

# **Risk-Based Design of Entrance Channel Depths: A Case Study At the Entrance Channel of Mombasa Port, Kenya**

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**Abstract:** The present design guidelines, which are based on a deterministic approach, for designs of channel depths are not comprehensive and practical. Applying such simplified guidelines can result in channel depths of questionable safety or excessive cost. This paper presents a risk-based method for design of entrance channel depths. The proposed method, which is based on a probabilistic approach, consists of two developed models: (1) a parametric model of the wave-induced ship motions; (2) a Poisson probability model of ship grounding induced by waves for a single ship passage. The final results derived from these models make it possible for analysis and selection of an optimal depth with a condition that an acceptable probability of ship grounding should be allowed. The method has been applied to the entrance channel of Mombasa Port, Kenya as a case study.

**Keywords:** Risk assessment, Ship Grounding, Channel Depth, Underkeel Clearance.

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## **1. INTRODUCTION**

Waterborne transport has proven its value and role in worldwide economic development and is a fundamental tool in the creating of global trading activities. To reduce the transportation cost and to meet the demand on overseas transport growing quickly over the years, the ability of worldwide shipping industry towards constructing larger ships seems to be never-ending. Accommodating these larger ships to present ports is an emerging problem. In the same time, marine infrastructure has not often been improved to keep the pace with this development because of natural condition and financial restrictions. This fact has been producing more potential risks in the waterborne traffic. Safer and more efficient shipping operations and protection of environment have therefore been of great interest in waterborne transport research. More efficient and accurate waterway design tools would always be a priority solution. This in turn has motivated new and improved techniques to offset the traditional approach to waterway design, an approach that can result in waterways of questionable safety, excessive cost, or both because of uncertainty, conservatism, and reliance on rules of thumb [1]. Trade-off between cost and benefit should be done.

The risk-based method for the design of channel depths developed in this paper based on an accepted probability of failure during its lifetime or during a single event. The failure of a channel to safely accommodate manoeuvring ships is defined as the ship touching the bottom, assumed as the ship grounding. The chance of a ship touching the bottom during a single transit is not allowed being higher than an acceptable value. The proposed method consists of two models: (1) a parametric model of the wave-induced ship motions; (2) a Poisson probability model of ship grounding induced by waves for a single ship passage. The final results derived from these models make it possible for analysis and selection of an optimal depth. The method has been applied to the entrance channel of Mombasa Port, Kenya as a case study.

## **2. PROJECT ONLINE AND DESIGN CONDITIONS**

### **3.1. Project Location**

The Port of Mombasa (the Port) is located at 4°2.5' S and 39°38.3' E (KPA Headquarters) on the east coast of Africa, facing the Indian Ocean. The Port has developed in the creeks surrounding the Mombasa Island, i.e. the Old Port on the east side and Port Kilindini and Port Reitz on the west side of

the island. The entrance channel of the port with the length of about 17.0 km composes two parts: inner channel and outer channel.

In recent years, the demand on cargo import from Europe and Japan has increased rapidly and ships entering the port are becoming larger and in fully loaded state beyond the present capacity of the entrance channel of the port. Therefore, in the present, Kenya Port Authority initiated an expansion project of the port [2] in which the entrance channel will be enlarged to allow the container ships of up to 6000 TEU (fully loaded) using a tide up for entering\leaving the port.

## 2.2. Design Ship

The design ship is a Post-Panamax 6,000 TEU as highlighted in the following table.

