PROBABILITY AND RISK CRITERIA
FOR CHANNEL DEPTH DESIGN AND CHANNEL OPERATION

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ABSTRACT

In harbour entrance and terminal approach channels and fairways that are exposed to waves or swell, the wave-induced vertical ship motions often form the dominant component of the underkeel clearance requirement. Such conditions lead to the requirement of a probabilistic approach to channel design and operation (allowance decisions). The risk, defined as probability times consequence, of bottom touching or even grounding should be related to the channel bed conditions, as well as to the type of cargo and the value of the local environment. The port or terminal authorities should decide on the level of risk that is acceptable for that particular port or terminal. This should be based on economic and environmental impact considerations, including possible mitigation measures.

The paper reviews the various levels of probability of bottom touching and risk criteria which are being used. This leads to a relationship between the statistically expected number of vertical ship motions in the channel during a single shipping event and the probability of bottom touching. In the long term, by using the shipping intensity, the probability of bottom touching during a number of years can be determined using a Poisson distribution. This approach may be carried out for all weather and shipping conditions or for selected extreme sea state and ship conditions only (as would be the case for ship allowance). The paper provides guidelines on choosing a correct level of risk and of the related probability of bottom or bank touching for channel design and operation.

BACKGROUND

The *design* of harbour entrance channels and fairways is more and more based on probabilistic computations, rather than on deterministic methods. This approach is recommended by PIANC (1997) and is presently the subject of PIANC Working Group 49. This holds both for the *depth and width design* of entrance and navigation channels. For *operational optimisation* of the port or terminal, the *allowance of deep-draught vessels* into existing channels and fairways is also more and more based on computation of the probability of bottom touching during the passing event. Both these aspects should be based on acceptable levels of risk, which, in this case, is the quantified consequence of the vessel touching the channel bed. The risk of bottom touching or even grounding should, therefore, be related to the channel bed conditions (e.g. mud, sand, rock), as well as to the type of cargo (e.g. LNG, oil or containers) and the value of the local environment (e.g. industrialised or RAMSAR site). The port or terminal authorities should decide on the level of risk that is acceptable for that particular port or terminal and shipping condition.

There can be significant cost benefits in designing an entrance channel that is not deeper or wider than what is required as a minimum on the basis of the operational specifications and safety criteria for the port. The need for optimisation of the depths of port entrance channels was already recognised in the 1970's (Bijker and Massie, 1978). For this purpose, a **probabilistic design method** was proposed, rather than a **deterministic design method**, which was current practice at that time. Differences between the probabilistic and the deterministic depth design of entrance channels are illustrated in PIANC (1985). A probabilistic design approach for the optimum design of the *channel width* was discussed in PIANC (1997) and applied by Iribarren (1997).

The probabilistic optimisation approach was further improved and applied in the design of Dos Bocas harbour in Mexico by Strating *et al* (1982). Their theory was applied by Rijkswaterstaat to develop a **probabilistic admittance policy** for the port of Rotterdam, incorporated in the HARAP model for the allowance of deep-draught ships. This model has since then been used successfully (Savenije, 1996). An important component of the probabilistic design method is related to the specified **acceptable risks** and the related **safety levels** for the channel usage.

Probabilistic design methods, to determine the optimum dimensions of a port entrance channel, are now more widely used and lead to significant savings compared to the deterministic design approach. These methods have also been extended to the optimisation of the operational use of entrance channels. Details of the probabilistic design methodology will be discussed in the following sections, as related to the optimum design of channel depth.

CHANNEL DEPTH DESIGN

General Design Aspects

The depth of port entrance channels is determined by a number of components, which are directly related to the water level, the ship and the channel bottom, as illustrated in Figure 1.

