ENRED. Engineering, Resources & Development, S.L. -- INGENIERÍA MARÍTIMA.

Inicio | Ingeniería Marítima | Buque Atracado | Obras Marítimas | Contacto

Maniobra de Buques

La R.O.M. (Recomendaciones para Obra Marítima) 3.1-99 "PROYECTO DE LA CONFIGURACION MARITIMA DE LOS PUERTOS; CANALES DE ACCESO Y AREAS DE FLOTACION" de Puertos del Estado (España) establece la importancia de realizar estudios de maniobra como medio para reforzar la operatividad portuaria, la seguridad y el dimensionamiento marítimo de las obras portuarias.

Este documento recoge una serie de criterios y propone una metodología para el dimensionamiento en planta y en alzado de los espacios navegables, pero además, *en su parte 9 hace referencia a que "Los modelos numéricos y simuladores de navegación y maniobra de buques suponen un potente medio para el estudio de proyectos marítimos y portuarios. Su aplicación se centra en el diseño y explotación de instalaciones portuarias, canales de acceso y áreas de flotación, con el objetivo de proporcionar al proyectista una orientación sobre las posibilidades y restricciones del buque en relación con la infraestructura y condiciones climáticas existentes."*

Los estudios de maniobras, además de para el dimensionamiento de espacios y para la operatividad y la seguridad de las operaciones de los buques en aguas restringidas, sirven para establecer límites operativos (tamaño de buques, condiciones meteorológicas, condiciones de marea, etc.), necesidades de remolque, evaluación de riesgos náuticos y, en general, todo lo referente a la evolución de los buques en zonas portuarias y restringidas.

De acuerdo con el alcance y objetivos de cada proyecto, la maniobrabilidad de los buques puede analizarse en tres niveles:

- Estudios Básicos de Maniobra. Aplicando normativas y recomendaciones deterministas como la propia ROM 3.1-99 (antes referida) o el recientemente (Enero - 2014)publicado "Harbour Approach Channels Design Guidelines" (WG-121 del PIANC. Permanent International Association of Navigation Congresses).
- Estudios de Maniobra con Modelos Numéricos. Mediante el uso de Modelos Numéricos que reproducen el comportamiento del Buque y que habitualmente trabajan con un sistema de Piloto Automático para seguir una trayectoria y estrategia pre-definida.
- Estudios de Maniobra con Simulación en Tiempo Real. Estas instalaciones permiten incorporar el factor humano en el estudio produciendo la "inmersión" en un entorno similar a las condiciones reales, con modelos visuales de gran detalle y reproducción del puente del buque y su instrumentación básica.

Novedades

Equipo

Gonzalo Montero

Enlaces de Interés

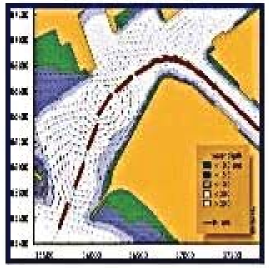
Blog de Ingeniería Marítima

Visitas

En línea 1

Modelos Numéricos

SHIPMA



Ver más Información del Modelo SHIPMA

El Modelo Numérico SHIPMA, desarrollado por MARIN y Delft Hydraulics (Holanda), reproduce el comportamiento del buque en maniobra, considerando su hidrodinámica (aguas profundas y aguas someras), sus sistemas de propulsión y gobierno, los medios auxiliares de maniobra (hélices laterales y remolcadores) y todos los agentes hidro-meteorológicos que afectan a su evolución (viento, oleaje, corriente, fondos, etc.).

Simulación en Tiempo Real

POLARIS es un SIMULADOR en TIEMPO REAL ("Full-Mission Simulator") desarrollado por Konsberg que permite la evaluación de las maniobras de los buques incorporando el Factor Humano. ENRED tiene un acuerdo de colaboración con el Centro Jovellanos de Salvamento Marítimo que dispone de una completa instalación de este tipo y de personal adecuado para la ejecución de las maniobras. Esta instalación, además para realizar estudios avanzados, es adecuada para la formación de Capitanes y Prácticos y para la presentación de proyectos, de forma que puedan implicarse en su evaluación los diferentes agentes implicados.

El personal de ENRED cuenta con más de 20 años de experiencia en el uso de simuladores en tiempo real y su aplicación a estudios de maniobra y a formación.

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Dokuz Eylul University Maritime Faculty

NAVIGATION ENGINEERING

DEPTH OF WATERWAYS

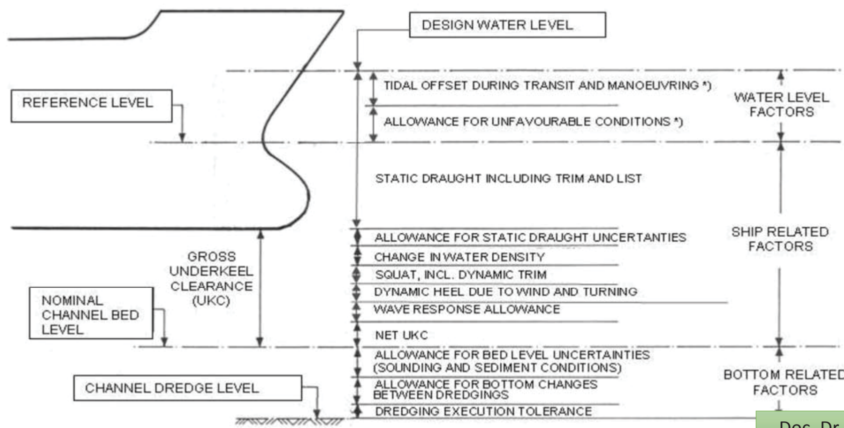
18.11.2014

Assoc. Prof. Dr. Selcuk NAS

NAVIGATION ENGINEERING

PIANC Report N° 121. 2014 - Maritime Navigation Commission - Harbour Approach Channels Design Guidelines

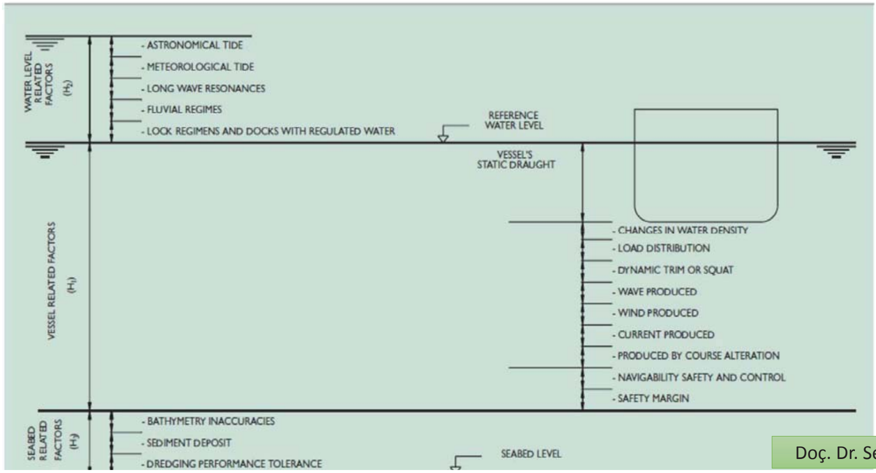
DEPTH OF WATER



NAVIGATION ENGINEERING

Recommendations for the Design of the Maritime Configuration of Ports, Approach Channels and Harbour Basins (ROM 3.1-99).

DEPTH OF WATER



NAVIGATION ENGINEERING

DEPTH OF WATER

Yaklaşım kanalı derinliğ hesabı için Ligteringen (2000) formülleri kullanılacak olur ise,

$$d = D + T + S_{max} + r + m$$

d : İhtiyaç duyulan derinlik
D : Gemi draftı
T : Harita datumun üzerindeki gelgit yüksekliği
S_{max} : Paralel Batma (Squat)
r : dalga nedeniyle düşey hareket Hs/2
m : emniyet derinliği
(dip yapısı çamur için 0,3 m, kum için 0,5 m, kaya için 1,0 m.)

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Squat Formulas

PIANC 121.2014

Tuck (1966)
Huuska/Guliev (1976)
ICORELS (1980)
Barrass3 (2004)
Eryuzlu2 (1994)
Römisch (1989)
Yoshimura (1986).

