Maniobra de Buques

La R.O.M. (Recomendaciones para Obras Navieras) 3.1-99 PROYECTO DE LA CONFIGURACIÓN MARÍTIMA DE LOS PUERTOS, CANALES DE ACCESO Y ÁREAS DE PLOTACIÓN de Pueblos del Estuario (España) establece la importancia de realizar estudios de maniobra como medio para refinar 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 altura de los espacios navieros, pero además, en su parte 5 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 cotejo de instalaciones portuarias, canales de acceso y áreas de flotación, con el objetivo de prever, en la proyección, 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 para la operatividad y la seguridad de las operaciones de los buques en aguas restringidas, sirven para establecer límites operativos (tamaño de buque, condiciones meteorológicas, condiciones de marea, etc.), necesidades de remolque, evaluación de riesgos relativos y, en general, todo lo referente a la evaluación 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 de Maniobra con Modelos Numéricos. Mediante el uso de Modelos Numéricos que reproduzcan el comportamiento del buque y que habitualmente trabajan con un sistema de Piloto Automático para seguir una trayectoria y estrategia predefinida.
- Estudios de Maniobra con Simulación en Tiempo Real. Estas simulaciones permiten incorporar el factor humano en el estudio prospectivo de la "maniobra" en las condiciones similares a las condiciones reales, con modelos visuales de gran detalle y reproducción del puente del buque y su instrumentation básico.

Modelos Numéricos

SHIPMA

Ver más información del Modelo SHIPMA

El Modelo Numérico SHIPMA, desarrollado por WARSH e Hidroïdymaniques (Francia), reproduce el comportamiento del buque en maniobra, considerando sus hidrodinámicas (aguas profundas y aguas bajas), sus sistemas de propulsión y soporte, los medios auxiliares de maniobra (helicos laterales y remolcadores) y todos los agentes hidrometeorológicos que afectan a su evolución (viento, marea, olas, corriente, acumulación, flujo, etc.).

Simulación en Tiempo Real

POLARIS es un SIMULADOR en TIEMPO REAL (Full-Dimension Simulator) desarrollado por Emteltec que permite la simulación de las maniobras de los buques incorporando el factor humano. ENRED tiene un acuerdo de colaboración con el Centro Español de Salvamento Marítimo que dispone de un completo desarrollo de este tipo de simuladores de personal adecuado para la ejecución de estas simulaciones. Estas simulaciones, además de realizar estudios de maniobras, es adecuada para la formación de Capitanes y Oficiales 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 30 años de experiencia en el uso de simuladores en tiempo real y su aplicación a estudios de maniobras y a la formación.

Yaklaşım kanalı derinliğinin hesaplaması için Ligteringen (2000) formülleri kullanılacak olur ise,

\[ d = D + T + S_{\text{max}} + r + m \]

- **d**: İhtiyaç duyulan derinlik
- **D**: Gemi draft
- **T**: Harita datumun üzerindeki gelgit yüksekliği
- **S_{\text{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.)
NAVIGATION ENGINEERING

Squat Formulas

PIANC 121.2014
Tuck (1966)
Huuaska/Guliev (1976)
ICORELS (1980)
Barras3 (2004)
Eryuzlu2 (1994)
Römisch (1989)
Yoshimura (1986).

ROM 3.1.99
Huuska/Guliev (1976)
ICORELS (1980)

Squat Formulas

\[ d_t = 2.4 \cdot \frac{\nabla}{L_{pp}} \cdot \frac{F_{rh}^2}{\sqrt{1-F_{rh}^2}} \cdot K_s \]

- \( d_t \) = Squat
- \( \nabla \) = Vessel's volume of displacement (m³)
- \( L_{pp} \) = Vessel's length between perpendiculars
- \( F_{rh} \) = Froude number = \( \frac{V}{\sqrt{g \cdot L_{pp}}} \) (non-dimensional)

The hydrodynamic resistance to a vessel's motion depends on this Froude number. When \( F_{rh} \) 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 \( F_{rh} \) 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.

