CHAPTER 237

Safe Underkeel Allowances for Vessels in Navigation Channels

J M A Spencer, E C Bowers and G H Lean[1]

Abstract

This paper describes methods used at Hydraulics Research to evaluate risks of ships grounding in navigation channels due to wave induced vertical motion. Risk assessments are then used as an aid to optimising channel depths with a view to minimising dredging. A mathematical model of ship response in waves in shallow water is presented and two case studies are considered to show how methods may be applied.

1. Introduction

Modern deep draught ships require long deeply dredged navigation channels for access to many ports. In many cases these are exposed to waves, and it is then necessary to ensure that sufficient allowance is made for vertical movement of any ship using the channel to prevent it damaging itself by bed contact (see Van Wyk and Zwamborn, 1988, for example).

At the same time, it is important not to design too deep a channel: each extra metre dredged in a channel 12 km long and 200m wide (Port Qasim, Pakistan) requires removal of at least an extra 2.4 million m^3 of material. This sort of amount of dredging represents a considerable capital expenditure for any port, and more maintenance dredging may be necessitated to maintain the deeper channel as well - thus adding to the expense.

It is therefore important to design channels to be of optimum depth: deep enough for groundings to be acceptably infrequent, usable in most wave conditions at the site and all at minimum cost. Finding such an optimum channel depth is thus an integral part of port design.

Deciding on depths to which channels should be dredged is an area in which empirical procedures are commonly used: a 'marine expert' is engaged to give his advice based on past experience but

---

[1] Hydraulics Research, Wallingford, Oxon, OX10 8BA, UK

the complexity of ship response in waves makes this a difficult judgement to make with precision. It seems probable that some navigation channels are overdredged due to unnecessarily cautious expert advice, while others suffer excessive downtime because a little too much emphasis was put on saving construction costs. Where such subjective decisions have to be made, departures from the optimum are inevitable.

Physical models using radio-controlled ships underway in random or irregular waves can and should be used as design tools to assist in obtaining an optimum channel. They are the most reliable method for predicting vessel vertical motion, and thus form a reliable basis for assessing bed contact risks. But comprehensive physical model test programmes are expensive and time consuming because of the large number of variables involved: wave direction, wave spectrum, underkeel allowance, vessel type and speed being just some of the major parameters. The cost and time factors have dissuaded many port designers from using model tests in many cases and particularly at early stages in design when little money may be available to develop a fledgling project.

Mathematical models promise to overcome the drawbacks of using physical models in feasibility studies and of over-reliance on expert opinion. Because of this, mathematical models will be of increasing importance in the field in years to come. By making accurate estimates of vessel vertical response, a good mathematical model enables good quantitative estimates of the risk of a vessel grounding in a channel to be made; objectivity can thus be added to necessarily subjective expert opinions, and margins of error in design will be reduced. A mathematical model has the advantage over a physical model of being much quicker and cheaper to use. It therefore has applications in feasibility studies where large numbers of test conditions need to be examined in a short time. Having proved the feasibility of a particular project the physical model should be used to examine critical cases, etc in order to further reduce margins of error.

This paper describes a mathematical model of ship response in waves, called UNDERKEEL. The model has been developed at Hydraulics Research (HR) specifically for coastal engineering applications, and its use for assessing dredged depth requirements in navigation channels is described here. Two case studies will be examined: one considers VLCC safety in the Dover Strait, and another considers the use of the access channel to Port Qasim (Pakistan) by PANAMAX container vessels.

2. Description of the Ship Response Model

UNDERKEEL is a frequency domain model of ship response to waves using calculations of water flow derived from linear potential theory. It being linear, superposition principles are applicable to its output and it can readily be used to compute ship response spectra for any given multi-directional wave spectrum.

The model is intended for use on ships in unprotected channels or moored at open quays; it is not appropriate to problems involving vessels close to wave reflecting obstacles like quay walls and canal banks. It does, however, model moving ship responses to waves as well as stationary ones.

UNDERKEEL has been developed specifically for coastal engineering applications in which the underkeel clearance between vessel hull and seabed is small compared to the vessel beam. Boundary element type models of ship response, commonly used in deep water applications, often have difficulty simulating flows in narrow gaps, and are thus not ideal for coastal usages. The difficulty is overcome in UNDERKEEL by using a semi-analytical approximate treatment of flow in the underkeel region. This gives an accurate model of ship response in shallow water, and has the further advantage of producing a model that is both quick to set up for a new ship and to run.

