

**PERMANENT INTERNATIONAL ASSOCIATION
OF NAVIGATION CONGRESSES**

**UNDERKEEL CLEARANCE FOR LARGE SHIPS
IN MARITIME FAIRWAYS WITH HARD BOTTOM**

**Report of a working group
of the
Permanent Technical Committee II**



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UNDERKEEL CLEARANCE FOR LARGE SHIPS IN MARITIME FAIRWAYS WITH HARD BOTTOM

REPORT OF A WORKING GROUP OF
PERMANENT TECHNICAL COMMITTEE II
(Maritime ports and seaways for commercial,
fishery and pleasure navigation)

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1. INTRODUCTION

Since port construction and maintenance dredging is costly, using maximum vessel draught when transiting harbour channels tends to minimize cargo transportation cost. Thus an economic trade-off has to be made between allowable draught and the dredged water depth in the navigable port area. In addition, safety considerations require that the maximum draught allowed be controlled to avoid vessel grounding.

For a vessel to safely transit a port area she must have adequate clearance under the keel. In the design and operation of ships, as well as in the design and maintenance of ports, the required underkeel clearance (U.K.C.), the term used to define the distance between the ship's bottom and the channel bed, becomes an important economic and safety consideration.

The following paragraphs review previous PIANC work on U.K.C.

The report of Working Group II of the International Oil Tankers Commission (pages 88 to 93 - PIANC - Bulletin n° 16, Vol. III 1973) gave available information about channel dimensions and manoeuvring areas for large oil tankers (100 000 to 300 000 tons deadweight) and formulated some recommendations. This same report underlined the need for further research [1].

The report of Working Group 4 of the ICORELS (x) (supplement to Bulletin n° 35, Vol. I-1980) in reviewing the relevant recommendations of the 2nd International Oil Tankers Commission came to the conclusion that, without further study and comprehensive site investigations on a comparable basis it was not yet possible to derive a general rule to determine the minimum U.K.C. of ships in harbour entrances and in the manoeuvring areas. The report did give an indication of required gross U.K.C. (pages 17 - 19) which varied from 7% of the draught (in manoeuvring and mooring areas) to 20% of the draught (in the open sea) [2].

In muddy areas the definition of the nautical depth may be difficult. A report, which gives a definition of navigable depth, describes the effects on the manoeuvrability of

a ship, and discusses measuring and presentation methods, is published in the PIANC's Bulletin n° 43 [3].

Recognizing that additional work was required on U.K.C., a Working Group was formed under the auspices of the Permanent Technical Committee II of PIANC to define the various factors which influence the vertical clearance under the ship's hull.

This report of the Working Group first identifies all the presently known factors which influence U.K.C.. It includes details for the determination of the ship related factors, but not of the water-level and fairway related factors.

The report also discusses the procedures for the combination of these factors, and methods currently available or under development, for determining the U.K.C.. This information can be used in the design of channels as part of engineering studies or for the determination, by port operators, of the necessary U.K.C. required by a certain ship in a channel. The methods presented, called deterministic, probabilistic or probablistic combined with experience factors, should be studied by the user to determine which method is most appropriate for his purposes.

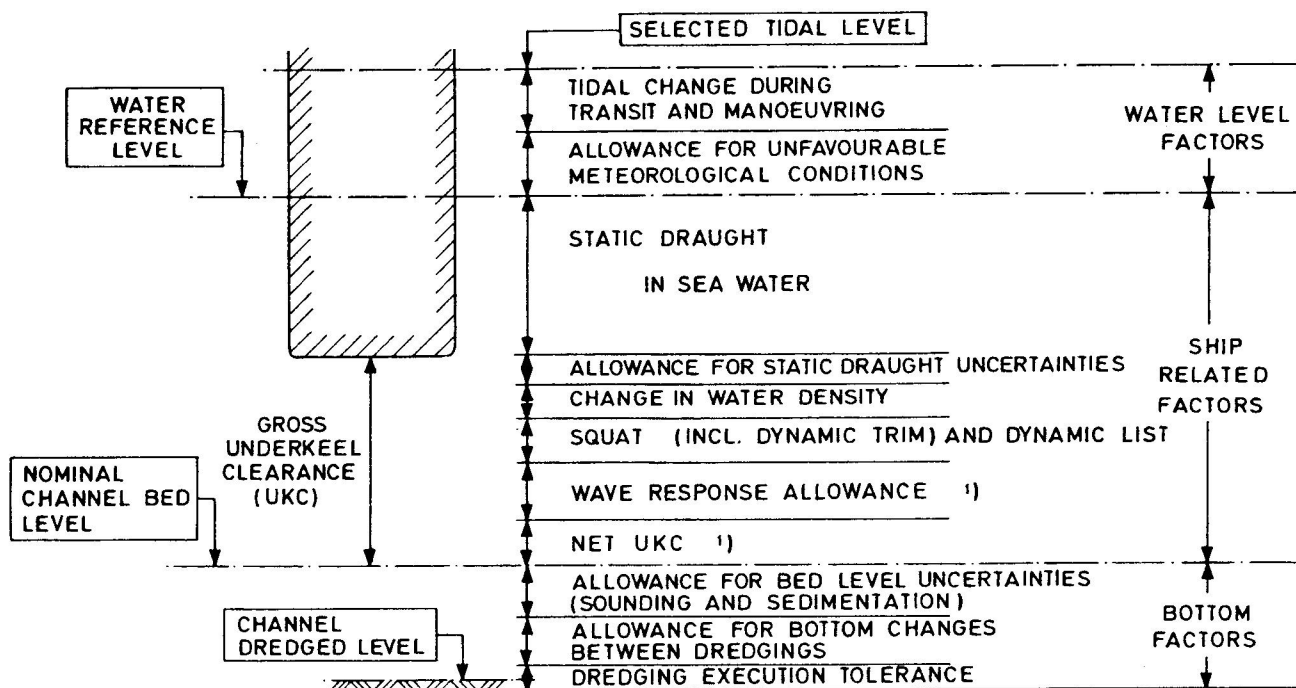
The report is confined to conventional vessel types only such as tankers, bulk-carriers, LNG and container ships as defined by the Icorels report [2].

The Working Group consisted of (in alphabetic order) :

- N.E. ERYUZLU, Canadian Coast Guard, Ottawa, Canada.
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- P. ROOVERS, Ministry of Public Works, Administration of Waterways, Antwerp, Belgium. (Chairman).

(x) The criteria used for the definition of "large vessels" is that adopted by the Commission of Large Ships of the I.A.P.H., namely :

- oil tankers, general cargo carriers and bulk carriers : 200 000 dwt and more;
- L.N.G. carriers, loading capacity of 125 000 m³ and more;
- container ships, length overall of 250 m and more.



1) NET UKC AND WAVE RESPONSE ALLOWANCE CONTRIBUTE TO THE MANOEUVRABILITY MARGIN (SEE CHAPTER 3.8)

Fig. 1. Factors determining the required underkeel clearance (UKC).

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2. DEFINITION OF TERMS

2.1. GENERAL

The required U.K.C. is dependent on a variety of different factors. They are related to the ship, to the bottom of the channel and to the water-level as indicated in Figure 1. A more detailed description of these factors is included in Appendix A.

Some of the factors have not yet been properly quantified. Therefore, any approach to this problem has to be twofold :

- calculation on the basis of one or more of the various methods available and
- comparison with measured data under similar conditions.

For this purpose a generally accepted, consistent system of definitions is essential. Both for the design of a channel and for the operation of ships, four sets of boundary conditions have to be defined, these are the "water reference level" and the "nominal channel bed level" (as indicated in Fig. 1) and also the "planning characteristic" and the "limiting operational conditions" as discussed in 2.2.3.

2.2. BOUNDARY CONDITIONS

2.2.1. Water reference level

The reference base for the U.K.C. at the upper end is the "water reference level", that is the water-level of the sea for the selected tidal conditions with due regard to reductions resulting from :

- lack of precision in water-level forecast and unfavourable meteorological conditions;
- tidal change during transit and uncertainty of the time and duration of transit of the ship.

It should be kept in mind that this "water reference level" is different from the chart datum, which may be sometimes considerably lower than the water reference level when vessels sail with the tide.

2.2.2. Nominal channel bed level

The reference for the U.K.C. at the lower end is the "nominal channel bed level", which is by definition the level above which no obstacles to navigation exist within the area considered.

From this it follows that the actual bed level must lie deeper. The "channel dredged level" should include an allowance for the limited accuracy of soundings and the dredging tolerance. In cases where siltation or other bottom changes may occur, an allowance for sediment deposits between two maintenance dredgings and/or between two sounding surveys must also be included.

2.2.3. Design Criteria

The two other sets of boundary conditions refer to the "design data" of a channel :

- the "planning characteristics", i.e. the maximum dimensions and minimum manoeuvrability characteristics of vessels accepted or to be accepted, and
- the "limiting operational conditions", i.e. the most unfavourable conditions of tide, current, swell, visibility under which the design vessels are allowed to transit the channel.

2.3. UNDERKEEL CLEARANCE

2.3.1. Gross Underkeel Clearance

"Gross underkeel clearance" is by definition the (theoretical) margin between the nominal channel bed level and the keel of a vessel as measured when stationary in calm water from the water reference level.

From this it follows that the gross underkeel clearance includes all ship factors (except for the static draught) namely :

- draught increases due to irregular load distribution
- changes in salinity
- the sinkage due to squat and other interactions
- wave and wind response and
- a safety margin.

2.3.2. Net Underkeel Clearance

"Net underkeel clearance" is in the conventional (deterministic) approach the minimum margin remaining between the nominal

channel bed level, and the keel of the vessel in the most unfavourable position under conditions of the design criteria. If all the other factors that determine the required gross U.K.C., are assessed as representative maximum values - the usual way - net U.K.C. can be considered as an additional safety margin against striking the bottom.

