m in 100m.

The recommendations in PIANC (1995) generally concur with those in PIANC (1980b). However, it is mentioned that most ship handlers prefer bends that require rudder angles of between 10° and 20°, as most ships respond well to this command, whilst retaining an adequate reserve. Some preliminary design curves for vessel turning radii and width of swept track have also been included although they are strictly valid for a single-screw/single-rudder container ship only. The recommended minimum distance between consecutive curves is reduced to 5L.

The DTp (1982) guidelines contain tables for prediction of additional channel widths in channel curves. However, the tables are given for a radius of curvature of 10L. No recommendations on the spacing of consecutive channel bends are included.

The guidelines contained in Thoresen (1988) suggest that if the required change in the vessel's heading at a bend is greater than 10°, each manoeuvring lane width should be increased by widening the inside of the bend from approximately 2B to 4B.

Both Thoresen (1988) and the DPWC (1969) guidelines make the following suggestions for channel layout, in terms of the radius of curvature of the bend, r, the ship length, L, and the change in vessel heading, or angle of deflection of the bend, α, as follows:

- $r \geq 3L$ for $\alpha < 25°$
- $r > 5L$ for $25° < \alpha < 35°$
- $r > 10L$ for $\alpha > 35°$
- Consecutive bends should be separated by a straight section of at least 2L. Thoresen (1988) adds that the minimum distance between channel bends should be 200m.

Thoresen (1988) also mentions that some proposals recommend the radius of curvature of the bend should be independent of the angle of deflection at approximately 8L to 10L. There is no information on additional channel width increases for radii of curvature smaller than the recommended values.

The DPWC (1969) manual continues by recommending that if the minimum radius of curvature for a particular bend cannot be met, the channel should be widened on the inside of the bend by at least 3m for every degree of channel deflection in excess of the stated value.

Whereas, the USACE (1983) manual states that the width if a channel through a bend should depend upon the amount of turn and the vessel speed, length, beam and manoeuvrability. It recommends that there should be an intermediate straight of at least 5 times the vessel length between consecutive bends, and where gradual bends are not possible, bend cut-offs should be considered. However, it gives no clear guidance on how to determine the extra width required.

Finally, the Japanese guidelines contained in Morihira et al (1984) indicate that the angle of channel bend deflection should not exceed 30°. If necessary, the channel should be widened to allow the vessel to turn with a radius not less than 4L.

Table 3 contains a summary of the current channel layout guidelines.

3.4 Summary of existing guidelines

Several sets of guidelines on the design of approach channel are currently available. In general, the recommendations are vague and unclear. It is clear from Tables 1 to 3 that there are large inconsistencies between the recommendations found in different guidelines. This is very confusing and as a result the guidelines in their present form are of limited practical use to port designers.

In general, the dimensions suggested by the guidelines are large compared to those found in most existing approach channels, especially in the UK. However, it should be remembered that the recommendations should guarantee that the channel is safe. Unfortunately, very few UK ports are in the position to implement the recommendations entirely due to local topography and financial constraints.

4 Approach channel depths

4.1 Introduction

Vessels may only use an approach channel safely if there is an adequate depth of water. Unfortunately, it is very difficult to predict with confidence a water depth that will be considered adequate in all weather conditions, since it will depend upon a large number of factors. These include:

- the dimensions of the vessel
- the vessel type
- the vessel speed
- wave conditions in the channel
- the seabed material

Ideally, an approach channel should be deep enough to allow the largest expected vessel to navigate the channel at all states of the tide and in all wave conditions. There are very few ports which are served by natural channels of this type and therefore, many ports are forced to either work within the constraints of a natural channel, or create an artificial channel by dredging bed material.

However, dredging is very expensive and in many cases it is uneconomic to create and maintain a channel deep enough to enable every vessel to access the port at all states of the tide, in any environmental conditions. In these cases restrictions are imposed, such as the designation of tidal or weather windows, or the setting of a wave condition threshold.

In the past, channel depths have been based on experience, and to some extent, trial and error. However, a more scientific approach is now in demand. The aim of the study described in this Chapter, was to investigate some of the factors which contribute to vertical motions of ships in restricted water depths, in the presence of waves, and to indicate guidelines for optimum channel depth design. The HR Wallingford numerical model UNDERKEEL was used to assess risk of ship-seabed contact due to wave action for a number of different ships, channel depths and wave conditions.

The physical phenomena which affect the vertical motion of ships in an approach channel were discussed in Section 1.2. This identified that main effects responsible for vertical motions are wave action and squat. These effects were taken into account in the modelling described in this Chapter.

4.2 The UNDERKEEL model

The UNDERKEEL program suite was written as a tool to aid navigation channel design and operation. Given a description of the sea state at a site as a directional wave spectrum and details of a ship, the model calculates the vertical motions of the lowest point of the ship at the bow and stern due to heave and pitch. The risk of the ship hitting the seabed in those waves is then calculated using a standard probability distribution.

The model is based on linear wave and potential theory to simulate water flow and wave diffraction around the ship. Hydrodynamic forces acting on the hull are determined by pressures in the water. Calculating the forces due to waves, with the vessel's inertia and hydro-static (buoyancy) forces, determines the ship's movement in response. A simple approximate adjustment to the forces enables allowance for the effect of forward motion and estimate vertical movement of a ship underway.

In the initial stage of the modelling process, only the responses to unit amplitude regular waves from specified directions relative to the ship are calculated. However, as linear theory is used, the principle of superposition can be invoked and the ship's response spectrum in any given sea condition can be calculated by multiplying together the directional wave spectrum and responses to the unit amplitude waves. Root mean square (rms, standard deviation) values and mean zero up-crossing periods (the average time that elapses between successive occasions when the ship moves up on the waves through its equilibrium position) are computed from the response spectrum. These values alone are sufficient to calculate bed contact risk in waves for any given underkeel clearance.

UNDERKEEL assesses the risk of ship-seabed contact due to wave action. Within the model there is an empirical formulation for predicting ship squat, which is based on the work of Barras (1981). In addition, the version of UNDERKEEL which was used did not include allowance for long period second-order wave effects, such as set-down. However, this effect was included separately. In addition, the version of UNDERKEEL used in this study did not model the roll motion, however, this is only a significant factor in the risk of seabed contact when beamy flat-bottomed ships are subject to beam seas. The subsequent version of UNDERKEEL does include roll motions and it is strongly recommended that any further work carried out takes account of the additional risk of seabed contact resulting from roll motions.

Further details on the UNDERKEEL program suite are given in HR Wallingford (1992).

4.3 Application of UNDERKEEL to this study

An UNDERKEEL model of an idealised channel was set up. The model consisted of a single, 5km long section of channel, with a nominal orientation of 90°N. Uniform wave conditions were set up to approach the channel from nominal directions of 180°N, 210°N, 240°N and 270°N. By representing the ships sailing in both directions along the channel, the waves can be modelled approaching the vessel from all directions relative to the ships motion.

The final output from the UNDERKEEL suite is in the form of a series of graphs showing the risk of bed contact for a specified stationary underkeel clearance, speed, wind wave and swell wave condition. The approach taken to analyse this information was to identify the wave conditions associated with an acceptable risk of bed contact. A risk of 1:33,333 was taken as acceptable, as discussed in Dand and Lyon (1993). This value was derived from a survey of the current rate of bed contact incidents per vessel movement in European ports. It was assumed, for the purpose of this work, that this risk was an acceptable risk. These graphs provide design information which allow the limits of acceptable wave height to be determined for each ship type/hull form travelling at a specific speed, with a fixed underkeel clearance, for a range of wave directions. The risk of seabed contact will be greater than 1:33,333 for wave heights greater than the predicted acceptable wave height, which, in the context of this report, constitutes an unacceptable risk.

4.4 Selection of wave conditions

In this study a wave steepness of 0.06 was been used to generate wave spectra for a range of significant wave heights between 0.7m and 6.1m. This was adequate to model the vertical motions of ships in underkeel clearances of up to approximately 40% of the vessel draught.

Typically, waves approaching the coast will have components of wave energy with a range of frequencies and directions. For this study formulations for spreading of wave energy in both the direction and frequency domain were used. JONSWAP spectral theory, described in Hasselmann (1973), was used to synthesise frequency spreading in energy spectra associated with waves.

The directional spreading of wave energy was modelled using Seymour's Method, where a standard spreading function is applied. Wind waves in open water were represented with a cosine-squared direction spreading function. Wind waves in confined waters tend to have a narrower range of direction components in their energy spectra. This was modelled with a cosine-sixth spreading function. True swell waves have a very narrow directional spread and may be represented by a cosine-sixth. distribution.

For these tests a uniform set of wave conditions were taken to be approaching the channel from seven directional sectors, representing a range of angles of wave attack relative to the ship's heading, as indicated in Figure 6.

4.5 Selection of test vessels

The vertical motion due to waves experienced by a vessel in restricted depths depends upon the vessel dimensions and behaviour characteristics. These include:

- the vessel length, beam and draught
- the vessel displacement
- the hull shape
- the radii of gyration for roll, pitch and yaw motions
- the position of the ship's centre of mass
- the vessel loading and trim

In order to get a representative selection of the vessels likely to use UK and worldwide ports a survey of vessels on a ship database was made. The ships were grouped into the following main vessel types according to the type of cargo they carry:

- tankers
- bulk carriers
- container vessels
- passenger vessels
- roll-on/roll-off vessels
- general cargo carriers
- 'reefers' - refrigerated unit carriers

The principle differences between the vessel types are the hull shapes, the proportions of the major vessel dimensions (length, beam and draught) and the range of vessel sizes.

In this study two basic hull forms were tested, referred to as Type A and Type B. Details of the ship types are:

Hull form	Template	Vessel types represented
A	container vessel	container vessels general cargo vessels reefers (passenger and ro-ro)
B	tanker	tankers bulk carriers

For the purposes of this study the performance of hull form type A was taken to be sufficient for the purposes of modelling ro-ro and passenger ferry ship types. As a result, ro-ro and passenger ship type hulls were not modelled directly.

The study concentrated on relatively large ships, as these are the vessels which will determine the limits of operation for an approach channel. Five vessels were selected for use in the UNDERKEEL model tests. Details of the ships used are:

Ship 1	Hull type	A
	LOA	207.0m
	Beam	32.0m
	Draught	12.0m

Ship 1 is representative of a 3rd generation Panamax vessel. This ship is used as the benchmark vessel against which to compare the behaviour of other vessels in this study.

Ship 2	Hull type	A
	LOA	281.0m
	Beam	32.0m
	Draught	12.0m

Ship 2 is typical of a 4th generation Panamax vessel. This ship was used to assess the influence of vessel length on risk of bed contact.

Ship 3	Hull type	B
	LOA	207.0m
	Beam	32.0m
	Draught	12.0m

This vessel has the same primary dimensions as Ship 1, with a different hull shape. This ship was used to investigate the influence of hull shape.

Ship 4	Hull type	B
	LOA	270.5m
	Beam	44.0m
	Draught	17.0m

This ship represent a post-Panamax vessel with deep draught. This vessel is representative of the largest vessels likely to use the approach channels to UK ports.

Ship 5	Hull type	B
	LOA	164.3m
	Beam	22.8m
	Draught	9.9m

Ship 5 is the smallest vessel tested and is typical of ships using the approach channels to medium sized UK ports.

4.6 Test programme

A summary of the UNDERKEEL model runs which were carried out as part of this study is given in Tables 4 to 8.

The base scenario for the tests was Ship 1, sailing at 10 knots in a sea with $\cos^2$ directional spreading of wave energy. This scenario was tested for a range of water depths considered representative of the conditions found in UK approach channels.

In addition, the influence of vessel speed, vessel length, hull form, vessel size and directional spreading of wave energy was investigated by testing different vessel scenarios.

4.7 Discussion of results

The results of the UNDERKEEL model investigations are presented in Figures 7 to 25. The results are in the form of graphs of acceptable significant wave height (m) against the angle of wave attack relative to the ship's heading (°).

It should be noted that the ships used in this study were based on hull form templates. Therefore the results should be taken as representative of a class of similar vessels and not an individual ship. In addition, the acceptable wave conditions specified in the results are a first estimate and, in the absence of calibration data, should not be taken as absolute values. However, the trends illustrated by the results will be representative of all similar ships.

4.7.1 Base scenario

The UNDERKEEL results for the base scenario are shown in Figure 7. This represents Ship 1 travelling at 10 knots in waves with a $\cos^2$ directional wave energy spreading, for a range of stationary underkeel clearances between 10% and 36% of the vessel draught (1.2m to 4.3m).

It is clear that the acceptable wave height for this vessel is dependent upon both water depth and angle of wave attack relative to the ship's heading. Acceptable significant wave heights of between 1.3m and 3.8m have been predicted by the model, which correspond to waves that are relatively frequent around the UK coast.

In general, the acceptable wave height increases as the water depth increases. Intuitively, this is as expected. However, increasing the water depth by 1.0m does not result in an increase in acceptable significant wave height of 1.0m. This is for two reasons.

- The vertical movement due to a wave increases as the underkeel clearance increases.

- The risk of bed contact is very sensitive to extreme ship movements, which are generally caused by large waves. If the significant wave height in a sea state increases by 1.0m, by definition the maximum wave height in the sea state increases by more than 1.0m. This leads to a non-linear increase in the risk of bed contact as the significant wave height increases.

There is a significant variation in the acceptable significant wave heights predicted for a particular angle of wave attack, but different ukc. For the tested conditions, acceptable significant wave heights approaching from the stern are in the range 1.3m to 3.8m, compared with 2.5m to 2.8m for head seas. This is caused by the relatively low wave encounter frequency with stern seas, compared with the much higher wave encounter frequency with head seas. This results in greater vertical ship movements as the speed of the waves from stern seas approach the vessel speed. With relatively large stationary underkeel clearances, the acceptable stern wave height is larger than the corresponding acceptable bow wave height. In contrast, with smaller underkeel clearances, the acceptable stern wave height is less than that for bow waves.

In most cases the ship is most sensitive to waves approaching from the beam, as the wave length to beam ratio is always smaller that the wavelength to length ratio. As a result, it is more likely that waves with wave lengths shorter than those which would cause vertical motions in stern or head seas, will cause significant vertical motions with beam seas. However, in cases where the stationary underkeel clearance is very small the results show that the critical waves approach from the stern. This is due to the large differences in the transverse added mass with small underkeel clearances, as compared to the longitudinal added mass.

At extremely small stationary underkeel clearances the acceptable bow wave height is larger than that predicted for slightly larger underkeel clearances. This is caused by the increase in viscous energy dissipation in the very small gap between the keel and the channel bed.

4.7.2 Influence of vessel speed

The results for the tests with Ship 1, a $\cos^2$ directional wave energy spreading, at speeds 5 knots and 15 knots are shown in Figures 8 and 9, respectively. The predicted acceptable significant wave heights at 5 knots, 10 knots and 15 knots for stationary underkeel clearances of 20%, 26%, 31% and 36% of draught are presented in Figures 10 to 13, respectively.

Comparing Figures 8 and 9 with Figure 10 shows that the general trends discussed above are also found at other vessel speeds. In general the results for the three sets of tests are very similar. Initially it may be surprising that predictions of acceptable wave heights do not seem to be influenced much by the vessel speed. However, the vessel squat at the speeds tested will be 0.2m, 0.7m and 1.7m at 5 knots, 10 knots and 15 knots respectively. Hence, it would be expected that a ship sailing at 15 knots would be more vulnerable to bed contact than the same ship at 5 knots. However, as the ship sails faster, the underkeel clearance becomes smaller, due to increasing squat, and, as previously mentioned, the vessel responses are attenuated as the underkeel clearance is reduced. This is also illustrated in Figure 8, where the acceptable wave heights for all angles of wave attack are marginally larger for a 5% stationary underkeel clearance than for a 10% clearance.

4.7.3 *Influence of vessel length*

The largest bow and stern responses tend to be associated with pitch rather than heave motions. Intuitively, it may be expected that an increase in vessel length may lead to an increase the risk of bed contact. However, the results presented in Figure 14 are associated with Ship 2, sailing at 10 knots in waves with $\cos^2$ directional spreading. A comparison of Figure 14 with Figure 7 shows that the response of the vessels is similar despite their difference in length. In general, the acceptable wave heights predicted for Ship 2 are slightly larger than the corresponding Ship 1 results. This is due to the changes in wave encounter period and the wave length to ship length ratio.

4.7.4 *Influence of hull shape*

The model results for Ship 3 sailing at 10 knots, in waves with $\cos^2$ directional spreading are shown in Figure 15. This ship has the same primary dimensions as Ship 1, however it has a different hull shape. To assess the influence of hull shape on vessel response to waves, Figure 15 was compared with Figure 7.

In general, the results suggest that Ship 3 could navigate in larger waves than Ship 1 with the same bed contact risk. As before, the acceptable wave heights are generally larger for increasing underkeel clearances, and the variation in acceptable wave height is greater for stern seas than head seas. At small stationary underkeel clearances the acceptable wave height for several angles of approach are marginally larger than for slightly greater underkeel clearances. However, at all the underkeel clearances which were tested, the acceptable wave height for waves approaching from the bow is larger than for waves from the stern.

4.7.5 *Influence of ship size*

One of the major considerations when designing an approach channel is the size of the design ship. To investigate the way different sized vessels behave in waves, Ships 4 and 5 were modelled travelling at 10 knots in $\cos^2$ directional spread waves, for a range of percentage stationary underkeel clearances. The results of these tests are presented in Figures 16 and 17 respectively.

It is difficult to draw direct comparisons between these results because the ships will have very different behaviour characteristics. However, the general trends in the results are similar to those already discussed. However, the results do indicate that the variation in acceptable wave height with underkeel clearance, increases as the vessel size decreases.

4.7.6 *Influence of directional wave energy spreading*

The final set of tests were designed to investigate the influence of directional spreading of wave energy. Figures 18 and 19 show the predicted acceptable significant wave heights at 10 knots and with a stationary underkeel clearance of 36% of the draught (4.3m), with $\cos^2$, $\cos^6$ and $\cos^{30}$ directional wave energy spreading for Ship 1 and Ship 3 respectively.

These results indicate that the acceptable wave heights for waves approaching the ship from the bow or stern increase with reduced directional spreading of wave energy. However, for the critical wave direction, usually a beam sea, the acceptable wave height decreases slightly as directional spreading is reduced.

This result was expected as with a narrow directional spread wave forces occur simultaneously along the length of the ship.

4.7.7 Other test results

Some additional tests were carried out to confirm some of the general trends observed in the earlier results. These tests were carried out using the largest ship in the test program, Ship 4, and the results are presented in Figures 20 to 24.

The results from these additional tests confirm the trends which were discussed in Sections 4.7.1 to 4.7.6.

4.8 Application of the results

The design curves presented in Figures 7 to 24 provide a first estimate of the acceptable wave height for vessels travelling in approach channels under the influence of wave action. For example, consider a 3rd generation container vessel, of Panamax dimensions, travelling at 15 knots, through a channel with an underkeel clearance of 26% of its draught. For head seas with a $\cos^2$ directional spread, the predicted acceptable wave height can be read from Figure 9 as 2.6m. Similarly for stern seas the acceptable wave height will be 2.3m. However, it is also indicated in Figure 9 that in stern seas, an increase in the underkeel clearance to 36% of the vessel draught will increase the acceptable wave height to 3.4m. This information could lead to an increase in the design depth of the channel or the specification of a weather window for this example channel, ie. when the wave height predictions for the site are greater than the acceptable wave height for the appropriate wave direction.

5 Investigation of approach channel layout and width through bends

5.1 Introduction

The design of an approach channel is an important factor in the design or modification of any port. The channel must be designed to ensure safe vessel transit in terms of adequate depth of water and manoeuvring space. However, the design of an approach channel may have a significant effect on the construction and operational costs of a port, and hence, should be considered with care. There is the potential for significant reductions in construction and maintenance costs through the optimisation of approach channel design, in terms of vessel access versus dredging requirements.

The basic layout and alignment of an approach channel will be primarily dictated by the local bathymetry and topography. In general, approach channels are designed to be either as short as possible or to take advantage of an existing deep water channel to minimise the dredging requirements. However, it is frequently necessary to introduce a bend into an approach channel. The discussion contained in Chapters 1 to 3 established that existing recommendations on the design of channel bends were mostly restricted to relatively large radius bends. However, it is generally accepted that additional channel width is necessary through a bend to account for the added difficulties of manoeuvring and the broader swept path of the vessel.

