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Ship Underkeel Clearance in Waves

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Abstract
A method is described for combining squat, heel and wave-induced motion calculations into an overall underkeel clearance (UKC) assessment, based on the “dynamic draft” at all the corners of the ship. Particular attention is given to predicting ship motions in shallow water. The effects of resonant roll, wave spreading and extreme motions are discussed. A general UKC assessment is proposed, valid for calm water or swell conditions. The principles are applicable to long-term UKC assessment for dredging optimization, as well as assessing specific transits through port approach channels, based on real-time or forecast wave conditions.

1 Introduction

The exposed coastlines around Australia and New Zealand mean that many of our port approaches experience long-period swell conditions. Ship vertical motions due to long-period swells have contributed to some recent grounding incidents, including Capella Voyager and Eastern Honour at Whangarei in 2003 (see www.msa.govt.nz). Having a better understanding of underkeel clearance in waves is an important issue in our region.

By contrast, most ports in Europe and Asia are fairly well-protected from long-period swells. Therefore the study of underkeel clearance in waves has not received much attention on a global scale to date.

The application of underkeel clearance calculations in waves falls into two main categories:

1. Choosing optimum dredging depths for approach channels, using measured annual wave climate
2. Developing underkeel clearance guidelines or software, for assessing the safety of specific ship transits

Here we shall describe how wave response calculations can be combined with other components of underkeel clearance. Methods for accurately calculating wave response in shallow water will also be discussed.

2 Components of underkeel clearance

Figure 1 shows the additive components in calculating underkeel clearance (UKC) of a ship in shallow water.

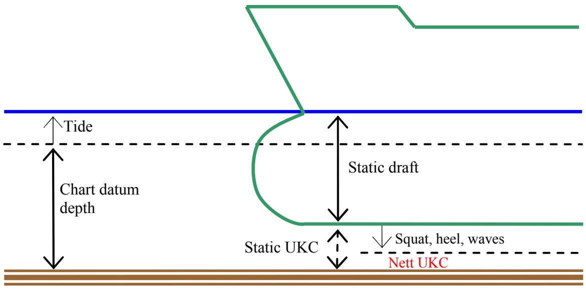

Figure 1: Components for calculating UKC of a ship in shallow water

In order for the transit to be considered safe, the “Nett UKC” must always remain greater than a pre-determined safety margin. The Nett UKC is calculated as follows:

[Nett UKC] = [Chart datum depth] + [Tide]
– [Static draft]
– [Squat, heel and wave response] (1)

According to experiments made by Guliev (1971) and Huuska (1976), the squat of a ship in waves is very similar to the squat of a ship in calm water. Therefore squat and wave response can be calculated independently and then the effects added together. Heel is also assumed to be uncoupled from squat and wave response.

Although squat, heel and wave response are calculated independently, these must be combined together before determining the overall allowance. This is because they each cause vertical motions at different parts of the ship, so that the combined allowance is less than the sum of the individual allowances.

The contribution of squat and heel to UKC will now be described briefly.

2.1 Squat

Several methods for predicting ship squat are described in the PIANC (1997) guidelines. For open water or a wide channel of near-constant depth, a method that is suitable for bulk carriers, tankers and containerships is based on Tuck’s (1966) shallow-water slender body theory. This predicts the bow and stern sinkage as

$$s_{\mathrm{bow}} = c_{\mathrm{bow}} \frac{\nabla}{\mathrm{L}_{\mathrm{PP}}^2} \frac{F_h^2}{\sqrt{1-F_h^2}}$$
$$s_{\mathrm{stern}} = c_{\mathrm{stern}} \frac{\nabla}{\mathrm{L}_{\mathrm{PP}}^2} \frac{F_h^2}{\sqrt{1-F_h^2}} \qquad (2)$$

where

s_{bow} = sinkage at the forward perpendicular due to squat

s_{stern} = sinkage at the aft perpendicular due to squat

L_{PP} = ship length between perpendiculars

$F_h = \frac{U}{\sqrt{gh}}$ = depth-based Froude number

U = ship speed through water (varies through transit)

g = acceleration due to gravity

h = water depth (varies through transit)

∇ = ship's displaced volume

c_{bow} = bow sinkage coefficient

c_{stern} = stern sinkage coefficient

The equations have very simple dependence on ship dimensions, with block coefficient, length / beam ratio, beam / draft ratio all captured through the volumetric coefficient $\nabla / \mathrm{L}_{\mathrm{PP}}^3$.