2.4. PROBABILITY ALLOWANCE

In a probabilistic approach the required gross underkeel clearance can be found from the summation of the mean values of all relevant factors and a true safety margin, called "probability allowance", to account for the inaccuracies, uncertainties, errors and variations in them.

To avoid confusion, the term "net underkeel clearance" should never be used in a probabilistic procedure.

Usually, not only ship related factors but also water-level and bottom related factors are subjected to the probabilistic approach. In this case the sum of the mean value of the ship related factors, minus the static draught, is thus not identical to the gross U.K.C. Therefore, for cross-checking with other methods or for comparative purposes with other fairways, the probability allowance has to be broken down to arrive at a comparative water reference level and a nominal channel bed level respectively.

2.5. MANOEUVRABILITY MARGIN

Both in a deterministic and a probabilistic approach, it has to be checked independently that sufficient manoeuvrability is ensured. The necessary margin between the nominal channel bed level and the lowest average position of the bottom of the ship, is called "manoeuvrability margin", following [33]. This term should never be confused with the term "net U.K.C.".

3. DETERMINATION OF SHIP RELATED FACTORS

3.1. GENERAL

A ship's immersion is dependent, not only upon her weight and hydrostatic balance (Archimede's principle) but also upon the hydrodynamic forces induced by her own movements through the water, by the interaction with the obstacles constraining the water flow (bottom, banks and other ships) and by the waves and wind.

These factors operate simultaneously and interact with each other, which makes the determination of the underkeel clearance and of the necessary safety margin very complex.

3.2. HYDROSTATIC DRAUGHT

The load determines the draught (at every point of the keel) and the trim and list angle of a ship, when stopped in calm water. The hydrostatic draught depends upon the water density (salinity).

The draught, trim and list will change during the voyage because of fuel consumption or transfer liquids. Knowledge of this is important because it modifies the draught and influences the effects considered in the following paragraphs.

When entering into an estuarial port, the master must take into account the salinity changes, which may vary with the tide. The draught, often measured in the waiting area, will increase when entering an estuary which has a lower water density. Draught should be measured fore, aft and midships to determine the ship's maximum draught, its stationary trim, and the amount of sagging or hogging.

Irrespective of whether the ship's draught is obtained through observation or calculation, the value always includes a certain error; ref. [5] quantifies these errors for tankers.

3.3. SQUAT

3.3.1. Definition

Squat is defined as the supplementary sinkage of a ship, relative to the original undisturbed water-level, which is caused by its movement at a given speed. It includes the vertical sinkage of the ship as a whole and the sailing trim.

3.3.2. Background

Many theoretical and experimental studies

have been made to determine squat and a few trials have been carried out.

The main theoretical studies were produced by Constantine [6], Thiele [28], Schijf [29] and Tuck [7], [8], [9].

Many laboratories executed or evaluated experimental trials with scale models (generally 1/50 to 1/200).

Results and predictions have been given by curves, data tables or formulae.

A number of references are given in the Reference List [10] to [20] and [34].

The resulting squat data converge qualitatively but sometimes diverge quantitatively.

Consensus has been reached on the following :

- Squat increases proportionally to a power of the ship's speed, which is about 2.
- Squat occurs in open water (quasi-infinite depth and width), and is produced by the movement of the water induced by the ship.
- Confinement of the ship by narrow banks or a shallow bottom increases squat.
- Ship movement and confinement change the trim. Squat by the bow (negative trim) is preponderant for large ships having a high block coefficient ($C_B^{(x)}$), and the effect will be increased if the initial trim is also negative. The trim may be positive for slender ships sailing at high speed or for ships sailing in very narrow and shallow waters (canals).

3.3.3. Evaluation of Squat

Several authors proposed methods for calculating or predicting the squat in constrained water.

Thiele [28] proposed (in 1901) the application of the formulae for the

(x) NOTATIONS

Ship

L_{pp} = length between perpendiculars (m)
 B = beam (m)
 T = draught (m)
 A_M = midship section ($\approx BT$) (m^2)
 ∇ = displacement (m^3)
 C_B = block coefficient ($\nabla / L_{pp} BT$)
 V = ship speed (m/s)
 Z = squat (m)

Waterway

W_S = width at water surface (m)
 h = depth (m)
 A_C = channel cross section (m^2)
 ΔA_C = reduction of A_C due to water level depression (m^2)
 S = blockage fact. ($= A_M / A_C$)
 F_{nh} = Froude depth number ($= V / \sqrt{gh}$)
 u = ship-induced return flow (m/s)

conservation of mass and energy :

$$VA_C = (V + u) (A_C - A_M - \Delta A_C) \text{ and } (1)$$

$$(V + u)^2 = V^2 + 2gz \quad (2)$$

Many authors followed this approach and presented small adaptations to it : Schijf [29] presented graphical solutions of these formulae, for $\Delta A_C = W_S Z$. He also added an empirical factor to the Thiele- formulae to account for the inequalities in the return flow. Constantine [6] derived an approximate solution for the Thiele- formulae :

$$Z = h S F_{nh}^2 / (1 - F_{nh}^2) \quad (3)$$

This formula is valid for a rectangular cross-section. McNown [30] presented mathematical solutions of the Thiele-method for trapezoidal and parabolic cross-sections. van de Kaa [31] showed that the squat in other types of cross-sections can be computed with sufficient accuracy by the approximation of $\Delta A_C = W_S Z$, as proposed by Schijf.

Based on a slender body approach, for a ship in shallow water Tuck [7], [8] and [9] has proposed :

$$Z = \frac{2\lambda}{\pi} \frac{F_{nh}^2}{\sqrt{1 - F_{nh}^2}} \frac{\nabla}{L_{pp}^2} \quad (4)$$

In (4), Z is the mean sinkage excluding trim (Tuck also gave a formula for the trim) and λ represents a very complex coefficient deduced from integrations of hydrodynamic effects on the hull. According to Tuck its value is between 2 and 2.4 for normal ships. Curves were presented showing a high increase of the squat when F_{nh} is close to 1.

After Hooft [17] and taking into account experimental results, Huuska [18] proposed the following formula for the maximum squat (combined effect of sinkage and trim)

$$Z = \frac{BT}{L_{pp}} C_B (C_Z + 0.5 C_e) \frac{F_{nh}^2}{\sqrt{1 - F_{nh}^2}} \quad (5)$$

This expression is similar to that of Tuck : $C_Z + 0.5 C_e$ depends on the form of the hull, similar to λ ; its mean value would be 2.4. The Finnish hydrodynamics laboratory [19] established that this value was too high for ferries and that a value of 2 would be more appropriate for such ships.

Huuska added that results must be

multiplied by two coefficients : K_S depending on the relative dimensions of the channel and K_L depending on the vicinity of a bank. These coefficients can be estimated from Guliev's curves [16].

Barrass [21] reviewed the former proposals and the known results of real trials and proposed the formula :

$$Z = 3.75 C_B \frac{V^2}{2g} \left(\frac{S}{1-S}\right)^{3/4} \left(\frac{V}{V_S}\right)^{1/12} \quad (6)$$

This was later simplified by Barrass, see Ribadeau-Dumas [22], to

$$Z = \frac{C_B}{30} \left(\frac{S}{1-S}\right)^{2/3} \frac{2.08}{V} \quad (7)$$

(Z in metres; V in knots)

Equation (7) was considered to be a safe approximation of (6) as the calculated squat was at the upper boundary of the experimental results (mainly of tankers) with which it was compared. This formula includes the channel confinement factor $\left(\frac{S}{1-S}\right)$ but does not take

into account a possible bank effect.

All the former formulae and some published curves give a zero squat in open water. Barrass suggested "influence limits", i.e. the maximum depth and width corresponding to water inertia in open water. These limits of influences depend upon the ship's form and may be calculated : their mean values are 7 times the draught and 10 times the beam, giving a mean value of 1/70 of the minimum blockage factor.

3.3.4. Concluding Remarks

The PIANC international commission for the reception of large ships (ICORELS), [2] reviewed the relevant literature published before 1979 and accepted Huuska's formula as the most valuable prediction.

The French Lighthouses and Navigation Authority reviewed theoretical and experimental results and concluded [22] with the adoption of Barrass' formula, because it is simple to use, whilst recognizing that it gives a convenient safety margin.

Kimon [5] developed squat and squat variance curves based on model tests, full scale trials and analytical predictions. Mean squat values appear to be smaller than those of Huuska, Barrass and the British Department of Transport [13] but the variances are relatively

high and the addition of one or two standard deviations gives good agreement.

H.G. Blaauw and F.C.M. van der Knaap [23] reviewed the validity fields of the squat prediction proposals summarized above and noted that they are generally applicable to large ships such as tankers but that there is a lack of useful information for vessels such as ferries and container ships.

Theoretical and experimental studies demonstrated that uncontrolled phenomena occur when the Froude depth number approaches 1. Schijf, Constantine and Tuck made clear the risk of a rapid increase of the squat and these instabilities are also mentioned in [22]. Care should be taken when such a situation occurs, especially with fast vessels.

3.4. INTERACTION WITH BANKS AND OTHER SHIPS

3.4.1. Problem Statement

These interactions result from the water flowing between a ship's hull and close lateral obstacles (banks or other ships). Two categories of effects may be distinguished :

- lateral forces : attracting (suction) or repulsing (cushion), which are not considered here;
- additional sinkage.

3.4.2. Additional Sinkage

This additional sinkage is to be added to the former squat prediction. General formulae such as that proposed by Barrass give the same results for a given channel section, whether it is narrow and deep, or wide and shallow, or whether the ship sails close to a bank or not.