In order to clarify the width requirements for large radius bends and to extend the guidelines to bends which are extreme, in terms of either angle of deflection, or radius of curvature, a series of ship navigation simulations were carried out.

The aim of this study was to investigate some of the factors which control the manoeuvring space required by vessels in confined channels. A series of channels were tested using the DYNATRACK ship simulator. Each configuration was based on an idealised approach channel, incorporating a single bend with varying angles of deflection and radius of curvature. The channels were tested with a range of ships and environmental conditions to evaluate the required manoeuvring envelopes.

5.2 Navigation simulation through approach channel bends

5.2.1 Basic considerations

Ships cannot make instantaneous changes in direction, but follow an arc. Therefore, design of approach channel bends must reflect the track that a vessel will actually take.

In the simplest bend to design and construct introduces a cut-off across the inside of the bend, as illustrated in Figure 25. However, this method is not ideal because can lead to a larger amount of dredging than is strictly necessary, since the ship, by virtue of its curved path alone, will never enter the shaded zone. Furthermore, in areas with high current flows the sharp corners in the channel banks can cause severe flow and siltation problems. A more sophisticated design uses curved channel banks, which mirror the path of the vessel. This reduces the amount of unnecessary dredging and should, therefore, be cheaper to implement and maintain. The fundamental problem is predicting the path a vessel will follow in a wide range of circumstances. In addition, the swept paths of the vessel must be assessed. This is the envelope defining the extreme positions of the bow and stern throughout the manoeuvre, as indicated on Figure 26.

The manoeuvring space required by a ship negotiating a bend is dependent on a large number of factors. These include the vessel dimensions, hull form, speed, rudder and propeller arrangements, the skill of the handler, water depth and underkeel clearance, channel bank slope and height, and environmental conditions. It is impossible to assess the influence of all of these contributing factors at once and therefore, some means of simplifying the situation was required.

5.2.2 Methodology

It has been observed that long slender ships tend to be more directionally stable than short ones. Therefore, a long slender ship, with a large length to beam ratio (L/B), is likely to have more difficulty negotiating a bend than those with a lower value of L/B. This study has investigated the interdependence between the required width of channel, angle of deflection, and radius of curvature through a bend, and the potential relationship between the manoeuvring envelope of a vessel and its L/B ratio using the DYNATRACK ship simulator.

The study described in this chapter has concentrated on the basic manoeuvring requirements of ships through bends. Complicating factors such as winds, waves, currents, changes in water depth were not modelled. A series of test were carried out which predicted the actual path of a vessel attempting to negotiate a bend. The deviation of the vessel from an ideal track was monitored and compiled over the test series. This data was used to predict a manoeuvring envelope through the bend.

5.2.3 DYNATRACK model

DYNATRACK is a fast time port design tool developed at Maritime Dynamics Limited. The behaviour of a ship is simulated by a mathematical model which represents the forces and moments acting on the hull. During a run, the ship is under the control of a track-keeping algorithm or 'autopilot'. The operator defines, in advance, a track which the autopilot should ideally follow. This model can represent the influence of environmental factors such as wind, waves, currents or visibility as well as restrictions in ship engine and rudder control.

5.2.4 Ships

The ship models that were used in this study were selected from a range of ships that had already been set up within DYNATRACK. The selected ship models had also been used in real time navigation simulation studies. Therefore, each model had been extensively tested and validated by experienced pilots and mariners.

Four vessels were selected from these verified ship models and are referred to as ships A to D. The chosen ships vary in size and type, but were selected to represent a range of length to beam ratios of between 5.6 and 8.5. The basic characteristics of the vessels are as follows and the details are supplied in Appendix 1:

Ship type indicator	Type	Length L (m)	Beam B (m)	Draught T (m)	L/B
A	Passenger ferry	119	22.6	5.2	5.2
B	Container vessel	260.8	39.4	11.0	6.6
C	Tanker	165	23	9.3	7.2
D	Tanker	273	32.2	12.8	8.5

5.2.5 Channel bends

The key design parameters for an approach channel bend are the angle of deflection, α, the radius of curvature, r, the channel width, W, and the water depth, h, as illustrated in Figure 5.

Within DYNATRACK, a channel is made up from a number of adjoining segments. Each segment is defined by a reference track line, the distances from the reference track to the bank toe to port and starboard, the channel bank height and the bank slope. In order to get relatively smooth curves, the extreme bends were built up from short sections rotated incrementally through 10°. In this way a series of idealised channels containing bends with angles of deflection between 20° and 120° were constructed.

In order to allow direct comparison between simulator runs for different test ships, the channel parameters were scaled with respect to the vessel dimensions. The key design parameters of radius of curvature and channel depth were scaled in terms of ship lengths, L, and vessel draught, T, respectively. In the channels tested, the channel depths were kept constant at 1.375T. However, a number of radii of curvature, ranging between one ship length and 10 ship lengths, were examined.

5.2.6 Autopilot control

Within DYNATRACK control of the autopilot is retained by varying parameters which correspond to controls for the ships engines and rudder.

Very early in the simulation test series it became clear that the manoeuvring envelope of the ships was highly dependent on where the vessel began to turn. This is controlled within DYNATRACK by varying the distance forward of the ship that the autopilot monitors the reference track, referred to as the look ahead distance. A short look ahead distance is analogous to poor visibility or sparse channel markings. Similarly, a longer look ahead distance represents good visibility and a well marked channel with possibly additional navigation aids.

5.3 Test results

5.3.1 Presentation of the results

The results from the simulator tests are presented in Figures 27, 28 and 30. The test results are presented in the form of graphs of relative required width of the manoeuvring envelope, w/B, against either relative radius of curvature of the bend, r/L, or angle of deflection through the bend, α. It should be noted that these tests considered the deviation from the reference track of the ship's centre of gravity. No account has been taken of the ship's instantaneous heading at this stage, and therefore the relative positions of the bow and stern. This means that the extremes of the vessel's swept path will lie outside the manoeuvring envelopes described. Due to the general nature of this model study it should be noted that the predictions for adequate channel widths should be regarded as an initial estimate. For final design it is recommended that site and vessel specific simulations are carried out.

5.3.2 Radius of curvature

A series of tests were carried out to investigate the sensitivity of the width of the manoeuvring envelope to the radius of curvature, in the absence of wind, wave and currents. The results are shown in Figure 27. In these tests Ship D was tested negotiating a 40° bend at 10 knots. The channel contained bends with radii of curvature between 2L and 10L. The results show that as the radius of curvature through the bend increases, the width of the vessel manoeuvring envelope decreases. This is to be expected as the vessel will have less difficulty negotiating a large radius turn.

5.3.3 Angle of deflection

The second series of test runs was performed using Ship D travelling at 10 knots through. The channel angle of deflection was adjusted to 20°, 40°, 60°, 90° and 120°, each with a radius of curvature of 2L. Again, these tests were carried out without wind, waves or currents. The results, shown in Figure 28, indicate that as the angle of deflection through the bend increases, the width of the manoeuvring envelope also increases. This too is consistent with practical experience, as ships find large angle bends more difficult to negotiate.

5.3.4 Look ahead distance

Given adequate information and warning, a pilot can use the optimum path along a curved channel. The ship can describe a smooth curve with a larger radius of curvature than the bend, whilst deviating only slightly either side of the reference curve, as shown by the dashed line on Figure 29. Clearly, in this situation the manoeuvring envelope is much reduced.

The simulator tests also showed that the manoeuvring envelope is also highly sensitive to the look ahead distance. Results from runs with the autopilot look ahead distance set to 1L, 2.5L and 3L respectively are also plotted in Figure 27.

The point at which the ship starts to turn is critical. If the pilot begins the manoeuvre too late, the ship overshoots the reference track, ending up on the outside of the bend. The autopilot is now likely to apply a very large correction using the rudder and engines. If the vessel is over-steered it will be unable to pull out of the correction in time and will end up on the inside of the bend. This results in wild oscillations around the reference track and consequently a very wide manoeuvring envelope. In addition, the vessel can take a considerable time to settle onto the new course, by which time the ship is a significant distance from the bend. This track is illustrated by the dotted line on Figure 29. If, however, the vessel starts to turn too soon, it is in danger cutting the corner and, unless the channel is very wide through the bend, grounding on the inside.

The sensitivity of the system to look ahead distance is also demonstrated in Figure 28. This time a wider range of look ahead distances, between 1L and 4L, were tested. These results suggest that increasing the look ahead distance from 1L to 3L significantly reduces the width of channel needed. However, an increase in look ahead distance beyond 3L did not result in significant further reductions in manoeuvring envelope width. It seems that there is a threshold look ahead distance below which the ships ability to negotiate channel bends safely is greatly impaired, but above which no significant saving in channel width can be made. Therefore, the solid lines on Figure 28 correspond to the lower limit on manoeuvring envelope widths for this ship in the channels.

5.3.5 Comparison of ships

A less extensive set of simulator tests using the remaining ships, A to C, confirmed that the basic trends identified above are applicable to other ships. The threshold values of look ahead distance varied slightly from ship to ship, but all were within a relatively narrow range between 2L to 3.5L.

A further set of simulator runs were used to directly compare the manoeuvring space needed by the four chosen ships. In these tests each ship was modelled negotiating channels with a 40° bend at 10 knots. Each channel was scale relative to the ship dimensions as discussed in Section 5.2.5 and the autopilot look ahead distance was set to the threshold value for the ship. The results are given in Figure 30. These results suggest that the required width of the manoeuvring envelope is to some extent dependent upon the length to beam ratio of the ship. In general, as the length to beam ratio increases, the required width also increases. However, the model predicted that the ship with the smallest length to beam ratio, Ship A, sometimes has a larger relative required width than vessels with a larger length to width ratio. Clearly, the required width is dependent upon at least one other ship-related factor.

5.4 Application of results

The results of the navigation simulation study indicate that it is possible to produce design curves to indicate the desired channel width through extreme bends. For example, the results shown in Figure 30 enable the required channel width through a bend to be assessed, in terms of ship beam, from the actual radius of curvature of the bend, depending on the length:beam ratio of the design ship. However, it has also become clear that the design of the channel sections immediately before and after a severe bend is critical. The results have shown that vessels may take a considerable time to settle onto a new course after a severe bend. During this time the ship handler has to correct any overcompensation in course alteration and become accustomed to the changes to the ships new course, under the influence of environmental conditions. Therefore, an increase in the width of the straight channel sections at the entrance and exit to a severe bend will enable safer manoeuvres.

It must also be noted that at many sites the width of a channel, and therefore the dredging requirements, may be minimised by providing better navigation aids to the ship handler. This provides additional information on the ship's position relative to the channel.

6 Guidelines for the hydraulic and navigational design of approach channels

The existing guidelines and advice for determination of channel depth, width and layout are described in Chapter 3 and presented in Tables 1, 2 and 3. A review of these guidelines found that:

- The recommendations are inconsistent, and hence they are confusing and of limited practical use.

- There is little advice on how to arrive at a safe design compromise, given that the ideal solution is not feasible.

- The recommendations make no distinction between vessels of different types and size. Such vessels are likely to behave in very different ways.

- Many of the guidelines have not taken into account the influence of wave agitation on ship behaviour. This is of great importance in the UK and many other sites worldwide, where ports are exposed to a significant level of wave activity.

The guidelines resulting from the modelling work described in Chapters 4 and 5 are summarised in this chapter to provide initial guidelines for the design of channel depth and width.

6.1 Channel depth

The results of the study which examined the risk of seabed contact for determination of guidelines for channel width, as described in Chapter 4, can be summarised for the conditions that were tested as follows:

- The acceptable wave heights for a range of underkeel clearances were assessed. It is essential to consider this channel design characteristic for the expected vessel type, vessel speed in the channel, and the predominant wave conditions and directions. However, the study showed that the vessel characteristics and hull form must also be considered in the assessment of channel design.

- The sensitivity of vessel response to the predominant wave direction must be considered as the predicted acceptable wave height varies significantly between head, beam and stern seas. These factors can be assessed from the design curves presented in Figures 7 to 25.

- Vessel response to the directional spreading of waves has been shown to be a significant factor which has been overlooked by existing guidelines. This must be taken into consideration for channel design due to large variations in the predicted acceptable wave height.

6.2 Channel width

The results of the navigation simulation study for determination of guidelines for channel width, as described in Chapter 5, can be summarised for the conditions that were tested as follows:

- The channel width needed through a bend is dependent to some extent on the length to beam ratio of the ship.

- It has been shown that the channel width in sections immediately before and after a bend is critical.

- The width of channel through a bend can be minimised by providing good channel marking and additional navigation aids.

6.3 General guidelines

The work described in this report shows that the design of approach channels is highly site specific. This causes difficulty in the specification of generally applicable design guidelines. The guidelines presented in this report have been determined from consideration of vessel dimensions and handling characteristics under the influence of environmental conditions and enable good first estimates of channel design to be made. However, if the guidelines show that problems may occur as the design proceeds, it is essential that model testing is carried out, through the use of, for example, real-time navigation simulation to provide more detailed design data and ensure safe navigation through the channel.

7 Recommendations

It is recommended that further studies are carried out to extend the work carried out in this study. In particular:

- Increase the range of ship hull forms for both channel depth and width determination and consider the effects of roll motions for guidelines on the design of channel depth.

- Increase the range of ship sizes to incorporate medium and small vessels.

- Increase the scope of this study to encompass wind and tidal current effects, and the impact of approach channel modification on tidal flows and sedimentation.

- Incorporate the use of real-time navigation simulation, controlled by experienced mariners, to provide more accurate design curves for channel width determination.

8 References

Barras C B (1981) The phenomenon of ship squat. Terra et Aqua 18, March 1981

Dand I W and Lyon P R (1993) The element of risk in approach channel design. International conference on Maritime Technology: Challenges in Safety and Environmental Protection, Singapore, November 1993.

DPWC (1969) Port Design Manual, Part 1, Functional Standards. Marine Engineering division, Department of Public Works of Canada, 1969

DTp (1980) Department of Transport. Ship behaviour in ports and their approaches. Part 2, Additional sinkage caused by sailing in the proximity of a channel bank, 1980

DTp (1982) Department of Transport. Ship behaviour in ports and their approaches. Part 7, A compendium guide to the design of navigation channels, 1982

Duncan H (1968) Harbour Entrances, Channels and Turning Basins, 1968

Hasselmann K et al. (1973) Measurement of wind wave growth, swell and decay during the Joint North Sea Wave Project (JONSWAP). Deutches Hydrographisches Institut, Hamburg, 1973

HR Wallingford (1992) The UNDERKEEL Model Training and User Manual. Report EX 2601, June 1992

IALA (1993) International Association of Lighthouse Authorities. Aids to Navigation Guide (Navguide), 2nd edition, November 1993

Kray C J (1973) Design of ship channels and manoeuvring areas. Journal of Waterways, Harbours and Coastal Engineering, ASCE, Vol 99 WW1, February 1973

Morihira M, Isiwata T, Suzuki S (1984) Pocket Book for Port Construction. Sankeido Press, Japan, 1984

NPC (1975) National Ports Council. Port approach design - a survey of ship behaviour studies. Volumes I and II, 1975

PIANC (1979) International Commission on the Reception of Large Ships. Report of Working Group I. Methods for analysing wind, wave and swell data to estimate on an annual basis the number of days, and the maximum duration of periods during which port and ship operations will be impeded by these elements (Availability of ports and terminals), Annex to PIANC Bulletin no. 32, Vol 1, 1979

PIANC (1980a) The extension of Port of Zebrugge, Belgium. Study pattern for the design and realisation of an access channel in open sea for the reception of large ships in the extended port. PIANC Bulletin no.37, 1980

PIANC (1980b) International Commission for the Reception of Large Ships. Report of Working Group IV. Optimal lay-out and dimensions for the adjustment to large ships of maritime fairways in shallow seas, seastraits and maritime fairways, considering: i) the influence of winds, currents, waves and bottom changes: ii) the means offered by modern technology for the execution and maintenance of works: iii) the navigational aids: iv) the control of navigation, Supplement to PIANC Bulletin no. 35, 1980

PIANC (1983) Navigation in muddy areas. Supplement to PIANC Bulletin no. 43, 1983

PIANC (1984) Statistical treatment of ship manoeuvring results for fairway design. PIANC Bulletin no. 45, 1984

PIANC (1985a) Report of the working group of the Permanent Technical Committee II. Dangerous goods in ports - Recommendations for port designers and port operators. Supplement to PIANC Bulletin no. 45, 1985

PIANC (1985b) Report of a working group of the Permanent Technical Committee II. Underkeel clearance for large ships in maritime fairways with hard bottom. Supplement to PIANC Bulletin no. 51, 1985

PIANC (1987) The design of approach channels and ship manoeuvring areas. PIANC Bulletin no. 56, 1987

PIANC (1995) Approach channels - Preliminary guidelines. Supplement to Bulletin no. 87, 1995

Schilperoort T, Strating J (1985) An integrated approach towards depth design and operational use of navigation channels. Delft Hydraulics Publication no. 346, September 1985

Strating J, Schilperoort T, Blaauw H G (1982) Optimisation of depths of channels. Delft Hydraulics Publication no. 278, September 1982

Thevenot M M (1992) Evaluation of width criteria for deep draft channels using computer simulation. PIANC Bulletin no. 78-79, 1992

Thoresen C A (1988) Port design. Guidelines and recommendations. Tapir Publishers, Trondheim, 1988

Turner H O (1984) Dimensions for safe and efficient deep draft navigation channels. Hydraulic model investigation, US Army Corps of Engineers Report HL-84-10, 1984

USACE (1983) US Army Corps of Engineers. Engineering and Design for Hydraulic Design of Deep Draft Navigation Projects. Manual number 1110-2-1613, 1983

Tables

Table 1 Summary of approach channel guidelines for channel depth

	PIANC (1980)	PIANC (1995)	DOT (1980)	USACE (1983)	DPWC (1969)	Thoresen (1988)	Morihira (1984)
Minimum recommended channel depth	ukc = 0.5m	ukc = 0.6m	-	soft bed : ukc = 0.6m hard bed : ukc = 0.9m 1.5m between water intake and silty bed	-	-	-
Recommended tolerance allowances	ukc = 0.2T vessel sailing in open sea exposed to large swell ukc = 0.15T stationary vessel exposed to large swell or vessel sailing in channel partially sheltered from waves ukc = 0.1T-0.15T vessel sailing in channel not exposed to waves	sheltered waters : $h/T \ge 1.1$ exposed to waves $H_s \le 1.0$m : $h/T \ge 1.3$ exposed to waves $H_s > 1.0$m with unfavourable periods and directions: $h/T \ge 1.5$	look-up tables to calculate adequate water depth to account for: squat speed/depth factor blockage bank interaction ship interaction wave and swell effects NOT accounted for	'efficiency' clearance, EC 1 - 3 feet additional clearance to account for dredging tolerance wave and swell effects NOT accounted for	look-up graphs to account for wave and swell effects	-	-

Where: ukc = underkeel clearance
T = design vessel draught
h = water depth

Table 2 Summary of approach channel guidelines for channel width

	PIANC (1980)	PIANC (1995)	DOT (1980)	USACE (1983)	DPWC (1969)	Thoresen (1988)	Morihira (1984)
Width of manoeuvring lane	- but additional 1B - 2B for drift allowance	1.3B - 1.8B plus look-up tables for drift allowances due to: vessel speed, wind, currents, waves; and additional safety margins for hazardous cargo, depth and provision of navigation aids	1.6B	1.6B favourable conditions 2.0B unfavourable conditions	1.4B one-way traffic 1.6B - 2.0B two-way and multilane traffic	1.6B - 2.0B	-
Width of bank clearance lane	1B - 2B	0.3B - 1.3B with look-up tables to take account of vessel speed and bank type	look-up tables available	0.6B - soft bed 1.5B - hard bed	0.7B - 1.4B depending upon the conditions and if vessel piloted	1B - 2B	-
Width of ship clearance lane	-	1B - 2.5B with look-up tables to take account of vessel speed and traffic density	look-up tables available	0.8B	1B	1B, but not less than 30m	-
Total channel width	5B + (drift allowance) one-way traffic 8B to 10B + (drift allowance) two-way traffic	1.9B - 7.7B plus allowances for environmental factors	-	2.8B - 5B one-way traffic 5.2B - 7.8B two-way traffic	2.8B - 4.2B one-way, single lane traffic 3.0B - 4.8B one-way, multilane traffic 5.6B - 7.8B two-way traffic	3.6B - 6B one-way traffic 6.2 - 9B two-way traffic	0.5L - 2L depending upon traffic density, number of lanes, overall length of channel

Where B = design vessel beam and L = design vessel length

Table 3 Summary of approach channel guidelines for channel layout

	PIANC (1980)	PIANC (1995)	DOT (1980)	USACE (1983)	DPWC (1969)	Thoresen (1988)	Morihira (1984)
Radius of curvature of bends	> 10L but less than 5L	such that vessel uses 15° - 20° of rudder angle	10L	'gradual'	$\alpha \leq 25°$, $r \geq 3L$ $25° < \alpha \leq 35°$, $r \geq 5L$ $35° < \alpha$, $r \geq 10L$		> 4L ($\alpha < 30°$)
Minimum intermediate straight between consecutive bends	10L	≥ 5L	-	-	2L	2L, but not less than 200m	-
Channel widening through bends	should be widened such that $W = \frac{L^2}{8r}$ change in width should not exceed 10m in 100m		look-up tables available, but for r = 10L only	if bend is not 'gradual', corner cut-off should be considered	if above recommendations not met, widen channel on inside of bend by 10 feet per ° in excess in α	if $\alpha > 10°$, increase width by 2B on inside of bend	widen enough to allow ship to turn with r = 4L

Where: r = radius of curvature
α = angle of deflection through bend
L = design vessel length
B = design vessel beam
W = channel width

Table 4 UNDERKEEL model runs for Ship 1

Ship	Hull type	LOA (m)	Beam (m)	Draught (m)	Speed (kt)	Squat (m)	water depth (m)	Underkeel clearance		Wave energy directional spreading factor		
								% of vessel draught	m	$\cos^2$	$\cos^8$	$\cos^{30}$
Ship 1	A	207.0	32.0	12.0	5	0.2	12.6	5	0.6	✓		
							13.2	10	1.2	✓		
							14.4	20	2.4	✓		
							15.1	26	3.1	✓		
							15.7	31	3.7	✓		
							16.3	36	4.3	✓	✓	✓
	A	207.0	32.0	12.0	10	0.7	12.6	5	0.6	n/a	n/a	n/a
							13.2	10	1.2	✓		
							14.4	20	2.4	✓		
							15.1	26	3.1	✓		
							15.7	31	3.7	✓		
							16.3	36	4.3	✓	✓	✓
	A	207.0	32.0	12.0	15	1.7	12.6	5	0.6	n/a	n/a	n/a
							13.2	10	1.2	n/a	n/a	n/a
							14.4	20	2.4	✓		
							15.1	26	3.1	✓		
							15.7	31	3.7	✓		
							16.3	36	4.3	✓		

Note: 'n/a' denotes a test which is not applicable due to excessive vessel squat.