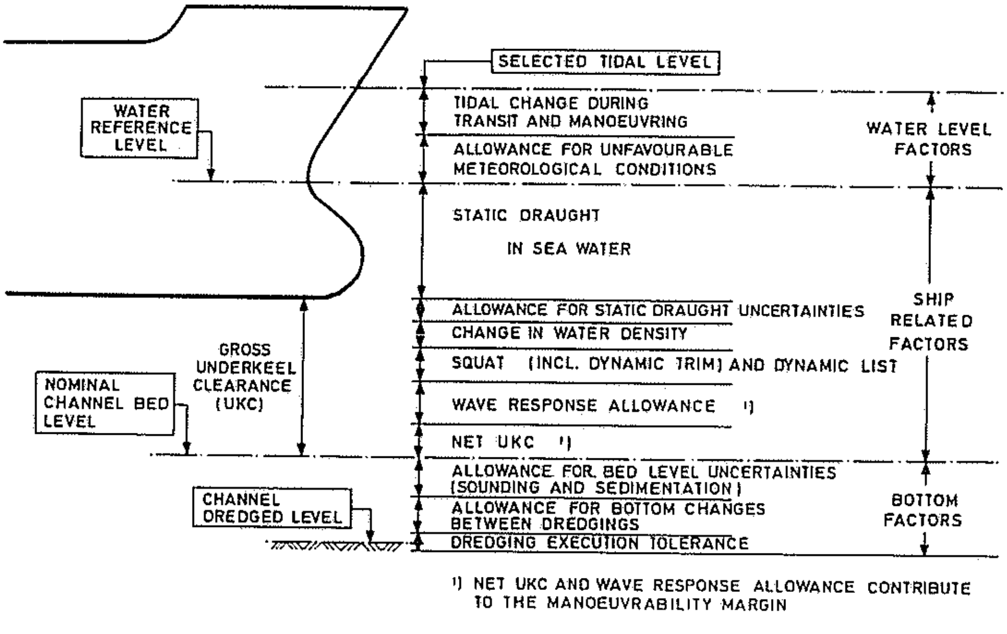

Figure 1 : Direct channel depth design factors

The components related to the **water level** fluctuations, relative to a fixed reference level, are mainly determined by astronomical tides and by meteorological and wave effects, such as wind- or wave-induced water level set-up or long-wave oscillations. The components related to the **channel bottom** concern uncertainties like those of depth sounding, allowance for siltation between dredging and dredging tolerances. The components related to the **ship** are the ship's (static, maximum) draught, squat, trim, wave-induced vertical ship motions and a net underkeel clearance. Variations in these values can occur due to variation in water density, in the ship's speed (trim) and measurement or computation uncertainties. For entrance channels which are exposed to significant wave action, the **maximum wave-induced vertical ship motion** is the largest probabilistic factor which contributes to the (gross) underkeel clearance. In such a case it is of **critical importance** to determine the design value of the wave-induced vertical ship motion with as much accuracy as possible.

Probability of Vertical Wave-induced Ship Motions

The maximum vertical downward motion of a ship exposed to wave action can be determined using a physical small-scale model, a numerical model or available Response Amplitude Operators (RAOs). For the **conceptual design phase**, use can be made of pre-computed sets of RAOs, that is, the ratio of ship motion amplitude over wave amplitude, for uniform wave conditions, to obtain an estimate of the significant vertical ship motions. Since the wave heights in a record, in conditions where waves are not depth limited, are distributed according to the **Rayleigh distribution**, this can also be accepted for the related ship motions. In the case of a conceptual design, the significant downward amplitude of ship motion A_{mo} can be taken as $A_{mo} = RAO_p.½. H_{mo}$, where RAO_p is the RAO value at the peak frequency of the wave spectrum or the spectral RAO for a specified wave spectrum. It follows then from the Rayleigh distribution that :

$$A_E = A_{mo}\ \sqrt{\{-½\ \ln(E)\}} = RAO_p.½.\ H_{mo}\ \sqrt{\{-½\ \ln(E)\}} \tag{1}$$

where :

A_E = expected vertical ship motion amplitude, related to an exceedance E (m)
H_{mo} = significant wave height (m), where $H_{mo} = 4.\sqrt{m_o} = 4.s$
m_o = zero-eth moment of the wave energy density spectrum (m^2)
s = standard deviation of the instantaneous water level motion (m)
E = probability of exceedance

The significant wave height chosen for the channel design is based on the limiting wave height for which the channel still would have to be operational for shipping (e.g. the 1% exceedance value). It can be expected that the channel will be closed for navigation of deep-draught vessels during extreme wave conditions, for example, where pilot transfer is realised by pilot boat and where such a transfer can only safely take place under certain limiting wave conditions. The selected maximum significant wave height for the channel design should be carefully considered in the design of a channel.