ROM 3.1.99

Huuska/Guliev (1976)
ICORELS (1980)

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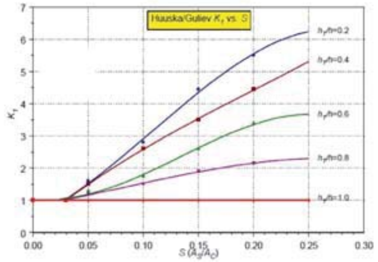
Squat Formulas

$$d_t = 2,4 \cdot \frac{\nabla}{L_{pp}^2} \cdot \frac{F_{nh}^2}{\sqrt{1-F_{nh}^2}} \cdot K_s$$

$$S_l = \frac{A_b}{A_c} = \frac{1}{K_l}$$

A_b = Area of the main cross section of the vessel's underwater body
B = Vessel's beam (m).
D = Vessel's draught (m).
A_c = Area of the channel's cross section located beneath the water level at rest (m²). For submerged channels, the equivalent area configured by the prolongation of the boundary slopes to the water surface will be considered:
K_l = Correction factor, a function of and of A_b/A_c and of h_z/h (see fig. 7.03).
h_z = Depth of the trench dredged referred to the mean seabed level (m). See



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NAVIGATION ENGINEERING

Squat Formulas

$$d_t = 2,4 \cdot \frac{\nabla}{L_{pp}^2} \cdot \frac{F_{nh}^2}{\sqrt{1-F_{nh}^2}} \cdot K_s$$

∇ = Vessel's volume of displacement (m³).
L_{pp} = Vessel's length between perpendiculars
F_{nh} = Froude number $= \frac{V_r}{\sqrt{gh}}$ (non dimensional)

The hydrodynamic resistance to a vessel's motion depends on this Froude number. When F_{nh} approaches 1.00, resistance to motion reaches very high values, which most vessels cannot overcome with the installed horsepower. Except for special cases of fast boats, all vessels sail at speeds which do not result in F_{nh} values above 0.60/0.70 (respectively oil tankers and container ships), which figures prove to be effective vessel speed barriers. Consequently, at the same time as draught requirements are being studied, the resulting Froude numbers must be checked to be compatible with the conditions arising in each case.

V_r = Vessel's speed relative to the water, excluding local effects (m/sec.).
g = Acceleration of gravity
h = Depth of water at rest, excluding local effects (m).
K_s = Non-dimensional correction coefficient for submerged or conventional channels (see fig. 7.02) (for areas with no lateral restrictions, K_s = 1.00 will be taken). The following expressions will be used to determine it:

$$K_s = 7.45 \cdot s_l + 0.76 \quad \text{for} \quad s_l > 0.032$$
$$K_s = 1.00 \quad \text{for} \quad s_l \le 0.032$$

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Squat Formulas

Derrett, D. R. and Barrass C. B. (1999) "Ship Stability for Masters and Mates" Revised by Dr. C. B. Barrass, Fifth Edition. Butterworth-Heinemann, Oxford.

$$\delta_{max} = \frac{C_b \,.\, S^{0,81} \,.\, V_k^{2,08}}{20}$$

$$S = \frac{B \,.\, d}{W \,.\, DOW}$$

δ : Squat
C_b : Blok katsayısı *(Block co-efficient)*
S : Blokaj faktörü *(Blockage factor)*
V_k : Suya göre gemi hız *(Ship Speed ralative to water)*

B : Gemi genişliği
d : Draft
DOW : Su Derinliği *(Depth of Water)*
W : Kanal genişliği

Konteyner gemilerinin blok katsayısı = 0,668*[1] *(C_b Block co-efficient)*

Açık Denizde Squat (metre) *[2]
DOW / d = 1,100 ~ 1,400 → $SQUAT_{max} = C_b \,.\, V_k^2 / 100$

Kanalda Squat (metre) *[2]
S = B.d / W. DOW = 0,100 ~ 0,265 → $SQUAT_{max} = C_b \,.\, V_k^2 / 50$

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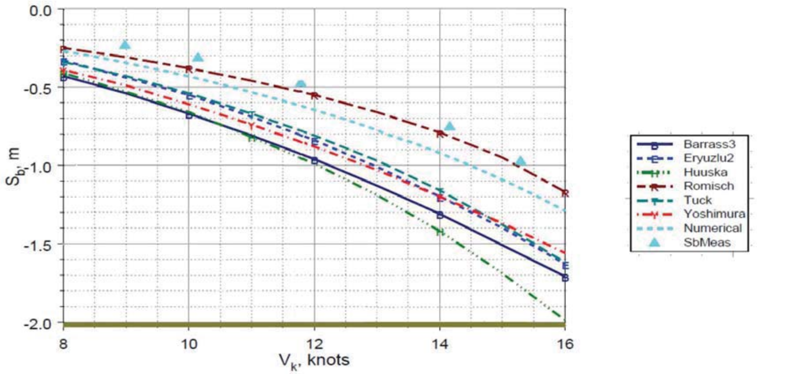
Squat With C_B

- Ship on even keel and $C_B = 0,7$ – Ship is squatting with no change of trim
- Ship on even keel and $C_B > 0,7$ – Ship is squatting and trimming to forwardt
- Ship on even keel and $C_B < 0,7$ – Ship is squatting and trimming to aft
- Ship with existing trim to aft – Ship is squatting with trim to aft
- Ship with existing trim to forward – Ship is squatting with trim to forward

NAVIGATION ENGINEERING

Squat Formulas



L_{pp} = 360 m, B = 55.0 m, T = 16.0 m, C_B = 0.68 and h = 18.0 m (h/T = 1.12)

PIANC Report N° 121. 2014 - Maritime Navigation Commission - Harbour Approach Channels Design Guidelines

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Block coefficient (C_B)

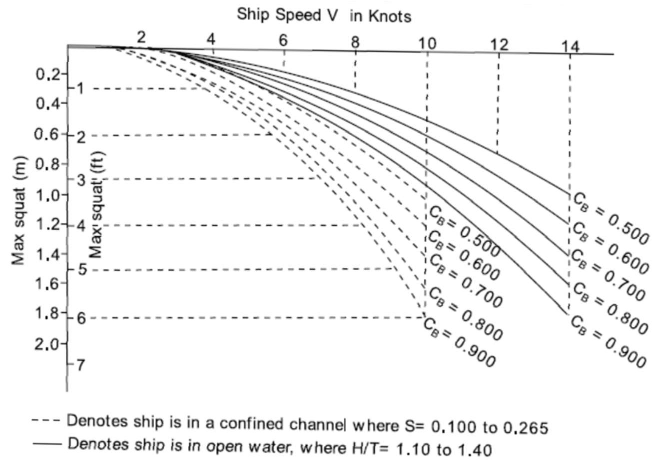
Type	50%	Standard deviation (σ)
General Cargo Ship	0.804	0.0712
Container Ship	0.668	0.0472
Oil Tanker	0.824	0.0381
Roll-on/Roll-off Ship	0.670	0.1140
Pure Car Carrier	0.594	0.0665
LPG Ship	0.737	0.0620
LNG Ship	0.716	0.0399
Passenger Ship	0.591	0.0595

Takahashi H., A. Goto and M. Abe (2006) "Study on Standards for Main Dimensions of the Design Ship" Technical Note of National Institute for Land Infrastructure Management No. 309.

Vessel type	C_B loaded condition.
Great Lakes ore carrier	0.88–0.92
Tanker	0.82–0.87
Bulk carrier	0.72–0.84
General cargo	0.55–0.78
Container ship	0.54–0.64
Ro/Ro	0.52–0.66
Barge carrier	0.58±
Passenger liner	0.55–0.65
Auto ferry	0.45–0.50
LNG	0.72

Gaythwaite, J. W. (2004) Design of Marine Facilities for the Berthing, Mooring, and Repair of Vessels

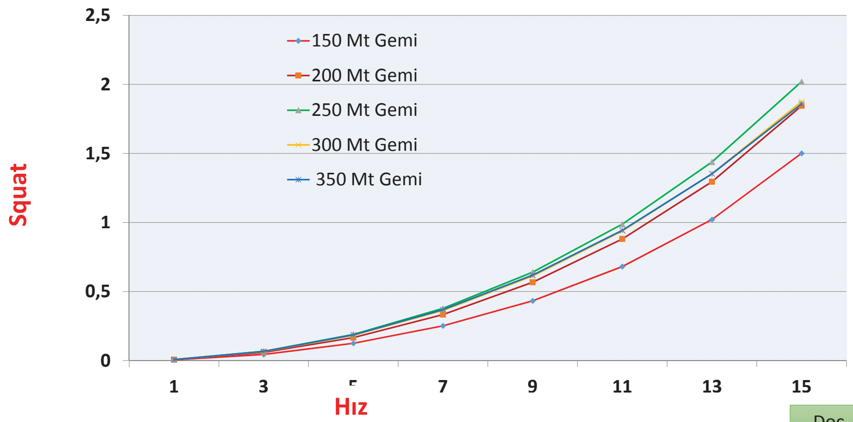
NAVIGATION ENGINEERING



Derrett, D. R. and Barrass C. B. (1999) "Ship Stability for Masters and Mates" Revised by Dr. C. B. Barrass, Fifth Edition. Butterworth-Heinemann, Oxford.