Table 5 UNDERKEEL model runs for Ship 2

Ship	Hull type	LOA (m)	Beam (m)	Draught (m)	Speed (kt)	Squat (m)	water depth (m)	Stationary underkeel clearance		Wave energy directional spreading factor		
								% of vessel draught	m	$\cos^2$	$\cos^6$	$\cos^{30}$
Ship 2	A	281.0	32.0	12.0	10	0.7	12.6	5	0.6	n/a	n/a	n/a
							13.2	10	1.2			
							14.4	20	2.4			
							15.1	26	3.1	✓		
							15.7	31	3.7	✓		
							16.3	36	4.3	✓		

Table 6 UNDERKEEL model runs for Ship 3

Ship	Hull type	LOA (m)	Beam (m)	Draught (m)	Speed (kt)	Squat (m)	water depth (m)	Stationary underkeel clearance		Wave energy directional spreading factor		
								% of vessel draught	m	$\cos^2$	$\cos^8$	$\cos^{30}$
Ship 3	B	207.0	32.0	12.0	10	1.0	12.6	5	0.6	n/a	n/a	n/a
							13.2	10	1.2	✓		
							14.4	20	2.4	✓		
							15.1	26	3.1	✓		
							15.7	31	3.7	✓		
							16.3	36	4.3	✓	✓	✓

Note: 'n/a' denotes a test which is not applicable due to excessive vessel squat.

Table 7 UNDERKEEL model runs for Ship 4

Ship	Hull type	LOA (m)	Beam (m)	Draught (m)	Speed (kt)	Squat (m)	water depth (m)	Stationary underkeel clearance		Wave energy directional spreading factor		
								% of vessel draught	m	$\cos^2$	$\cos^6$	$\cos^{30}$
Ship 4	B	270.5	44.0	17.0	5	0.2	17.9	5	0.9			
							18.7	10	1.7			
							20.4	20	3.4			
							21.4	26	4.4	✓		
							22.3	31	5.3	✓		
							23.1	36	6.1	✓		
	B	270.5	44.0	17.0	10	1.0	17.9	5	0.9	n/a	n/a	n/a
							18.7	10	1.7			
							20.4	20	3.4			
							21.4	26	4.4	✓		
							22.3	31	5.3	✓		
							23.1	36	6.1	✓		
	B	270.5	44.0	17.0	15	2.3	17.9	5	0.9	n/a	n/a	n/a
							18.7	10	1.7	n/a	n/a	n/a
							20.4	20	3.4			
							21.4	26	4.4	✓		
							22.3	31	5.3	✓		
							23.1	36	6.1	✓		

Note: 'n/a' denotes a test which is not applicable due to excessive vessel squat.

Table 8 UNDERKEEL model runs for Ship 5

Ship	Hull type	LOA (m)	Beam (m)	Draught (m)	Speed (kt)	Squat (m)	water depth (m)	Stationary underkeel clearance		Wave energy directional spreading factor		
								% of vessel draught	m	$\cos^2$	$\cos^6$	$\cos^{30}$
Ship 5	B	164.3	22.8	9.9	10	1.0	10.4	5	0.5	n/a	n/a	n/a
							10.8	10	1.0	n/a	n/a	n/a
							11.8	20	2.0	✓		
							12.4	26	2.6			
							12.9	31	3.1			
							13.4	36	3.5	✓		

Note: 'n/a' denotes a test which is not applicable due to excessive vessel squat.

Figures

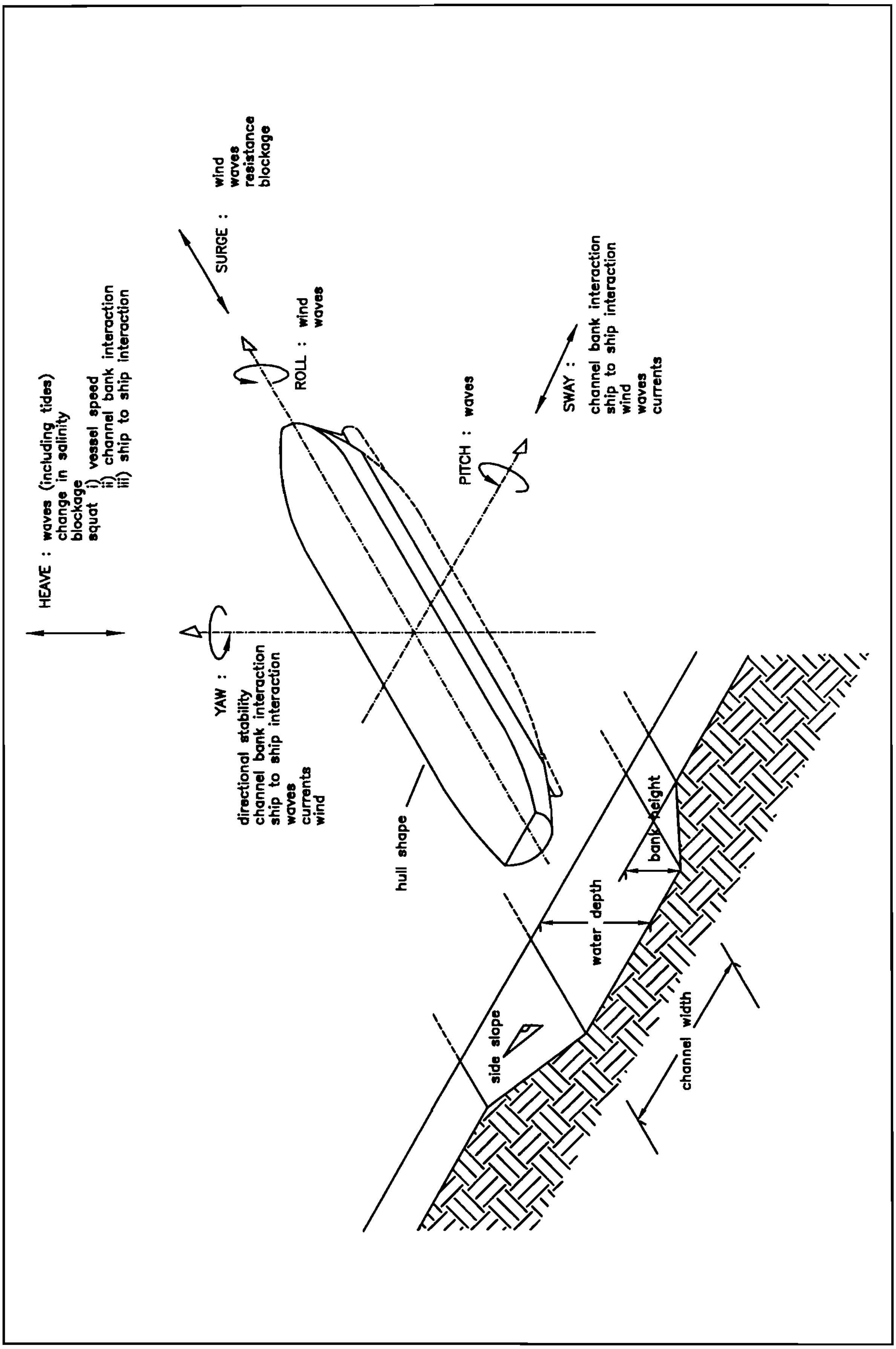
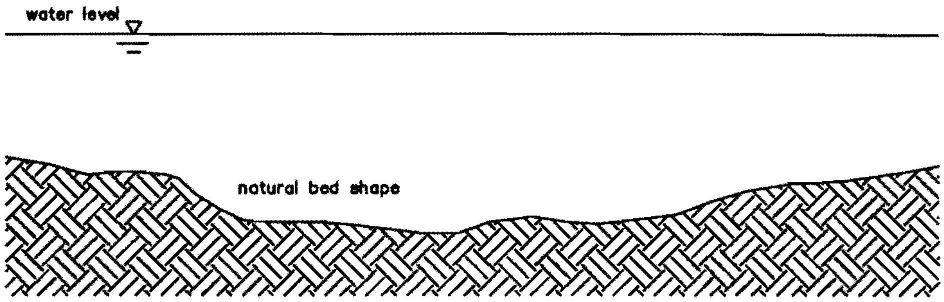
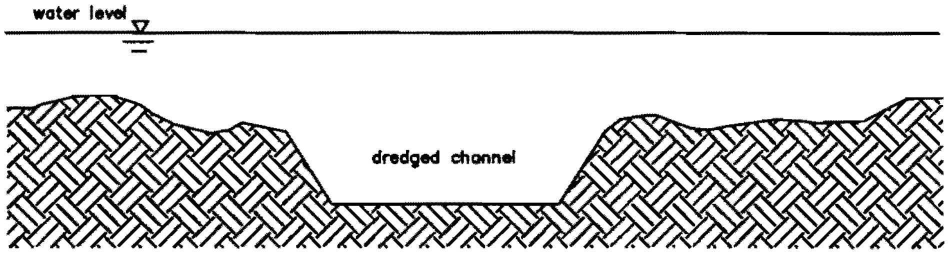


Figure 1 Physical processes which affect ship behaviour

a) undredged channel



b) partially dredged channel



c) fully dredged channel

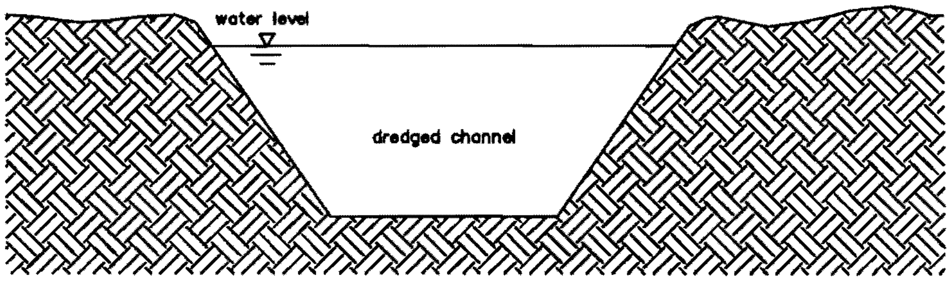
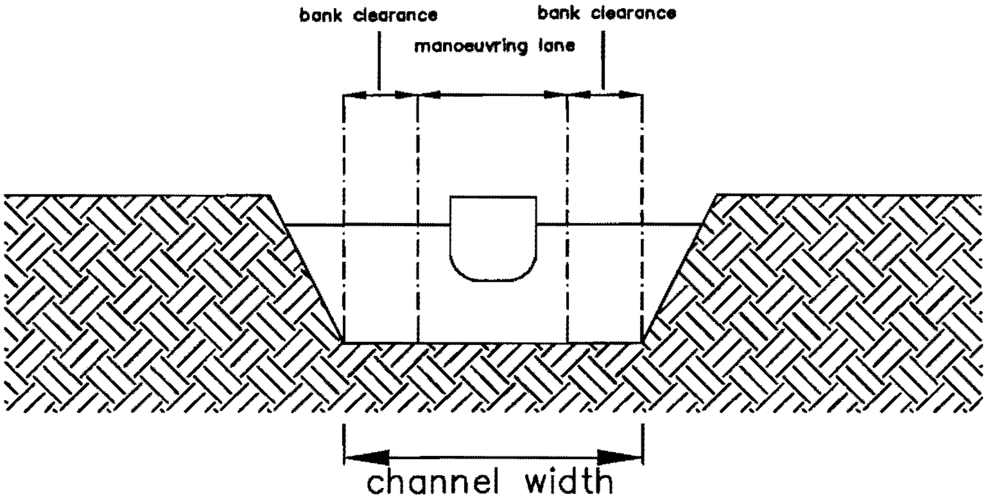


Figure 2 Dredged channel types

a) single lane channel



b) two lane channel

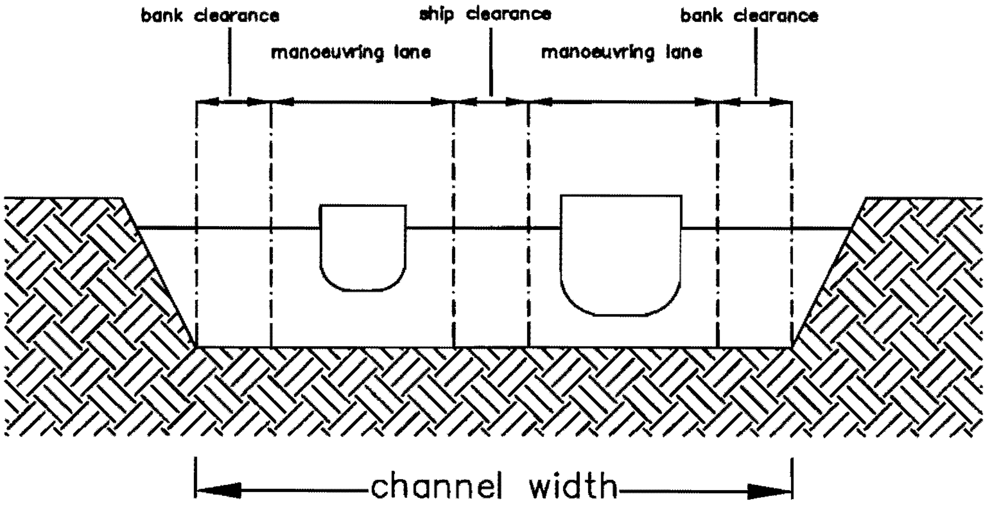
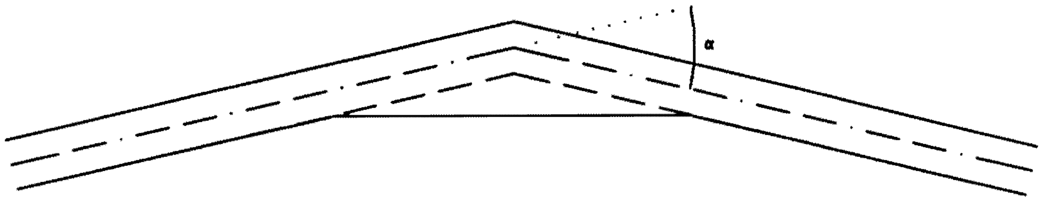