Model trials, in particular those of British N.M.I. [13], showed that a vertical bank at a distance of one half-beam from the ship side produced an additional sinkage of about 47% with $h/T = 1.1$ and 25% with $h/T = 1.2$, when the ship's speed corresponded to $F_{nh} = 0.3$. At a distance of one beam, the sinkage increase is only 24% and 16%. This influence disappears when the distance between the ship and the bank is more than 3 times the beam.

This additional sinkage may exceed the safety margin given by a general formula when a ship sails close to a bank or another ship.

3.5. BOTTOM RELIEF

A rapid change in the depth modifies the water flow and can have an important effect when the water pushed by the ship hits local shoaling of the bottom. Available data have

been given only by the "Finland ships hydrodynamic Laboratory" [19]. According to model tests a 100 000 dwt tanker with a speed of 6 to 8 knots suffers an additional sinkage of 10 to 20% of the maximum squat corresponding with the lower waterdepth, when depth decreases from $h/T = 1.7$ to $h/T = 1.1$ or from $h/T = 1.8$ to $h/T = 1.24$ with a declivity of $1/6$. This sinkage increase should be added to the squat corresponding to the lower depth.

3.6. WAVES

3.6.1. Problem Statement

Vertical ship motions - heave, pitch and roll - induced by waves can result in a considerable draught increase of the ship, which should be taken into account when determining the required U.K.C.

The magnitude of the vertical motions depends on the wave parameters (height, period and direction) as well as ship related parameters (ship type, draught, loading condition and speed) and the waterdepth. The greatest motions appear when the frequency of wave encounter coincides with the natural frequency of the ship, so that resonance occurs. Since the natural periods for heave, pitch and roll lie above 8 s for large ships, long waves will have the greatest effect on ship motions.

3.6.2. Response functions

Generally speaking, ship motions may be characterised by a response amplitude operator (RAO), which gives the ratio between motion and wave amplitude for each wave frequency. The frequency to be used is the relative wave frequency, in relation to the speed of the ship and to the direction of waves. For each point at the ship's bottom the total vertical motion due to the heave, pitch and roll can be determined and given by an RAO function. This function has a value of one for very long waves (period more than 30 s) but is much smaller for short waves (period less than 5 s). The RAO has a peak near the resonance frequency for pitch and/or roll, and can reach a value of about 5 [24]. When the natural frequencies for pitch and roll lie close to each other the RAO will have a high value which can result in severe vertical motions.

3.6.3. Effect of water depth

In shallow water, the motions of a ship which is underway decrease when the U.K.C. decreases. A small depth of water under the

keel tends to damp the ship motions and to modify roll and pitch periods, according to the change in added masses. However it must be emphasized that the amplitude of roll is hardly reduced in shallow water, when the apparent period of the waves is close to the ship's own roll period.

3.6.4. Effect of wave direction

In head waves and especially head quartering waves the pitch motion dominates and the ship's bow or stern will have the biggest immersion. In beam waves and in stern quartering waves the roll motion becomes high and the maximal vertical motion appears at the ship's shoulders.

3.6.5. Effect of wave height

Since ship motions appear to increase linearly with the wave height, the vertical motion is high when, within the wave spectrum, a considerable amount of energy is concentrated around the resonance frequency for pitch and/or roll motion. When the roll response gives rise to large vertical motions some non linear trends must be expected. It depends on the ship type as to which wave period and direction causes the greatest motions.

3.6.6. Effect of Set-down

At very low wave frequencies the vertical motion corresponds with the set-down. The set-down is a second-order wave effect related to wave grouping. According to [35] a set-down of 0.2 m can be obtained in very long swell ($H_S = 1.5$ m; $T_m = 15$ s).

3.6.7. Determination of RAO'S

The RAO is valid for one ship type, ship speed, waterdepth, wave direction and type of motion. The RAO's can be determined by one of the following methods :

- through calculations by mathematical models. Generally a two-dimensional strip program or three-dimensional diffraction program is used;
- through measurements in physical models. Measurements in regular waves as well as in irregular waves (spectra) are used.
- prototype measurements in waves which have similar spectra to those in the area considered.

3.6.8. Extreme vertical motions

The resultant maximum ship motions at any point of the ship are due to oblique and beam waves. Depending on the ship type and local

conditions, the draught increase due to waves may be several metres.

On the coast of South Africa maximum vertical motions (sinkages) of 100 000 to 160 000 dwt bulk carriers, travelling at normal manoeuvring speeds through a variety of swell conditions which include very long waves were found to fall between $0.5 H_S$ and $2 H_S$, where H_S is the significant wave height ($H_S = H_{1/3}$) [25].

3.7. WIND

The wind acting on a vessel can cause the vessel to heel, thereby temporarily increasing the draught. Should the wind be blowing in squalls, oscillations can be induced. The wind effect is obviously dependent on wind strength, angle of encounter and freeboard of the vessel. With deeply loaded ships such as tankers and other bulk carriers, the effect is small. However, the effect can be substantial with high freeboard vessels such as gas carriers and container vessels. The increase in draught (T) due to heel (list) can be calculated from the following formula :

$$T = 1/2 B \tan \alpha \quad \text{where } B = \text{Beam}$$

$$\alpha = \text{Angle of heel}$$

As an example the supplementary draught increase of a 300 000 dwt loaded tanker having a heel of 1° is about 0.4 m but may reach 1.75 m for a 125 000 m³ gas carrier having a heel of 5° . It will be smaller for container ships and ferries because of their hull form.

3.8. MANOEUVRABILITY

3.8.1. Problem Statement

Ship manoeuvrability in this context may be defined as the vessel's ability to perform the manoeuvres intended by the master without the assistance of tugs. The ability of a vessel to manoeuvre will start to decrease when the actual clearance is reduced below a certain critical value which is called "manoeuvrability margin".

From boundary layer calculations it can be determined that, if the actual clearance of large ships is less than 1 m, a return current between ship and channel bottom can no longer exist. Under such conditions the resistance increases and the propeller efficiency decreases significantly.

3.8.2. Ship Manoeuvrability

Model test and full scale measurements both show that the turning abilities of tankers and

bulk carriers decrease with the actual clearance, as the resistance increases. For example, trials in the Gulf of Mexico with a 280 000 dwt oil tanker showed that the turning circle diameter increased by 50% at a depth-draught ratio (h/T) of 1.2 and by 75% at h/T = 1.1, when compared to the turning circle diameter in much deeper water. However, it is important to note that at vessel speeds below 4 knots and with an actual clearance of app. 2 m, the ship remained manoeuvrable.

Model tests with container vessels and gas carriers showed that the negative effect of decreasing underkeel clearance on turning ability is much stronger for these ship types than for oil tankers and bulk carriers.

3.8.3. Effect of Waves

When a ship sails in waves the actual clearance may become very small. However, these small underkeel clearance values have a duration of only seconds. During recent model tests [27], it appeared that they had no important effect on the manoeuvrability of several ship models when sailing on a straight course, even under wave conditions where the channel bottom was occasionally touched. It should be pointed out that in fact a combined effect of a varying underkeel clearance and wave drift forces was observed. These drift forces may, under particular circumstances, have a significant effect on the manoeuvrability.

3.8.4. Effect of Currents

Current forces on ships increase significantly when the underkeel clearance is small [26], and manoeuvring is sometimes favourably affected by small clearances in the presence of currents especially when the current is from ahead.

3.8.5. Final remarks

From the foregoing it may be inferred that the actual clearance between ship and channel bottom should exceed a minimal value to safeguard adequate manoeuvrability. The required "manoeuvrability margin" depends on the ship type. The critical value will probably be less than 1.0 m (and may be dependent on channel width, ship type and other traffic). However, at this time information on the manoeuvrability of different ship types at very low underkeel clearance is scarce. Additional information is required before more general rules can be applied.

In practice, particularly in confined

harbour waters, supplementary manoeuvrability assistance for a vessel is provided, usually in the form of tugs. The manoeuvrability margin is not therefore a critical factor under these circumstances but it may need to be considered in approach channels and fairways outside the harbour, where tug assistance is not always available.

3.9. INTERACTION OF EFFECTS

Generally the various factors making up the U.K.C. are simply added. In confined waters, the water flow is disturbed and interactions are probable, however not enough is known about these interactions to include such effects in U.K.C. evaluations.

Section 3.4 showed that the form of the channel section, the position of the ship in relation to the channel boundaries, and the proximity of other ships will affect the squat.

Because of the movements induced by the waves, the water layer thickness between the hull and the bottom is continuously changing, which could affect the squat.

The safety margin should take into account possible interactions when several effects are to be combined.

3.10. UNCERTAINTIES

The uncertainties concerning the actual underkeel clearance may be classified into two categories :

- the uncertainties of the behaviour of a ship sailing in given conditions;
- the uncertainties of these conditions (see Chapter 2).

The first uncertainties result from the limited knowledge of the actual behaviour of ships, especially in shallow waters.

The second uncertainties result from the limited knowledge of the prevailing conditions during the ships passage for instance, the wave conditions which may result in uncertainties in vertical motions.

It is difficult to evaluate the consequences of these various uncertainties since deviation may not only have a cumulative effect, but also interactive effects may occur.

Thus a decrease of salinity, or the occurrence of siltation produces a decrease in underkeel clearance not only by itself, but also by increasing the squat effect.

The various uncertainties may be considered

at random, but their distribution functions are not obvious and they are not independent as shown by the salinity example above. Moreover, the maximum risk occurs in bad weather when environmental conditions are disturbed.

It is therefore very difficult to determine precisely how various uncertainties may be combined, taking into account possible interactions.

4. PROCEDURES FOR THE COMBINATION OF FACTORS DETERMINING UNDERKEEL CLEARANCE

4.1. GENERAL

Experience factors are clearly an important consideration when designing ports and determining operational requirements for underkeel clearance. However, calculation procedures which take into consideration the various factors that contribute to underkeel clearance can be a useful supplement.