According to slender-ship theory, the sinkage coefficients $c_{\mathrm{bow}}, c_{\mathrm{stern}}$ depend only weakly on hull shape, and can be calculated analytically. An improvement to this method is to use the above equations, but tune the coefficients to agree with experimental data. This approach has been used by Huuska (1976), Icorels (1980) and Gourlay (2006) using model experiments. Ideally, full-scale squat measurements should be used, such as the measurements described by Hatch (1999), Härting & Reinking (2002) on bulk carriers, or Gourlay & Klaka (to be published) on containerships.

2.2 Heel

Heel causes the bilge corner to come closer to the seabed, so must be allowed for when calculating Nett UKC. During the transit, both turning and wind cause the ship to heel. Heel effects are small for bulk carriers, but significant for containerships.

For a given heeling moment M, the resulting angle of heel ϕ (radians), assuming hydrostatic equilibrium, is given by

$$\phi = \frac{M}{mg\overline{GM}} \qquad (3)$$

where m is the ship's mass and $\overline{GM}$ is the transverse metacentric height.

The heel angle ϕ causes an extra sinkage at the bilge corner, approximately equal to ϕ times half the ship's beam.

Standard methods exist for calculating the heeling moment M due to turning or wind (see e.g. Clark (2005) and IMO (2005) respectively).

3 Hull extremities and dynamic draft

The vertical movements of squat, heel and wave response each affect different parts of the ship's hull, so different parts of the ship's hull should be considered separately when calculating underkeel clearance. A useful way of doing this is to use the concept of "dynamic draft", which is the static draft of each part of the hull, plus the downward sinkage that it experiences due to the combined effects of squat, heel and wave response.

For example, in calm water a bulk carrier with level static trim will normally have significant dynamic trim by the bow, but very little heel, so the maximum dynamic draft will occur at the bow (Figure 2). With swell present and therefore roll, the maximum dynamic draft will often occur at the forward shoulders of the bilge corners.

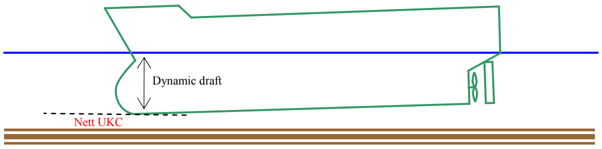

Figure 2: Example dynamic draft for bulk carrier with bow squat

A containership with level static trim may have significant heel due to wind and turning in calm water, so the maximum dynamic draft may occur at the bilge corner (Figure 3).

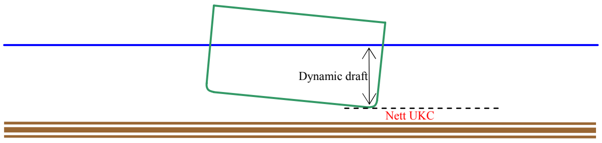

Figure 3: Example dynamic draft for midship section of heeling containership

A containership with static trim by the stern will often have its maximum dynamic draft at the stern, despite the bilge corners having larger sinkage.

The hull extremities used for calculating static draft, sinkage and dynamic draft are the most vulnerable outward extremities of the hull bottom, as shown in Figure 4. Four points are used for containerships and six points for bulk carriers.

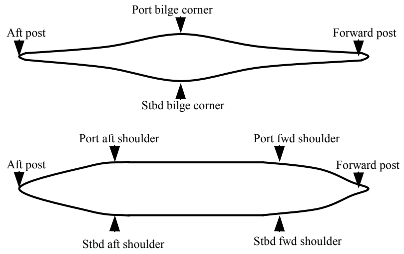

Figure 4: Keel waterplane of containership (top) and bulk carrier (bottom), showing hull extremities used for analysis

The overall dynamic draft is the maximum dynamic draft over all the vulnerable extremities of the ship. This is the point on the ship most likely to hit the bottom.

The Nett UKC is calculated as the available water depth for each part of the transit, minus the overall dynamic draft.

4 Ship motion calculations in shallow water

In order to calculate the nett underkeel clearance of a ship in shallow water with waves present, the heave, pitch and roll of the ship are first calculated in given wave conditions. Both the amplitude and phase of these vertical motions must be calculated, in order to correctly combine the motion components into overall vertical motions of each part of the ship.