Figure 3 Channel width definitions

a) widening by apex, or cutoff method



b) widening by parallel banks method

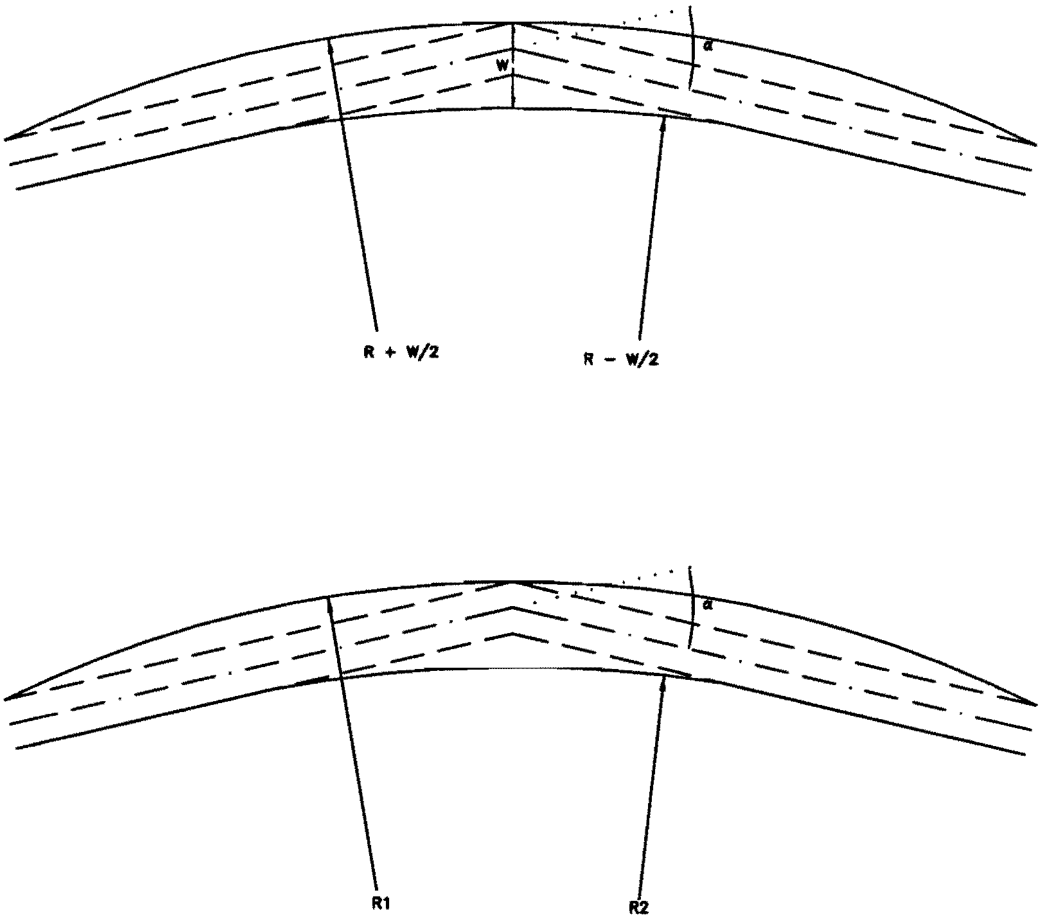


Figure 4 Methods of channel widening through bends

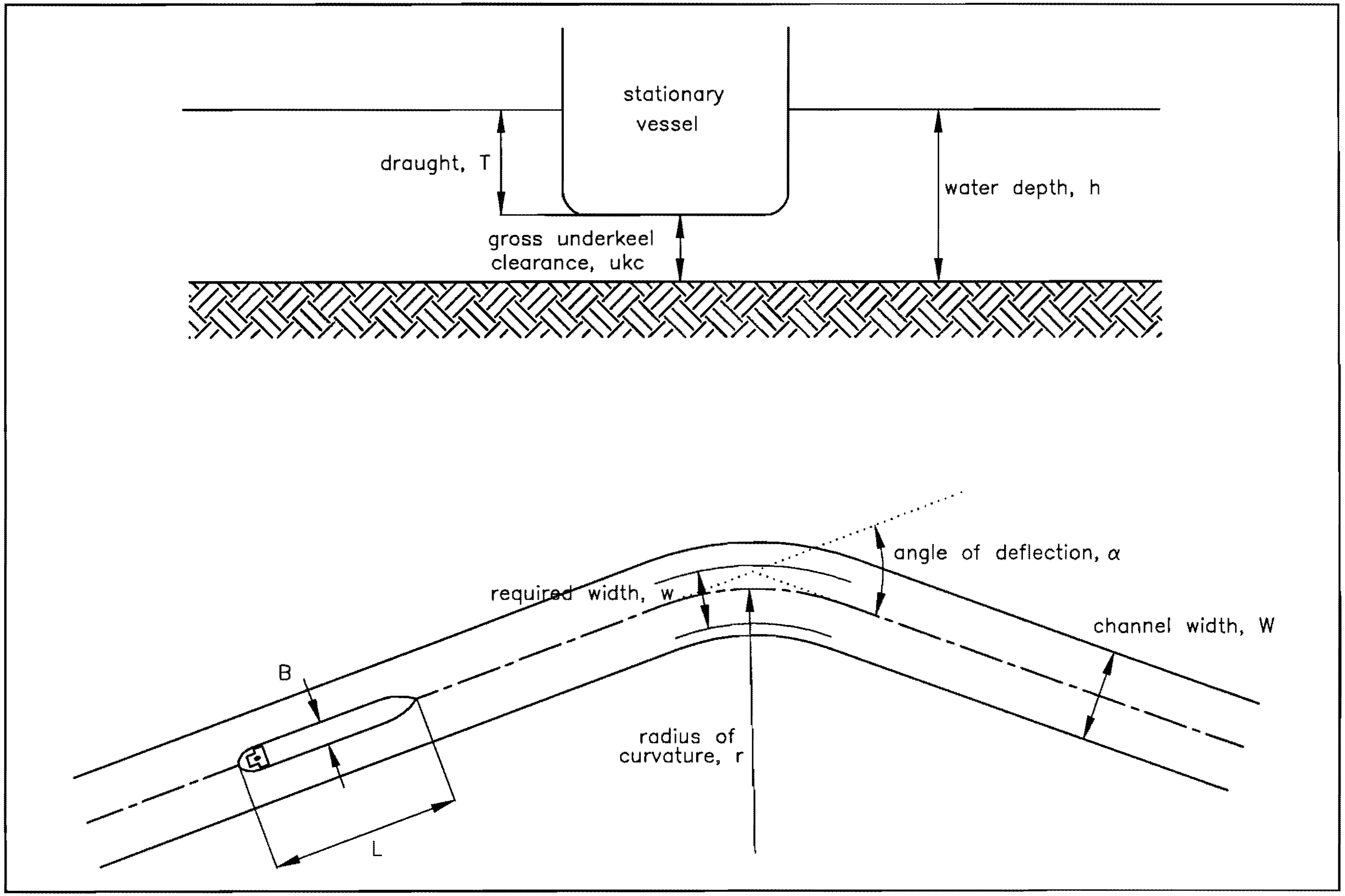


Figure 5 Channel design parameter definitions

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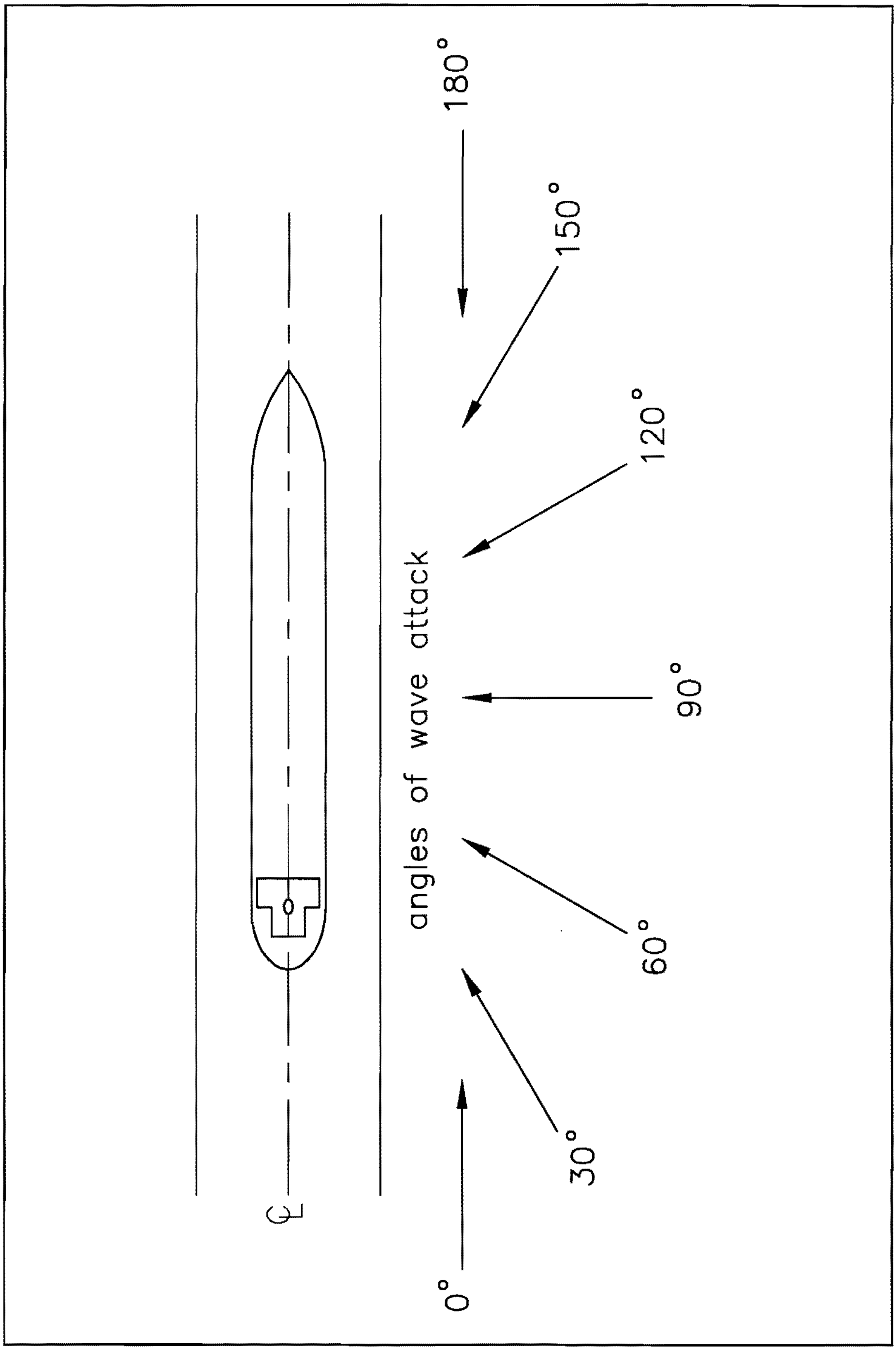
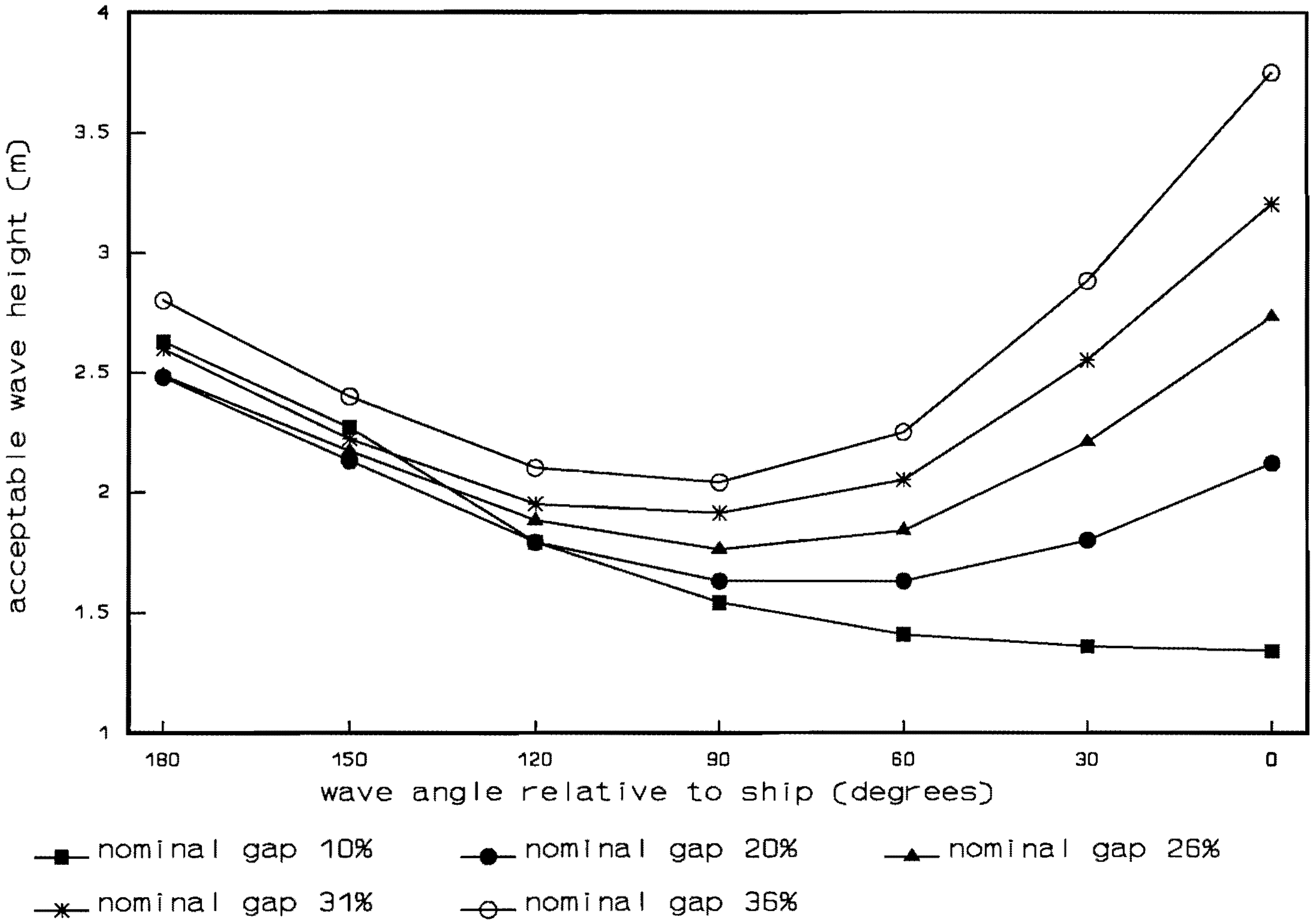


Figure 6 Angles of wave attack



180 degrees = bow sea 90 degrees = beam sea 0 degrees = stern sea

Figure 7 UNDERKEEL results - Ship 1 at 10kts (base scenario)

Figure 8 UNDERKEEL results - Ship 1 at 5kts

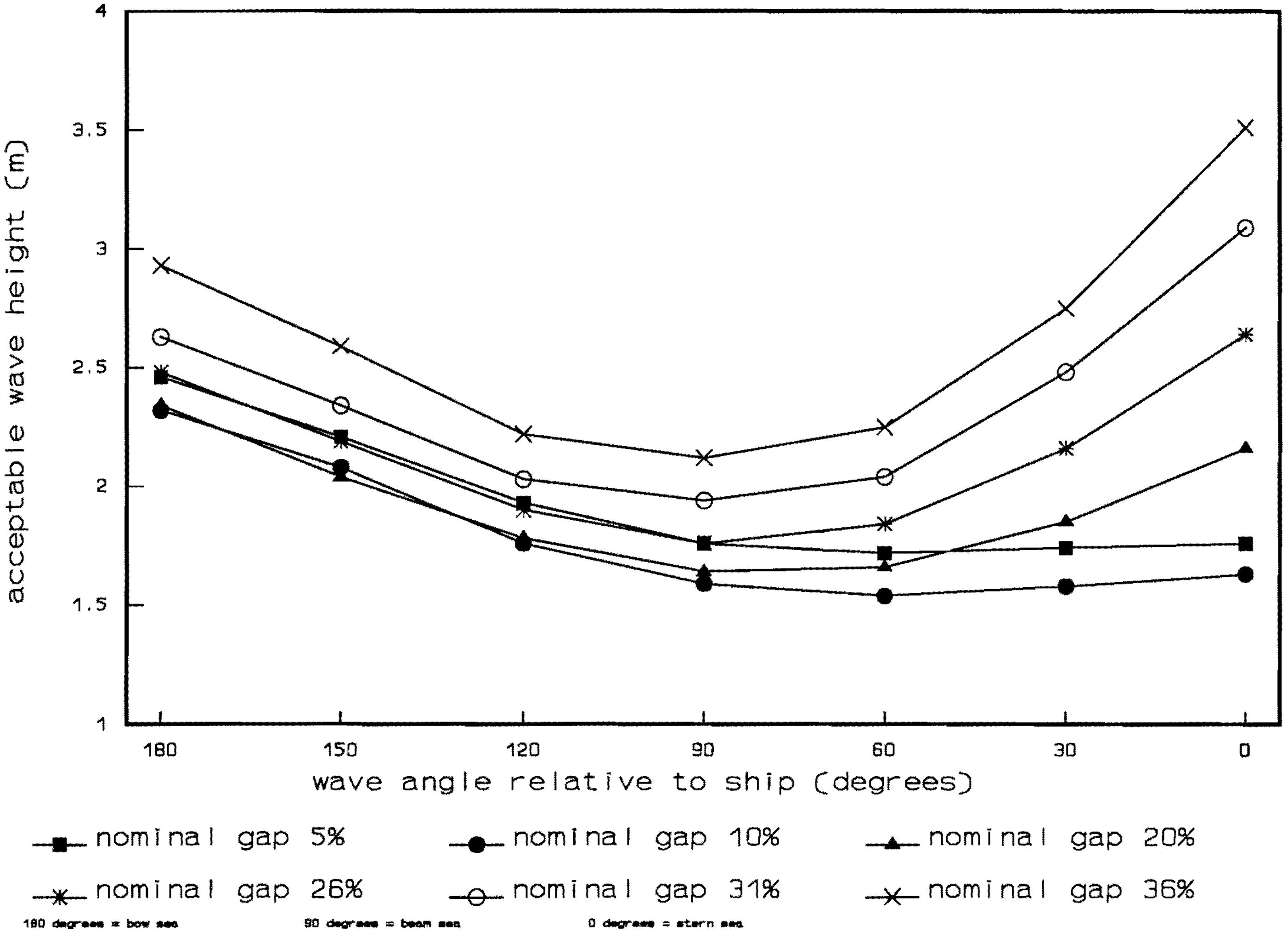
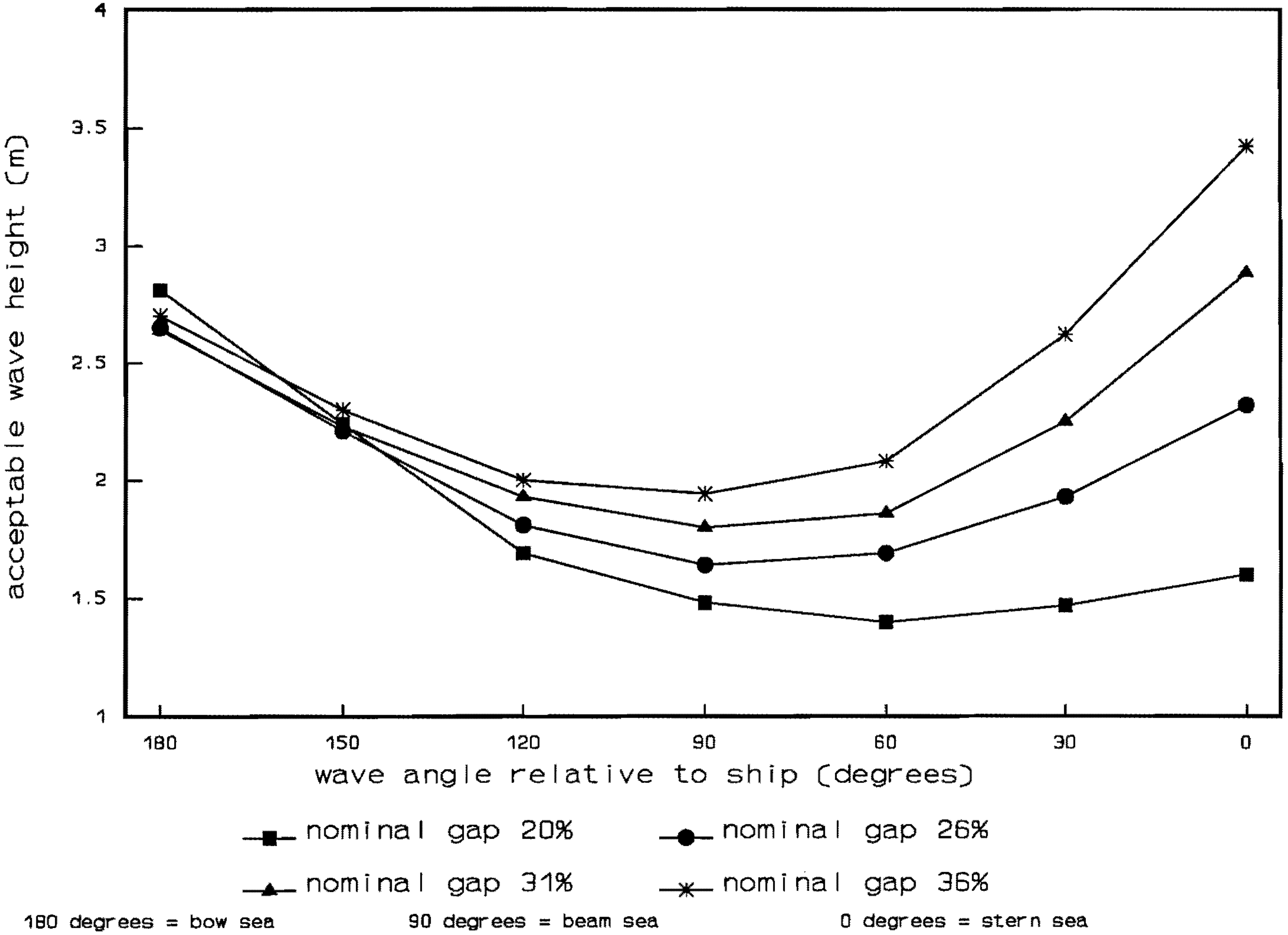