The ideal calculation procedure would include all of the water level factors, ship factors and bottom factors identified in Chapter 2. Furthermore, the procedure should be capable of analyzing any type or size of ship operating in any type of port. The type of port could be anything from an open coastal port having an unprotected berthing area and offshore fairway approach, to an inland port which could include an offshore fairway approach, river or protected channel, turning basin and berthing areas. While the development of such a comprehensive model has not been, and may never need to be, developed, significant progress has been made in the last decade to develop good engineering approximate procedures. This chapter will describe the type of calculation procedures now available for combining underkeel clearance factors to determine the optimum underkeel clearance.

4.2. BASIC CONSIDERATIONS AND CALCULATION METHODS

In using any type of procedure, it is useful to divide the port into geographical sections where conditions over the whole of each section are about the same. As an example, a typical protected port might be divided into the offshore fairway approach channel, the protected channel, the turning basin and the berth area. Furthermore, each of these sections might be further subdivided if conditions are not nearly constant over the whole section. Finally, many of these sections, or parts of

them, may not need to be analyzed as they clearly pose no danger due to inadequate underkeel clearance. Such areas could include a natural deep and wide section of offshore fairway or protected channel, or a large and deep turning basin or berth area. Clearly, each port must be studied individually and sectioned accordingly.

There are basically two fundamental methods now being used to calculate the underkeel clearance, the conventional or deterministic approach and the probabilistic approach. The second method has not yet been developed to its possible extent, but some procedures and mathematical models which yield practical results are already available. Either method, appropriately combined with experience factors, may be used for channel design purposes, or for determining operational requirements for a particular ship movement within a port if the necessary data are available.

4.3. DETERMINISTIC COMBINATION OF FACTORS

In the conventional or deterministic approach, discrete numerical values are found for the appropriate factors shown in Appendix A, but the uncertainty factors are not accounted for explicitly. The factors contributing to the ship's depth are subtracted from factors making up the water depth to arrive at an underkeel clearance. An additional margin of safety may be added to ensure that a vessel will indeed have little chance of striking the seabed. More details are given in the ICORELS-report [2] and also in [13]. In the ICORELS-report the numerical values of the different factors are considered to be representative "maximum" values.

The advantage of using the deterministic approach is that it is a simple matter to carry out the required arithmetic once values are obtained for each of the factors used in the calculation, and also it facilitates a comparison of different waterway systems. The disadvantage of this procedure is that it leaves the question open to which extent the estimated maximum values could possibly appear simultaneously. Obviously, the addition of true peak values can unduly overcompensate for the underkeel clearance. But the opposite may also occur, if to avoid overcompensation, lower representative (maximum) values are selected. This makes the process somewhat subjective.

A principal drawback of a deterministic summation is that a trade-off between channel

and/or port accessibility on the one hand and safety of channel transits on the other hand, cannot be clearly made since this requires the quantification of variations and uncertainties in a statistical sense.

4.4. BASIC PRINCIPLES OF THE PROBABILISTIC APPROACH

As mentioned in Chapters 2 and 3, there are variances and uncertainties associated with the underkeel clearance factors. These uncertainties arise for many reasons, for example from errors in measurement and in the observation and prediction of hydrological and meteorological conditions. Such uncertainties are functionalized in probabilistic methods for the determination of underkeel clearance.

Appendix B outlines the approach required for a complete probabilistic solution. However, such a complete probability approach is not possible at this time. Simplified probabilistic models for channel depth design are able to calculate the probability that a ship penetrates a horizontal surface. As an example, for the design of the Euro-Maas Channels such a model was used to determine the "nominal channel bed level". Maintenance dredging is carried out to ensure that the bed will not rise above this level. The only "unwanted event" in this approach is that a ship penetrates this nominal bed. To correlate this event to its possible effects a risk analysis may be helpful (see Chapter 5).

Practically, what has been developed to date can be termed semi-probabilistic approaches. In such a semi-probabilistic approach, the variations in, and uncertainties associated with many of the factors shown in Appendix A are quantified and become a part of the overall calculation procedure - see Appendix C. These variances, once quantified, are added together and then combined with the so-called average or steady factors, shown on Appendix A.

Finally, using statistical rules, one can calculate sufficient underkeel clearance for having a probability of the ship striking bottom below a given value. Like the deterministic procedure, by using some simplifications, the probabilistic procedure can be reduced to relatively few arithmetical steps.

4.5. SEMI-PROBABILISTIC COMBINATION OF FACTORS

4.5.1. General Approach

It will be obvious that a realistic probabilistic modelling of all the relevant processes in a deterministic and statistical sense requires a computer model. Although the underlying theory is straightforward, such a model is complicated by the (many) interactions between the processes and the large amount of data to be handled.

Though, in principle, such a model can be used to determine the operational limits of a single ship passage, in practice they are only used at present for channel design purposes. An example is the use of such a model built to calculate the required depth of the entrance channels to Rotterdam to allow navigation with 22 m draught ships. It appeared that the depth of the whole channel could be reduced by 0.7 m compared to the preliminary (deterministic) design while the downtime remained the same [4].

A semi-probabilistic approach was also used in a paper describing underkeel clearance requirements for tankers operating in port channels and berthing areas [5]. In this semi-probabilistic approach, (Appendix D) the procedure has been reduced to a simplified arithmetical calculation based on a series of easily used plots. Thus, it is virtually as easy to use as the deterministic procedure discussed earlier.

4.5.2. Advantages of Probabilistic Methods

While the probabilistic method is in its infancy, it has already demonstrated advantages compared with the older conventional or deterministic method. For instance, it gives the ability to perform sensitivity studies in levels of touching the seabed. For example, in reference [5], it was found that in the absence of waves, increasing U.K.C. by about 17% decreased the probability of grounding by a factor 10 (say from 10^{-4} to 10^{-5}). Also, insight can be gained into the effect of varying, or controlling, each of the variance factors. This will highlight the significance of each factor that contributes to U.K.C. This, in turn, can lead to physical or operational modifications of the port with a clear

understanding on the effect of changes in underkeel clearance and the sensitivities to grounding. During the Euro-Channel design studies [4], it appeared, for example, that the predictability of wave conditions had a great impact on the downtime of the channel. For that reason, a better wave prediction model was developed.

4.5.3. Disadvantages and limitations of probabilistic methods

A disadvantage of the probabilistic procedures may be the inability of the average user to understand the theory behind the approach, which can lead to doubt the calculated answers.

A further disadvantage lies in the effort required or the limited possibilities to quantify the uncertainty factors with the accuracy necessary for very low probabilities and to determine precisely how these uncertainties may be combined regarding possible interactions. As yet, there are very few fairways where sufficiently accurate statistical descriptions of these factors are at least partly available. For example for the probabilistic design of the Euro-Maas Channels, there was a complete and extensive set of hydrological, meteorological and geomorphological data available. Nevertheless, during the design process several conservative (safe) assumptions had to be made with respect to uncertainties in these factors. Thus the calculated probabilities are at most "approximate values".

The determination of the chance of grounding by a simple addition of variances (multiplication of a number of standard deviations) is only an uncertain approximation, because many factors are not independent as mentioned in 3.10 and iterative calculation is necessary as indicated in [13]. To avoid this, the sequence of the probabilistic calculations has to be deliberately chosen (see Appendix C). The number of global standard deviations to be kept is subjective; the experience of nearby ports may be the cause of errors because sea phenomena can be very different in nearby sites. Resulting true safety margins are just as uncertain as in deterministic approaches.

When all of the relevant processes and factors (a.o. including the decision of the masters with respect to the operational limits and conditions for channel transit) are

observed, as should be done in case of a semi-probabilistic channel depth design, complex mathematical models are required. However, it must always be recognized that the results of even the most sophisticated and complex calculation methods can never be better than the input data.

5. SAFETY CONSIDERATIONS WITH RESPECT TO UNDERKEEL CLEARANCE

5.1. GENERAL

For reasons of economy (channel bed level, draught and harbour downtime), the operational limits for a channel transit should be chosen such that the number of tides and/or times that the channel is closed should be minimized, while the tidal windows should be as large as possible whilst still meeting the required safety criteria. The operational limits may be widened by adequate information to mariners and to port operators. [4]

The safety criteria with respect to the underkeel clearance should fulfil the requirements below [33] :

- There should be no significant increase of the chances of stranding and collision by reduced manoeuvrability due to a decrease of underkeel clearance.
- The probability that ship-bottom contact in the long term results in the loss of a ship, or large-scale contamination of the marine environment or the beaches, should be virtually zero.
- The probability that a ship touches the seabed during a passage should be so low that its contribution to "unwanted events" such as ship damage, cargo spills, and temporary reduced access to the harbour will be small.

5.2. METHODS OF APPROACH

5.2.1. Deterministic approach

In a deterministic approach the evident safety criterion applied is the minimum net underkeel clearance. The ICORELS report [2] recommends a minimal value of 0.5 m, and suggests a value of 1.0 m under conditions where the possible consequence of touching the bottom (on ship, crew and/or environment) is large (e.g. in case of a bottom of solid rock). It presupposes, however, that inaccuracies, uncertainties, errors and variations are already incorporated more or less in the other

identified factors that determine the underkeel clearance.

5.2.2. Probabilistic Approach

For the acceptable probability for a ship to touch the channel bed, a method is proposed in [5] to determine a criterion for ports where the local authorities leave the permissible draught and/or operational limits to the ship operators. This "individual safe passage-criterion" is found by comparison with the safety level in similar ports where there is sufficient experience in this respect. The method is somewhat subjective but has the attraction of being simple.