It is important that ship motion calculations are performed in shallow water, rather than deep water. This is for several reasons:

1. For a given wave period, the wave length is shorter in shallow water than in deep water. This changes the wave exciting forces over the length of the ship.
2. For a given wave period, the wave speed is less in shallow water than in deep water. This changes the wave encounter frequency and shifts the peak reponse to different wave periods.
3. Heave and pitch added mass and damping are generally much larger in shallow water than in deep water. This tends to reduce the motions.

These effects combine to give ship motions that are usually, but not always, smaller in shallow water than in deep water.

The study of ship motions in deep water is well-developed, but in shallow water comparatively little research has been done. Kim (1968) developed a ship motions theory for arbitrary ship speed in head seas, but it was only valid for depth / draft ratios greater than 1.5. Beck & Tuck (1972) developed a slender-body theory for ship motions, for zero ship speed, that was valid for small depth / draft ratios. An alternative strip theory approach for calculating the hydrodynamic coefficients at zero ship speed was developed by Keil (1974).

As discussed in Beck (2001), these linear methods have their limitations, since shallow-water waves are inherently nonlinear, and this nonlinearity should really be included in the wave excitation forces. At present however, linear methods are all that are available for routine use.

Ship motion in waves is the most complicated UKC effect to model. This is partly due to the complexity of the analysis, and partly due to the large number of variables. The list of relevant variables includes:

- Ship dimensions and weight distribution
- Ship heading and speed
- Water depth
- Measured significant wave height, mean wave period, wave direction, spectral shape
- Wave attenuation away from wave measurement site

However, by performing sensitivity studies on the effect of each variable, the list of important variables can be decreased slightly.

5 Initial seakeeping calculations

For more efficient UKC assessment, the basic seakeeping properties of example ships can be pre-calculated, so that less calculations are involved when inputting actual measured wave conditions. The initial calculations can be performed as follows:

5.1 Outputting the correct vertical motions

Heave causes the same vertical motions over the whole ship, whereas pitch causes the largest motions at the bow and stern, and roll causes the largest motions at the beam ends. In addition, these motions are all out of phase with each other, so that the vertical displacements will be very different for each part of the ship. Typically, vertical displacements will be calculated at the hull extremities as shown in Figure 4.

These vertical displacements can be calculated geometrically from the output heave, pitch and roll, with careful treatment of the phase differences between each motion component.

5.2 Example ships

If the UKC assessment is for only a few specific ship types, these exact ship dimensions can be used for the seakeeping calculations. If the UKC assessment is to be valid for a wide range of ships, a list of “example ships” can be chosen for the seakeeping calculations.

The chosen list of example ships will depend on how much variation there is in the total list of ships that we wish to model. For each type of ship, e.g. bulk carriers with reasonably similar length-to-beam and beam-to-draft ratios, ship length is the most important variable. In that case, it is possible to interpolate between the pre-calculated results for example ships of different sizes, based on the actual ship length.

If interpolating between example ships of the same type but different size, care must be taken to account for the roll effects of varying beam, GM and radius of gyration. Methods for coping with this will be described in Section 6.

5.3 Modelling the full range of wave conditions

For each example ship, motions can be calculated using shallow-water seakeeping software. An example of such software is “Seaway”, developed at Delft University (see www.amarcon.com). This method is based on classical wave loads in shallow water, using the correct ship speed and shallow-water wave speed and length, and uses Keil’s (1974) method for determining the shallow-water hydrodynamic coefficients.

The initial seakeeping calculations can be designed to cover the full range of encountered wave conditions, as follows:

- A typical wave spectral shape is chosen that best represents measured wave spectra in the particular area
- Due to the near-linearity of the seakeeping method, all initial calculations are performed using a significant wave height of 1.0m
- A full range of mean wave periods is chosen, e.g. 2 – 20 seconds in 2 second increments
- A full range of wave directions relative to the ship heading is chosen, e.g. 0° - 360° in 22.5° increments

These initial calculations then yield a matrix of vertical motions over the full range of wave directions and mean wave periods. When it comes to predicting ship motions in measured wave conditions, this matrix can be interpolated to the correct wave direction and mean wave period, and multiplied by the correct significant wave height.

Example motions for a 230m L_{PP} bulk carrier in head seas with significant wave height 1.0m are shown in Figure 5, as calculated using “Seaway” software. The significant vertical displacements shown correspond to the average amplitude of the ⅓ largest motions in an irregular seaway of a given mean wave period.