**Table 1: The ship specifications**

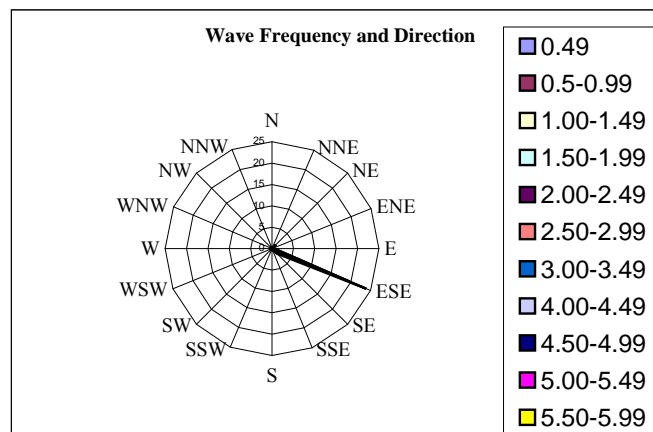
Items	Unit	Dimensions
Ship Capacity	TEU	6,000
DWT	Ton	60,000
Ship length (LOA)	m	286
Ship width (B)	m	36.5
Draft (D)	m	13.8
Berth depth	m	15.4

## 2.3. Wave conditions

Sea waves at the sea side area of the Likoni area, i.e. the Outer Channel area, are usually generated by wind. The wave height is rather high during the ESE Monsoon seasons. The waves in the inner channel, however, are minimal due to the short fetch length in the creek. The quantitative figures of the waves were assessed by means of appropriate wave hindcast methods as presented in Figure 1. In this paper, the wave parameters were calculated by means of “Global Wave Hindcast Method” based on the actual meteorological data.

According to the calculation, the wave characteristics are:

- Prevailing wave was from ESE direction, which accounted for 88.21% of all directions. The significant wave height of this direction ranged from 1.0 m to 3.0 m and accounted for 73.65%.
- All of wave period recorded  $T_p \leq 10$  sec. of which 94.9% wave period is less than or equal to 8 sec.



**Figure 1: Wave rose at the project site**

## 2.4. Tide

Tide at Mombasa Port is predominantly *semi-diurnal*. According to the KPA publication, tidal levels range from a highest level of 4.1m to a lowest level of -0.1m. Table 2 below shows the tidal levels observed at Kilindini Harbour.

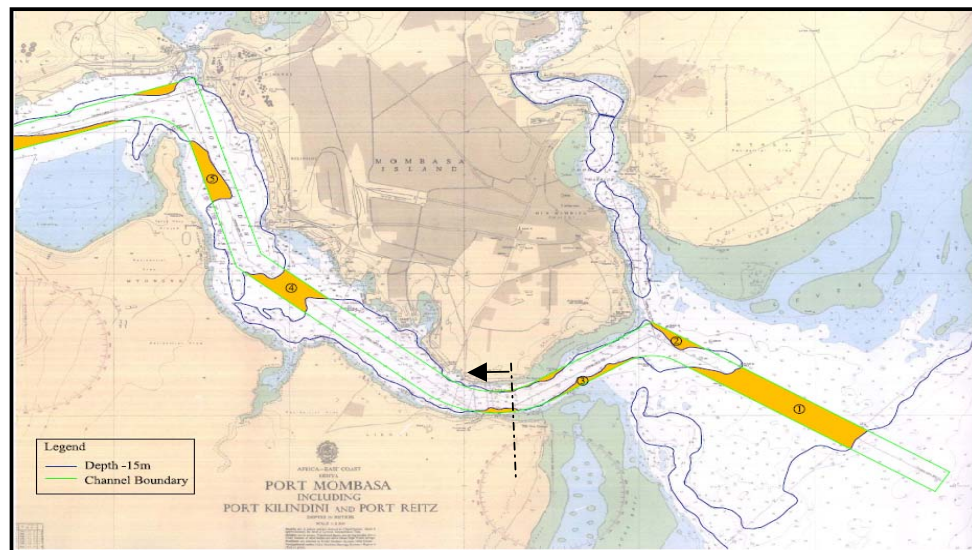
**Table 2: Tidal Levels in Mombasa Port**

Highest sea level (HSL)	+ 4.10 m
Mean high water level (MHWL)	+ 3.50 m
Mean sea level (MSL)	+ 1.86 m
Chart datum level (CDL)	0.00
Lowest sea level (LSL)	- 0.10 m

## 2.5. Existing approach channel

Alignment of the proposed entrance channel is shown in Figure 2. The whole channel is divided into to parts:

- Part one (outer channel): this part exposes to the open sea, the channel alignment is nearly parallel to the dominant wave direction. So the out-bound of ships will face to incoming waves. This fact results in the most critical in the viewpoint of ship touching the bottom.
- Part two (inner channel): this part is located inland and almost protected from the wave.