Doç. Dr. Selçuk NAS

Squat Formulas



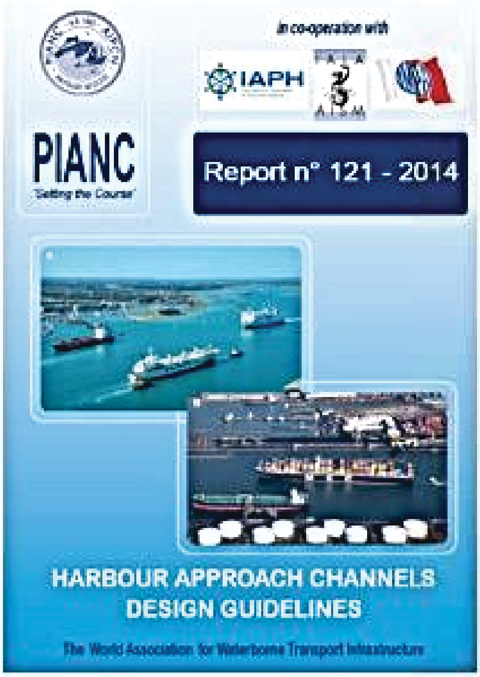
HOMEWORK

1. Fixed your working group
2. Obtain data of your design ship
3. Calculate the max. squat of your design ship for the speeds of between 5 – 25 Knots using Huuska and Derrett/Barrass formulas.
4. State the particulars of the design ship on the excel sheet
5. Prepare the excel sheet for the squat formulas.
6. Please draw your graphic for calculated squat and speeds of the design ship

PIANC: Guía para el diseño de canales y áreas de maniobra y fondeo

Publicado el 6 de febrero de 2014

PIANC acaba de publicar el Report nº 121 bajo el título de "Harbour Approach Channels Design Guidelines".



Este documento es una actualización del famoso "Approach Channels. A Guide for Design" del WG-049 publicado en Junio de 1997 que a su vez complementaba el "Approach Channes. Preliminary Guidelines" de Abril de 1995.

El nuevo documento hace referencia expresa a los métodos español (ROM 3.1-99: Designing the Maritime Configuration of Ports, Approach Channels and Floatation Areas') y japonés (Design standards for port and harbour channel widths) y además del dimensionamiento horizontal y vertical (incluyendo espacios aereos) de las zonas navegables, hace referencia al análisis de riesgos, al squat y a la navegación en zonas fangosas, entre otros.

Este documento, igual que sus antecesores, es una referencia mundial para el dimensionamiento de espacios navegables y una guia esencial para ello.

En futuros "posts" iremos analizando las novedades y los aspectos relevantes que su publicación introduce a partir de ahora en este campo.

Fdo. Gonzalo Montero

Grupos de Trabajo PIANC. Report 121

Publicado el 10 de marzo de 2014

Hoy hemos disfrutado de una interesante iniciatica de la ATPYC (Asociación Técnica de Puertos y Costas) que como miembro nacional del PIANC está intentando dar mayor difusión y presencia a los grupos de trabajo del PIANC y a los documentos de referencia resultantes de los mismos.

En esta I Jornada de Presentación de Grupos de Trabajo PIANC ha contado con la presentación del WG-121 "Harbour Approach Channels Design Guidelines" por parte de sus representantes españoles (Carlos Sanchidrián -PROES- y Jose R. Iribarren -SIPORT XXI-) y además se ha completado con las ponencias "Análisis de Operatividad del Canal de Acceso del Puerto de Santander" (Natividad Sánchez y Jesús Corral -ACCIONA Ingeniería-) y "Aplicación de datos AIS al estudio y análisis de maniobras de buques" (Enrique Tortosa – Puertos del Estado-).

Todo ello ha servido para hacer un interesante repaso sobre la maniobrabilidad de buques y su acceso a Puertos, además de poner en valor este tema que a veces queda un poco marginal tanto en proyectos de obra marítima como en la operatividad de los Puertos.

Con una asistencia de unas 50 personas, se puede afirmar que esta Primera Jornada ha tenido una estupenda acogida que esperamos anime a que se repitan reuniones de este tipo, de carácter técnico y profesional.

Fdo. Gonzalo Montero

January 21, 2014

NEW PIANC PUBLICATION AVAILABLE

PIANC

The World Association for Waterborne Transport Infrastructure

Title:	"Harbour Approach Channels – Design Guidelines"
Author's:	MarCom Working Group 121
Price:	€ 150,00 (320 pages)
Available at:	www.pianc.org -> publications (http://www.pianc.org/technicalreportsbrowseall.php)

Introduction:

This report provides guidelines and recommendations for the design of vertical and horizontal dimensions of harbour approach channels and the manoeuvring and anchorage areas within harbours, along with defining restrictions to operations within a channel. It includes guidelines for establishing depth and width requirements, along with vertical bridge clearances.

The report supersedes and replaces the joint PIANC-IAPH report 'Approach Channels – A Guide for Design' published in 1997 (PIANC MarCom Working Group 30) in cooperation with IAPH, IMPA and IALA. This report has been widely accepted worldwide by port designers. This new report has again been compiled in close co-operation with IAPH (International Association of Ports & Harbours), IMPA (International Maritime Pilots Association) and IALA (International Association of Marine Aids to Navigation and Lighthouse Authorities).

The objectives of the Working Group were to review, update and, where appropriate, expand on the design recommendations on vertical and horizontal dimensioning as presented in the Working Group 30 report of 1997 on approach channels. Recent developments in ship design, better understanding of ship manoeuvrability and behaviour in waves and further research in ship simulation and modelling required a comprehensive update to the 1997 report.

The Working Group has paid particular attention to:

- Vertical motions of ships in approach channels (due to squat, wave-induced motions, dynamic effects, etc.)
- Air draught for vertical clearances under bridges, overhead cables, etc.
- Horizontal dimensions of channels and manoeuvring areas
- Simulation of ships in channels
- New and future generation ship dimensions/manoeuvring characteristics
- Wind effect on ship navigation and manoeuvring
- Human errors and project uncertainties
- Environmental issues
- Safety criteria, assessment of levels of risk and appropriate clearance margins

All sizes of approach channel for commercial shipping are considered in this report; the problems of catering for small coasters in a small port may be as great as those for a large tanker at an oil terminal.

<u>NOTE</u>: The objective of this report is to provide information and recommendations on good practice. Conformity is not obligatory and engineering judgement should be used in its application, especially in special circumstances. This report should be seen as an expert guidance and state of the art on this particular subject. PIANC disclaims all responsibility in case this report should be presented as an official standard.

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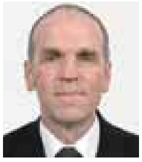
Harbour approach channels – design guidelines



Dr Mark McBride, *Manager, Ships Group, HR Wallingford, UK*

Ensuring the continued safety and efficiency of ships transiting channels requires designers and naval architects to better understand the handling and manoeuvrability of both existing and new generation ships in shallow and restricted waters. In particular, PIANC, the World Association for Waterborne Transport Infrastructure, wishes to provide the best possible advice on the issues of horizontal and vertical dimensions relating to shipping channels and manoeuvring areas.

Consequently, PIANC recently published 'Harbour Approach Channels – Design guidelines', a report from its Working Group 121 (previously MarCom Working Group 49). This report provides guidelines and recommendations for the design of vertical and horizontal dimensions of harbour approach channels, manoeuvring and anchorage areas within harbours, along with defining restrictions to operations within a channel. It includes guidelines for establishing depth and width requirements in addition to vertical bridge clearances.