- \( V \) = 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:

- \( K_s = 7.45 + 0.76 \) for \( s_i > 0.032 \)
- \( K_s = 1.00 \) for \( s_i \leq 0.032 \)

Doç. Dr. Selçuk NAS
NAVIGATION ENGINEERING

Squat With Cb

- Ship on even keel and Cb = 0.7 – Ship is squatting with no change of trim
- Ship on even keel and Cb > 0.7 – Ship is squatting and trimming to forward
- Ship on even keel and Cb < 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

\( L_{sb} = 360 \text{ m}, B = 55.0 \text{ m}, T = 16.0 \text{ m}, C_b = 0.68 \text{ and } h = 18.0 \text{ m}(h/T = 1.12) \)


NAVIGATION ENGINEERING

Block coefficient (Cb)

<table>
<thead>
<tr>
<th>Type</th>
<th>50%</th>
<th>Standard deviation (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Cargo Ship</td>
<td>0.804</td>
<td>0.0712</td>
</tr>
<tr>
<td>Container Ship</td>
<td>0.668</td>
<td>0.0472</td>
</tr>
<tr>
<td>Oil Tanker</td>
<td>0.824</td>
<td>0.0381</td>
</tr>
<tr>
<td>Roll-on/Roll-off Ship</td>
<td>0.670</td>
<td>0.1140</td>
</tr>
<tr>
<td>Pure Car Carrier</td>
<td>0.594</td>
<td>0.0665</td>
</tr>
<tr>
<td>LPG Ship</td>
<td>0.737</td>
<td>0.0620</td>
</tr>
<tr>
<td>LNG Ship</td>
<td>0.716</td>
<td>0.0399</td>
</tr>
<tr>
<td>Passenger Ship</td>
<td>0.591</td>
<td>0.0895</td>
</tr>
</tbody>
</table>


NAVIGATION ENGINEERING

NAVIGATION ENGINEERING

<table>
<thead>
<tr>
<th>Vessel type</th>
<th>Cb loaded condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Great Lakes ore carrier</td>
<td>0.88-0.92</td>
</tr>
<tr>
<td>Tanker</td>
<td>0.82-0.87</td>
</tr>
<tr>
<td>Bulk carrier</td>
<td>0.72-0.84</td>
</tr>
<tr>
<td>General cargo</td>
<td>0.55-0.78</td>
</tr>
<tr>
<td>Container ship</td>
<td>0.54-0.64</td>
</tr>
<tr>
<td>RoRo</td>
<td>0.52-0.66</td>
</tr>
<tr>
<td>Barge carrier</td>
<td>0.58</td>
</tr>
<tr>
<td>Passenger liner</td>
<td>0.55-0.65</td>
</tr>
<tr>
<td>Auto ferry</td>
<td>0.45-0.50</td>
</tr>
<tr>
<td>LNG</td>
<td>0.72</td>
</tr>
</tbody>
</table>


**NAVIGATION ENGINEERING**

**Squat Formulas**

<table>
<thead>
<tr>
<th>Hız (Knots)</th>
<th>Squat for Different Ship Sizes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>1.5</td>
</tr>
<tr>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td>2.5</td>
</tr>
<tr>
<td>15</td>
<td>3</td>
</tr>
</tbody>
</table>

- 150 Mt Gemi
- 200 Mt Gemi
- 250 Mt Gemi
- 300 Mt Gemi
- 350 Mt Gemi

**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”.


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 guía 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 iniciativa 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 -SIHORT 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
NEW PIANC PUBLICATION AVAILABLE

Title: “Harbour Approach Channels – Design Guidelines”

Author’s: MarCom Working Group 121

Price: € 150.00 (320 pages)

Available at: www.pianc.org -> publications

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 Ma-Com 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.

NOTE: 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.

PLEASE NOTE, that for only € 95.00 (€ 35.00 for students) you can become an Individual member of PIANC. Individual members receive a login and password to access the members only pages on our website. There you can download all published (English) PIANC reports and the new PIANC E-Magazine “On Course” FOR FREE. You’ll also receive the new PIANC YEARBOOK as a hard copy.

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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
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. 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.

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.