**Figure 2: Plan of the approach channel to Mombasa Port**

## 3. RISK-BASED DESIGN OF CHANNEL DEPTHS

### 3.1. General equation

The channel is divided into two parts as discussed, to determine the required depths for each one, the following formula can be used:

$$d = -H_{tide} + (D + S_{max} + B_f + h_l + AUC) \quad (1)$$

Where  $d$  is the required depth to reference level (CDL);  $D$  is the draft of ship;  $H_{tide}$  is the tidal elevation above reference level;  $S_{max}$  is the maximum sinkage due to squat and trim;  $B_f$  is the bottom factors;  $h_l$  is the heeling, vertical lowering of the ship on one side, due to ship turning;  $AUC$  is the allowance for wave or wave allowance underkeel clearance.

### 3.2. Tide, $H_{tide}$

Because the channel should be designed to allow the ship entrance for all time without delaying,  $H_{tide}$  must therefore be zero.

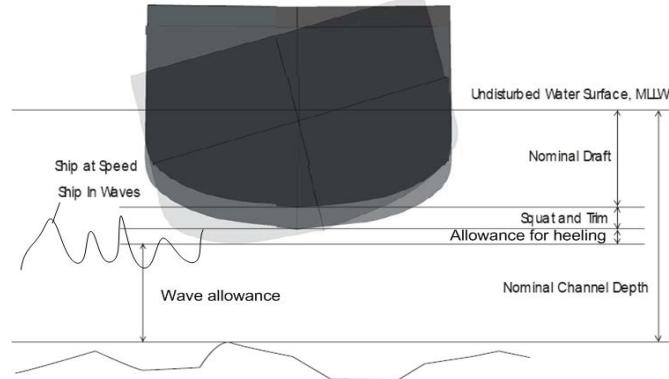


Figure 3: Channel depth allowance and components

### 3.3. Maximum sinkage, $S_{max}$

A vessel sailing with a certain speed will suffer some sinkage, this is named squat. Trim is caused by uneven loading of the ship. For determination of the sinkage due to squat and trim, different formulas have been developed. As long as the underwater bank height is less than 40%, the channel can be considered as unrestricted.

For this channel, the Barass II formula is used [3]. This formula is generally applicable in shallow water and slightly conservative for an unrestricted entrance channel, like this one. The formula is given in equation (2). It is applied for the situation with no water currents and only one ship in the entrance channel.

$$S_{max} = \frac{C_b S_2 V_k^{2.08}}{30} \quad (2)$$

Where  $S_{max}$  is the maximum sinkage due to squat and trim [m];  $C_b$  is the block coefficient;  $S_2$  is the blockage ratio =  $S/(1-S)$ ;  $S$  is the blockage factor =  $A_{s-vertical} / A_{ch}$ ;  $A_{s-ver}$  is the vertical midship section area [m<sup>2</sup>];  $A_{ch}$  is the channel cross-section area [m<sup>2</sup>];  $V_k$  is the vessel speed through the water [knots];

The equivalent channel width of unrestricted shallow water to determine the blockage factor is:

$$W_{eq} = B \left[ 7.7 + 45(1 - C_w)^2 \right] \quad (3)$$

Here  $W_{eq}$  is the effective width of waterway in unrestricted shallow water [m];  $C_w$  is the water plane area coefficient of the vessel =  $A_s/(B \times L)$ ;  $A_{s-plane}$  is the vessel cross-sectional area in the plane of the water surface [m<sup>2</sup>];  $B$  is the vessel width [m];  $L$  is the vessel length [m].

The water plane coefficient is 0.9, which is a representative value for this container ship. This coefficient leads to an equivalent channel width of 297.475 m. This is the width that will be used in the calculation of the squat.