A better approach - that is only feasible if more detailed information on ship, channel and boundary conditions is available - is to start with a risk analysis of the hazards associated with ship-channel bottom contact. Such an approach was followed in the Euro-Channel design studies [33]. It included a.o. "first reconnaissance" - studies of the forces due to ship bottom contact and the damage that this may cause to an oil tanker. The results were combined in event trees. It appeared that under average circumstances only approx. 0.5% of all nominal bottom contacts in this channel could lead to heavy damage, with a serious chance of foundering of the vessel, large cargo spills and temporary channel closure. The results are only valid in the Euro Channel with the prevailing bottom material, wave climate and entrance regime. When, for example, a ship sails in very heavy swell, the probability that bottom contact will result in heavy damage is much greater (order-of-magnitude : 5%). When the bottom consists of solid rock a probability of "one" could be approached.

The probability that ship-bottom contact results in large-scale contamination of the sea and beaches and the wrecking of a ship should be so small as to be negligible (see above). For the Euro-Channel the probability of an accident with heavy damage due to ship-bottom contact was limited to approximately 10^{-4} per annum. With approximately 500 passages of tide- and channel-bound ships a year, this resulted in the following "environmental" safety criterion.

- "The average value of probabilities that channel-bound ships touch the nominal channel bed should not exceed $5 \cdot 10^{-4}$ per passage".

Of this probability $4 \cdot 10^{-4}$ is attributed to the channel proper and $1 \cdot 10^{-4}$ to the turning places and anchorages.

The "environmental" safety criterion reduces the average risks (for the marine environment, for harbour access and for all ships concerned) due to bottom contact, to an acceptable level. However, it does not exclude the possibility that this risk may be incurred, completely, by one or just a few ships' passages under conditions that seldom occur, such as a combination of negative surge and heavy swell. Insofar as such exceptional conditions can be forecast it is not reasonable to impose such a risk on the pilots, the crew and the owners of the ships concerned. To avoid this, a second "individual safe passage" criterion is required :

- "The probability that the nominal channel bottom is touched at least once during one particular ship passage may not exceed "P".

The numerical value of P may be derived by a comparison with the often better known risks of stranding and collision. Based on such a comparison a value of $P = 10^{-2}$ was found for the Euro-Channel [33] under extreme conditions. Some aspects of human error, with the associated effect on U.K.C., were included in this risk analysis.

5.2.3. Manoeuvrability

To ensure adequate manoeuvrability, both in the deterministic and probabilistic approach a minimum "manoeuvrability margin" between ship and channel bottom is required. So far, no generally applicable rules are available regarding the limits of manoeuvrability, however, when using a deterministic approach the ICORELS-recommendations will probably be sufficient. As the controllability of a ship is not strongly influenced by vertical ship motions due to swell, such motions may be allowed to penetrate this manoeuvrability margin. From studies of the manoeuvrability of deep draughted vessels in the approaches to Rotterdam a manoeuvrability margin of 1 m was considered sufficient under the circumstances prevailing - without tug assistance. In Richard's Bay Harbour, a minimum manoeuvrability margin of 1 m is also used as operational limit [25] but ships are reported to become extremely sluggish and difficult to manoeuvre with this small underkeel clearance.

5.3. DETERMINATION OF TIDAL WINDOWS IN THE ABSENCE OF WAVES

5.3.1. Factors involved

For a particular ship passage in a given channel or sea lane, only the water-level, currents, wind and wave climate are relevant environmental factors for the probability of ship-bottom contact and, thus, for the limiting operational conditions associated with it. The limiting operational conditions can be described by means of a tidal window. The width of this window will often vary along the channel/sea lane. The least information that is required to determine these limits is then the nominal channel bed level, the magnitude of the ship factors and the relevant water reference level during transit. When no information regarding the tide is available the chart datum may be used as water reference level. In the "water-level uncertainties" particular attention is then required for the effect of water-level depression due to the wind. The tidal window is then either infinitely wide or zero.

5.3.2. Operational Criteria

As most shallows and/or entrance channels can be transitted within some hours, information on the astronomical tide will allow deeper draughted ships to transit if they sail within a tidal window.

Squat-speed-local tide relationship can be used on board to "optimize" the passage of the shallows/channel. The maximum allowable ship draught for a given transit is found if the width of the tidal window thus established is zero at any place.

If a shore-based tidal advisory service is available, this can supply additional information on actual and expected water-levels. The reduction in the water-level uncertainty can be effective in terms of allowing for passage of deeper draughted ships and widening tidal windows. Also information on the actual available "overdepth" can have similar benefits.

In a deterministic approach the water reference level can be determined from the nominal bed level by adding the net underkeel clearance criterion to the different ship factors and water-level factors (including inaccuracies etc., see 5.2.). The boundaries of the tidal window are attained if the

predicted/expected waterlevel is equal to the water reference level. Using the ICORELS recommendations this will in general also yield an adequate manoeuvrability margin.

When an "individual safe passage" criterion is applied the water reference level- and corresponding tidal windows- can be determined from the relevant bed level (either the nominal channel bed or the results of a recent sounding survey) by adding a margin for all uncertainties to the "mean" underkeel clearance factors (see Appendix D). Due attention should be paid then to safeguard an adequate manoeuvrability margin to avoid collisions or strandings.

In harbours with an entrance regime based on several safety criteria (see 5.2) the level of safety of individual ship passages may vary, even if they sail under the "limiting operational conditions". This will be the case if a maximal harbour accessibility/tidal window/draught has to be achieved. Even though a very high standard of safety is assured in this way, a drawback of such an entrance regime is that it is difficult to explain it to the personnel on board and the actual safety cannot be checked by them.

5.4. DETERMINATION OF TIDAL WINDOWS IN THE PRESENCE OF WAVES

5.4.1. Problem Statement

Wave-induced ship motions necessitate a decrease in the width of the tidal windows or may even result in postponing the passage to a later tide.

To predict the ship motions that can be expected during a ship passage, information on wave direction, height and frequency is required.

5.4.2. Wave data

There are conditions/areas where information on waves can be approximately estimated by visual observation of experienced personnel. More often this is not the case.

Also, in general the local wind is not suitable for predicting swell, as was found from extensive measurements along the Dutch and French coasts.

A one-parameter measure for the wave climate is the so-called low-frequency energy (for instance the area of the wave spectrum for frequencies below 0.1 Hz). Although container ships may respond also significantly

to higher frequencies. Even this measure appears to be very difficult to predict with any accuracy and it is only relevant for a given wave direction.

Two-parameter measures of the relevant part of the wave spectrum (e.g. significant swell height and significant swell period) are even more difficult to predict. Both inaccuracies in wave energy and wave frequency have a strong impact on the induced ship motions. This is particularly true for the wave direction.

5.4.3. Operational Criteria

As far as the limiting operational conditions with respect to waves are concerned, a "rough-and-ready" approach is to "close down" the channel if a certain wave climate is surpassed. Up to 1985 this was, for example, the case in the approaches to Rotterdam-Europoort when the expected low-frequency-energy level surpassed 150 cm². As swell under this level may still cause considerable motion to the tidal-bound ships, for all other conditions a "deterministic" allowance for ship motions was incorporated in the gross underkeel clearance. The corresponding safety level against striking the nominal channel bed was very low ($\ll 10^{-2}$).

In general, the problem in a deterministic approach to determine the operational limits is to establish the clearance that is required for wave-induced ship motions. Therefore, a clearance is often chosen which has a very low probability of exceedance.

If no local hydro-meteo information service is available the wave-induced ship motions can be taken into account only if a good visual estimate of the waves can be made or the ship motions can be measured on board with some accuracy. The treatment of prediction accuracy of the wave parameters along the track should then be given the attention that they require.

5.4.4. Limiting Operational Conditions

When a local hydro-meteo advisory service is available an entrance regime can be formulated that gives proper attention to the wave climate. The limiting operational conditions can be calculated in advance and presented in tables for different ship types and draughts, tides and tidal residuals and waves. In calculating these limiting conditions due attention should be paid to the prediction accuracies. Such an entrance regime is applied nowadays for the approaches to some ports in

Europe [4] and South Africa [25].

6. SUMMARY AND CONCLUSIONS

6.1. GENERAL

In any assessment of underkeel clearance it is important to identify all of the factors. This report identifies and describes all of the presently known factors associated with the water level, ship behaviour, and fairway bottom which should be considered in determining underkeel clearance over a hard bottom. Each factor associated with ship behaviour is then discussed in some detail. Information on factors having to do with the water level and fairway bottom are intentionally not covered in detail.

6.2. NEW DATA SINCE THE ICORELS' WORK [2]

British scale model trials gave valuable data on squat supplementary effects caused by the vicinity of banks or other ships ([13] and N.M.I. reports).

Finnish scale model studies [19] drew the attention to the supplementary sinkage produced when the depth decreases rather quickly.

Real trials carried out in South Africa [24], [25] showed that high waves with very long periods may produce vertical movements of large ships greater than those considered by ICORELS (up to 25% of the draught).

There is still a lack of field data from real trials, on ship response as function of wave height, period and direction for near design conditions, especially for large bulk carriers, tankers and other large ships while passing through channels of limited depth and width.

6.3. PROGRESS IN THE METHODOLOGICAL FIELD

The British Department of Transport [13] underlines the iterative process to be followed, taking into account the interaction of several factors on each other.

Probabilistic methods have been developed in The Netherlands [32] and U.S.A. [5]. In deterministic approaches, the simple addition of uncertainties may produce a too large safety margin. By considering various factors as hazardous variables it is possible to take into account average values and some kind of overall deviation. Thus it should be possible to evaluate, in probabilistic terms, a better risk

estimate resulting from safety margins than in an only deterministic approach.

To evaluate the consequences of accidents and the acceptable probability of accidents in a given situation a risk analysis was conducted in the Netherlands [33].

6.4. COMPARISON OF THE DETERMINISTIC AND PROBABILISTIC APPROACH

In the deterministic approach the minimum safe underkeel clearance can be determined by approximating the magnitude of the various factors related to the ship characteristics, the channel bottom and to the water-levels. This approximation, however, involves certain allowances and a safety margin to account for the uncertainties in measurements as well as in calculations using the presently available methods. The results obtained may lead to significant overdesign or even possibly underdesign.