The report supercedes and replaces the

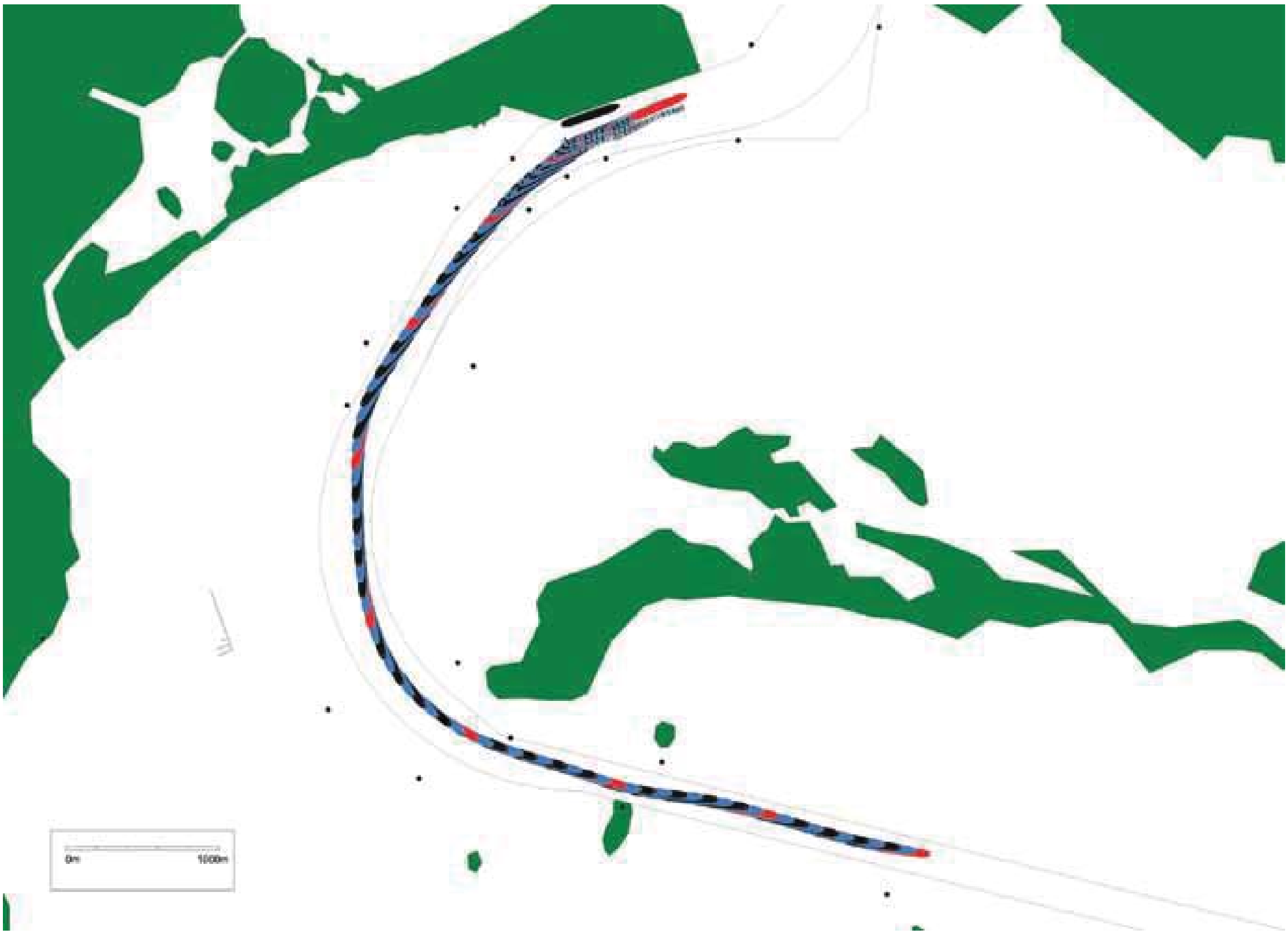


Figure 1. Complex channel design requires robust design techniques.

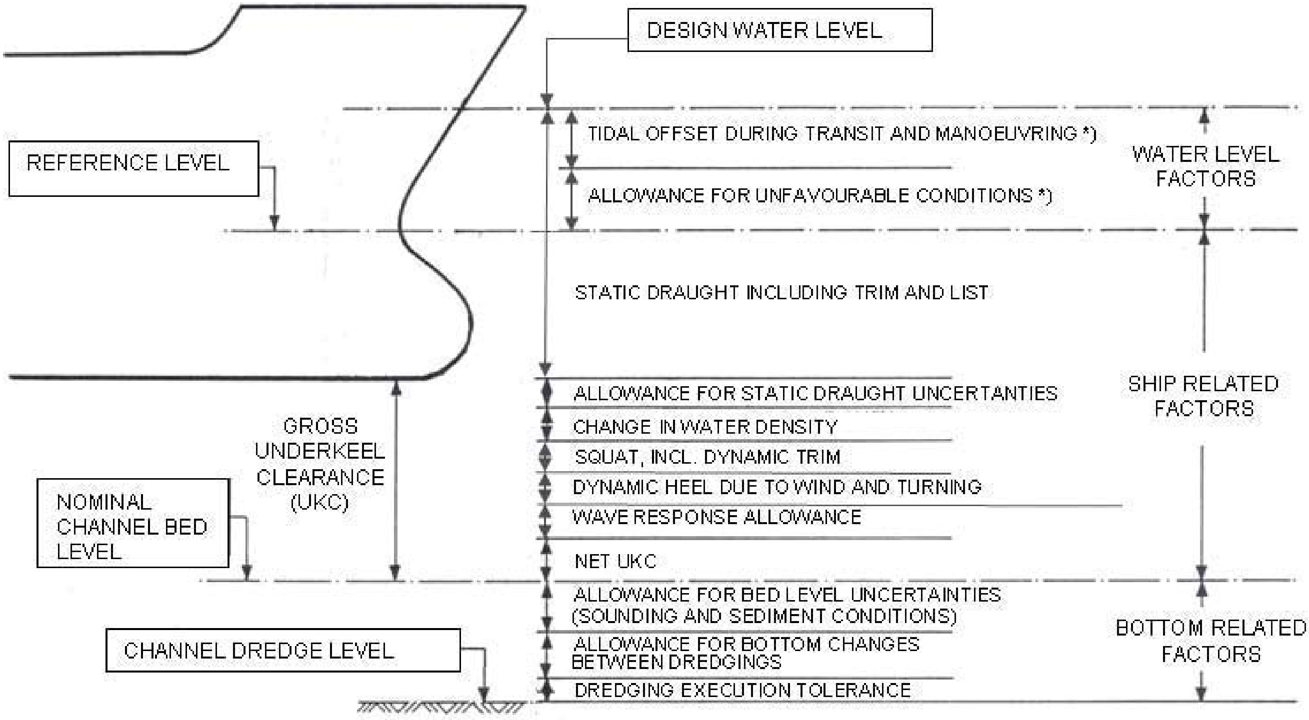


Figure 2. Channel depth design components.

joint PIANC-IAPH report 'Approach Channels – A Guide for Design', which was published in 1997 (from PIANC MarCom Working Group 30). This report was widely accepted worldwide by port designers.

The new report has been compiled once more in close cooperation with IAPH (International Association of Ports and Harbours), but also with IMPA (International Maritime Pilots Association) and IALA (International Association of Marine Aids to Navigation and Lighthouse Authorities).

Historical context

The design of approach channels and fairways was first considered by PIANC in a report published by Working Group 2 of the PIANC International Oil Tankers Commission (IOTC) in 1972. Some years later, this work was reviewed by Working Group 4 of the PIANC International Commission for the Reception of Large Ships (ICORELS) in a report published in 1980. The subject was most recently considered by the joint PIANC-IAPH Working Group PTC II-30 in co-operation with IMPA and IALA. Their findings were published, first as a preliminary set of concept design guidelines in 1995, followed by the 1997 final report 'Approach Channels – A guide for design'. This quickly became the world's definitive reference for maritime channel design.

Updated guidelines

In 2005, Working Group 121 (WG121) was created with 20 members from 12 countries, including three members from the previous Working Group 30 (WG30). It was to review, update and, where appropriate, expand on the design recommendations as presented in the WG30 report of 1997. In doing so, the Working Group considered recent developments in simulation and other design tools, along with the sizes and handling characteristics of new generation vessels. In addition, further attention was given to the design of the vertical dimensions of channels than had previously been provided.

The overall report was completely restructured to present the vertical and horizontal aspects separately, with conceptual and detailed design techniques presented in each main chapter.