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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
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:
  - Channel width – sum of ship beams, modified version of previous WG30 method;
  - Channel 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 taken 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
Dr Mark McBride is the manager of the Ships Group at UK-based HR Wallingford and has over 25 years of experience in port and maritime design related work. He has been involved in numerous projects regarding the design of approach channels, turning circle and manoeuvring areas, berth locations, ship mooring analysis, and operational simulation studies examining optimisation of transportation networks, berths and storage facilities. He was the Chairman of PIANC Working Group 121 which produced the report described in this paper. In addition, he is the author of many technical papers on port operations, ship navigation and mooring-related topics.

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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Tel: +44 (0)1491 835381
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Abstract
PIANC has recently updated its recommendation for the design of harbour approach channels by adding 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 channel. However, as mentioned in the recommendation, these aspects are interlinked. Particularly, once that the channel dimensions as well as the operation rules that give 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 believed 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 of the passages that take place during each lifetime. This approach takes into account the interlink between safety and operability of the system by estimating the probability of bottom touching during each passages as well as waiting times for 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 common terminal of the Cedeira Bay harbour.

5.1. Channel initial design
The starting point for the proposed methodology is an initial canal design that includes its geometry, its operation rules and its maintenance policy. Following PIANC (2014) as well as other recommendations (e.g. ROM 1995) it is possible to obtain preliminary and detail design of the channel. Regarding the operation 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 in the proposed model (see sections 3.5). 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. stochastic tides and storm surge 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. Mosher et al. 2007). In this work the methodologies described in Solari and Losada (2015) are used.

5.3. Environmental variables transformation
The value of the environmental variables at each channel stretch is calculated using absorbing (e.g. Goda’s wave diffraction abacus; ROM 1995, etc.), simplified models (e.g. Saint’s law for wave reflection) or more sophisticated physics-based numerical models. Nowadays the use of physics-based numerical models for waves, wind speed and currents is widespread among harbour designers, so that particular reference will be given with regards to this. However, bearing in mind that the proposed methodology for channel depth optimisation is based on Monte Carlo simulations, it is recommended that physics-based numerical models are used for obtaining 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 sophisticated methodologies, as proposed by Camus et al. (2011).

As an alternative to interpolation, the physics-based numerical model results could be used for the calibration (smoothing) of box-boost models, whether these are linear (e.g. Autoregressive with eXogenous variables) or nonlinear (e.g. Natural Networks).

5.4. Channel depth evolution
By knowing the value of the environmental variables at each 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 it 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.

5.5. Time series of ships calling at port
This module 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 ships call and for the distribution of the ship dimensions for each type of ship, it is possible to use the values included in ROM (2011).

5.6. 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 warning zones, one for entrance transit and one for exit transit. Within each set, there may be several zones for different ship types and priority levels, to be defined in the operation rules. In turn two sets 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 systems it is required to define the operation rules of the channel (section 3.1) and the service time of the ship at berths, which may depend 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 crossing channel way marks, the inability of the pilots to access the ship due to severe environmental conditions, unavailability of berths, etc.

### 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 waves, 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 of the ship oscillations produced by the waves are assumed to follow a Rayleigh distribution, which has two parameters: the mean and the standard deviation.

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, therefore it is considered stationary and not analysed. 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 ground 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 not assumed 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 (\(P_{\text{bottom}}\)) times the expected cost of the consequences given by Eq. (1), since during the lifetime of the channel more than one ship may touch the bottom, while Eq. (1) is the expected cost of only one ship touching the bottom, i.e.

\[
C_{\text{bottom}} = \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij}(P_{\text{bottom}})C_{\text{con}}(i,j)\]

where \(c_{ij}\) is the cost of each one of the \(n\) maintenance dredging carried out during the lifetime, \(P_{\text{bottom}}\) is the worst-case time of each one of the \(n\) transits, \(C_{\text{con}}(i,j)\) is the unit cost of waiting and \(C_{\text{con}}(i,j)\) is the risk of touching the bottom during each transit, estimated as the probability of touching the bottom per unit time of the expected cost of the consequences of bottom touching given by PCon (Bottom touching).

The expected cost of the consequences of touching the bottom during a given transit is estimated with Eq. 3, considering a set of \(n\) possible consequences. Each possible consequence has an associated cost \(C_{\text{con}}\) and an occurrence probability conditioned to the bottom touching given by PCon.(Bottom touching).

\[
E[C_{\text{bottom}}] = \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij}(P_{\text{bottom}})C_{\text{con}}(i,j)\]

In Eq. (1) it is assumed that waiting for a transit results in a constant cost per waiting hour and any other consequence arising from the waiting is considered unlikely and not analysed. 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.