Figure 9 UNDERKEEL results - Ship 1 at 15kts



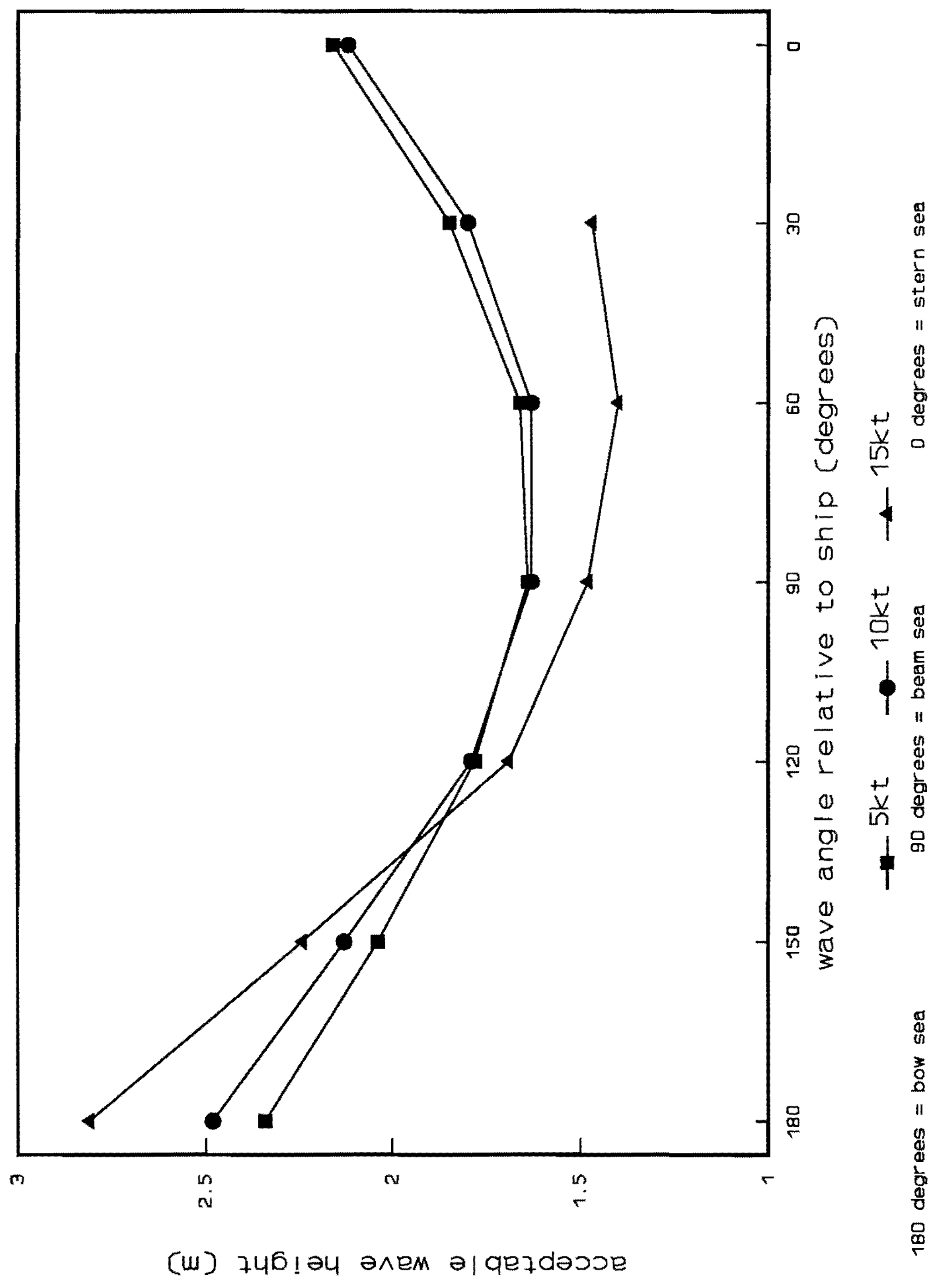


Figure 10 UNDERKEEL results - Ship 1 with 20% ukc

Figure 11 UNDERKEEL results - Ship 1 with 26% ukc

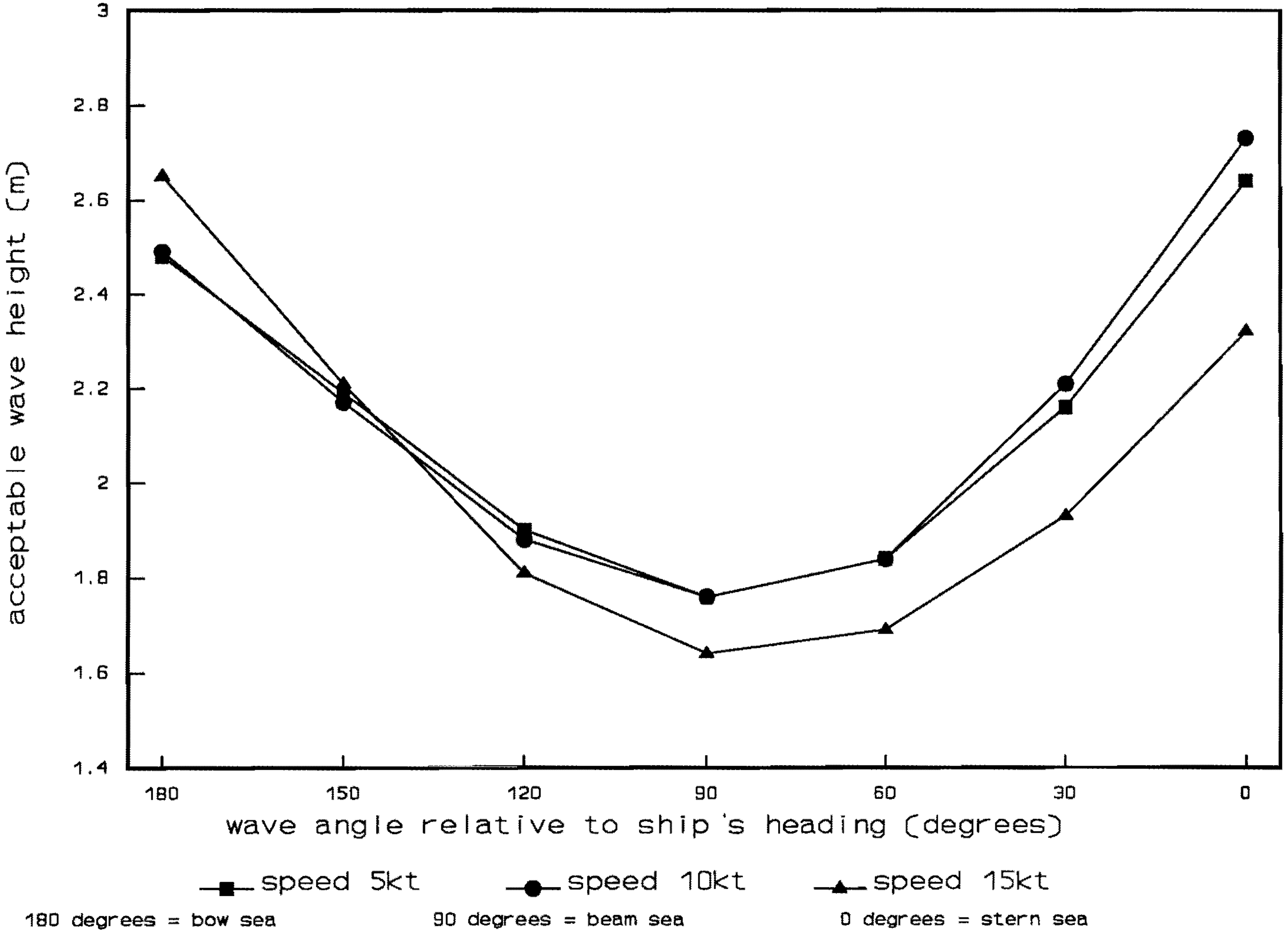
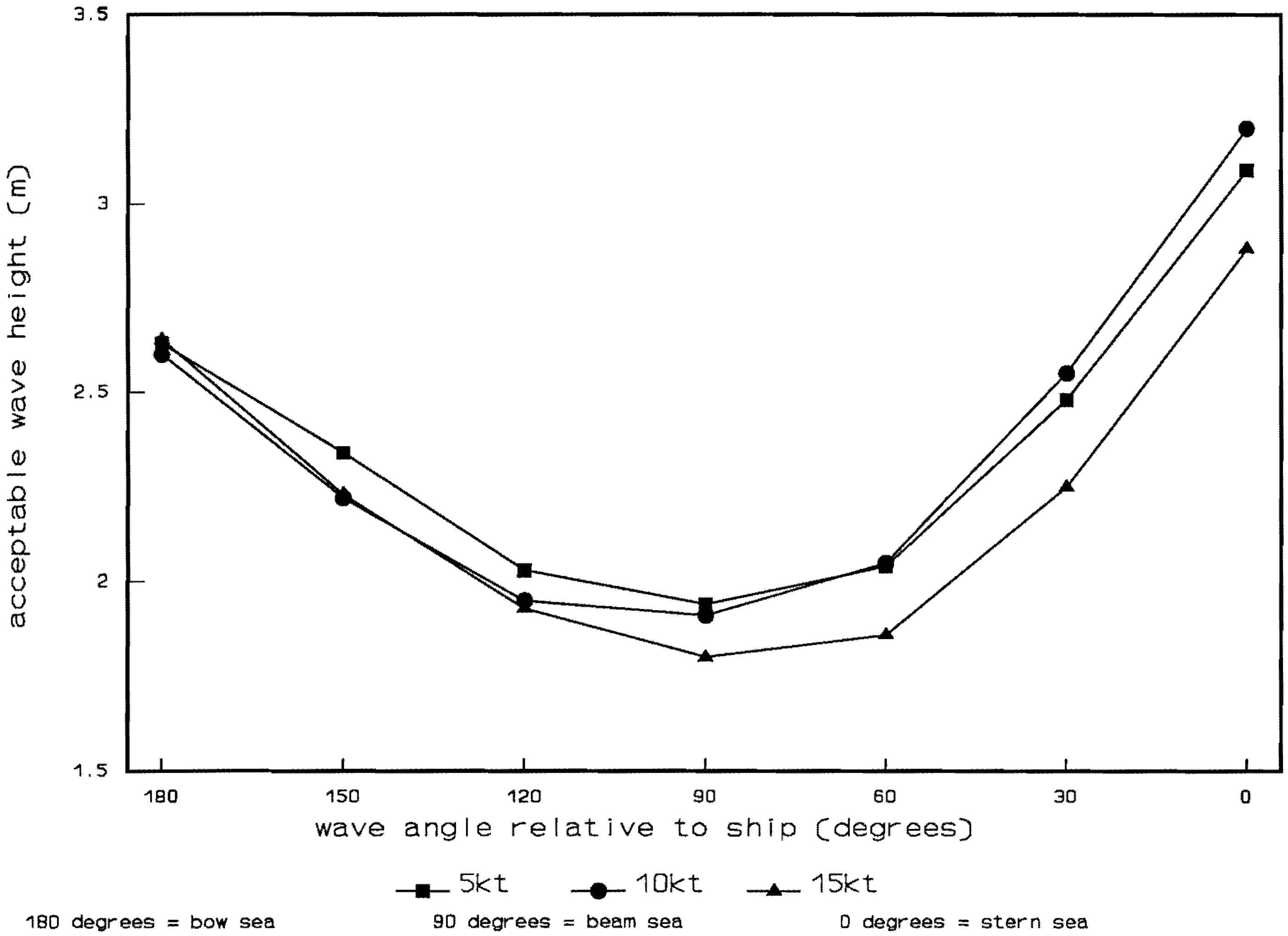


Figure 12 UNDERKEEL results - Ship 1 with 31% ukc



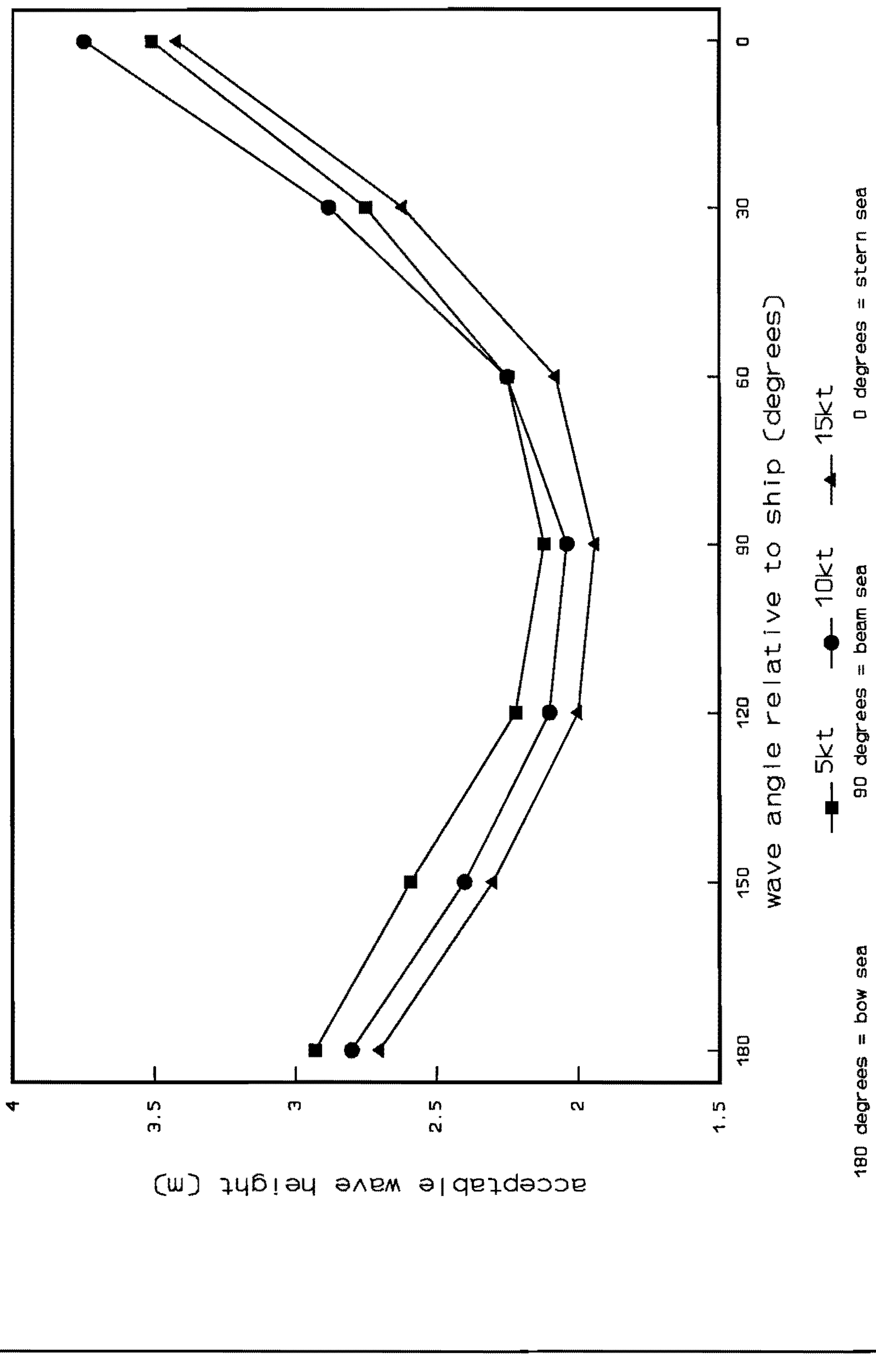
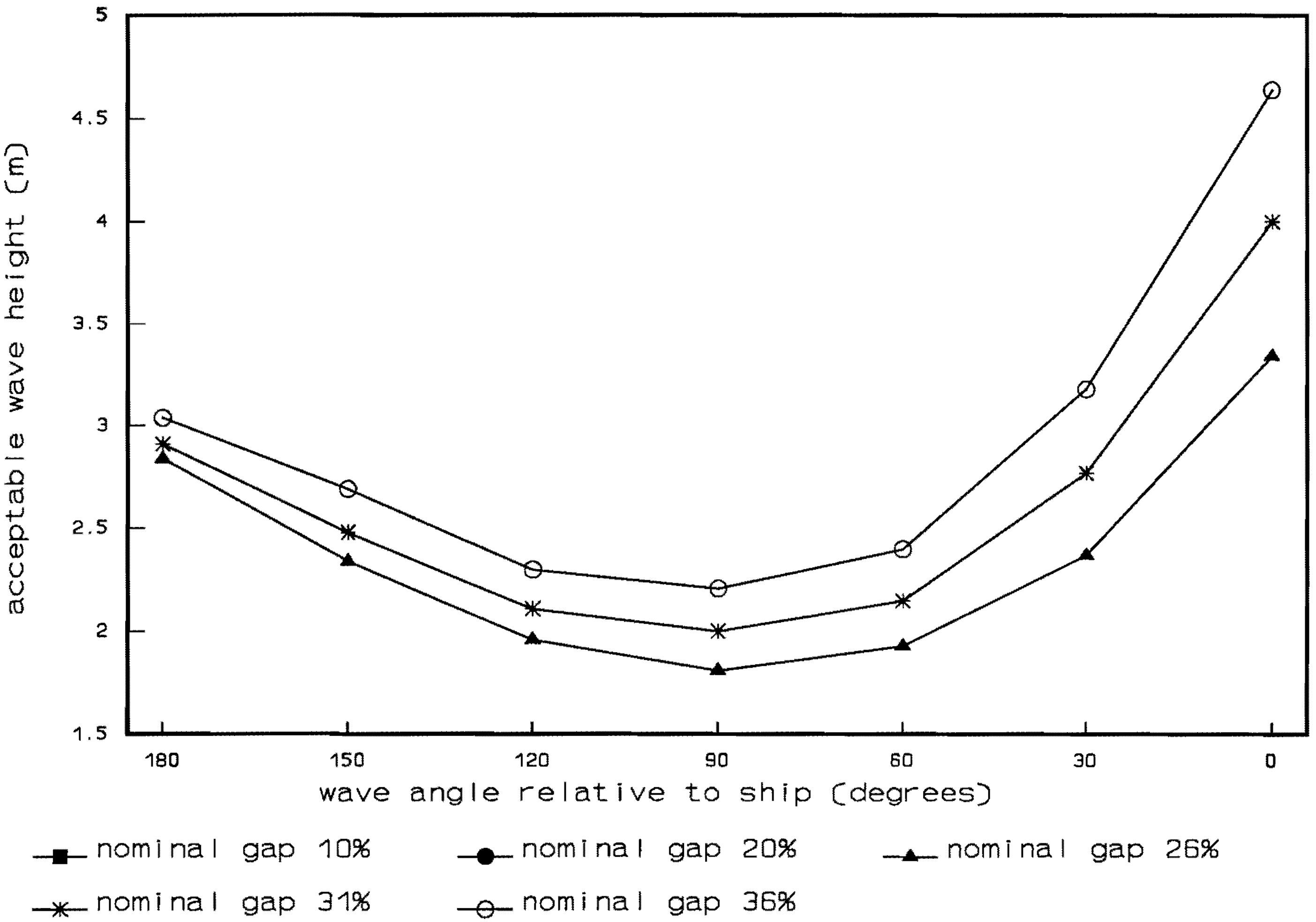


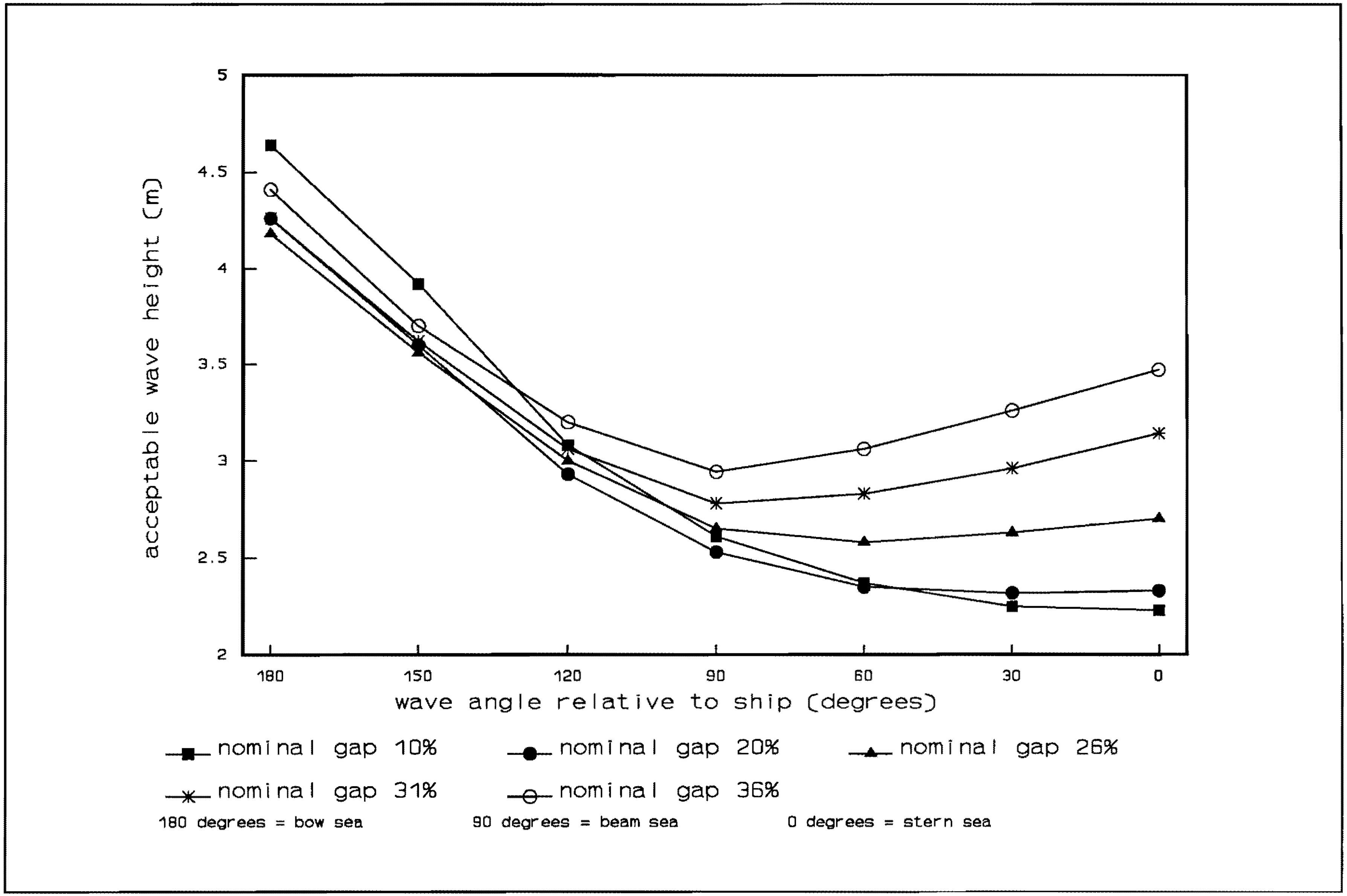
Figure 13 UNDERKEEL results - Ship 1 with 36% ukc