The probabilistic approach provides more flexibility and insight to the designer in spite of its complexity. It may result in depths smaller than for the deterministic approach and consequently may effect substantial cost savings. It may also be used to present cost-benefit analysis.

6.5. FURTHER STUDIES

In view of the above, and the fact that often the limiting conditions are determined mainly by the response and characteristics of the largest category of the anticipated traffic, it is clear that studies on e.g. squat and wave effect would be useful for design and regulatory purposes only when the emphasis is on situations relating to rather large vessels in channels of limited depth/width configuration. The accuracy with which these situations can be analysed will determine the degree of confidence in establishing channel depth and vessel speed limitations.

Little use has been made so far of the transmission of experiences gained with certain depth-draught ratios from one channel to others. At least on an international level exchange of experience and information is hampered by the lack of/or insufficient familiarity with an internationally recognised consistent system of terms and definitions.

PIANC has introduced such a system [1][2]; see also Chapter 2 of this report. But it needs

application and practice. Therefore, to promote introduction it would be extremely helpful to establish for some important and well-studied fairways an inventory of all relevant levels and factors contributing to UKC including their known variations, based on the PIANC nomenclature. This would be also the best way to find out if and when further improvements of this system might be necessary.

6.6. FINAL CONCLUSIONS

Due to the uncertainties presently inherent in the determination of the factors affecting vessel underkeel clearance, establishing the final safe water depth and draught relationship remains to a certain degree an approximation process requiring in-depth familiarity and experience on the part of harbor designers and ship operators. However, when designing ports and determining operational requirements for underkeel clearance, calculation procedures which take into consideration the various factors that contribute to underkeel clearance can be a useful supplement.

7. RECOMMENDATIONS

7.1. Further systematic laboratory and field research into vertical vessel motions in waterways of limited configuration should be encouraged. Approximation of factors related to the ship characteristics remains the most questionable due to possible divergence of results dependent on the method selected. The emphasis should be, therefore, on response to wave action, squat and current effects of large vessels in restricted channels which, in the majority of applications, determine the limiting factors both from economical as well as safety considerations.

7.2. Additional model or full scale measurements on squat and vertical motion are necessary for smaller ships, container ships and ferries. Such data are required to check the validity of existing equations.

7.3. There is a need to quantify the draught uncertainty for different types and sizes of vessels. Very little work has been done on this subject.

7.4. The correctness and usefulness of the

various types of underkeel clearance calculation procedures that are available to-day need to be tested. These calculations, for design or operational purposes, should be done preferably by cross-checking several methods most suitable for the particular waterway system.

- 7.5. To facilitate such a cross-checking and to provide engineers, mariners and scientists with a reliable set of all relevant U.K.C.-data for a variety of fairways,

PIANC should install a Working Group to collect the data available and assure that the inventory is consequently based on or checked to the PIANC system of terms and definitions - see Chapter 2.

- 7.6. Further development of the probabilistic approach and especially a systematic research on the validity and limitations of results and method would be desirable in providing waterways designers with a more reliable alternative or supplement to the deterministic method.

APPENDIX A.

SYNOPSIS OF THE FACTORS DETERMINING THE REQUIRED UNDERKEEL CLEARANCE

In principle, the same factors determine the required Underkeel Clearance in both a deterministic and probabilistic approach. However, differences occur in how they are combined. For both approaches Fig. 2 gives an idea of the differences and similarities between the relevant factors, and of the corresponding water levels and bed levels. In addition, an explanation of the scheme is given, starting from top to bottom.

EXPLANATION

Level A : Selected tidal level, is the starting point for the assessment of the required Underkeel Clearance, for instance high or low tide.

Factor 1 : Tidal change during transit and manoeuvring

From the planned transit and from tables of the astronomical tide (or from other information on the local tide), the difference between the selected tidal level and the water level during passage can be determined along the channel/shallow. Depending on the selected tidal level the factor may have a positive or negative value. In a deterministic approach, unfavourable transit time deviations from the planned passage are taken into account.

Level B : Expected water level during passage, is in the probabilistic approach the reference base for the underkeel clearance at the upper end.

Factor 2 : Water level uncertainty. This is primarily an allowance for unfavourable meteorological and/or hydrological conditions, such as negative surges and other tidal residuals, but also uncertainties in the astronomical tide "if any" and - in a probabilistic approach - deviations from the planned passage should be taken into account. In the probabilistic approach this uncertainty is treated as a variance, in the deterministic approach as a margin.

Level C : Water reference level, is in the

deterministic approach the reference base for the underkeel clearance at the upper end.

Factor 3 : Static draught, is the maximum underwater depth of the ship at any place of the ship's bottom, thus including the static trim and static list. It is defined in sea water with a specific mass of 1025 kg/m^3 for a zero ship speed (relative to the water).

In the deterministic approach this factor is a representative maximum value, taking into account the uncertainty in the draught measurement and/or calculations. In the probabilistic approach a best approximation of the static draught is used, and the uncertainties are treated separately as variances.

Factor 4 : Change in water density.

The effect of uncertainties in the water density on the ships' sinkage (due to uncertainties in the salinity and temperature of the water) is treated as a variance in the probabilistic approach. In the deterministic approach the uncertainty is incorporated in the "representative maximum" value of the factor.

Factor 5 : Squat and dynamic list, includes the effects of the dynamic trim due to the speed and the dynamic list due to beam winds. Uncertainties arise from the limited accuracy of the squat prediction models and the uncertainties in the exact ship speed (relative to the water), wind speed, wind direction, underkeel clearance, beam currents etc. They are treated in the same way as in factor 4.

Factor 6 : Wave response.

In the deterministic approach, a representative maximum value is determined of the wave response, within the operational limits. This implies that the most unfavourable wave condition in which the transit of the ship is still justified is the base for the calculations. In the probabilistic approach a probability is calculated that the wave-induced vertical ship motion exceeds the wave response allowance. Uncertainties occur in the wave climate, due to inaccuracies in wave observation/ measurement, limited accuracy of the description of the wave spectrum (often described by only one or a few parameters), changes in the predicted wave climate during ship transit. They may have a large impact on the required wave response allowance. Models

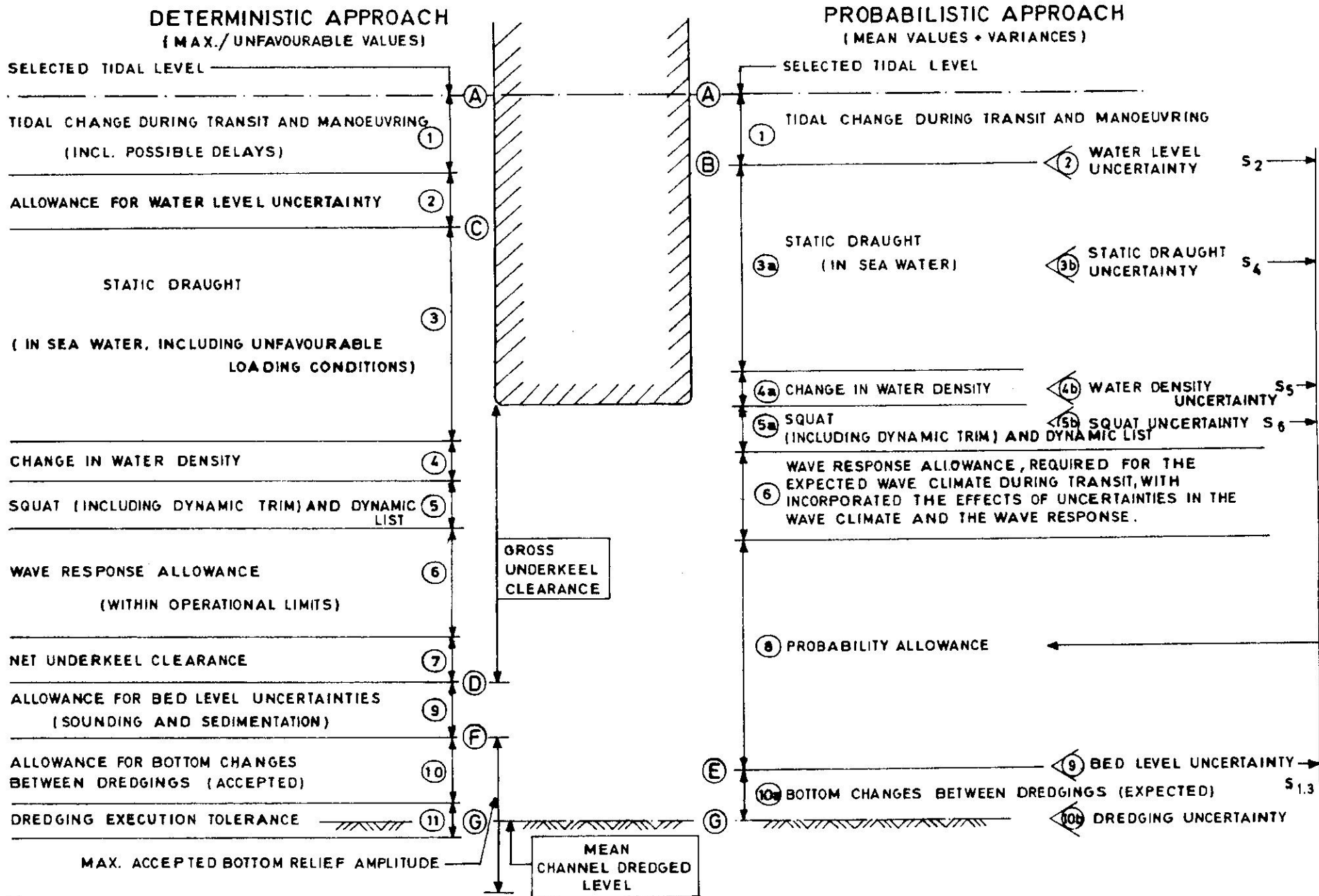


FIG.2 SYNOPSIS OF DETERMINISTIC AND PROBABILISTIC APPROACH

are available for the treatment of these uncertainties and the uncertainty in the response of the ship to the wave. For the combination of this allowance in the probability allowance, see also Appendices C, D and litt. [5], [32].