Standard output from the model is in the form of response functions: amplitudes of ship motion in response to unit amplitude regular waves of specified frequency and direction of propagation. Both horizontal ship movements (surge, sway, yaw) and vertical movements (heave, roll, pitch) can be simulated. As the vertical motions affect bed contact risks, this paper will focus on them although coupling between the various movements is taken into account.

There is a difficulty modelling roll response using any model, like UNDERKEEL, based on potential theory. The problem arises because most of roll damping in nature is due to eddy shedding and other viscous effects that are not present in the model. Adopting a conservative philosophy, we neglect all forms of viscous and eddy shedding roll damping in UNDERKEEL and include only the wave making damping predicted by potential theory; this course of action can be anticipated to lead to over-prediction of roll in nearly all circumstances.

But roll is often not a significant determinant of grounding risks. Most harbour entrance channels are aligned roughly perpendicular to the coastline and approximately colinearly with dominant directions of wave propagation after wave refraction is taken into account. Head and stern seas do not excite roll in ships. Thus, in these channels roll can be anticipated not to contribute to grounding risks.

2.1 Comparison with Experimental Results

Response functions calculated using UNDERKEEL may be compared

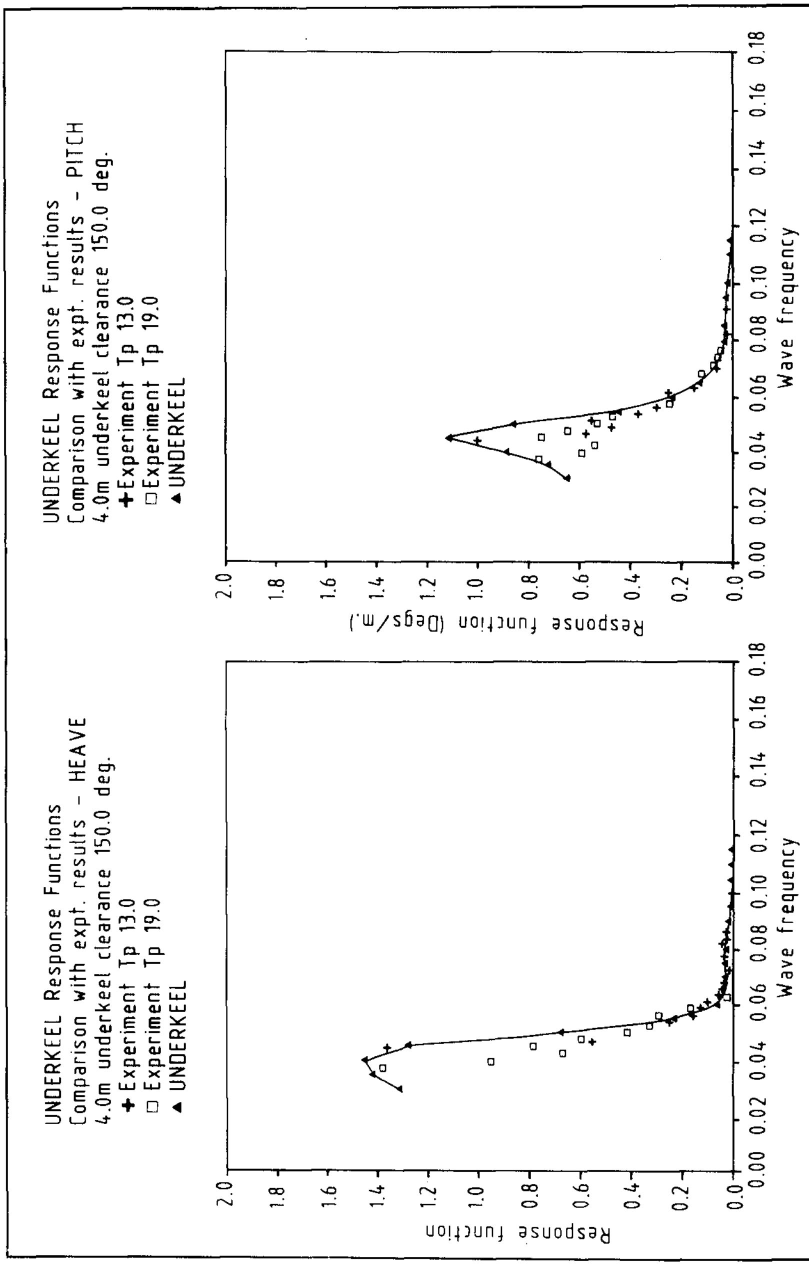

Fig 1(a) Heave at 12kts, 150°.