An estimation of vessel speed at different locations has to be made. The local speeds could have been measured at different locations along the channel trajectory. However, the choice could be made to use a vessel manoeuvring simulation model, so-called ship-handling simulator. This program is able to



The best way to obtain a local wave climate is to conduct measurements for a number of different locations in the outer entrance channel. This may be a very costly operation. A local wave climate therefore can be obtained either from available numerical models (e.g SWAN, WAFO) or by real time simulation experiment results, which will be conducted for this project. For this initial calculation, it is assumed that the wave data is equally applied to the whole outer channel. For further detail calculation, the local wave climate generated from simulation experiments will be used.

It is recommended that the wave direction from ESE with the wave parameters  $H_s=3.5\text{m}$  and  $T_p=9$  second will be used as the design wave for calculation of the ship motion. This is the most critical wave acting on the ship since the out-bound of the ship will face to the incoming wave. The occurrence frequency of wave heights exceeding this design wave is 1.52%. It means that we have to accept 1.52% downtime due to the channel close during the lifetime of the channel service.

For calculation of wave spectrum, Pierson-Moskowitz wave model has been used [4]. This is a suitable model for fully developed sea, i.e. a sea state where the wind has been blowing long enough over a sufficiently open stretch of water. The P-M spectrum parameterization used is:

$$S(\omega) = 0.11H_s^2 \left( \frac{2\pi}{T_m} \right)^{\frac{4}{\omega^5}} \exp \left\{ -0.44 \left( \frac{2\pi}{T_m \omega} \right)^4 \right\} \quad (4)$$

$$T_m = T_p / 1.2965$$

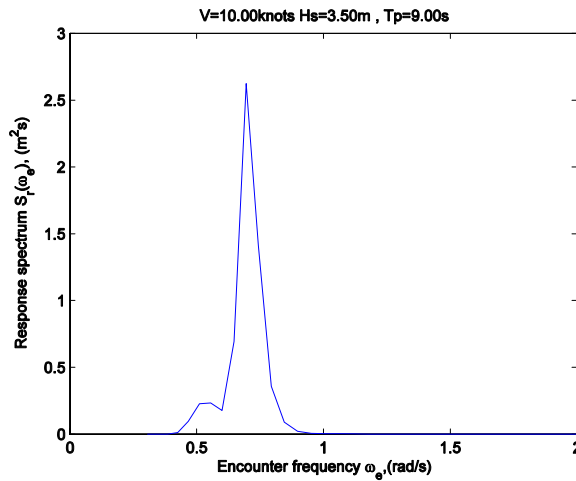
Where  $H_s$  is the significant wave period;  $T_p$  is the wave peak period

- *Calculation of ship motion response spectrum.*

Having determined the wave motion spectrum and for a given transit condition (ship speed and draft), the spectrum of wave-induced motion response can be determined as [5]:

$$S_r(\omega_e|V,d) = |H(\omega_e|V,d)|^2 S(\omega_e) \quad (5)$$

Here  $\omega_e$  is the encounter frequency depends on the ship speed,  $V$ ;  $|H(\omega_e)|$  is the encounter frequency transfer function is determined from a numerical model of ship motion.



**Figure 5: Response spectrum**

Figure 5 shows the response spectrum of ship motion is obtained for the design wave with the speed of 10 knots and fully loaded draft.

- Calculation of the ship motion,  $r$

Widely used determination method of a level of ship motion,  $r$ , due to wave is based on the Poisson model. A level of the motion can be determined as a function of the motion characteristics and a probability,  $\alpha$ , of the motion exceeding this level as follows [6]:

$$r = \sqrt{m_0} \sqrt{-2 \ln \left\{ \frac{\ln(1-\alpha)}{\frac{T_o^2}{2\pi} \sqrt{\frac{m_2}{m_0}}} \right\}} \quad (6)$$