Factor 7 : Net underkeel clearance, see 2.3.2.

Level D : Nominal channel bed level, is in the deterministic approach the reference base for the underkeel clearance at the lower end.

Factor 8 : Probability allowance, see 2.4.

Factor : Manoeuvrability margin, see also 3.8, may overlap the net underkeel clearance and the wave response margin. (not indicated in Fig. 2)

Level E : Expected bed level during transit, is in the probabilistic approach the reference base for the underkeel clearance at the lower end.

Factor 9 : Bed level uncertainty, takes into account the inaccuracies and uncertainties in the sounding equipment, in the recorded water level and in possible vertical motions of the survey vessel during the depth measurement, but also undiscovered shoals or objects on the bed, and unexpected/unpredictable sediment deposits between sounding surveys, e.g. caused by storms. It is treated as a margin (det. approach) or a variance (prob. approach).

Level F : Maintenance level. When the recorded bed level during a sounding campaign lies above this level maintenance dredging should start as soon as possible (in a deterministic approach for channel management).

Factor 10 : Bottem changes between dredgings.

In a deterministic approach this is the maximum accepted sediment deposit between two dredging campaigns. In a probabilistic approach this is the mean expected sediment deposit since the last dredging campaign/sounding survey.

Factor 11 : Dredging execution tolerance is due to the inability of dredgers to attain the envisaged bottom level exactly.

Level G : Mean channel dredged level lies in general well below the actual bed level for reasons explained above.

Remark on Fig. 2 :

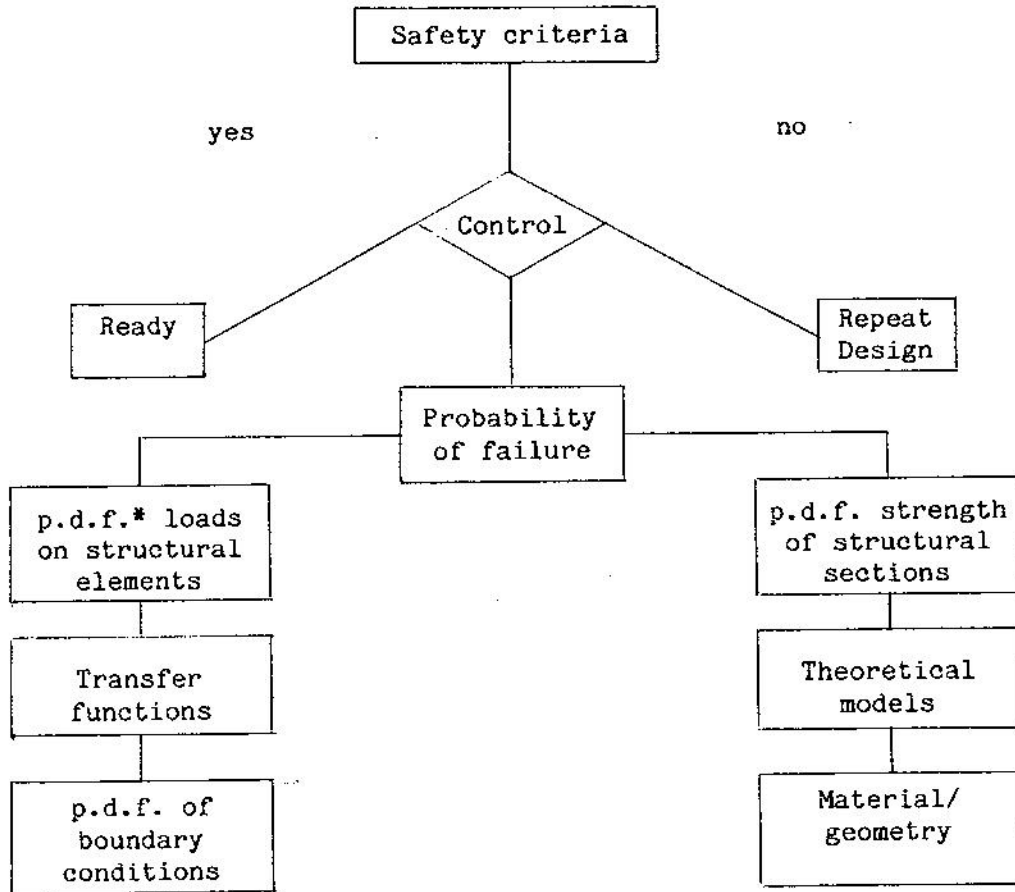
A schematic comparison between the deterministic and probabilistic approach is not easily presentable because of their fundamental differences. The correspondent values 3a, 4a, 5a and 10a are mean values. The uncertainties concerning the effects of these factors are indicated on the right side as 2, 3b, 4b, 5b, 9 and 10b. These uncertainties are combined in the probability allowance 8 which includes, as the net underkeel clearance 7 the necessary manoeuvrability margin.

The used indices S are those of the method explained in Appendix D and don't correspond with the present numbering of the factors.

APPENDIX B.
PRINCIPLES OF A COMPLETE PROBABILISTIC APPROACH

Two items are at stake in a probabilistic design of a structure (see fig. 4) :

1. a statistical distribution of forces (boundary conditions); and
2. a statistical distribution of the structural properties.



* p.d.f. = probability density function

Fig. 4 - Principle of a probabilistic design of a structure.

Convolution of both distributions results in the probability that the structure collapses or, in general, that "unwanted events" occur. When dealing with the design of or the navigation in a channel, the "unwanted events" are accidents like collisions, strandings or penetrations of the seabed, leading to damage

to the ship or its cargo, personal injuries, reduced harbour attainability or pollution of the environment. These probabilities should be limited by safety criteria. The principles of a complete probabilistic approach and the corresponding safety criteria are treated extensively by Van de Kaa [33].

Categories of processes	Relevant boundary conditions in each category			
	Static ship properties	Dynamic ship properties	Channel properties	Hydrol. & meteor. conditions
1. Randomly changing b.c. between each channel transit	-ship : type, dimensions -static draught, trim, list [1,2] -installed engine power -cargo : weight, distribution [1,2]	-ship track [1,2] -transit time schedule [1,2]	-sedimentation, siltation, erosion, wrecks etc., i.e. variation in time of channel cross-section [1,2]	-astronomical tide -tidal residuals [1,2] -current conditions [1,2] -wave conditions [1,2] -wind conditions [1,2] -water density [1,2]
2. Deterministically changing b.c. within each channel transit (between discerned channel sections)	-(squat response to : speed, channel cross-section, beam currents etc.) [1,2] -(list response to wind) [1,2] -(draught response to water density) [1,2]	-(speed) [1,2,3] -(course angle) [1,2,3] -(drift angle) [1,2,3] -(bank clearance) [1,2,3]	-alignment -depth, width, cross-section; i.e. variation in place of prismatic channel [1,2]	-astronomical tide [1,2,3] -tidal residuals [1,2,3] -current conditions [1,2,3] -wave conditions [1,2,3] -wind conditions [1,2,3] -water density [1,2,3]
3. Randomly changing b.c. within each channel transit (within discerned channel sections)	-(squat response to non-prismatic channel) [1,2] -(list response to non-steady wind) [1,2]	-(speed) [1,2,4] -(course angle) [1,2,4] -(drift angle) [1,2,4] -(bank clearance) [1,2,4]	-depth, width, cross-section : i.e. variation in place of non-prismatic channel [1,2,4]	-astronomical tide [2,4] -tidal residuals [2,4] -current conditions [2,4] -wind conditions [2,4]
4. Random wave-induced vertical ship motion (within discerned channel sections)	-(ship response to waves) [1,2]	(duration of transit of channel section) [1,2]	(actual UKC)	wave conditions [1,2,4]

Legend :

-boundary conditions between brackets are dependent on those indicated under "lower" categories
 [1] predicted and for expected mean values; [2] uncertainties, inaccuracies, variation;
 [2,3] variation between channel sections; [2,4] variation within channel sections

FIG. 3. CLASSIFICATION OF BOUNDARY CONDITIONS

APPENDIX C.

SEMI-PROBABILISTIC MODELLING OF BOUNDARY CONDITIONS FOR CHANNEL DEPTH DESIGN

The processes that are relevant for channel depth design can be classified in 4 categories [32].

1. randomly changing boundary conditions between each channel transit, for example ship draught;
2. deterministically changing boundary conditions within each channel transit, for example change of channel cross-section;
3. randomly changing boundary conditions within each channel transit, for example non-flat channel bed;
4. wave-induced (random) vertical ship motion.

The boundary conditions that are relevant for the behaviour of the ships relative to the channel bed can be attributed to these categories, see Fig. 3. Such a classification is required to arrive at a proper sequence of the calculations in a semi-probabilistic model for channel depth design.

To model these processes the sequence indicated below can be followed : for each transit and for each channel section within which the deterministic changes of boundary conditions are negligible, probability density functions are generated of the relevant boundary conditions. The "uncertainties" are treated as if the frequency of occurrence follows a normal distribution. Next, for each combination of boundary conditions the frequency of occurrence, the duration of transit of the channel section and the actual underkeel clearance is determined. Then for each relevant combination of wave condition, ship wave response function and actual underkeel clearance the probability of touching the channel bottom is calculated using a Poisson process description. The frequency of occurrence of each combination of boundary conditions is multiplied with the intensity of the Poisson process of the ship touching the channel bed. Summation of all products results in the average number of times that the bottom is touched in one transit. The average number is compared with a safety criterion. Depending on this comparison the operational limits may be made more narrow or widened (or the channel may be deepened resp. maintenance dredging may

be postponed).