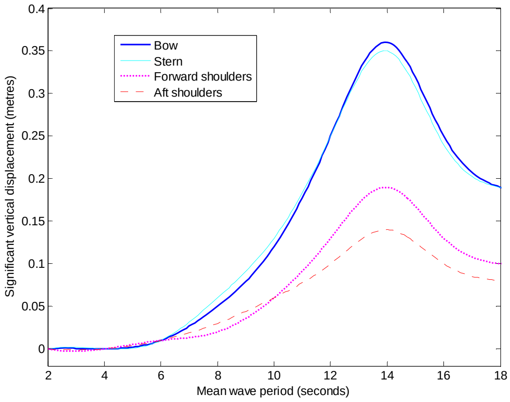

Figure 5: Significant vertical displacements for a 230m L_{PP} bulk carrier in head seas of varying mean wave period. Significant wave height = 1.0m, spectrum = JONSWAP.

In head seas, as shown here, the port and starboard sides experience the same motions, however for general wave directions they will be different. Also, for wave directions closer to the beam, the forward and aft shoulders experience larger motions than the bow and stern.

For this bulk carrier in head seas, the combined effect of wave response and squat by the bow mean that, for level static trim, the bow is most in danger of grounding. For wave directions closer to the beam, the combined effect of squat and waves means that the port or starboard forward shoulder will normally be most at risk of grounding.

6 Adjusting the seakeeping outputs

The results from the initial seakeeping calculations should now be adjusted to allow for uncertainty in the peak roll response, and wave spreading.

6.1 Uncertainty in peak roll response

For wave directions close to the beam, roll can become the most important factor governing UKC. Roll has the specific problem that it is fairly narrow-banded about the ship’s natural roll period. Therefore there is a risk of seriously underpredicting the roll motion if the seakeeping predictions are not exactly right.

The major factors affecting natural roll period are ship beam, transverse GM, and roll inertia. Due to the difficulty in accurately specifying transverse GM and roll inertia, it is a good idea to artificially “widen out” the roll peak, so it covers a wider range of natural roll periods. This is done only at hull extremities on the bilge corners, for headings close to the beam.

When modelling specific ships, only a small amount of widening is needed, however when interpolating example ships to different ship dimensions, more widening is needed to make sure that the roll peak is not missed.

6.2 Wave spreading

The seakeeping calculations usually performed are for uni-directional or “long-crested” waves. In reality, waves are normally “short-crested”, with variations in wave direction about an average value. The tends to decrease the peak motions, as compared to a long-crested seaway.

In order to more accurately simulate a short-crested seaway, a spreading function may be applied (see e.g. Lloyd 1989). The results for each wave direction are modified by taking the weighted average of the surrounding wave directions, to account for wave spreading.

7 Motions for actual wave conditions

Having pre-calculated each ship's vertical motions over a full range of wave directions, periods and heights, results can now be calculated for the actual wave conditions being considered. These wave conditions may be:

- *Historical* wave conditions, a full set of which is used for long-term UKC calculations, such as determining optimal dredging depths for a port approach channel
- *Forecast* wave conditions, for planning transits within the wave forecast period
- *Real-time* wave conditions, for monitoring UKC for an imminent transit, or during a transit

Firstly, mean wave period, significant wave height and wave direction must be calculated for the entire transit, using wave attenuation from the measurement or forecast location. The required complexity of the wave modelling depends on the geography.

The ship's course along each part of the transit, together with the wave direction along each part of the transit, gives the wave heading relative to the ship along each part of the transit.

Significant vertical amplitudes for each hull extremity can now be interpolated to the correct wave heading, wave period and wave height for each part of the transit.

8 Maximum likely motions

Wave-induced motions, like a real seaway, are a statistical phenomenon. It is always possible to encounter a larger set of waves, and hence have larger motions, than any reasonable estimate made in advance. Hence choosing a wave-induced motions allowance is a matter of choosing an acceptably low grounding risk and working with this.

An irregular sea has a wide variety of different wave heights and hence wave-induced vertical motions. We wish to find not just the vertical motion on a single wave, but the maximum likely motion over a whole transit, or even better over a large number of transits.

The significant amplitudes described above ($z_{1/3}$) represent the average of the highest 1/3 vertical amplitudes, so the largest motions are considerably more than this.