The new report can be purchased from the PIANC website or for PIANC Members, it can be downloaded free of charge at http://www.pianc.org/edits/articleshop.php?id=2014121.

Methodology

Aims and objectives

The aim of the updated guidelines was to provide the best international practice for the design of approach channels that was available to the port engineering community. The goal was to produce a practical set of guidelines, which are easy to understand and apply. However, as with the previous version of the guidelines, their use still requires proper engineering judgement.

The main objectives of WG121 were to review, update and, where appropriate, expand on the design recommendations on vertical and horizontal dimensioning as presented in the WG30 report of 1997. Recent developments in ship design, better understanding of ship manoeuvrability and behaviour in waves, and further research in ship simulation and modelling required a comprehensive update to the 1997 report.

The Working Group paid particular attention to:

- Vertical motions of ships in approach channels (due to squat, wave-induced motions, dynamic effects, etc.);
- Air draught for vertical clearances under bridges, overhead cables etc;
- Horizontal dimensions of channels and manoeuvring areas;
- Simulation of ships in channels;
- New and future generation ship dimensions/manoeuvring characteristics;
- Wind effect on ship navigation and manoeuvring;
- Human errors and project uncertainties;
- Environmental issues, and
- Safety criteria, assessment of levels of risk and appropriate clearance margins.

All sizes of approach channel for commercial shipping were considered, as the problems of catering for small coasters in a small port may be as great as those for a large tanker at an oil terminal.

Revised report

The new WG121 guidelines update the conceptual design techniques presented in the previous WG30 work for both

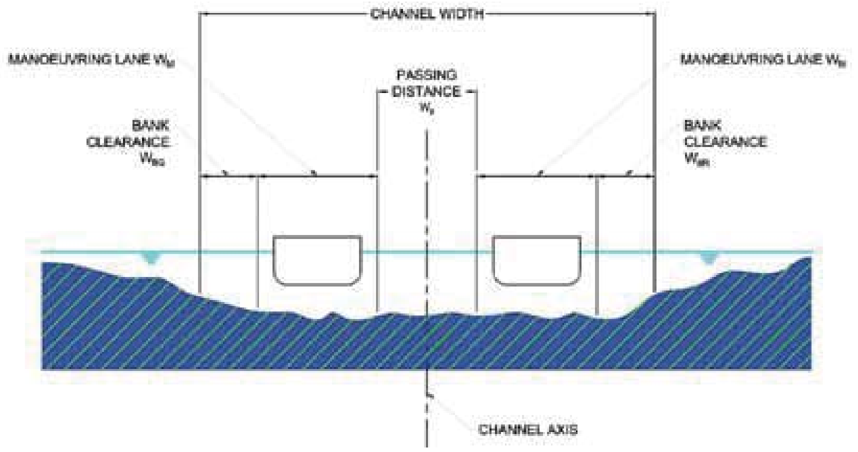


Figure 3. Channel width design components.

horizontal and vertical dimensions. The horizontal dimension guidelines include revised and updated allowances for channel width design, along with providing mention of Spanish ROM and Japanese MLIT standards, which need to be applied in those particular countries. The vertical dimension sections were also revised and updated with additional methods and examples to illustrate the techniques. The new guidelines provide:

- Conceptual design empirical methods:
  - o Channel width – sum of ship beams, modified version of previous WG30 method;
  - o Chanel depth – new initial estimate method and 'intermediate' calculation methods;
- Guidance on detailed design methods;
- Emphasise that results of conceptual design empirical methods are not a final design;
- Expect conceptual design to be conservative, and
- Optimise using detailed design methods described in the guidelines.

Much of the effort of WG121 was focused on detailed design guidelines, and in particular, probabilistic design and risk aspects, reflecting the requirements of modern engineering design principles.

The vertical dimension guidelines include further discussion and examples for predicting vertical ship motions due to waves that include deterministic, statistical and probabilistic methods. They also include sections on squat and muddy channel beds, which have been updated based on recent research and developments. In addition, with recent accurate (PDGPS) measurements of ship squat and calibrated theories, squat can now be predicted with more accuracy and this information is incorporated in the new guidelines.

Another aspect was the recent development of Post and Ultra-Post-Panamax container vessels (with capacities of up to 18,000 TEU), large car carriers, and QFlex- and QMax-size LNG carriers. These vessels have specific characteristics (high windage, larger bulbous bows, wider transom sterns, minimal parallel mid body/flat of side, etc.), which may require specific risk mitigation measures that can have an impact on access channel design and operation. The new guidelines take these new design changes into consideration.

Furthermore, the use of advanced numerical models of wave propagation and ship response to waves, along with ever realistic ship manoeuvring simulation, have become common practice in port engineering design. The new guidance includes more details and examples of their use.

Capacity simulation models can also be used to evaluate the safety of port infrastructure and are described with an example. Today, there is a more continuous range of tools available, so that each type of simulator/simulation can be used in different stages and detail of channel design.

Recent developments have led to a more integrated approach for environmental aspects for channel design. In the previous approach, the conceptual design was first completed and was then used as the basis for the Environmental Impact Assessment (EIA). After completion of the EIA, detailed design was undertaken, which led to long and interrupted design periods. Now, the EIA study is integrated with both the conceptual and detailed design stages, which leads to a faster design process, with environmental aspects being taking into account throughout the engineering design process.

Conclusion

The new WG121 harbour channel design guidelines provide best practice recommendations for the design of horizontal and vertical channel dimensions, and for manoeuvring area dimensions within harbours. These include consideration of many factors, including design vessels, operational limits, risk, economic and environmental considerations, support craft requirements, and aids to navigation.

About the author

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About the organisation

PIANC is the World Association for Waterborne Transport Infrastructure. It provides a forum where professionals around the world join forces to provide expert advice on cost-effective, reliable and sustainable infrastructures to facilitate the growth of waterborne transport. Established in 1885, PIANC continues to be the leading partner for government and the private sector in the design, development and maintenance of ports, waterways and coastal areas. As a non-political and non-profit organisation, PIANC brings together the best international experts on technical, economic and environmental issues pertaining to waterborne transport infrastructures. Members include national governments and public authorities, corporations and interested individuals.

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Risk and Whole Life Cost -based verification and optimization of harbour approach channel depth

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Abstract

This paper presents the development of a methodology for the verification and optimization of the depth of a harbour approach channel based on the expected total cost over its lifetime. This methodology provides a framework that is general and flexible, which is easily adaptable to medium-sized projects, where it can be applied using the basic and detail design tools given in recommendations PIANC (2014) and ROM (1999), as well as to large projects, where each of the steps involved can be analysed with more complex and accurate numerical and/or physical models. Here the methodology is applied to a case study at the Bay of Cádiz Harbour, Spain.

1. Introduction

PIANC has recently updated its recommendation for the design of harbour approach channels by editing PIANC (2014). This document provides the design engineer with the methodology and tools needed to perform basic and detail design of a harbour approach channel, and also includes some guidelines on how to perform probabilistic verification thereof, particularly in relation to their vertical dimensions (PIANC 2014, Section 2.5). The design process arises, roughly, into three blocks: vertical design, horizontal design and verification of operability and capacity of the channels. However, as mentioned in the recommendation, these aspects are interlinked. Particularly, once that the channel dimensions as well as the operation rules that gives a satisfactory level of safety during passages are defined, the operability and the capacity of the system is determined, so that an iterative process is required to achieve a design that meets both the required operability and safety.

Therefore, PIANC (2014) lays the foundations for progress towards a comprehensive verification and optimization of harbour approach channels, taking into account aspects of safety and operability together. It is believe that the most appropriate method for this is, once basic and detail design stages are finalized, to carry out channel verification and optimization based on the minimization of the total expected cost in its lifetime, including the initial investment costs, the expected maintenance costs and expected costs due to occurrence of failure modes and operational stoppages.

The methodology and the model proposed here are based on the calculation of the expected costs in the lifetime by means of Monte Carlo techniques, simulating a large number of lifetimes and each of the passages that take place during each lifetime. This approach takes into account the interlink between security and operability of the system by estimating the probability of bottom touching during each passages as well as waiting times of each ship, taking into account the uncertainty of each of the involved environmental variables as well. This paper gives directions and references required to implement the methodology and shows an example application to the project of a container terminal of the Cadiz Bay harbour.