Fig 1(b) Pitch at 12kts, 150°.

with physical model results. One such set of comparisons is shown in figure 1 for a VLCC sailing at 12 knots. Experimental results were obtained using a 1:100 scale model (radio controlled) of a 330m long, 22m draught VLCC. Details of the experiments are given by Bowers (1989).

The experimental results in figure 1 are for long crested random waves approaching the bow at an angle of 30°. Spectral peak periods are at 13s (significant wave height 5.0m representing storm conditions) and at 19.0s (significant wave height 1.5m representing swell conditions). It can be seen that response functions derived from the two different experimental spectra are similar despite the differing wave heights involved. This similarity of response is good evidence that heave and pitch response is linear which justifies the assumption of linearity made in UNDERKEEL. Comparison between UNDERKEEL and the experimental results show good correlation.

The full physical model programme involved testing the VLCC with a range of underkeel clearances. UNDERKEEL was found to predict the trends in the results very well as the following table shows (% changes in response are presented in going from a 4m to a 6m underkeel clearance).

Wave condition	Sea direction	% change in standard deviation response Physical model	 Mathematical model
T_p = 19s	Stern sea	-5	-5
H_s = 1.5m	Head sea	+33	+33
T_p = 14.5s	Stern sea	-16	-9
H_s = 2.8m	Head sea	+38	+24
T_p = 13s	Stern sea	-11	-5
H_s = 5.0m	Head sea	+25	+33
T_p = 11s	Stern sea	-12	-4
H_s = 4.8m	Head sea	+31	+40

2.2 Comparison with Boundary Element Model

Comparisons have also been made between responses computed using UNDERKEEL and NMI-WAVE developed by Standing (1978), a more conventional boundary element model of a type often used in offshore work. Figure 2 shows a comparison for heave and pitch. Responses in this case are computed for a 320m long hulk with a 60m beam and 24m draught. No physical model data is available for comparison. Response functions are plotted as a function of wave direction for a fixed 0.06 H_z wave frequency. The hulk was stationary. Underkeel clearance was 20% of draught.

UNDERKEEL agrees well with NMI-WAVE but UNDERKEEL requires a great deal less computer time and resources to run; the exact