For linear seakeeping methods, such as the "Seaway" software and most other seakeeping software, a Rayleigh distribution can be used to estimate maximum values with a given probability of exceedence.

Suppose we choose a vertical motion allowance $z_{\text{allowance}}$. Then the Rayleigh distribution (see e.g. Bhattacharyya 1972) tells us that

$$\Pr(z > z_{\text{allowance}}) = \exp\left\{-2\left(\frac{z_{\text{allowance}}}{z_{1/3}}\right)^2\right\} \tag{4}$$

By calculating the average number of longer-period waves experienced over the dangerous part of the transit (N_{waves}) and choosing an acceptable exceedence probability for each transit (P_{transit}), the probability that the allowance will be exceeded on each wave is

$$\begin{aligned}\Pr(z > z_{\text{allowance}}) &= \frac{P_{\text{transit}}}{N_{\text{waves}}} \\ &= \exp\left\{-2\left(\frac{z_{\text{allowance}}}{z_{1/3}}\right)^2\right\}\end{aligned} \tag{5}$$

Therefore the vertical motions allowance is given by

$$\frac{z_{\text{allowance}}}{z_{1/3}} = \sqrt{0.5 \ln\left(\frac{N_{\text{waves}}}{P_{\text{transit}}}\right)} \tag{6}$$

The number of waves experienced over the dangerous part of the transit (N_{waves}) can be estimated based on the mean wave period, and the time that the ship spends in the shallow, exposed part of the transit.

The acceptable grounding probability for each transit (P_{transit}) can be calculated based on long-term grounding probabilities, as mentioned in the PIANC (1997) guidelines. For example, Savenije (1996) describes the acceptable grounding probabilities used for assessing transit safety in the Euro-Maas channel. In that case it is assumed that 1 in 10 bottom touches will result in more than minor damage, and the acceptable probability for having more than minor damage is 10% over 25 years. This allows the acceptable bottom touching probability (P_{transit}) to be determined, based on the expected number of transits over a 25 year period.

The chosen 25-year grounding probability should also depend partly on the type of seabed and therefore the consequences of grounding.

Using typical values of N_{waves} and P_{transit}, equation (6) gives a wave-induced motion allowance $z_{\text{allowance}}$ in the order of 2.0 – 3.5 times the significant amplitude. The resulting wave-induced motion allowance is different for each hull extremity, set of wave conditions, and position in the transit.

9 Overall squat, heel and wave motions allowance

Methods have been described for calculating the squat, heel and wave-induced motion allowances independently. These can now be added together, to give the total squat, heel and wave-induced motion allowance, which must be done using the correct values for each hull extremity.

As described in Section 3, the sinkage at each hull extremity due to squat, heel and waves, can be added to the static draft at each hull extremity, to give the "dynamic draft" at each hull extremity. The maximum dynamic draft over all the hull extremities is then the overall dynamic draft. The difference between the overall dynamic draft and the available water depth is the nett underkeel clearance.

In calm water, we can assess overall transit safety based on the PIANC (1997) guidelines. These suggest that the Nett UKC should never fall below a certain "safety margin", which is suggested to be 0.3m for a muddy seabed, 0.5m for a sandy seabed, and 1.0m for a rocky seabed. Therefore this method is deterministic, in that fixed formulae are used for the squat and heel allowances, and the safety margin ensures sufficient clearance for the cases where these formulae under-predict the squat or heel.

With swell present, the method changes from a deterministic to a probabilistic assessment. In that case, the PIANC (1997) guidelines suggest that the safety allowance should not be needed, since grounding probabilities have been calculated explicitly, and are required to be kept below a certain value.

However, the ideal UKC assessment needs to be valid for both calm water *and* swell conditions, with a smooth transition between the two. For example, an obvious requirement is that the static UKC in any sort of swell conditions must never be smaller than the calm-water value.

One simple approach is to include the "safety margin" in all conditions, so that the method will be valid when no waves are present. In swell conditions, this safety allowance serves as an uncertainty in the wave response calculations. A fixed allowance serves better than a percentage uncertainty, since wave-induced motions are predicted to be very small under some conditions.

Therefore in calm water the approach follows the PIANC guidelines in the usual manner, while in swell conditions the probabilistic assessment remains valid, with the safety allowance serving as an uncertainty in the wave response calculations. Corrections to this method can then be made based on quantified errors in the seakeeping analysis.

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