2. Objectives

The objective is to establish a methodology to optimize the depth, the operation rules and the maintenance policy of a harbour approach channel by minimizing its whole life costs, while fulfilling the minimum safety and operability criteria pre-established by the recommendations, including in the whole life cost the initial investment for opening or deepening the channel, the maintenance costs and the expected costs associated with the operational downtimes and with the risk of ships touching the bottom.

3. Methodology

The proposed methodology is based on the simulation, by means of Monte Carlo technics, of several lifetimes of the channel, calculating for each lifetime the overall failure probability due to bottom touching and the operability of the channel, as well as the bottom touching probability and the waiting time for each ship transit. From these results the whole life cost of the channel is estimated. The simulation is repeated for different channel depths, operation rules and maintenance policies, in order to find which combination minimizes the expected whole life costs of the channel.

Figure 1 shows an outline of the proposed methodology. It starts from an initial channel design, which is defined by a geometry, a set of operation rules and a maintenance policy (section 3.1).

Multivariate time series of the environmental variables are simulated in an offshore location (section 3.2) and transferred to each channel stretch (section 3.3). Then, knowing the flow in and around each stretch of the channel, the siltation rate is estimated and, taking into account the maintenance policy, the time evolution of the channel depth as well as the number and magnitude of the maintenance dredging are calculated (section 3.4).

On the other hand a time series of ships calling at port is simulated, characterizing ships size and the type and amount of cargo to be loaded and/or unloaded (section 3.5). This information is managed by the traffic control module (Section 3.6), which keeps track of each ship from the moment it calls at port until it leaves. This module also determines the operating condition of the channel depending on its depth and on the value of the environmental variables, and determines when a given transit starts, storing for each transit the waiting time. Each time a ship transits the channel the bottom touching probability is calculated and stored (Section 3.7).

Lastly, the whole life cost of the channel is calculated by adding the initial investment costs to the costs associated with the maintenances, the waiting times and the risk of bottom touching (section 3.8).

Guidelines and references regarding the tools and data required for the implementation of each step of the methodology are given next, on sections 3.1 to 3.8. Details on how to perform the Monte Carlo simulation and on how to calculate failure probabilities for each transit and for the lifetime of the channel are given on section 4.

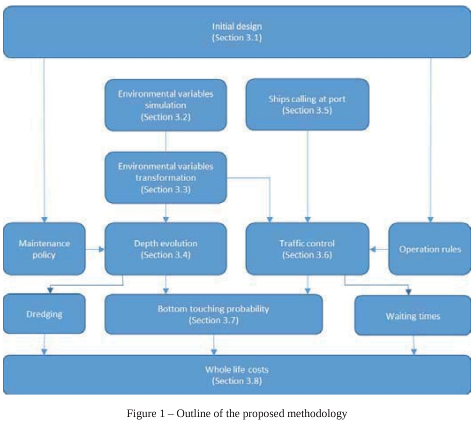

Figure 1 – Outline of the proposed methodology

3.1. Channel initial design

The starting point for the proposed methodology is an initial cannel design that includes its geometry, its operation rules and its maintenance policy. Following PIANC (2014) as well as other recommendations (e.g. ROM 1999) it is possible to obtain preliminary and detail design of the channel.

Regarding the operations rules, it is required to define not only the limiting operation conditions but also the ship transit speed at each channel stretch, the minimum distance between ships, etc.

Limiting operation conditions could be defined by a set of thresholds of the environmental variables (deterministic definition) or by a threshold bottom touching probability (probabilistic definition). The deterministic approach is the most commonly used in practice; however, it is straightforward to include the probabilistic approach on the proposed model (see section 3.7).

For the initial definition of the operation rules the previously given reference could be used as well.

3.2. Time series of environmental variables

The environmental variables module simulates, for one or more offshore locations, the multivariate time series of the meteorological and oceanographic variables that are relevant for the safety and the operability of the channel. Usually this includes, at least, water levels and winds, as well as waves in the case of maritime harbours and river discharges in the case of fluvial or estuarine harbours.

Time series of the environmental variables have several deterministic and stochastic components of different time scales (e.g. astronomic tides and storm surges in the case of water level, mean

annual cycle and extreme storm conditions in the case of wind and waves, etc.). Furthermore, the variables have both auto- and cross-correlation.

There are several methodologies for the simulation of multivariate time series of environmental variables that are able to take into account the non-stationarity of the variables as well as their auto- and cross-correlation (see e.g. Monbet et al. 2007). In this work the methodologies described in Solari and Losada (2015) are used.

3.3. Environmental variables transformation

The value of the environmental variables at each channel stretch is calculated using abacus (e.g. Goda's wave diffraction abacus; ROM 1995, etc.), simplified models (e.g. Snell's law for wave refraction) or more sophisticated physic-based numerical models. Nowadays the use of physic-based numerical models for waves, water level and currents is widespread among harbour designers, so no particular reference will be given with regards to this. However, bearing in mind that the proposed methodology for channel depth optimization is based on Monte Carlo simulations, it is recommended that physic-based numerical models are used for generating a data base from which to interpolate the whole series of environmental variables. This could be done by linear interpolation in a hypercube constructed with model results, or resorting to more sophisticate methodologies, as proposed by Camus et al. (2011).

As an alternative to interpolation, the physic-based numerical model results could be used for the calibration (training) of black-box models, whether these are linear (e.g. Autoregressive with exogenous variables) or nonlinear (e.g. Neural Networks).

3.4. Channel depth evolution

By knowing the value of the environmental variables at every stretch of the channel it is possible to estimate the siltation rate in them. For this it is recommended to use PIANC (2008) and references thereof.

The siltation rate, combined with the pre-defined maintenance policy, is used to calculate the time evolution of the channel depth and the number and magnitude of the maintenance dredging carried during the lifetime of the channel.

When a new channel is being optimized there may be not enough information for the calibration and verification of the siltation rate model. As a consequence one would expect this model to give a high level of uncertainty. In such cases it is recommended to verify the model once the channel is in operation and, if required, to perform a new optimization of the maintenance policy incorporating the new information.

3.5. Time series of ship calling at the port

This modules simulates the time series of ships calling at the port, defining for each ship the date and time of calling, its type, dimensions and amount of cargo to be handled.

The definition of the design fleet and its evolution on time are part of the previous studies required for performing an initial design. In case of lacking specific information regarding the probability distribution of ship calls and/or the distribution of the ship dimensions for each type of ship, it is possible to use the values included in ROM (2011).

3.6. Traffic control

The traffic control module determines at what point each transit take place, allowing for the calculation of the waiting time for each transit. For this the module keeps track of the location of every ship that is in the system at every time step and of the waiting queues for using the channel.

Depending on the operation rules and on the value of the environmental variables, this module determines whether the channel is in operation or not, and defines which ship is using the channel at each point.

Figure 2 shows a schematic of the traffic control module. There are two sets of waiting queues, one for entrance transits and one for exit transits. Within each set there may be several queues for different ship types and priority levels, to be defined in the operation rules. In turn two servers are included: the channel and the berths. The latter must be included in order to determine the time at which the ship is ready to leave the harbour. For programming the servers it is required to define the operation rules of the channel (section 3.1) and the service time of the ships at berth, that may depends on the type and amount of cargo of each ship and on the expected throughput of the berths. Information regarding berths throughput and service times is found in ROM (2011).

This module stores the waiting times for each transit, differentiating between those produced by depth limitations and those produced by other causes, such as constraints imposed to avoid exceeding channel way marks, the inability of the pilots to access the ship due to severe environmental conditions, unavailability of berths, etc.

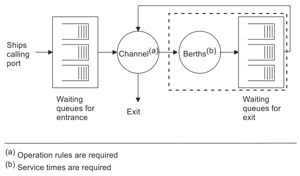

Figure 1 – Outline of the traffic control module

3.7. Probability of touching the bottom during transit

The probability of a ship touching the bottom is calculated for every transit that take place during the lifetime of the channel. To this end each transit is divided into *transit states*, during which the vertical movements of the ship caused by the action of the environmental variables is assumed statistically stationary. Then, the probability of bottom touching during the entire transit is calculated using the probability of bottom touching calculated for each of the transit states that comprise the transit (see section 4 for details).

For calculating the bottom touching probability during a transit state the squat and the dynamic heel (produced by winds, currents and turning) are assumed to be stationary, and the amplitude of the ship oscillations produced by the waves are assumed to follow a Rayleigh distribution, whose parameter may be obtained from PIANC (2014), ROM (1999) or, in the case of larger projects, from specific numerical or physical models (see PIANC 2014). In any case, the parameter will depend on the dimensions of the ship and on the wave state parameters.