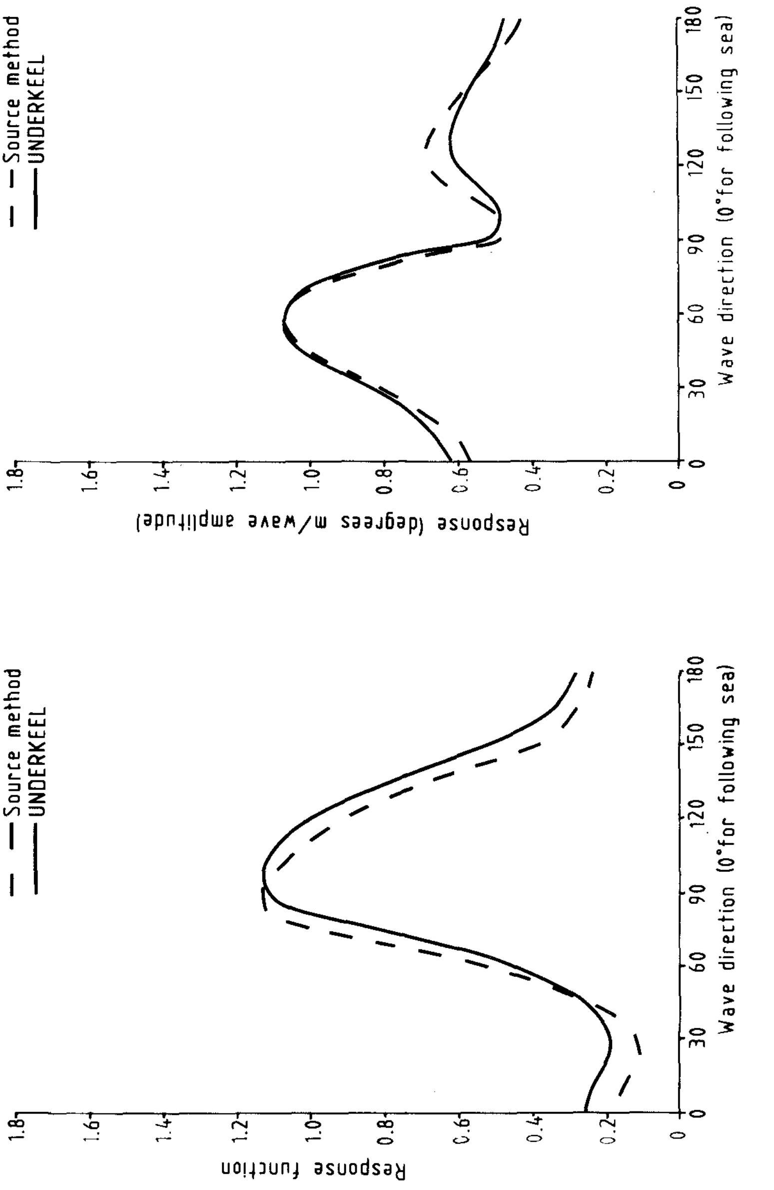

Fig 2(a) Heave response of stationary ship at 0.06Hz

Fig 2(b) Pitch response of stationary ship at 0.06Hz difference will depend on the application, but ten times the speed of calculation should be easily achievable in practice. Perhaps more important, there are similar differences in ease and speed of setting up data describing any ship for calculation. UNDERKEEL is also more easily applicable in the limit of very small underkeel clearances.

3. Grounding Risk Calculations

Given a response function for the vertical motion of a point on a ship hull, $R(f,\Theta)$, which is a function of wave frequency and direction, and which may be obtained using UNDERKEEL, and given also a directional wave spectrum, $S(f,\Theta)$, (directions taken relative to the ship) then the spectrum $S_v(f)$ of vertical movement of the point may be computed:

$$S_v(f) = \int_{\Theta=0}^{360} R^2(f,\Theta).S(f,\Theta)\, d\Theta \tag{1}$$

The root mean square vertical movement amplitude, σ, is calculable from the response spectrum:

$$\sigma = m_0^{\frac{1}{2}} = \left(\int_{f=0}^{\infty} S_v(f)\, df\right)^{\frac{1}{2}} \tag{2}$$

The second spectral moment of response is:

$$m_2 = \int_{f=0}^{\infty} \int_{\Theta=0}^{360} \frac{R^2\ (f,\Theta)}{T_e^2\ (f,\Theta)} S(f,\Theta)\, d\Theta\, df \tag{3}$$

Here, T_e is the ship's response period which contains a Doppler shift due to forward motion. This makes T_e different from the wave period $T = 1/f$.

$$T_e = \frac{\lambda T}{\lambda - TU\cos\Theta} \tag{4}$$

where

λ = wavelength

U = ship speed

The zero up-crossing period of vessel motion - the average period between successive upwards movements through its equilibrium position - is defined as:

$$T_o = \left(\frac{m_0}{m_2}\right)^{\frac{1}{2}} \tag{5}$$

The Gumbel probability distribution was found in experiments

(Bowers, 1989) to define the risk, of points at the bow and stern of the vessel, moving down from its mean position more than a distance d in a stationary sea state producing a root mean square vertical movement σ,

$$p(\sigma,d) = 1 - \exp\left[-\frac{t}{T_0}\exp\left(-\frac{d^2}{2\sigma^2}\right)\right] \tag{6}$$

Here, t is the length of time the vessel is in a channel section,

$$t = \frac{\text{channel section length}}{\text{vessel speed}}$$

Such a distribution can be expected if the vessel response is linear, which appears to be the case for heave and pitch.

