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Anna Mujal-Colilles, Xavier Gironella, Agustín Sanchez-Arcilla, Carol Puig Polo & Manuel Garcia-Leon

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Technical note

Erosion caused by propeller jets in a low energy harbour basin

ANNA MUJAL-COLILLES, Post-Doctoral Fellow, *Department of Civil and Environmental Engineering, UPC – BarcelonaTech, Barcelona, Spain*
Email: anna.mujal@upc.edu (author for correspondence)

XAVIER GIRONELLA, Full Professor, *Department of Civil and Environmental Engineering, UPC – BarcelonaTech, Barcelona, Spain*
Email: xavier.gironella@upc.edu

AGUSTÍN SANCHEZ-ARCILLA (IAHR Member), Full Professor, Chair in Marine Engineering, *Department of Civil and Environmental Engineering, UPC – BarcelonaTech, Barcelona, Spain*
Email: agustin.arcilla@upc.edu

CAROL PUIG POLO, Full Professor, *Department of Civil and Environmental Engineering, UPC – BarcelonaTech, Barcelona, Spain*
Email: carol.puig@upc.edu

MANUEL GARCIA-LEON, PhD Student, *Department of Civil and Environmental Engineering, UPC – BarcelonaTech, Barcelona, Spain*
Email: manuel.garcia-leon@upc.edu

ABSTRACT
Field data of a harbour basin are compared with analytical formulations for predicting maximum scouring depth due to propeller jets. Spatial data analysis of seven-year biannual bathymetries quantifies the evolution of the scouring hole along with the sedimentation process within a harbour basin. The maximum scouring depth is found to be of the order of the propeller diameter with a maximum scouring rate within the first six months of docking manoeuvring. Three of the analysed expressions yielded realistic results while observed discrepancies between the theoretical predictions and field data are related to scaling factors. The outcomes of this analysis can be extrapolated to other harbours to improve their management. The obtained results highlight the importance of field data in developing combined physical and numerical models.

Keywords: Erosion control; erosion processes; field studies; flow–structure interactions; sedimentation; turbulence–sediments interactions; velocity measurements

1 Introduction

Morphodynamic changes inside marinas due to ship manoeuvring represent an increasing problem for harbour authorities. The rise in shipping activities along with the size of vessels and an increase in engine power over the last 20 years have led to growing economic and structural problems. The increase in the size of vessels has given rise to morphodynamic changes in the harbour basin due to two different but linked problems: scouring effects in the vicinity of the structures affecting the stability, and sedimentation of the scoured material in the harbour basin that reduces the average depth of the basin. In particular, old marinas designed to host ships with lower depths and engine powers have to either fill the scouring holes or dredge the sedimentation areas quite often, or alternatively implement bed protection measures in the harbour basins. Both factors decrease the efficiency and operability of the harbour, causing significant economic losses. This problem affects several harbours around the world with different configurations, morphologies and tidal ranges (e.g. Berg & Magnusson, 1987; Chait, 1987;

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Fuehrer, Pohl, & Römish, 1987; Hamill, Johnston, & Stewart, 1999; Hamill, Ryan, & Johnston, 2009; Schokking, Janssen, & Verhagen, 2003).

Theoretical and experimental expressions to predict the dimensions of the propeller scouring actions were published in the 1987 report of the World Association for Waterborne Transport Infrastructure (PIANC) (Berg & Magnusson, 1987; Chait, 1987; Fuehrer et al., 1987; Hamill, 1987; Robakiewicz, 1987) and in the last technical report by PIANC (2015). The problem of ship scouring during docking and undocking manoeuvring was first addressed by simulating the effects of the helices with a water submerged jet. However, Verheij (1983) concluded that water jets and propeller jets produce different effects due to the rotating effect of the latter and the suppression zone directly underneath the propellers. From then on, different authors have proposed equations to predict the size of the scouring hole caused by the propellers. Most of these equations are based on experimental studies (e.g. Chiew & Lim, 1996; Hamill, 1987; Hamill & McGarvey, 1996; Hamill, Kee, & Ryan, 2015; Hong, Chiew, & Cheng, 2013; Ryan & Hamill, 2013; Schokking et al., 2003; Stewart, 1992). Interestingly, Ryan, Hamill, and Johnston (2013) proposed a new methodology based on artificial neural networks to predict maximum erosion as a result of ship docking manoeuvring. Real studies were only used for problem definition and real data were not used for the experimental formulations (Berg & Magnusson, 1987).