Safety Criteria for Probability of Exceedance

For channel design and operational allowance, the choice of the probability of exceedance E is important, as this relates directly to the shipping safety. One of the earliest summaries of safety criteria for deep-draught vessels in port entrance channels has been compiled by van de Kaa (1984). He lists various probability levels associated with ship manoeuvring incidents, such as collisions, strandings, accidents and ship-bed contact. Four of his listed probability criteria for ship - channel bed contact are :

1. Accident per passage under average environmental conditions 5.10^{-4}

2. Accident with heavy damage per passage under average conditions $2{,}5.10^{-7}$
3. Accident per passage under extreme environmental conditions 1.10^{-2}
4. Accident with heavy damage per passage under extreme conditions 5.10^{-4}

PIANC (1997) has also listed probabilities of grounding. The results of an analysis of groundings in Northern European ports by Dand and Lyon showed in 1993 that grounding occurs with a probability of 0,03 incidents per 1 000 ship movements (a probability of 3.10^{-5} or one ship grounding per 33 000 ship movements). It should be realised that these ship movements probably relate to all movements of the larger-size ships under general environmental conditions. This probability value would, therefore, be in between the above quoted criteria 1 and 2 of van de Kaa. The present practice at the Port of Rotterdam has been summarized by Savenije (1996), who quotes the two criteria presently in use at the port :

1. During 25 years the probability of touching the channel bottom, with maximum minor damage, must not be more than 10%.
2. The probability that a vessel during its transit touches the channel bottom must always be less than 1% for all weather condition.

Another criterion is that the underkeel clearance should never be less than 1 m. However, this is primarily a navigation criterion and should be added to the underkeel clearance requirements of all other underkeel clearance factors, but excluding the wave-induced vertical ship motions. Such a "net underkeel clearance" should not be used in probabilistic computations (PIANC, 1985).

The factor of 10% in Savenije's criterion 1 means that only one out of ten bottom touches results in more than minor damage. The other nine bottom touches only lead to zero or at most minor damage. This criterion is based on a shipping intensity of 250 deep-draught vessels calling at the Port of Rotterdam per year. This would mean that it is accepted that one bottom touch with damage is accepted per 25 years or per 6 250 shipping events. This is a probability of bottom touching of $1{,}6.10^{-4}$ per shipping event, which is of the same order of magnitude as criterion 1 of van de Kaa, with a probability of 5.10^{-4}. The second criteria of Savenije, with the stipulation "for all weather conditions", is the same as criterion 3 of van de Kaa.

Risk

It should be realized that **risk is defined as the probability of occurrence multiplied by the financial and impact consequences.** Therefore, in using the above probability criteria, one should optimize the risk, which include the (financial and environmental) consequences of bottom touching. The consequence components of the risk are higher for touching a rocky channel bed than a muddy bed, are also higher for tankers than for general cargo vessels and are higher for sensitive environments than for industrialized areas. One should select risk criteria that are applicable to the local environment.

The choice of acceptable risk of grounding should be taken by the relevant Port Authority, considering all associated risks. This is usually related to an acceptable number of groundings during the lifetime of a channel. For example, if the shipping intensity would be on average four depth-limited ship passages per day during a 25 year period, this would mean one bottom touch per 36 500 such ship passages or a bottom touch probability of $2{,}7.10^{-5}$.