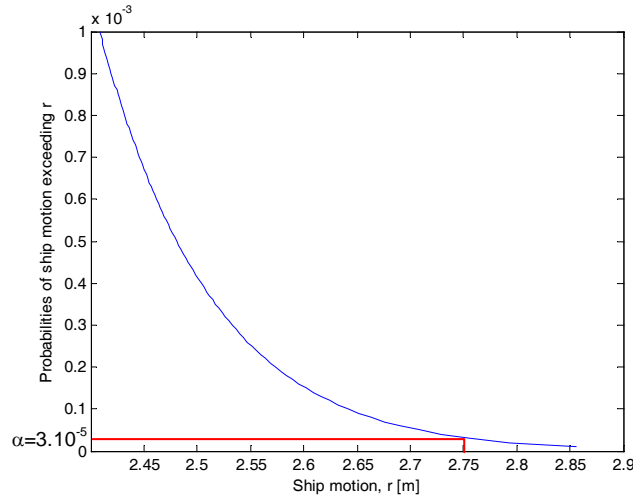
Where  $m_o$  and  $m_2$  represent zero and second moments of the response, respectively, which can be determined by the following equations:

$$m_o = \int_0^{\infty} S_r(\omega_e) d\omega_e \quad (7)$$

$$m_2 = \int_0^{\infty} \omega_e^2 S_r(\omega_e) d\omega_e \quad (8)$$

And  $T_o$  is the time of ship transit in the channel. Assuming that the ship speed is constant during the transit,  $T_o$  is determined as  $L_{ch}/V$ ;  $L_{ch}$  is the length of outer channel =4000 m.

Figure 7 shows levels of ship motion,  $r$ , for different probabilities of ship exceeding this level applying the above-mentioned equations.



**Figure 7: Ship motions vs. the probabilities of their exceeding**

- Definition of an allowance underkeel clearance for the design wave,  $AUC$

Now to define an allowance underkeel clearance for the design wave, the value of  $\alpha$  should be known. It should be understood that this value can be considered as the probability of ship touching the bottom due to waves for an allowance underkeel clearance  $AUC=r$ .

The value of  $\alpha$ , so-called risk acceptance, is one of the key issues in the design or operation of any approach channel. The risk acceptance is defined for a particular to satisfy the condition that an allowance underkeel clearance must be larger or at least equal to  $r$  for the safe transit. PIANC reported

this probability for Northern European ports of 3 per 100,000 (i.e.  $3 \times 10^{-5}$ ) ship movements. Statistics appeared in the literature [7] that accident probabilities ranged from a low of 4 per 100,000 ( $4 \times 10^{-5}$ ) to a high of 83 per 100,000 tanker movements. These figures should, of course, include all types of accidents. From the safety point of view and the study concerns one failure mechanism of the bottom touch only, the risk acceptance  $\alpha=3 \times 10^{-5}$  as observed in Northern European ports might be reasonably assigned for this case.

From Figure 7 an allowance,  $AUC$ , for wave should be 2.755m. The final results of required depths for both outer and inner channels are summarised in Table 3.

**Table 3: Calculation results of channel depth**

Sections	$s_{max}$	$B_f$	$h_l$	$AUC$	Draft $D$	Calculated $d$	Designed depth
Outer	0.658	0.4	1.597	2.755	13.8	17.613	17.50
Inner	0.314	0.4	1.597	0	13.8	16.111	16.00

#### 4. CONCLUSION

Many ports worldwide are facing the problem of siltation and sedimentation. Dredging work is often very costly. Every additional ten centimeters of depth can add millions of dollars not only in initial construction stage but also annual maintenance dredging costs over the life cycle of a project. Thus, there is a strong incentive to the optimization of navigational depths. The scientific contribution of this work is the development of a new risk-based model for optimal design of channel depths by taking the risk of ship accident (grounding) induced by wave impacts into account.

The limitations of existing guidelines for the underkeel clearance allowances have been investigated by taking wave parameters and transit conditions into consideration. These results could be useful for development of a probabilistic method on the waterway design with a condition that an acceptable probability of ship grounding should be allowed; the accessibility policy for the ship entrance as well as for approach channel design will therefore be more accurately and practically established.

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