Figure 14 UNDERKEEL results - Ship 2 at 10kts



180 degrees = bow sea 90 degrees = beam sea 0 degrees = stern sea

Figure 15 UNDERKEEL results - Ship 3 at 10kts



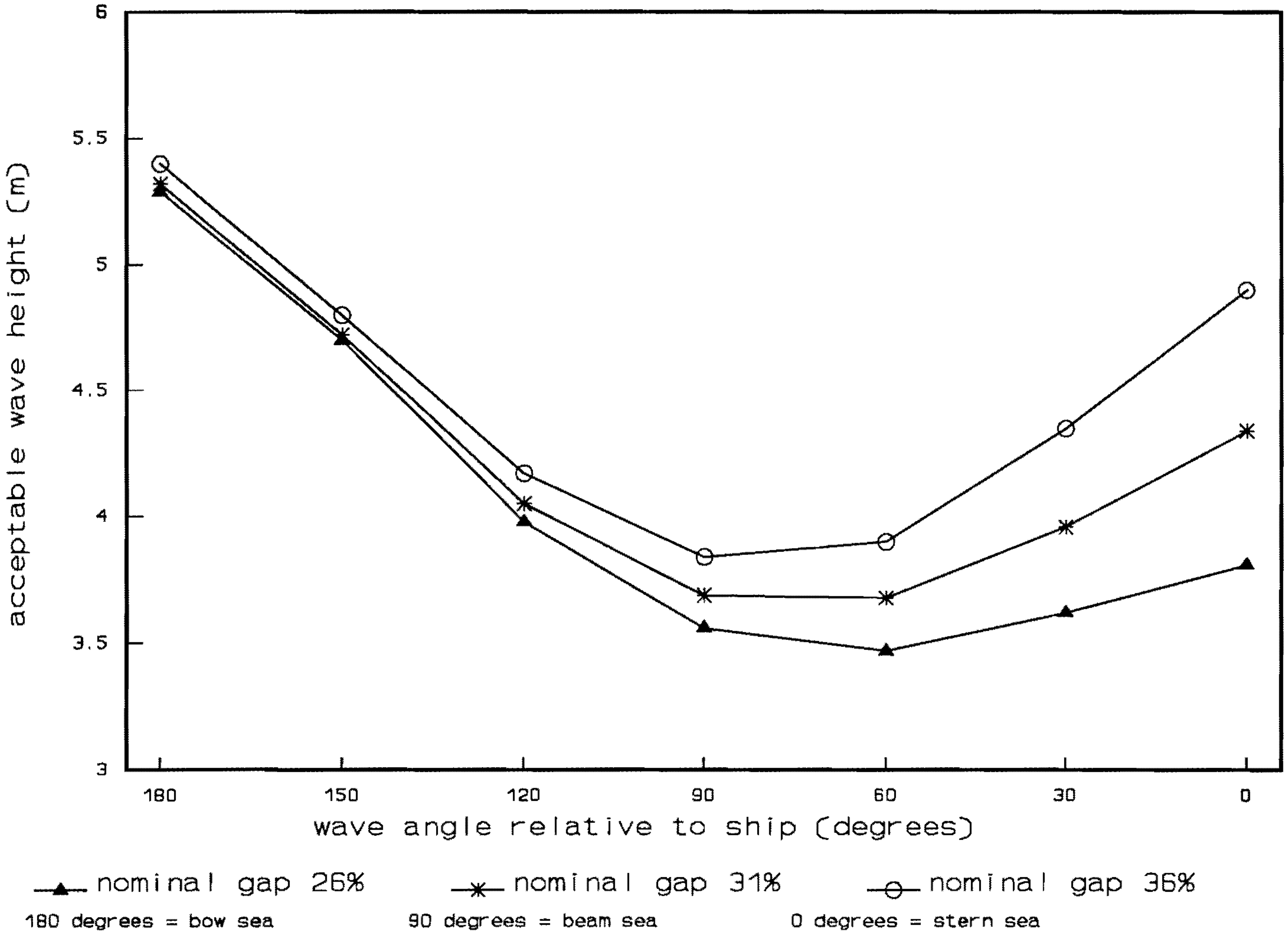
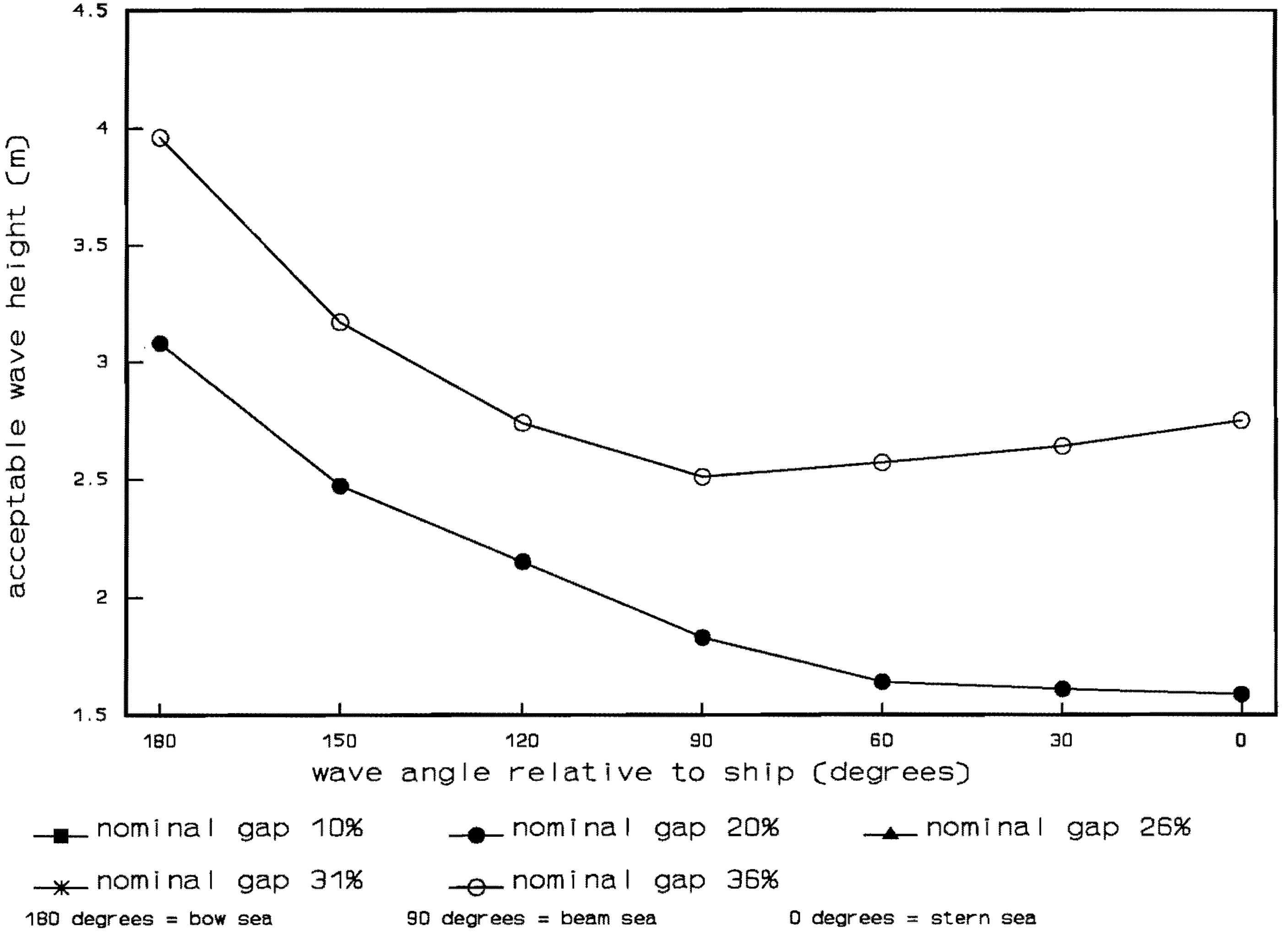


Figure 16 UNDERKEEL results - Ship 4 at 10kts

Figure 17 UNDERKEEL results - Ship 5 at 10kts



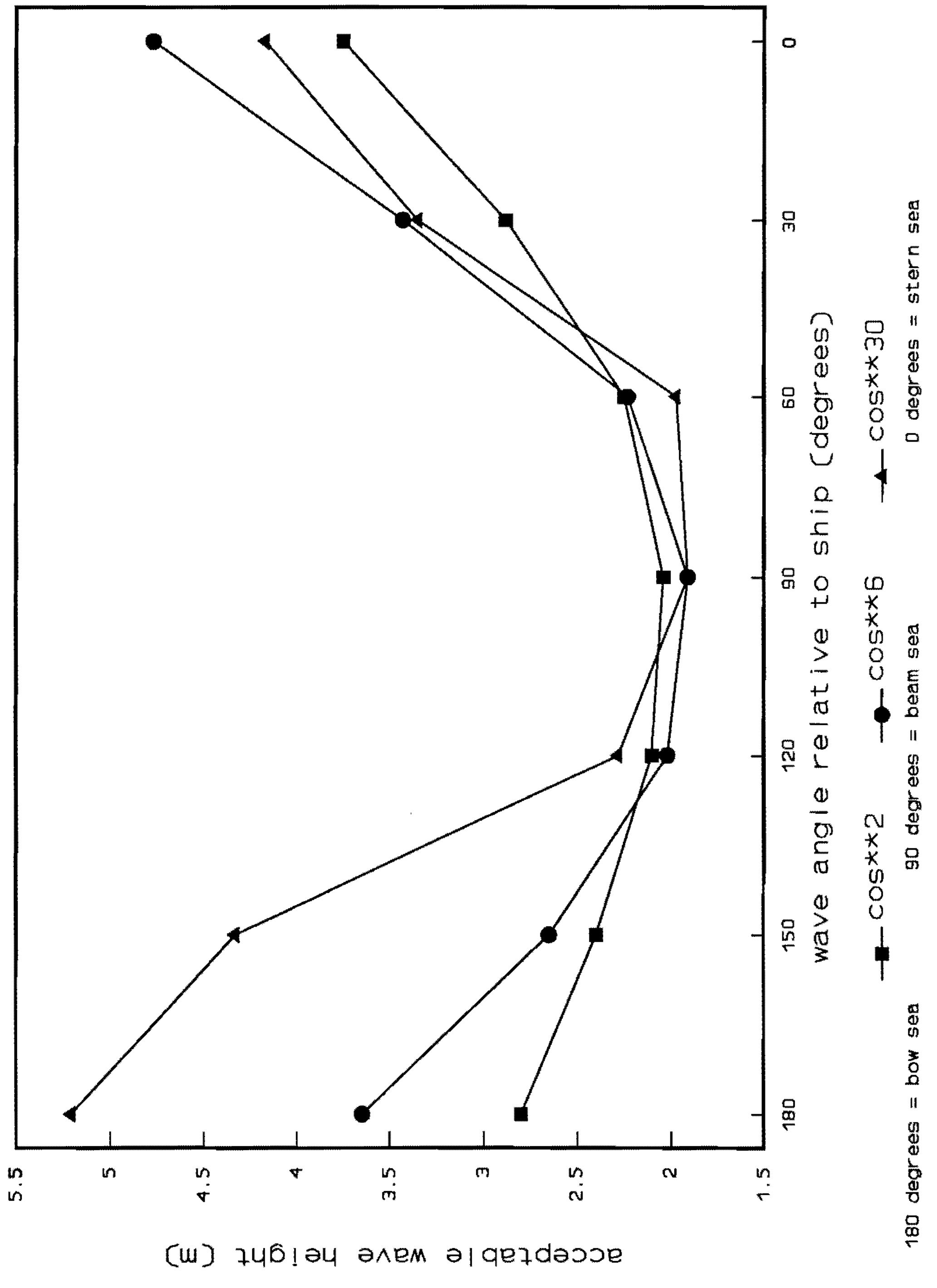
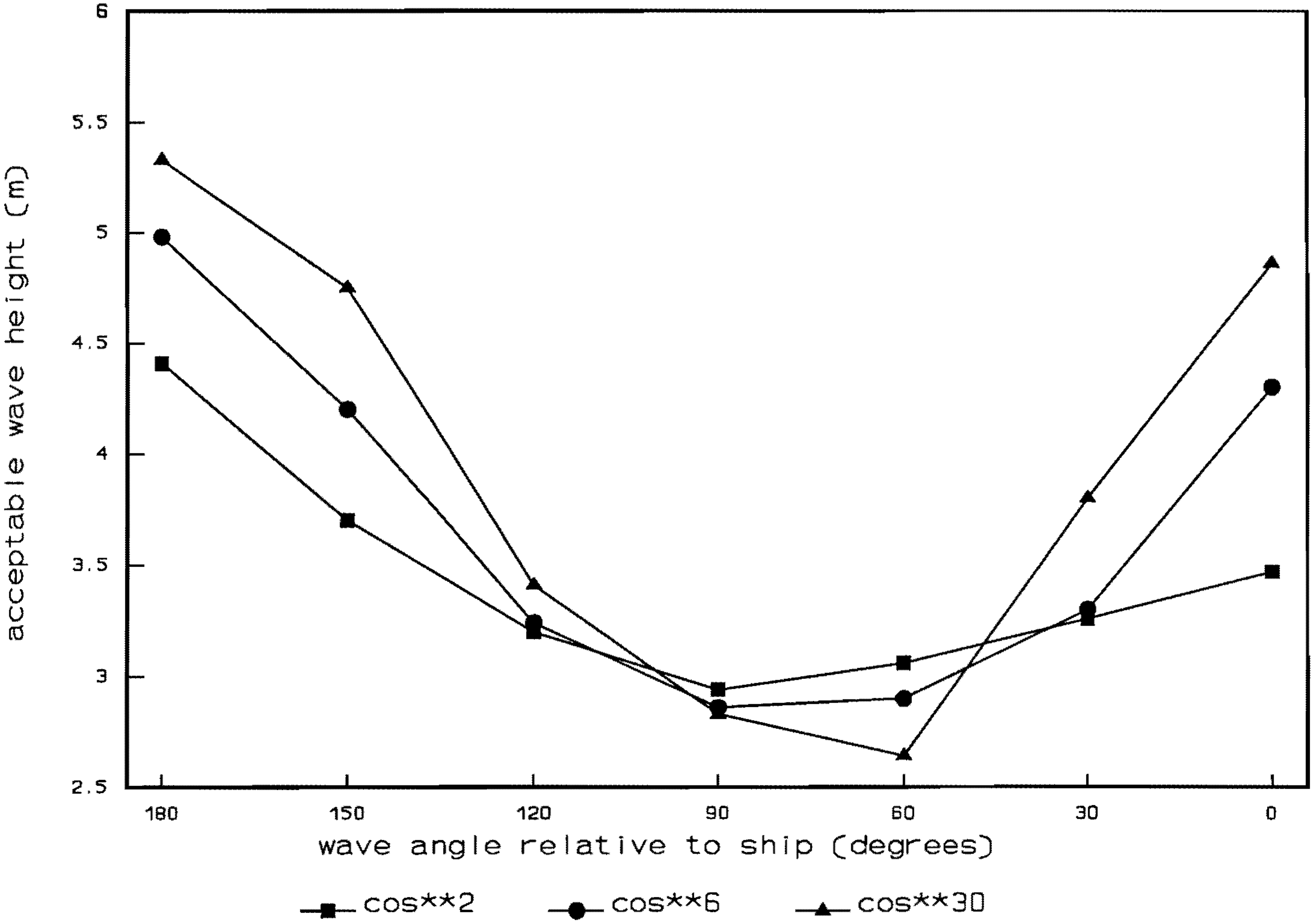