In general, and in the two applications that follow, navigation channels are aligned such that the vessels using them do not experience particularly beamy seas. In these cases rolling is not sufficient to cause quarter points on the keel to experience the largest downward movements. Therefore, we assume points on the vessel at the bow and stern experience the largest vertical movements. The probability p defined by equation (6) is simply the risk of grounding of a given point on the vessel if the mean underkeel clearance, when underway, is equal to d. We make the further assumption that risks at the bow (p_b) and stern (p_s) are independent (they typically have different average movements and periods) leading to a conservative estimate of the total risk of grounding (p_t)

$$p_t = p_b(\sigma_b,d) + p_s(\sigma_s,d) - p_b(\sigma_b,d)\ p_s(\sigma_s,d) \tag{7}$$

Thus, using UNDERKEEL we can calculate the risk of grounding in waves with a directional spectrum $S(f,\Theta)$ using equations (1) to (7).

For determining design criteria for channels, figures such as the expected number of groundings in a year's (or century's) operation are required. This would depend on the volume of traffic through the port and on average bed contact risk to vessels in all wave conditions.

This average risk is found by weighting risks in different wave conditions according to the likelihood of those wave conditions occurring and then summing. In outline, wave prediction in a typical ship response application would involve parameterisation of offshore wave spectra. Using significant wave height, H_s, and mean wave direction, $\bar{\Theta}$; a probability function (eg Weibull) is fitted to parameterised offshore wave data. A number of offshore wave spectra describing wave conditions of specified return period from different directional sectors are constructed and then refracted inshore to positions along the navigation channel by mathematical modelling. Ship responses can then be computed in these inshore waves.

If $p_t(H_s, \bar{\Theta}, d)$ is the risk of grounding in the channel in wave conditions with an offshore significant wave height H_s and mean direction $\bar{\Theta}$, and $f(H_s, \bar{\Theta})$ is the probability density function for those wave conditions, then the average risk of grounding in a transit through the channel with an underkeel clearance d is:

$$P(d) = \int_{\bar{\Theta}=0}^{360} \int_{H_s=0}^{\infty} p_t(H_s,\bar{\Theta},d) .\ f(H_s,\bar{\Theta})\ dH_s\ d\bar{\Theta} \qquad (8)$$

In the applications that follow two approaches to the calculation of safe underkeel allowances are used. In one approach the requirement is assumed to exist that safe passage must be possible in all weather. Having (subjectively) decided on an acceptable risk (P_{acc}) of grounding, equation (8) can be used to find the underkeel allowance (d) for vessel motion in waves that produces that risk

$$P(d) = P_{acc}$$

In an alternative approach a limit can be placed on the wave conditions in which it is safe to transit the channel. This limit must, of course, lead to an acceptable level of channel downtime. In this case the underkeel allowance (d) has to be chosen to satisfy

$$\int_{\bar{\Theta}=0}^{360} \int_{H_s=0}^{x} p_t(H_s,\bar{\Theta},d)\ f(H_s,\bar{\Theta})\ dH_s\ d\bar{\Theta}\ +$$

$$\int_{\bar{\Theta}=0}^{360} \int_{H_s=x}^{\infty} p_t(x,\bar{\Theta},d)\ f(H_s,\bar{\Theta})\ dH_s\ d\bar{\Theta} = P_{acc} \qquad (9)$$

In the above, the limiting H_s value is x and if the wave height exceeds x when a vessel arrives, passage is assumed to take place after waiting for the wave height to drop to the acceptable level.

In both the "all weather" and "weather window" approaches it is also important to ensure that individual risks to a vessel, as defined by (6) and (7) are acceptable in extreme conditions, eg the 100 year storm for an "all weather" channel and limiting conditions in the case of "weather windows".

4. Case Study I - Dover Strait

The Dover Strait is not a harbour navigation channel, but it poses similar problems for the transit of Very Large Crude Carriers (VLCCs) with draughts of up to 22m carrying oil to Rotterdam. On this north east (NE) bound route charted depths (at lowest astronomical tide) of 27.5m occur in known sand wave areas with a large uncertainty in seabed level.

The planning guide for the NE route (Deep Draught Planning Guide 1985) makes no use of the tide to aid passage (the passage takes about six hours in normal weather so delays due to fog could result in a vessel experiencing low water) and no particular restrictions are placed on weather conditions during passage. This guide recommends an underkeel allowance of 5.7m for a 22m draught VLCC in the central region of the Strait. Given all the factors to be taken into account: vessel movement in waves, vessel squat, negative tidal surges, seabed level uncertainties, the quoted allowances are not obviously safe. As a result the UK Department of Transport approached Hydraulics Research (HR) with a view to independently establishing safe allowances within the Strait. The work at HR involved both mathematical modelling (to predict wave climates and vessel response using UNDERKEEL) and physical modelling (to verify UNDERKEEL).