Table 1 provides an **illustration of the possible probability values** that could be used for the depth design of channels as function of certain risk levels. The values in the table are the **number of years** where a single bottom touch by one of the vessels would be acceptable. In this way, the responsible and affected persons can easily understand the level of risk that is associated with the design. In the table, **E1** indicates an industrialised marine environment, **E2** a medium sensitive marine environment and **E3** a very sensitive marine environment.

Table 1 : Illustration of probability levels (No. of years) as related to risk factors

	Channel bed condition		
Cargo type	**Hard**	**Medium**	**Soft**
Dangerous	E1 : 50 E2 : 100 E3 : 200	E1 : 25 E2 : 50 E3 : 100	E1 : 10 E2 : 25 E3 : 50
Medium	E1 : 25 E2 : 50 E3 : 100	E1 : 10 E2 : 25 E3 : 50	E1 : 5 E2 : 10 E3 : 25
Safe	E1 : 10 E2 : 25 E3 : 50	E1 : 5 E2 : 10 E3 : 25	E1 :1 E2 :5 E3 :10

The probability of exceedance E in Equation 1 can be determined, using the number of oscillations of the design ship(s) during the number of years in Table 1. The number of vertical ship motion oscillations N_o during a passage in the channel is equal to the passage time of the ship in the channel (section) (T_h), divided by the average (spectral) oscillation period (T_{mo2}) : $N_o = T_h / T_{mo2}$. The value of E is then $1/(N_o \times N_p \times N_y)$, where N_p is the average number of passages per year and N_y is the number of years as shown in Table 1.

Long-term Probability Criterion

The probability that the underkeel clearance will be exceeded during *several ship passages* under these design conditions can be computed from a **Poisson distribution** for the long-term occurrence of these events (Strating *et al*, 1982) :

$$P = 1 - \exp(-E_p.N_p) \qquad (2)$$

(for $E_p.N_p < 0{,}01$, this relationship can be approximated by : $P = E_p.N_p$)

For example, during the operational lifetime of the channel of 50 years, where the design ship makes $N_p = 12 \times 50$ passages through the channel (section), with a probability of exceedance per passage of $E_p = 8{,}3.10^{-4}$, it follows that P = 0,39. The probability that during this 50-year period, for this particular case, the expected maximum value is reached or exceeded is, thus, 39%. A general design value for the exceedance during the lifetime of the channel of 10% is being used for Europort/Rotterdam (Savenije, 1996). In this case, with P = 0,1 it follows from Equation 3 that $E_p.N_p = 0{,}105$. With $N_p = 36\,500$ it follows that $E_p = 2{,}9.10^{-6}$ (or one bottom touch per 346 400 ship oscillations). With Equation 1 it follows that in this case $A_{E,max} = 2{,}53.A_{mo}$.

Probabilistic Design

The contribution of the various other probabilistic factors to the underkeel clearance, as shown in Figure 1, is not through a direct addition of the expected extreme values. The probability of combined occurrence of the extremes, if considered as independent variables, is lower than the sum of the individual factors. Therefore, a direct addition would lead to an "over-designed" channel depth. Bijker and Massie (1978) argue that, for a probabilistic approach of the design of the depth of port entrance channels, the *instantaneous* vertical ship motions should be used, as distinct from their oscillations (which are represented by the Rayleigh distribution). The instantaneous elevations of the wave-induced vertical ship motions can be expressed by a **Normal or Gaussian distribution**, with the variable expressed by the *standard deviation.*

If all probabilistic components, which contribute to the required underkeel clearance, are expressed by their mean value and standard deviation, the combined distribution of these components can be expressed by the sum of their mean values and the square root of the sums of their individual standard deviations squared :

$$s_c = \sqrt{(s_s^2 + s_b^2 + s_w^2 + \ldots\ldots)} \qquad (3)$$

where :

s_c = combined standard deviation
s_s = standard deviation of the motions of the design ship (= *½.A_{mo})*
s_b = standard deviation of channel bed irregularities
s_w = standard deviation of water levels

These computations can be executed for a number of channel sections, each with their specific wave climate, channel bed condition and water level variation. If a *Normal or Gaussian distribution* is accepted for the combined distribution of the variables, together with an underkeel clearance amplitude (UKC) of, for example, $4s_c$, this channel depth will then be associated with a probability of exceedance of 0,000 032% (or 1 min out of 526 hours). This indicates the expected percentage of the ship's passage time that the ship's keel will be at or below the channel bed. The proclaimed or nominal channel bed level should be chosen to be a sufficiently safe value, with a specified standard deviation and probability of exceedance.