Figure 18 UNDERKEEL results - Ship 1 at 10kts with 36% ukc



180 degrees = bow sea 90 degrees = beam sea 0 degrees = stern sea

Figure 19 UNDERKEEL results - Ship 3 at 10kts with 36% ukc

Figure 20 UNDERKEEL results - Ship 4 at 5kts

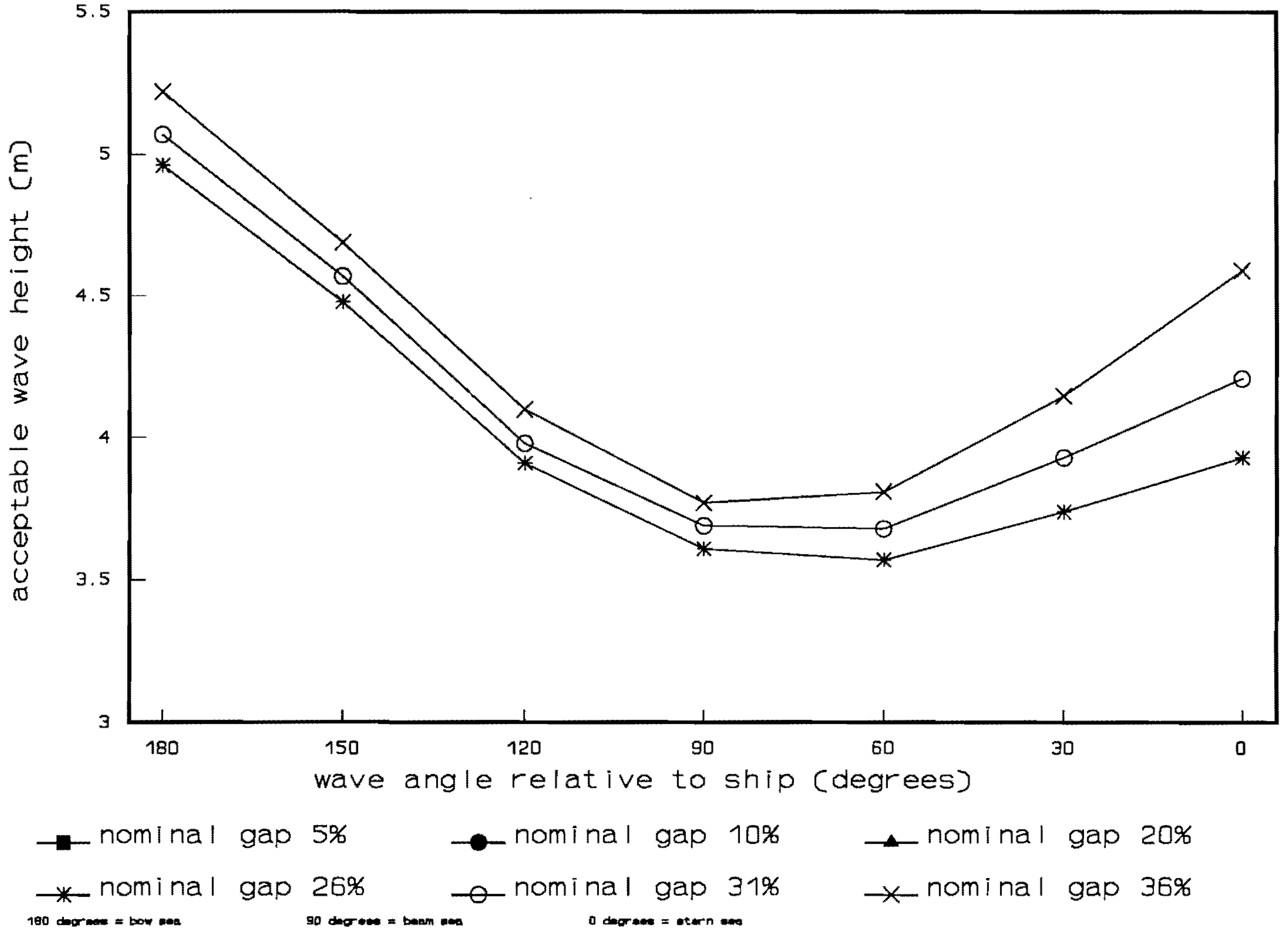
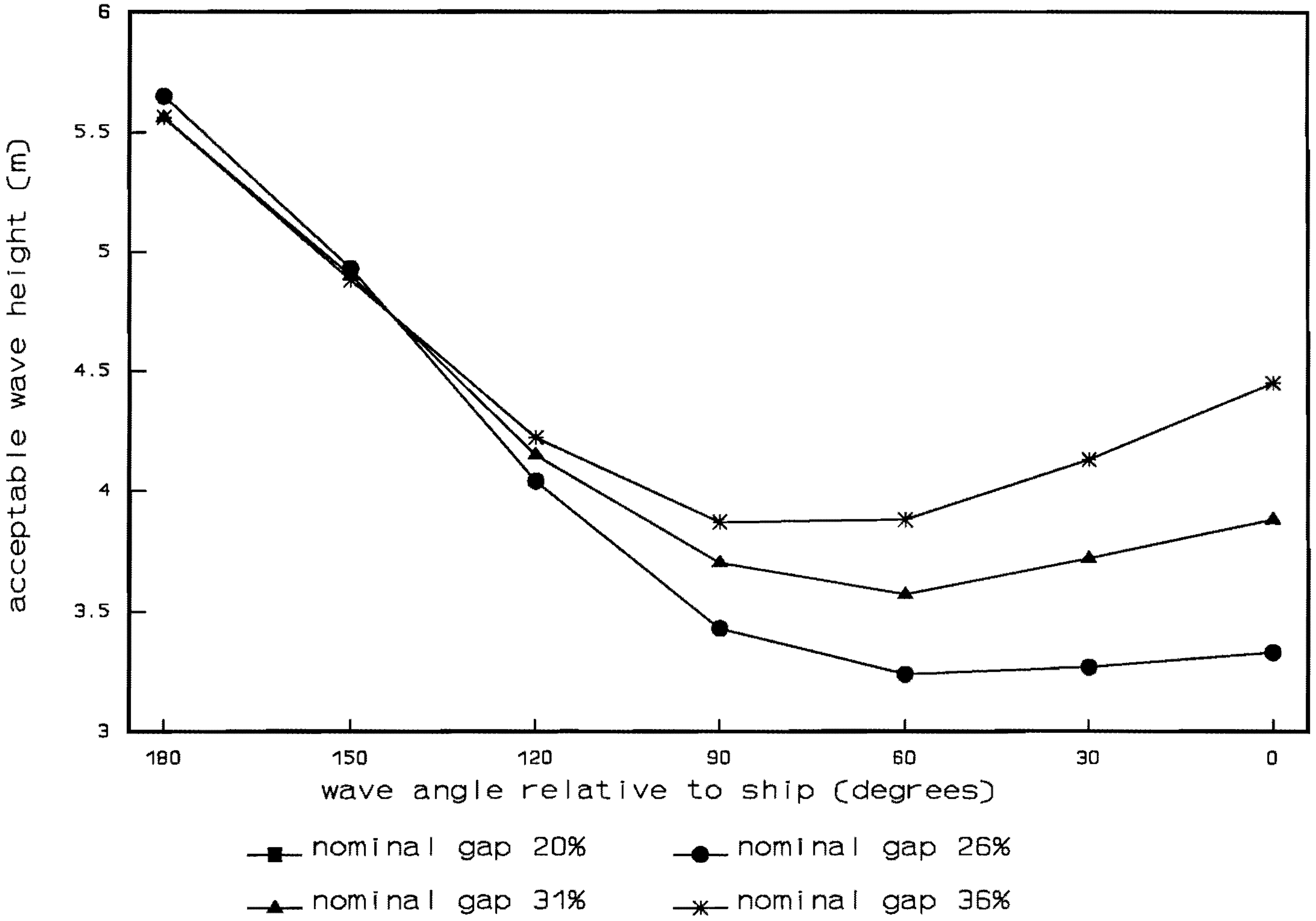
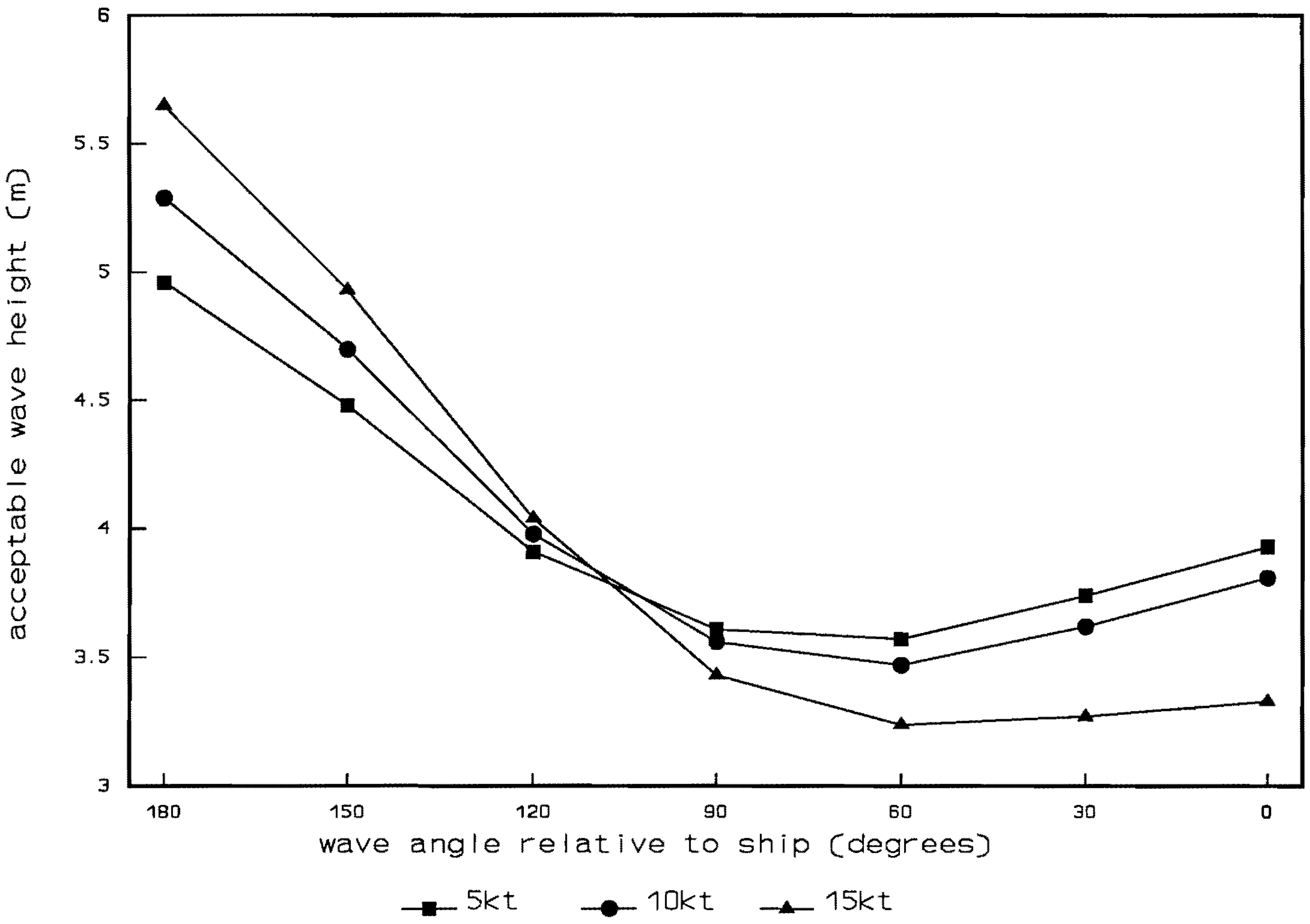


Figure 21 UNDERKEEL results - Ship 4 at 15kts

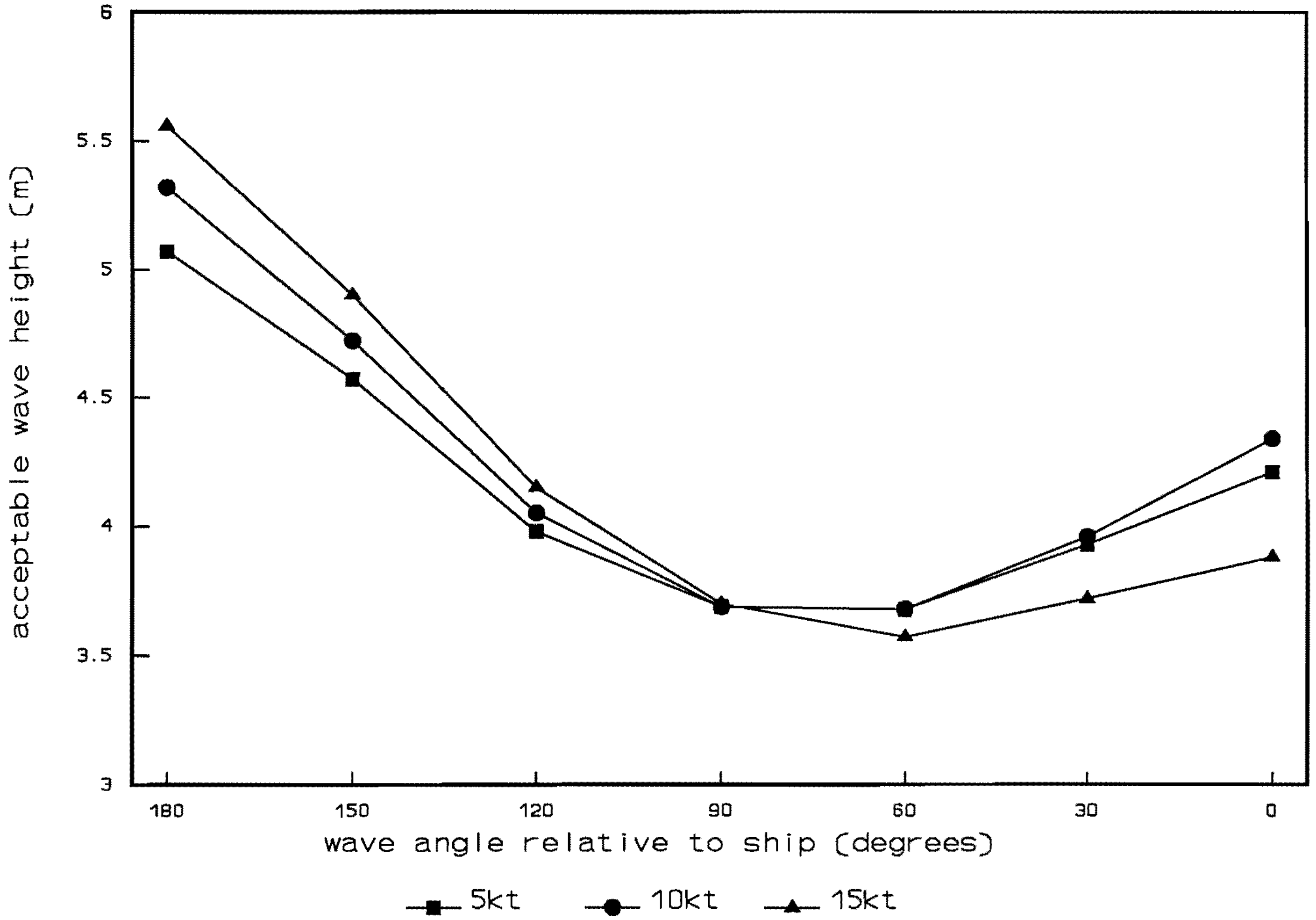


180 degrees = bow sea 90 degrees = beam sea 0 degrees = stern sea

Figure 22 UNDERKEEL results - Ship 4 with 26% ukc



180 degrees = bow sea 90 degrees = beam sea 0 degrees = stern sea



180 degrees = bow sea 90 degrees = beam sea 0 degrees = stern sea

Figure 23 UNDERKEEL results - Ship 4 with 31% ukc

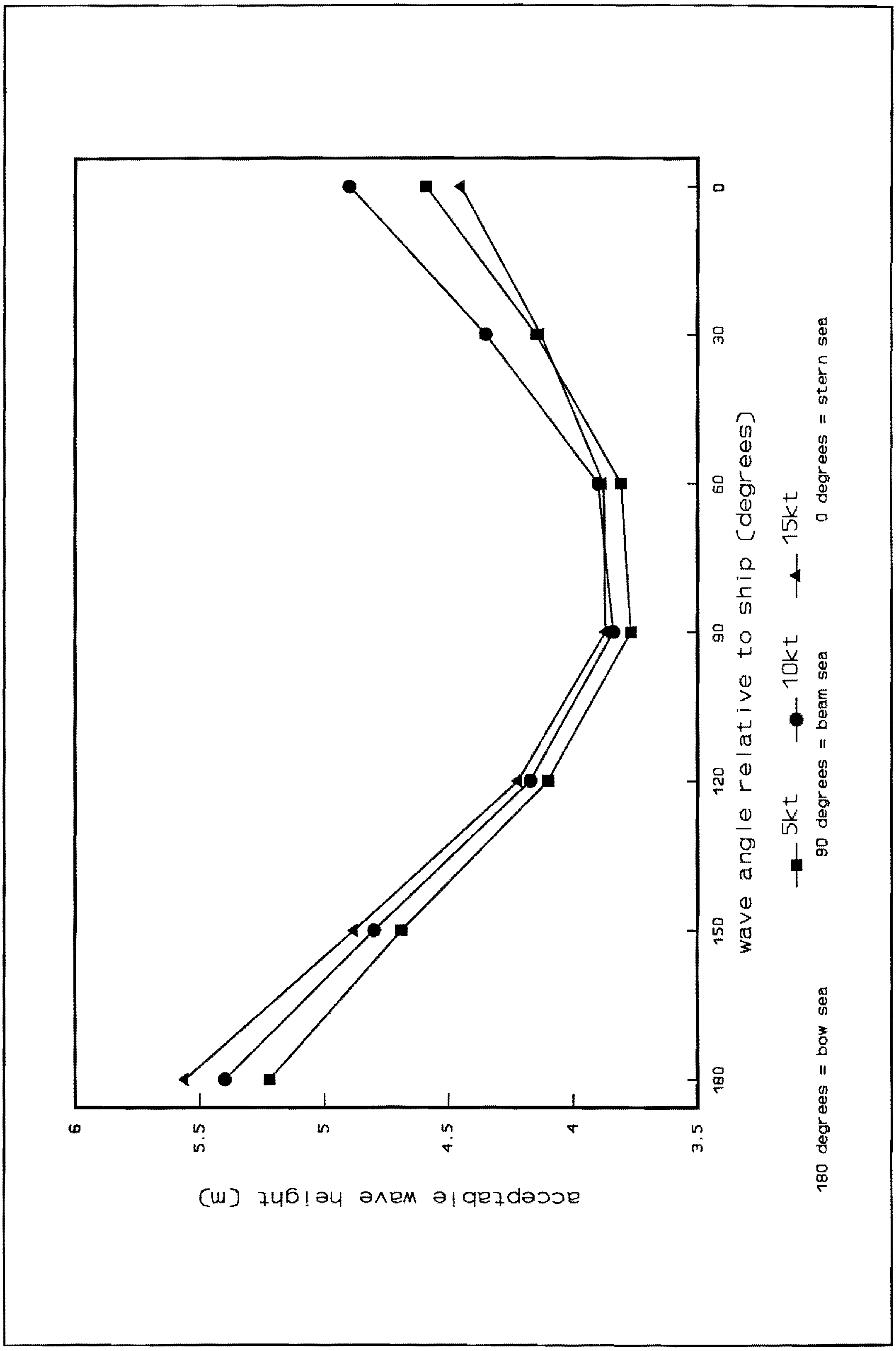


Figure 24 UNDERKEEL results - Ship 4 with 36% ukc

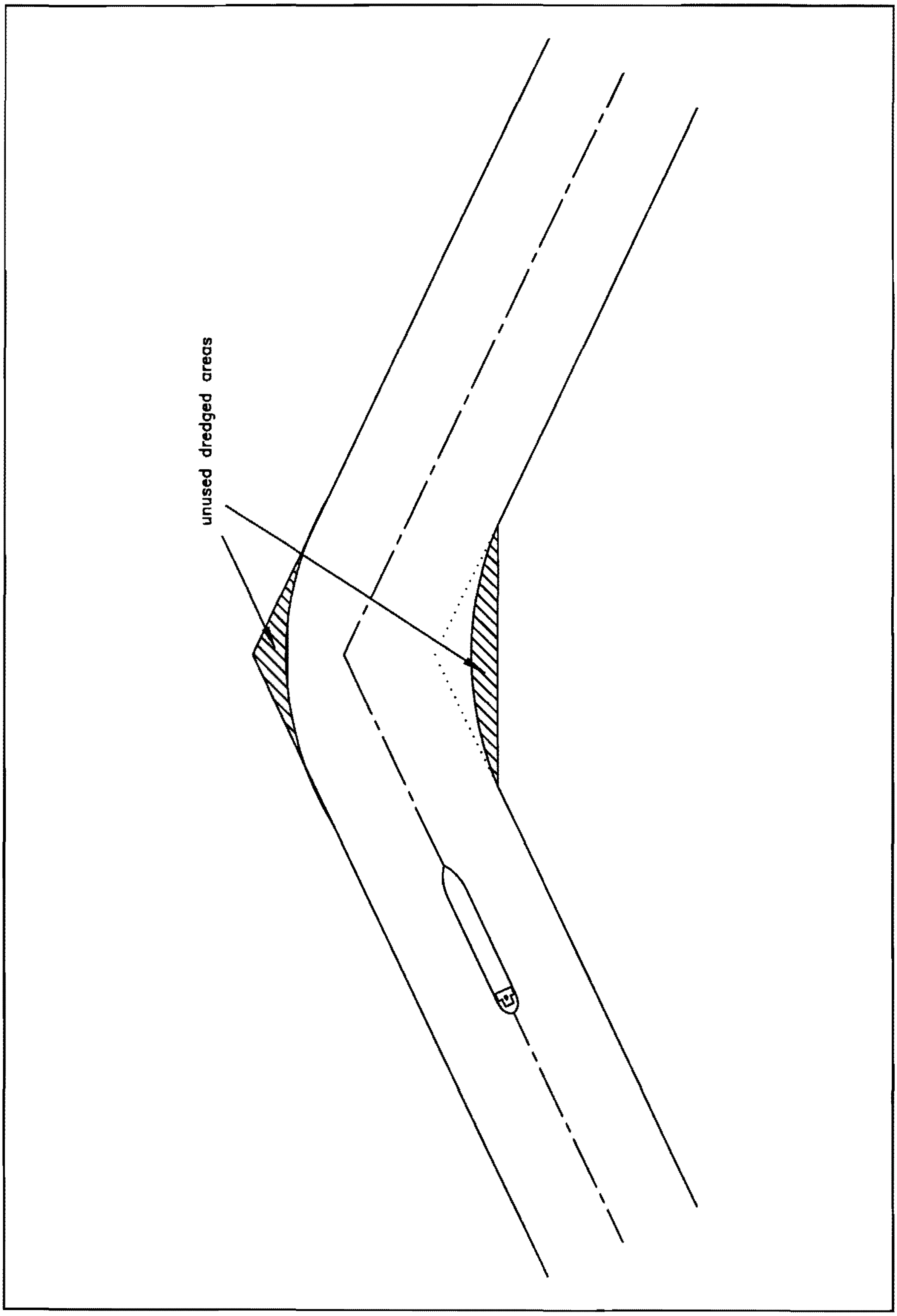


Figure 25 Plan showing unused dredged areas within a channel bend with cut-off widening