For wave prediction purposes the deep water NE bound route was divided into eight sections. In each section, storms with return periods of 3, 10, 30 and 100 years from all relevant directional sectors were predicted. Corresponding wave spectra were obtained taking into account local wave generation by winds and refraction around the many sand banks. Similarly, spectra were obtained for swell waves after taking into account refraction. The model used to make these predictions made use of extensive wind records after calibration against measured data from the Sandettie WSW buoy and the Dyck and Varne light vessels. The comparison between measurements and hindcasts from the prediction model showed good correlation provided wave refraction was taken into account.

It was then necessary to obtain ship responses. This was a two stage process. The first stage was done entirely by mathematical modelling using UNDERKEEL in the manner described earlier in this report. Grounding risks were estimated on the basis of these results and critical parameters identified.

In stage two physical model tests were performed to calibrate UNDERKEEL (see section 2.1 of this paper). This calibration showed good correlation between the physical model and UNDERKEEL and it was deemed better to base our definitive risk calculations on calibrated UNDERKEEL responses rather than on purely physical model results. This avoided a very large physical model test programme.

All risk calculations we did were based on a typical VLCC hull form: sensitivity tests carried out with UNDERKEEL having already been carried out in stage one of the study to quantify the effects of varying hull dimensions, ship speed and underkeel clearances.

A feature of the Dover Strait is that depth uncertainties are a greater factor in risk assessment there than they are likely to be in a normal navigation channel. They arise from several causes. Surveying inaccuracies, which are likely to be greater in the open sea. Bed mobility - at certain places sand waves and dunes encroach into the deep water channel, and these constantly move around. Storm surges can reduce grounding risks because those storms causing the greatest vessel movement in the Dover Strait will tend to raise water levels. However, some storms (producing little vessel movement in the Strait) can cause a negative surge and such surges could occur at the same time as swell in the Strait.

We had to modify equation (8) to take account of all these possible depth uncertainties by introducing a probability density function, g(x), expressing the likelihood of depth variations. The probability calculation became:

$$P(d) = \int_{\bar{\Theta}=0}^{360} \int_{H_s=0}^{\infty} \int_{x=-\infty}^{\infty} p_t(H_s,\bar{\Theta},d+x)\ f(H_s,\bar{\Theta})\ g(x)\ d\bar{\Theta}\ dH_s\ dx \tag{10}$$

Using this probability calculation and ship responses from the calibrated model, and adding an allowance for vessel squat and trim underway, the following acceptably safe allowances were obtained:

NE vessel route	HR allowance	Planning Guide (Neth. Navy)
West of the Strait	6.2m	6.5m
	9.5m	6.5m
Central part of Strait	5.7m	5.7m
	5.3m	5.7m
	6.4m	5.7m
East of the Strait	6.4m	6.5m

On the whole, the HR results agree well with the Dutch allowances for the NE bound route. Only in two sections (one west of the Strait and one in the central part of the Strait) does HR suggest a larger allowance. In these sections tankers are exposed to quartering seas, which UNDERKEEL and physical model tests agree are prone to cause particularly large pitch responses as well as rolling. However, these sections are deep enough not to affect vessel safety.

5. Case Study II - Port Qasim

Port Qasim is a developing port in Pakistan on the Indus Delta. Its approach is by a 12km long outer navigation channel with, until recently, a maintained depth (after allowing for siltation) of 12.4m CD through an offshore sand bar. This outer channel has experienced severe sedimentation problems due to combined wave and current action. Wave heights along the outer channel have been monitored using waverider buoys. Although primarily for sedimentation study purposes, this supply of high quality, frequently sampled wave data from several points along the channel was also of immense help in predicting waves at the site for use in estimating safe underkeel allowances.

In 1987, Port Qasim Authority (PQA) proposed a container facility at the port for handling PANAMAX vessels of up to 12m draught. Such ships would obviously require deepening of the approach channel, particularly for service during the months of the south west (SW) monsoon (May-September) when significant wave heights at the Fairway Buoy can reach over 3.5m which, with spectral peak periods of 13 seconds, will cause considerable vertical vessel movement. The question was how much deeper should the channel be? Hydraulics Research was commissioned to investigate.