As mentioned in section 3.1, this module could be used for verifying the limiting operation conditions of the channel if they are defined in terms of a maximum allowable bottom touching probability during transit (probabilistic approach).

3.8. Whole life costs

The whole life cost of the channel $C_{Lifetime}$ is estimated with Eq. (1)

$$C_{Lifetime} = C_{Ini} + \sum_{D=1}^{N_D} C_D + \sum_{T=1}^{N_T} \left(R_T + T_{Wait,T} C_{Wait} \right) \tag{1}$$

where C_D is the cost of each ones of the N_D maintenance dredging carried out during the lifetime, $T_{Wait,T}$ is the waiting time of each one of the N_T transits, C_{Wait} is the unit cost of waiting and R_T is the risk of touching the bottom during each transit, estimated as the probability of touching the bottom $P_{F,T}$ times the expected cost of the consequences E[C]

$$R_T = P_{F,T} \mathrm{E}\left[C \right] \tag{2}$$

The expected cost of the consequences of touching the bottom during a given transit is estimated with Eq. 3, considering a set of N_{Con} possible consequences. Each possible consequence Con_j has an associated cost $C(Con_j)$ and an occurrence probability conditioned to the bottom touching given by $P(Con_j \mid \textit{bottom touching})$.

$$\mathrm{E}\left[C \right] = \sum_{j=1}^{N_{Con}} C\left(Con_j \right) P\left(Con_j \middle| \text{bottom touching} \right) \tag{3}$$

In Eq. (1) it is assumed that waiting for a transit results in a constant cost per waiting hour and any other adverse consequence arising from the waiting is considered unlikely and not analyzed. Given that the objective is to optimize the depth of the channel, only the waiting times caused by depth limitations are considered in costs estimation.

The consequences of bottom touching are more complex to analyze, and go from almost negligible (e.g. no damage and no inspection required) to the most severe (e.g. the ship grounds and blocks the channel, or even sinks). To simplify the calculations, in Eq. (1) and Eq. (2) it is assumed that: (a) the probability of touching the bottom at each transit state is independent of the other states that comprise the transit; (b) the set of possible consequences, their conditional probability and their cost are independent of the channel stretch and of the transit state.

It is noted that the expected risk of bottom touching during the lifetime of the channel cannot be estimated as the overall bottom touching probability in the lifetime ($P_{F,Lifetime}$) times the expected cost of the consequences given by Eq. (3), since during the lifetime of the channel more than one ship may touch the bottom, while E[C] is the expected cost of only one ship touching the bottom, i.e.:

$$\sum R_T \neq P_{F,Lifetime} \mathrm{E}\left[C \right] \tag{4}$$

4. Simulation model and calculation of the probabilities

This section presents details regarding the implementation of the proposed methodology and formalized some concepts required for the calculation of the bottom touching probability at each transit and during the lifetime of the channel.

The simulation methodology is based on Losada et al. (2009). The procedure, outlined in Figure 3, is to perform a large number of experiments (M experiments) to obtain the expected value and the probability distribution of the whole life cost and other objective variables (e.g. overall bottom touching probability in the lifetime of the channel, operability, waiting times). Each experiment is the simulation of a channel lifetime, which consists of N years. In each of the simulated years, a series of transits follow one another across the channel. Each transit is divided into transit states

(see sections 4.1 to 4.3) in which the response of the ship is statistically stationary, making it possible to calculate the bottom touching probability as described in section 3.7.

Since the calculation method is based on the concept of *transit state*, that in turn is related with the concepts of *channel stretch* and *environmental state*, these three concepts are discussed next in sections 4.1 to 4.3. In section 4.4 it is shown how to calculate the transit and lifetime bottom touching probabilities from the probabilities estimated for each transit state.

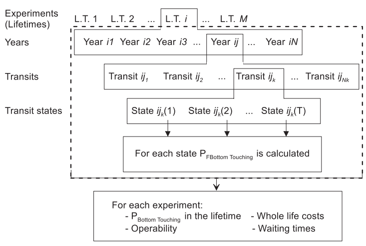

Figure 3 – Outline of the simulation methodology (modified from Losada et al. 2009).

4.1 Channel stretches

The channel is divided into stretches in which the level of the actions exerted on the ship is uniform. This condition can be expressed in terms of the environmental variables and the transit conditions. So, for a ship in a given stretch there should be uniform the height and direction of the waves, the intensity and direction of the current, the speed and wind direction, the sea level, and the speed and direction (and in its case the turning rate) of the ship.

4.2 Environmental state

The environmental state is the period of time during which the level of the actions exerted on the ship by the environmental variables, at a given channel stretch, can be assumed to be stationary or statistically stationary. For simplicity, instead of estimating the actions on the ship, the environmental state is defined in terms of the value of the environmental variables.

Each environmental variable has a characteristic time scale over which it is assumed stationary or statistically stationary. For waves and wind it is approximately one hour; tidal range is constant in a diurnal or semidiurnal scale, then depending on its amplitude, sea level can be considered stationary on a scale of minutes to hours, etc.

The time scale used in the model to define the environmental state duration must be equal to or less than the minimum time scale of the environmental variables involved.

4.3 Transit state

The transit state is the time step used for the calculation of the probability of touching the bottom. During a transit state the ship moves through a stretch of the channel under a given environmental state, i.e. the actions exerted over the ship are stationary or statistically stationary. Thus, the duration of a transit state ($\Delta T_{TransitState}$) is defined by Eq. (5) as minimum time required for one of

two possible events to happen: (a) the environmental variables change their state ($\Delta T_{EnvState}$), or (b) the ship moves to another stretch ($\Delta T_{Stretch}$).

$$\Delta T_{Transit} = \min\left\{ \Delta T_{EnvState}, \Delta T_{Stretch} \right\} \tag{5}$$

It is noted that transit states comprising a given transit should be calculated for each specific transit, with $\Delta T_{TransitState}$ depending on the ship transit speed and on when the transit starts.

4.4 Transit and lifetime bottom touching probabilities

The probability of touching the bottom during a transit state ($P_{F,State}$) is calculated following section 3.7.

The probability of touching the bottom during a complete transit ($P_{F,Transit}$) is calculated with Eq. 6 as the complement of the probability of not touching the bottom during the transit, that is the product of the probabilities of not touching the bottom at every one of the N_E transit states that comprises the transit

$$P_{F,Transit} = 1 - \prod_{State=1}^{N_E} \left(1 - P_{F,State} \right) \tag{6}$$

Analogously, the probability of touching the bottom during the lifetime of the channel ($P_{F,Lifetime}$) is calculates with Eq. 7 as the complement of the probability of not touching the bottom during the lifetime, that is the product of the probabilities of not touching the bottom at every one of the N_T transit that occurred during the lifetime of the channel.

$$P_{F,Lifetime} = 1 - \prod_{Transit=1}^{N_T} \left(1 - P_{F,Transit} \right) \tag{7}$$

5. Case study

5.1. Bay of Cádiz Harbour

Bay of Cádiz Harbour is located on the south-west coast of Spain, at the Gulf of Cádiz, on the Atlantic Ocean. During 2007-2008 a project for a new container terminal was developed, for which deepening of the current harbour entrance channel was required (see Figure 4).

In order to optimize the depth to which the channel should deepen the model described in the previous sections was implemented, with some simplifications: the design fleet was composed by a single ship and the siltation rate of the channel was not considered. On the other hand, the manoeuvring circle was included in the model.

5.2. Project criteria

The project design criteria, shown in Table 1 (lifetime, maximum failure probability in the lifetime and minimum operability), were estimated following ROM methodology (ROM, 2001). The optimum depth and operational rules for the channel will be the ones that minimize the whole life cost of the channel, fulfilling the criteria listed in Table 1.

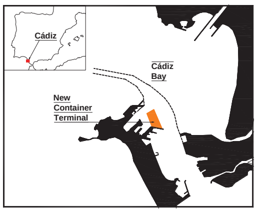

Figure 2 – Location of the Bay of Cádiz Harbour and outline of the projected expansion

Table 1 – Design criteria for the channel

Criteria	Value
Lifetime	25 years
Maximum failure probability in the lifetime	0,10
Minimum operability	95%

5.3. Initial design and operational rules

The initial design for the optimization is that of the existing channel at the time of the project.