### 3.8. Whole life costs

The whole life cost of the channel \(C_{\text{whole life}}\) is estimated with Eq. (1):

\[
C_{\text{whole life}} = \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij}(P_{\text{bottom}})C_{\text{con}}(i,j)\]

where \(c_{ij}\) is the cost of each one of the \(n\) maintenance dredging carried out during the lifetime, \(P_{\text{bottom}}\) is the worst-case time of each one of the \(n\) transits, \(C_{\text{con}}(i,j)\) is the unit cost of waiting and \(C_{\text{con}}(i,j)\) is the risk of touching the bottom during each transit, estimated as the probability of touching the bottom per unit time of the expected cost of the consequences of bottom touching given by PCon.(Bottom touching).

The expected cost of the consequences of touching the bottom during a given transit is estimated with Eq. 3, considering a set of \(n\) possible consequences. Each possible consequence has an associated cost \(C_{\text{con}}\) and an occurrence probability conditioned to the bottom touching given by PCon.(Bottom touching).

### 4. Case study

#### 4.1. Bay of Cádiz Harbour

The 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 6).

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 one single ship and the ship duration during the passage was not considered. On the other hand, the manoeuvring circle was included in the model.

#### 5. Project criteria

The project design criteria, shown in Table 1 (lifetime, maximum failure probability in the moment of failure and minimum opening), were established using the following methodology. All the minimum depth and operational rules for the channel were the ones that minimize the whole life cost of the channel, fulfilling the criteria listed in Table 1.
5. 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 tow, the transit results in exceeding the channel way marks or not exceeding it but not probability of exceeding the way marks is given by the fast-track model. A total of 10,000 transits are simulated under different scenarios, covering a wide range of conditions: 50 wave conditions combined with 9 current conditions, 40 wind conditions and well up to 5 tows in different positions.

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

\[ \text{Op} = \begin{cases} 1 & \text{if } H_{\text{umb}} > H_{\text{opt}} \text{ and } \text{Wind } > \text{Wind}_{\text{opt}} \text{ and } \text{Current } > \text{Current}_{\text{opt}} \text{ and } \text{in } \text{other cases} \end{cases} \]

where Op=1 means that the channel is operating, Op=0 means it is not operating, and \( H_{\text{umb}} \) and \( H_{\text{opt}} \) 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.

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 downtime and bottom touching risk. Detailed 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 shows the potential of the methodology to be used in different projects.


Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum operability</td>
<td>99%</td>
</tr>
<tr>
<td>Maximum failure probability</td>
<td>0.01</td>
</tr>
<tr>
<td>Lifetime</td>
<td>25 years</td>
</tr>
</tbody>
</table>

5.4 Simulation

Depths from 1.4 m to 1.45 m are simulated with the operational rules established above, with \( \omega = 1 \) and \( H_{\text{umb}} \) varying between 1.4 m and 2.8 m. A total of 1,000 lifetimes are simulated for each combination of channel depth and \( H_{\text{umb}} \), with each lifetime being 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 to 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 \( H_{\text{umb}} \). The area in grey indicates the combinations of depth and \( H_{\text{umb}} \) that do not meet 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 \( H_{\text{umb}} \) from these simulated, is marked with a green dot, corresponding to a channel depth of 1.4 m and \( H_{\text{umb}} = 1.4 \) m.
Table 2 – Absolute and conditional probabilities assigned to the different consequences scenarios

| Consequences | P(Cj) | P(Cj|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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About the author

Sebastián Solari is civil engineer from Universidad de la República, Uruguay, since 2006. In 2011 he obtains his doctoral degree from University of Granada, Spain, with the thesis entitled “Metodologías de simulación de agentes naturales y desarrollo de sistemas. Modelo de verificación y gestión de terminales portuarias. Aplicación al puerto de la Bahía de Cádiz”. Nowadays he is postdoctoral fellow at the Institute of Fluid Mechanics and Environmental Engineering (IMFIA) at Universidad de la República, Uruguay, working on probabilistic design of maritime works and navigation areas, with focus on Montevideo harbour area.