The above computations can be repeated for a range of depths to determine the relationship between channel depth, ship draught and **downtime**. This is done by schematising the range of tidal, wave and weather conditions into a set of **discrete environmental conditions,** each with a specific probability of occurrence. For each of these discrete conditions and ship draught the percentage downtime can be calculated according to the above methods. These computed discrete downtimes are then multiplied by the associated probability of occurrence of the conditions to determine the overall downtime. This will also allow the computation of the channel downtime as function of the channel depth and ship draught. The optimum channel depth can be determined by calculating the financial consequences of having to delay ship operations in the channel, together with the costs of deepening the channel.

A different approach would be to use a **Monte Carlo simulation** technique. In this case, usually the probability distributions of all environmental and shipping conditions are described and fed into the simulation. However, the simulated conditions should be limited to tidal-bound and channel-bound ships. Service or small vessels that would "never" touch the channel boundaries should be excluded from the simulation, as these could unrealistically reduce the overall risk. The selection of relevant ship types for the Monte Carlo simulation is a subjective component of this approach. For representative stable results, the number of conditions to be tested could easily be millions, but with fast computers, such a simulation could be carried out expediently.

Operational Channel Allowance

The use of an existing channel can be optimised for each particular ship passage by using similar computations as for the channel design. To determine the probability that the vessel exceeds an available underkeel clearance UKC, which is based on the ship's *oscillations* rather than on the instantaneous variation in underkeel clearance, the Rayleigh distribution as represented in Equation 1, could be used. If the underkeel clearance UKC is chosen to be equal to a specific value of A_E, the probability of exceedance of UKC can be computed by the inverse of Equation 1. For example, for $UKC/A_{mo} = 2$ it follows that :

$$E = \exp\{-2(UKC/A_{mo})^2\} = \exp\{-2(2)^2\} = 3{,}35.10^{-4} \qquad (4)$$

This means that during the passage of the ship at this particular underkeel clearance the probability for the underkeel clearance to be exceeded will, in this case, statistically be during 1 in 2 981 ship oscillations. The percentage of time when a ship of a particular class or draught can not be safely allowed into the channel (for this ratio of UKC/H_{mo} as accepted level of safety, i.e. when the computed $A_E > UKC$), is called the **channel downtime** for this class of ship. This can also be computed using Equation 1, using the relevant RAOs and yielding a particular maximum allowable value of H_{mo}.

CONCLUSIONS AND RECOMMENDATIONS

Vertical wave-induced ship motions remain the largest contributing component to the channel depth design of ports that are exposed to significant wave action. This implies that the vertical ship motions have to be determined with the greatest accuracy possible and e.g. supported by modern ship motion modelling and measurement technology. Acceptable risk levels for an entrance channel or fairway should be chosen on the basis of the consequences of a vessel exceeding the available underkeel clearance or the channel boundaries. Such a choice should take into consideration the type of cargo carried by the vessels, the channel bed and side slope conditions in terms of hardness and the local environment, such as an industrial area or a recreational area or RAMSAR site. The Port Authority is ultimately responsible for such a choice, which should be motivated as part of the EIA process for the port design.

The methods outlined above to determine the probabilities of exceeding a specified underkeel clearance and associated risks can be used for the **design and optimisation of port entrance channels**, but also to determine the **operational conditions** for the safe utilisation of the entrance channel. Most present port operational systems are based on fixed-rule or semi-probabilistic methods. These should be modified to take full advantage of advanced probabilistic methods.

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