A more extensive description of the categories of processes and their incorporation in a probabilistic design of channel depth is given by Strating et al [32].

APPENDIX D

EXAMPLE OF A SEMI-PROBABILISTIC APPROACH

1. CALCULATION METHODS

The semi-probabilistic approach was used in a paper describing underkeel clearance requirements for tankers operating in port channel and berthing areas [5]. This procedure is used to calculate the underkeel clearance required to produce an exceedingly small chance of grounding. The method is applicable to virtually any port area, which could include an offshore fairway with waves or swell present, a protected channel having passing ships and a berthing area. It can be used either for ship draught requirements for port entry or for channel depth design. A prerequisite is that the boundary conditions are not changing within one channel transit (because category 2 and 3 processes of Appendix C cannot be treated). By applying this procedure to deliberately chosen fairway reaches, this disadvantage will become of minor importance.

Factors included in this procedure are the charted depth, tide, static draught, squat, wave-induced motions, siltation (sediment build-up), undercut, and the uncertainties in these factors.

2. U.K.C. WITHOUT WAVES

In the absence of waves and swell, the underkeel clearance (U.K.C.) can be described by the following relation :

$$(UKC) = K_1 \sqrt{S_1^2 + S_2^2 + S_3^2 + S_4^2 + S_5^2 + S_6^2 + \text{Squat}}$$

probability allowance

where :

- S_1^2 = Charted depth variance
- S_2^2 = Tide variance
- S_3^2 = Siltation variance
- S_4^4 = Static draught variance
- S_5^2 = Water density variance

S_6^2 = Squat variance

The constant K_1 can be used to represent the number of standard deviations required to limit the probability of hitting the seabed to sufficiently low values. As an example, if an acceptable level (safety criterion) of touching the seabed once in 10,000 ship transits is accepted (i.e., 10^{-4}), then the value of K_1 , using the normal probability density distribution, becomes 3.718.

Numerical values for each of the variances were obtained from observation or calculation. Each variance is considered to be normally distributed. This datum was then reduced to graphical form. This makes it a simple matter for the user to enter each graph with the appropriate arguments to obtain a value for each variance factor. The added "Squat" factor, on the right side of the expression, represents the average value of squat for a given operating condition.

Some prerequisites for this approach are :

- the different factors can be considered to follow a normal distribution;
- the factors are independent among themselves;
- the seabed/channel bottom is flat.

For a "first reconnaissance" these will in general be acceptable simplifications. Under particular circumstances, this is no longer the case. For example, both large siltation variances and a very uneven seabed may strongly influence the ship's squat.

3. U.K.C. WITH WAVES

Another section of the procedure in [5] accounts for the effect of wave-induced motion on underkeel clearance. Using ship motion model tests, calculated data, standard normalized wave spectra, and established ship motion theory, approximate significant ship motions (RMS-values) were developed for one foot wave heights using response operators. To convert the one foot RMS values to the maximum wave induced immersion, it is multiplied by the significant wave height for the channel section in question (limiting sea state for vessel entry) and a wave encounter multiplier. This multiplier reflects the duration of voyage in the approach channel or area, and is a function of the number of wave encounters the ship will experience.

Finally, the procedure was developed so

that the extreme vertical motion the vessel might experience will not exceed the wave allowance, e.g. the value obtained by using the above procedure, more than once in 10 000 transits (10^{-4} probability). The procedure can be altered if some other probability level is desired.

In the final steps of the procedure, the U.K.C. allowance in the absence of waves is first added to the wave allowance. A correction factor must be applied to account for the statistical combination of the normal probability distribution of the steady variances with the distribution of ship motions in waves, which are assumed to be Raleigh distributed. To the corrected sum of the U.K.C. allowance and wave allowance is added the average value of squat. This total sum, then represents the required gross underkeel clearance.

To obtain the maximum permissible draft for transit, the required gross underkeel clearance is subtracted from the available water depth (i.e. charted depth), plus or minus tide, minus siltation, plus undercut). Likewise, for channel design purposes, the required water depth is found by adding the required gross underkeel clearance to the known draught of the ship selected for the study.

REFERENCES

- [1] PIANC. 1973. Second International Oil Tankers Commission : Final Report - Bulletin n° 16, Brussels.
- [2] PIANC. 1980. Icebergs : Final Report - Supplement to Bulletin n° 35, Brussels.
- [3] PIANC. 1983. Navigation in muddy Areas - Bulletin n° 43, Brussels.
- [4] VLEMMIX W. et al. 1985. Reception and discharge of large Coal Carriers. PIANC's 26th Int. Nav. Congress - Sect. II - Subject I, Brussels.
- [5] KIMON P.M. 1982. Underkeel Clearance in Ports. Ship-Transport Symposium, Rotterdam.
- [6] CONSTANTINE T. 1960. On the movement of Ships in restricted Waterways. Journal of Fluid Mechanics. Manchester University.
- [7] TUCK E.O. June 1964. A systematic asymptotic Expansion Procedure for slender Ships.
- [8] TUCK E.O. December 1965. Shallow Water Flows past slender Obstacles. David Taylor Model Basin, Washington D.C.
- [9] TUCK E.O. and TAYLOR J.P. 1972. Shallow Wave Problems in Ship hydrodynamics. University of Adelaide - Australia.
- [10] SOGREAH Laboratory. September 1958. Summary Report on "Tankers Transit through Canals", Shell International Marine Ltd - Grenoble, France.
- [11] DAND I.W. and FERGUSON A.M. "Squat" two Papers from the Shipping Chamber Symp. "Ship behaviour in confined Waters" - January 1973. "Ship behaviour in

- Ports and their Approaches", National ports Council - London 1980.
- [12] YAMAGUCHI et al. January 1968. Full Scale Tests on sinkage of Supertanker through shallow Water. Nautical Society of Japan.
- [13] U.K. DEPARTMENT OF TRANSPORT. 1982. Ship behaviour in Ports and their Approaches. London.
- [14] SJOSTROM C.H. September 1965. The Effect of shallow Water on speed and trim. SNAME Metropolitan Section - New-York.
- [15] FUJINO M. February 1980. Experimental Studies on Ship manoeuvrability in restricted Waters. International Ship Building Progress - Vol. 17.
- [16] GULIEV J.M. 1971. On Squat Calculation for Vessels going in shallow Waters and through Channels. PIANC Bulletin N° 7.
- [17] HOOFT J.P. December 19.. The behaviour of a Ship in head Waves at restricted Water depth - ISP21.
- [18] HUUSKA O. et al. 1976. On the evaluation of Underkeel Clearance in Finnish Waters. Ships Hydrodynamic Laboratory OTANIEMI - Finland - Report n° 8.
- [19] HAATAINEN Pandalü. 1978. Experimental investigation on the Squat in changing Water depth Conditions. Ships Hydrodynamics Laboratory - OTANIEMI - Finland - Report n° 14.
- [20] ERYUZLU N.E. and HAUSSER R. 1978. Experimental investigations into some aspects of large Ships Navigation in restricted Waterways. Delft IAHR Symposium.
- [21] BARRASS C.B. October 1978. Ship Squat. Lorne and Mac Lean-Luton (U.K.).
- [22] RIBADEAU-DUMAS L. March 1982. Squat. Revue technique des Phares et Balises n° 53 - Paris
- [23] BLAAUW H.G. and van der KNAAP. Antwerpen 1983. Prediction of Squat of Ships sailing in restricted Waters. International Port Congress.
- [24] VAN WIJK A.C. 1982. Wave induced Ship Motions in Harbour Entrances. A Field Study. Proc. 18th I.C.C.E. - Cape Town.
- [25] CAMPBELL N.P. and ZWAMBORN J.A. 1984. Richards Bay Harbour - Port Operational Manual, Mark I. PIANC Bulletin n° 45. Brussels.
- [26] PIANC. 1979. Report of Working Group I - Supplément to Bulletin n° 32 - Brussels.
- [27] DELFT HYDRAULICS LABORATORY. 1984. Tests on the controllability of LNG-Carriers in Waves in shallow Water. Delft Report M 1967. (In Dutch : not published).
- [28] THIELE A. 1901. Schiffswiderstand auf Kanalen - Centralblatt der Bauverwaltung n° 56 (pp. 345-347).
- [29] SCHIJF J.B. 1949. Section I. Communication 2 pp. 61-78. PIANC's 17th International Navigation Congress, Lisboa, (1949) (in French).
- [30] Mc NOWN J.S. 1976. Sinkage and Resistance for Ships in Channels. A.S.C.E. Journal of the Waterways, Ports, Coastal and Ocean Division, Vol. 102 (1976) WW3 August (pp. 287-300).
- [31] van de KAA E. J. Discussion of Sinkage and Resistance for Ships in Channels. A.S.C.E. Journal of the Waterways, Ports, Coastal and Ocean Division, Vol. 103 (1977) WW3 August (pp. 389-392).
- [32] STRATING A.J. et al. Febr. 1983. Optimization of depths of Channels. Int. Shipbuilding Progress, Vol. 30, n° 3452.
- [33] van de KAA E.J. September 1984. Safety Criteria for Channel Depth Design. 3rd Meeting of the U.S. - Dutch M.O.U. on Dredging and related Technologies. Charleston, South Carolina.
- [34] ERYUZLU N.E. and SAUCET J.Ph. October 1984. Vessel Squat in Shallow Waters. Canadian Coast Guard. Hydraulics Research Center. (On going Study, to be published).
- [35] HUYSMANN R.H.M. and DALLINGA R.P. Oct. 1983. Non linear Ship Motions in shallow Water. Berkeley - Int. Workshop on Ship and Platform Motions.