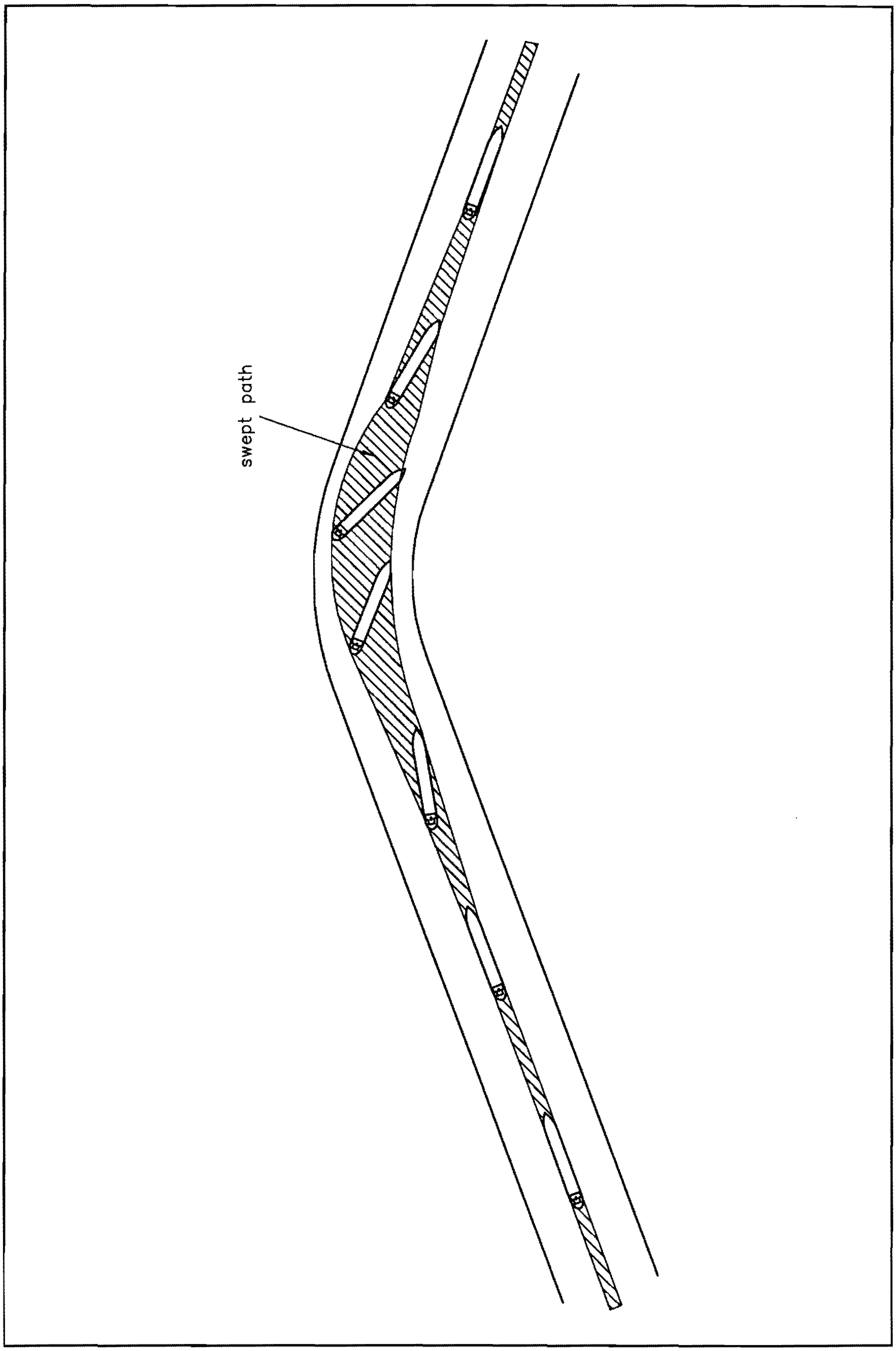


Figure 26 Swept path of a vessel negotiating a channel bend

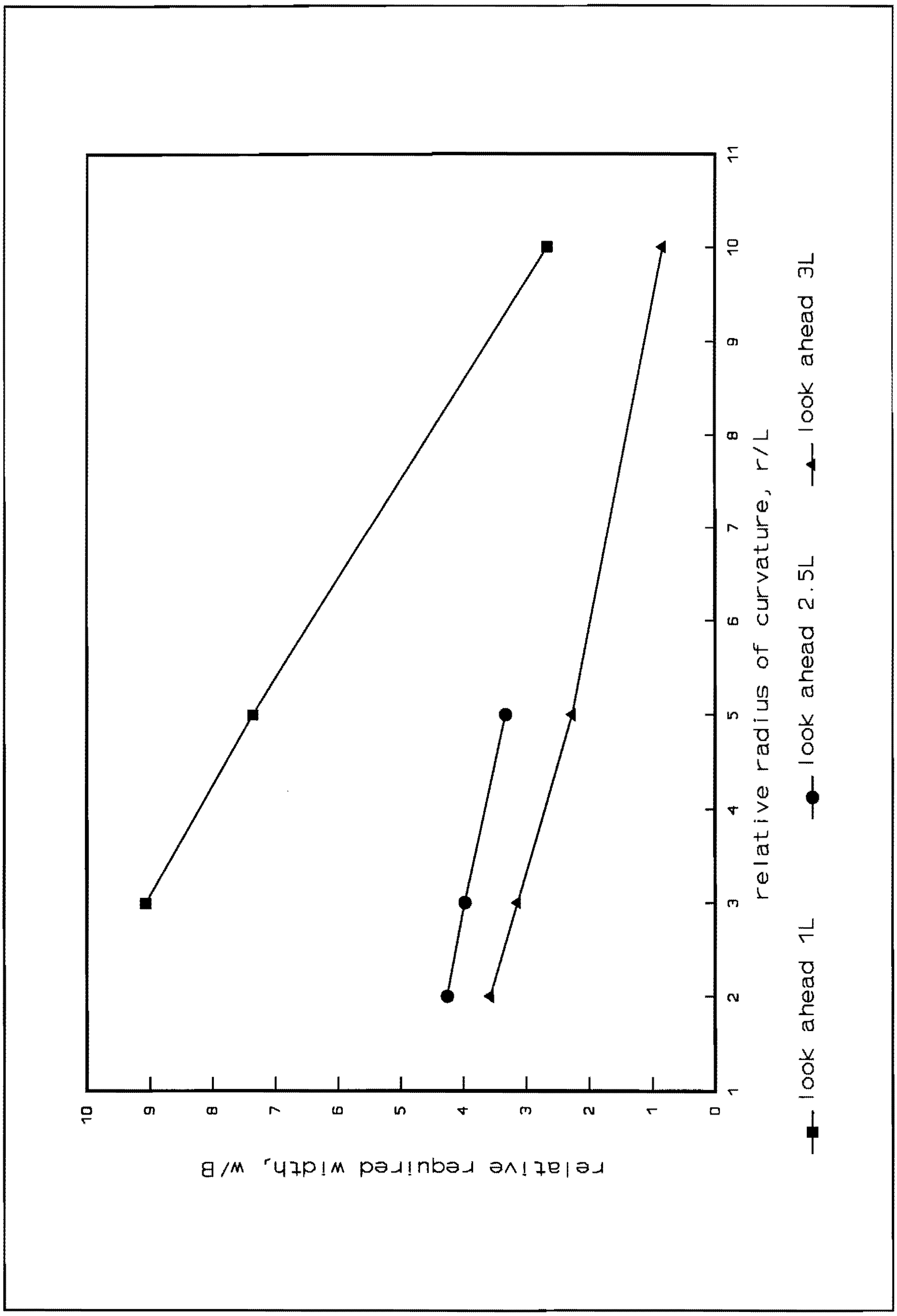


Figure 27 DYNATRACK results - Ship D sensitivity to radius of curvature and look ahead distance

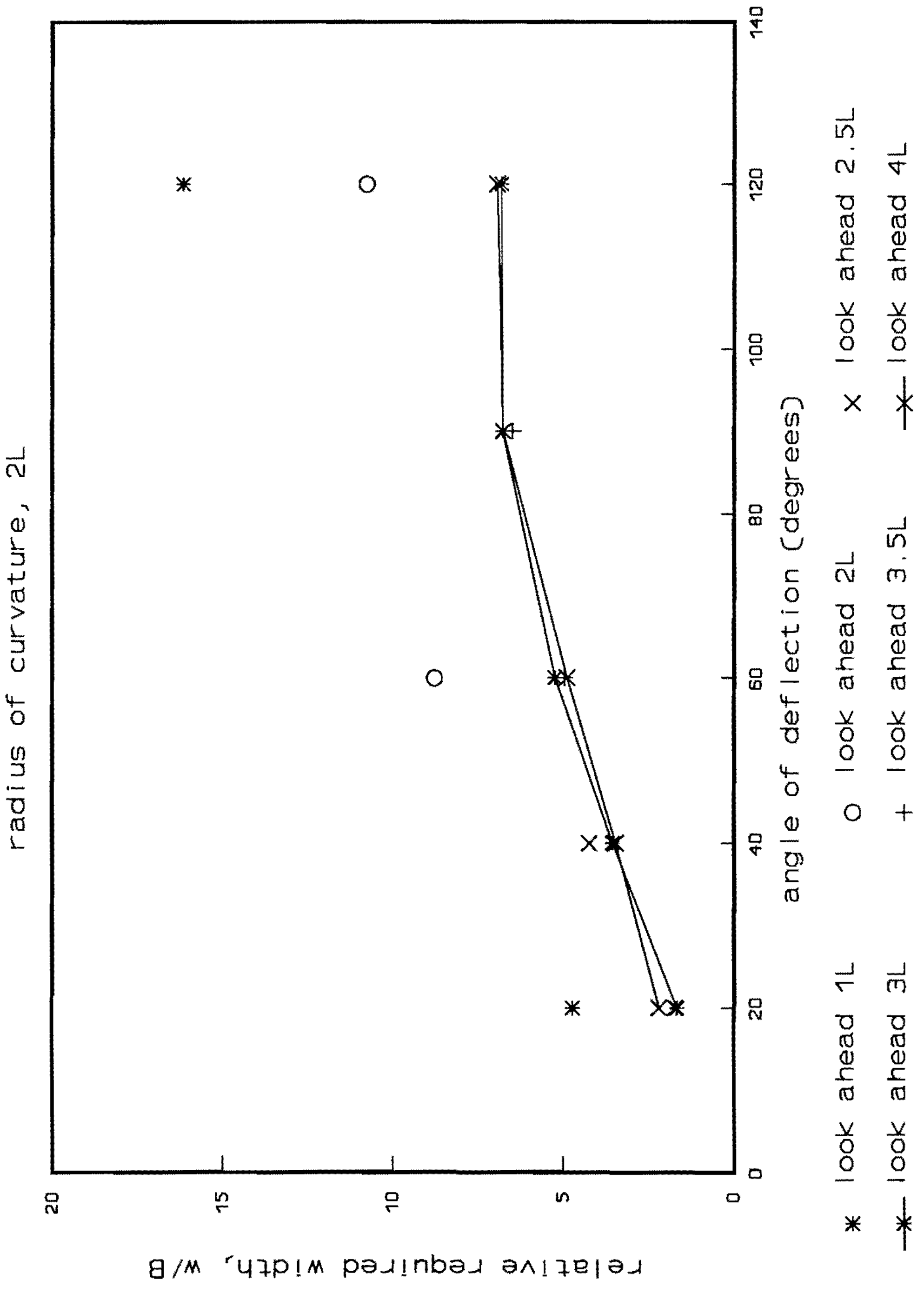


Figure 28 DYNATRACK results - Ship D sensitivty to angle of deflection through channel bend

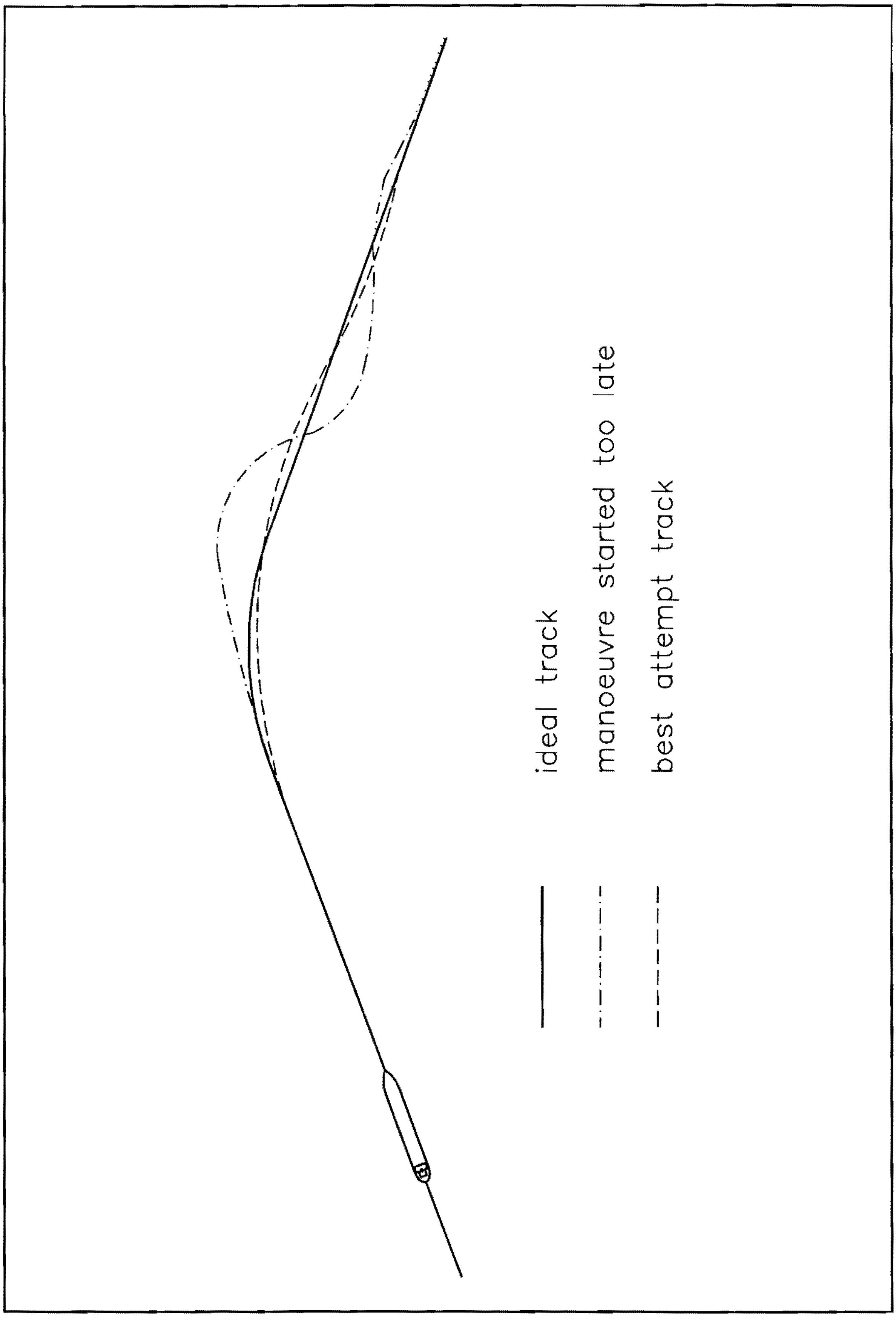


Figure 29 Plan showing typical tracks of vessels negotiating a channel bend

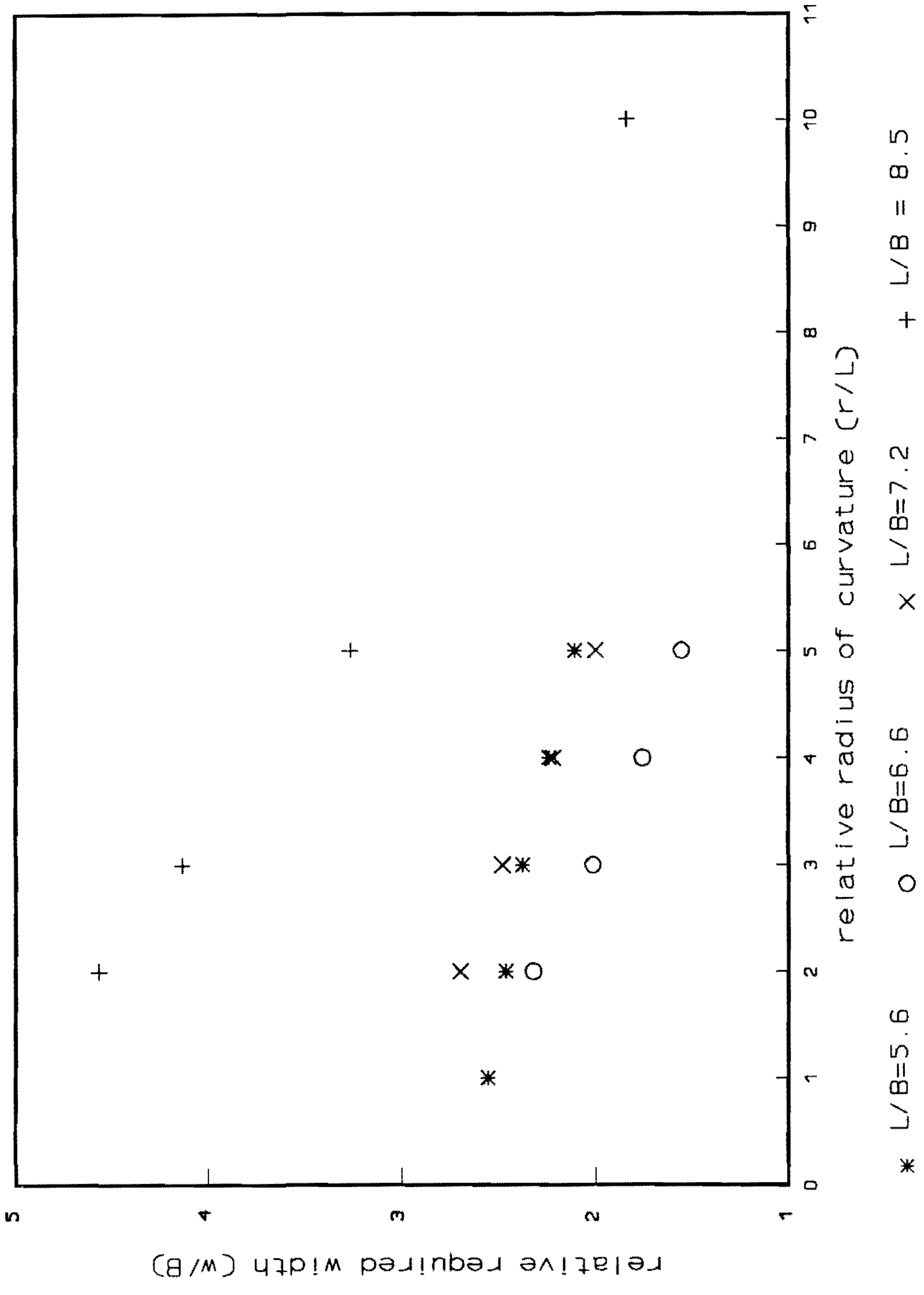


Figure 30 DYNATRACK results - Ships A, B, C and D

Appendices

Appendix 1

Vessel characteristics used in the navigation simulation model

Appendix 1 Vessels characteristics used in the navigation simulation model

Ship A

Type	Passenger Ferry
Deadweight	1,830 t
Length between perpendiculars	119.0 m
Beam	22.6 m
Draught	5.2 m
Depth	12.8 m
Engines	4 x Medium Speed Diesel
Power	17,600 hp
Number of propellers	2
Service speed	21 knots
Windage, lateral	1,852 m^2
Windage, longitudinal	752 m^2

Ship B

Type	Container
Deadweight	41,250 t
Length between perpendiculars	260.8 m
Beam	39.4 m
Draught	11.0 m
Depth	23.6 m
Engine	Slow Speed Diesel
Power	57,000 hp
Number of propellers	1
Service speed	24 knots
Windage, lateral	8,728 m^2
Windage, longitudinal	1,550 m^2

Ship C

Type	Tanker
Deadweight	20,000 t
Length between perpendiculars	165.0 m
Beam	23.0 m
Draught	9.3 m
Depth	11.8 m
Engine	Slow Speed Diesel
Power	9,000 hp
Number of propellers	1
Service speed	16 knots
Windage, lateral	1,000 m^2
Windage, longitudinal	530 m^2

Ship D

Type	Tanker
Deadweight	55,000 t
Length between perpendiculars	273.0 m
Beam	32.2 m
Draught	12.8 m
Depth	19.0 m
Engine	Slow Speed Diesel
Power	23,800 hp
Number of propellers	1
Service speed	17 knots
Windage, lateral	3,161 m^2
Windage, longitudinal	1,066 m^2