Offshore wave predictions were based on visual observations of wave heights and directions by shipping in the Arabian Sea. This was necessary because waveriders do not record wave direction. Predicted wave spectra were then refracted inshore. The waverider records then formed an excellent check on the accuracy of these offshore predictions and the resulting refraction process after allowing for bottom friction. Bottom friction was found to be a significant factor in attenuating inshore wave energy. The calibration against measured data resulted in friction factors that were in the expected range (0.01 to 0.04). Good correlation was achieved between measured and predicted wave spectra at various points along the channel showing that wave height variation along the channel was well predicted.

Having predicted wave conditions, grounding risk calculations were as described in section 3 of this paper. To date, no physical model tests have been authorised for this study so responses are based solely on UNDERKEEL. The hull form used represented a third generation container vessel 207m long sailing at 11 knots. Sensitivity tests were performed to check the effects of underkeel clearance and of vessel speed and dimensions (including testing a 280m long, fourth generation hull, which proved far less vertically mobile than the much shorter version).

Our standard case was chosen for being the one that moved most in Port Qasim wave conditions.

Calculations indicated that, after taking into account allowances for vessel squat, set-down and vertical motion in waves, the maintained depth of the approach channel would need to be increased by at least 4.6m to allow acceptably risk-free all weather operation at high tide in June and July, at the peak of the monsoon. Dredging could be minimised by only deepening the more exposed outer 8km length of the approach channel but it was anticipated the costs involved would still make the scheme unviable.

Instead, the adoption of weather windows was suggested. PQA already had much successful experience of operating waverider buoys, and this experience could be utilised in monitoring wave heights at the seaward end of the channel (which is not visible from the port itself). The following table shows the percentage of time month by month we estimated the channel would be usable if a weather window were introduced for various underkeel allowances for vessel motion in waves (2m was available at high tide in the channel with a declared depth of 12.4m CD after allowing for vessel squat and trim).

	u/k allowance for vessel movement in waves (metres)				
Month	1	2	3	4	5
April	97	100	100	100	100
May	83	96	100	100	100
June	0	2	34	73	89
July	0	0	14	52	83
August	13	33	60	85	100
September	77	91	99	100	100

Thus, deepening the channel by 3m to give an underkeel allowance of 5m (instead of deepening by 4.6m for all weather operations) and using a weather window controlled by a standard waverider would allow almost uninterrupted port operations throughout the year except in June and July. In those months three to five days of disruption of container traffic is expected. This might be more acceptable than the cost of dredging and maintaining an all weather channel.

Also, one effect of deepening the channel would be to change wave refraction patterns; in general, a deeper channel would be expected to refract more waves away from itself, resulting in a calmer sea with less grounding risk and less channel downtime. In practice then, the 83% expected utilisation in July is probably an underestimate.

A further possibility, and one we recommend to PQA, is to measure wave direction as well as height at the channel entrance.

This can be done using a directional wave buoy. Vessel response is very sensitive to wave direction, so fairly high waves from some sectors generate less response than lower waves from other directions. This sensitivity can beneficially be built into weather windows. By allowing operation in higher waves from less sensitive directions, we estimate June-July channel usage can be greatly improved. For example, with just a 3m underkeel allowance and a directional weather window, the channel would be usable 58% of the time in June and July instead of an average usage of 24% for the two months with non-directional wave monitoring.

6. References

BOWERS, E C (1989). Safe underkeel allowances for vessels in restricted depths. Recent Advances in Hydraulic Physical Modelling, Lisbon, Portugal. NATO ASI Series E Vol 165, Kluwer Academic Publishers.

Deep Draught Planning Guide. Greenwich Buoy to Europoort for vessels with a draught between 20.7m and 22.0m. Second edition (1985). Published by the Hydrographer fo the Royal Netherlands Navy.

STANDING, R G (1978). Applications of wave diffraction theory. Int J Num Meth in Engrg, Vol 13, p49.

VAN WYK, A C and ZWAMBORN, J A (1988). Wave induced ship motions in harbour approach channels. Proceedings of 21st ICCE, Malaga, Spain.