Initial limiting operational conditions are established based on the analysis of the horizontal dimensions of the channel. A fast-track model is used to establish the limiting environmental conditions (waves, winds and currents) and towing requirements for a transit not to exceed the channel way marks. The response of the fast-track model is deterministic; that is, given a set of environmental conditions and a number and position of tows, the transit results in exceeding the channel way marks or in not exceeding it, but no probability of exceeding the way marks is given by the fast-track model. A total of 18,000 transits are simulated under different scenarios, covering a wide range of conditions: 50 wave conditions combined with 9 currents conditions, 40 wind conditions and with up to 5 tows in different positions.

Then, the limiting conditions established from the analysis of the horizontal dimensions is combined with the following function (Eq. 8) for establishing the operational condition of the channel

$$Op=\begin{cases}1 \quad \text{si} \quad H_{m0}\ge H_{umb} \text{ y } NM \ge \alpha\left(H_{m0}-H_{umb}\right)\\ 1 \qquad\quad \text{si} \quad H_{m0}<H_{umb}\\ 0 \qquad\qquad \text{other cases}\end{cases} \tag{8}$$

where Op=1 means that the cannel is operating, Op=0 means is no operating, and α and H_{umb} are parameters to be determined through optimization. Eq. 8 is applied after checking the limiting conditions established from the horizontal analysis.

Operational rules regarding transit speeds were taken from ROM (1999) and only one ship is allow to use the channel at a time.

5.4 Simulation

Depths from 14 m to 14,5 m are simulated with the operational rules established above, with α=*1* and H_{umb} varying between 1,4 m and 2,8 m.

A total of 1,000 lifetimes are simulated for each combination of channel depth and H_{umb}, were each lifetime is 25 years long, as listed in Table 1. Then, the whole life cost is calculated for each one of the simulated lifetimes, along with the overall bottom touching probability, the mean operability and the probability distribution of the waiting times.

The calculation of the whole life cost is performed following the methodology described in section 3.8, using the cost estimation described in the Appendix.

5.5. Results

From the simulation it is obtained a sample of 1,000 data for the three objective variables, namely: whole life cost, overall bottom touching probability and mean annual operability. In order to take into account the uncertainty of the results, related in this case mainly with the stochastic nature of the environmental variables, 90% confidence intervals are estimated for each variable. The analysis that follows is performed with the upper limit of the confidence interval in the case of the whole life cost and the overall bottom touching probability, and with the lower limit of the confidence interval in the case of the operability.

Figure 6 shows the iso-cost curves for different channel depth and H_{umb}. The area in grey indicates the combinations of depth and H_{umb} that do not meets the minimum operability required by the project criteria, considering a 90% confidence interval. The area in blue indicates the combinations that results in an overall bottom touching probability higher than the maximum failure probability established on the project criteria (considering a 90% confidence interval). Optimal combination of depth and H_{umb}, from those simulated, is marked with a green dot, corresponding to a channel depth of *14,1 m* and H_{umb}*=1,6 m*.

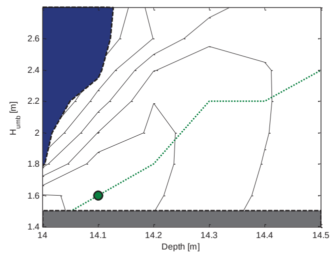

Figure 3 – Iso-cost curves as a function of cannel depth and H_{umb}. Grey area: operability under the minimum value establish by design criteria. Blue area: bottom touching probability over the maximum value given by design criteria. Green dot: optimal combination among those analysed.

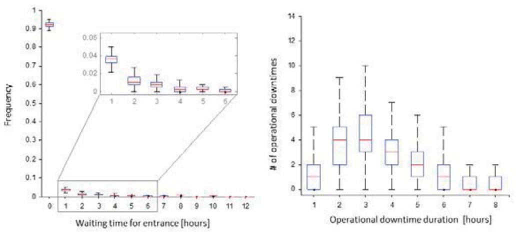

Figure 4 – Left: Frequency of the waiting times for entering the port. Right: Number and duration of operational downtimes produced by Eq. 8.

Figure 7 (left) shows the frequency of the waiting times for entrance transits, along with its confidence intervals, for the optimal combination of channel depth and H_{umb}. It is seen that approximately 92% of ships that call to port do not wait for entering the harbor. Figure 7 (right) shows the histogram of the channel downtimes produced by limiting conditions stated in Eq. 8, with α=*1* and H_{umb}*=1,6 m*. It is seen that the most frequent operational downtimes last for no more than 3 hours, and that there is a high level of variability in the number and duration of the operational downtimes, as is evidenced by the confidence intervals.

6. Discussion and conclusions

During the design process of harbor approach channels it is sought to maximize their safety and operability, meeting the design criteria pre-established by current regulations or recommendations, minimizing total costs incurred during its lifetime, namely: initial investment, maintenance and consequences of the occurrence of failure modes and operational stoppages.

A methodology was proposed for optimizing channel depth and its operation rules and maintenance policy by minimizing the whole life costs associated with the vertical dimension of the channel, namely: initial investment for opening or deepening the channel, maintenance costs and costs associated with the operational downtimes and bottom touching risk. Detail description of the calculation procedure as well as general guidelines on the tools and references required to implement the model were given.

The case study exemplifies the results that are obtained with the proposed methodology, and makes clear the need to take account of the uncertainties that are inherit from the stochastic nature of the environmental variables when optimizing the channel dimensions and its operation rules.

The proposed methodology can be easily implemented to small- and medium-scale project using the tools and figures included in PIANC (2014) or ROM (1999), along with the simulation procedure summarized in Solari and Losada (2015), as was done in the case study. For bigger projects, more complex tools, as described in PIANC (2014), can be used for implementing the different modules of the methodology.

Some modules of the proposed methodology may have a high degree of uncertainty associated with the calculation tools and models (e.g. siltation rates) or to the input data (e.g. expected number of ships calling at port in the long term). However, the proposed methodology could be

used during the lifetime of the channel to re-optimize the operation rules and the maintenance policy each time new relevant information is available.

In this work only the failure mode *exceeding way marks*, related mainly with the horizontal dimensions of the channel, was not included in the simulations, and was considered only when defining the operation rules in the case study. However, the proposed methodology allows to include the *exceeding way marks* failure mode in addition to the *touching the bottom* failure mode. This way, both vertical and horizontal dimensions of the channel would be optimized at the same time based on the minimization of the whole life cost. For this it would be required to include an additional module in the methodology that calculates the probability of exceeding way mark for any given transit state.

Acknowledges

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Appendix – Estimation of the expected cost of the consequences of touching the bottom

In this work the assessment of the bottom touching consequences included in Abdelouarit (2010) is used. However, further analysis of the consequences may be required for future applications.

For waiting times produced by depth limitations (Eq. 8) a cost of 10.000 €/6hrs is assigned. No cost is assigned to waiting time produced by other causes.

Abdelouarit (2010) defines five scenarios of consequences for a ship that touches the, along with their absolute probability (listed on Table 2):

C_1: There is little to no damage to the hull; E[C_1] = 1 mill. €.
C_2: There is some damage to the hull, with possible minor loss of cargo and disturbance to the transit of other ships; E[C_2] = 11 mill. €.
C_3: The ship grounds but is able to sail with high tides; E[C_3] = 1 mill. €.
C_4: The ships grounds and needs rescue for sailing again; E[C_4] = 5 mill. €.
C_5: The ship grounds and sinks; E[C_5] = 50 mill. €.

Here, the absolute probabilities *P(C_j)* are used to estimate conditional probabilities *P(C_j | bottom touch)*, by means of

$$P\left(C_j\middle|\text{ bottom touch}\right)=\frac{P\left(C_j\right)}{\sum_{i=1}^{5}P\left(C_i\right)}$$

Using the listed expected costs and conditional probabilities (Table 2), the expected cost of the consequences of a bottom touching is estimated using Eq. 3 as E[C]=4,35 mill. €.

Table 2 – Absolute and conditional probabilities assigned to the different consequences scenarios

Consequences	$P(C_j)$	$P(C_j \mid \text{bottom touch})$
C1	$5x10^{-4}$	0,3267
C2	$5x10^{-4}$	0,3267
C3	$5x10^{-4}$	0,3267
C4	$3x10^{-5}$	$1{,}96x10^{-2}$
C5	$2{,}5x10^{-7}$	$1{,}63x10^{-4}$

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