This research aims to evaluate the existing formulations published so far and compare their results to real scouring data. We based our research on a unique set of data at a particular basin obtained during the period 2007–2014: morphodynamic changes were identified after periodic bathymetries of the basin, dominated by a single ship berthing at different docking locations in time. For the first time, this enabled the testing of formulations obtained through physical model studies in a real case. Additionally, the detailed study of a long set of bathymetries was used to evaluate the effects produced by vessels during docking and undocking manoeuvring with real data of the manoeuvring frequencies and duration. The real location of the harbour basin data used in this research is kept confidential at the request of the harbour authorities.

2 Methodology

2.1 *Data description: real case*

Periodic bathymetric surveys were carried out with a multibeam system SeaBeam1185, Elac-Nautik, Germany. The blanking distance from the floating line was 0.65 m and data were recorded at 180 kHz with a boat speed ranging from 3 to 5. The data acquisition average error was around 0.1 m due to an upper layer of mud within the harbour basin of an estimated thickness of 0.5 m.

A detailed study of the frequency and vessel type, Domingo (2014), concluded that most of the scouring process was caused by a RoPax vessel type. The prototype vessel was chosen as a combination of the docking frequency (daily), and the total draft of all the vessels using the same harbour basin over one year (7 m). The vessel had two stern propellers with a diameter of 5.6 m and an engine power of 11,000 kW each. The effect of other vessels docking at the same areas could also be considered but with the aim of being conservative, only the RoPax vessel has been taken into account in the current research.

Figure 1 plots bathymetric data of a real harbour basin with a depth of 12 m above sea level (asl), where the evolution of berthing depth is represented for seven years together with the trajectories of the docking and undocking manoeuvring. Geological studies performed by the harbour authorities yield sediment characteristics below the mud layer of $d_{50} = 0.3$ mm and $d_{90} = 1.0$ mm, normal sizes for a harbour located in a deltaic zone. According to the geological studies, the sediment layer with these characteristics reaches up to the -26 m asl level, which is thick enough to assume that the equations can be used with a single value of d_{50}.

The docking location of the RoPax vessel changed during the period of 2007–2014. Until 2008 the ship docked with a daily frequency at the NW corner with docking manoeuvring clearly seen in the bathymetry (Fig. 1b). In 2010 (Fig. 1c), the docking location changed to the NE corner and again manoeuvring operations left an eroded track on the harbour basin bed. In October 2012 harbour authorities decided to dredge the areas with a lower depth in the harbour basin without rectifying the already-existing scouring problems. The same RoPAx vessel changed the docking location in 2013 to the SW corner, as seen in Fig 1d. Parallel to the scouring action of the vessel, a sedimentation process occurred between 2009 (Fig. 1b) and 2011 (Fig. 1c), with the sediment deposition located parallel to the west dock (Fig. 1c). The effects of the two propellers in the erosion pattern at the three docking locations are visible in the analysis of the bathymetric data in Fig. 1.

Two detailed sections of the scouring and eroding processes within the harbour basin are plotted in Figs 2 and 3. In Fig. 2 (a section parallel to the north quay) the comparison between the profiles from May 2010 to November 2010 in the NE dock shows an increase in the scouring hole of up to 2 m, at a rate of 1 m every three months. Moreover, the sedimentation rate in the same period of time is of the order of 1 m. At the NW dock, as regards daily operations between April 2007 and December 2008, the maximum scouring rate occurred between April 2007 and July 2008, with a total increase in water depth of 3 m (Figs 2 and 3). In the same location (the NW dock), the scouring action that occurred post-2008 cannot be accounted for by the same RoPax vessel, since the RoPax vessel changed the docking location at the beginning of 2009. The third docking location at the SW dock, with daily operations post-November 2013, produced a scouring rate of 2 m within seven months, which represents the same order of magnitude as the previous docking locations.

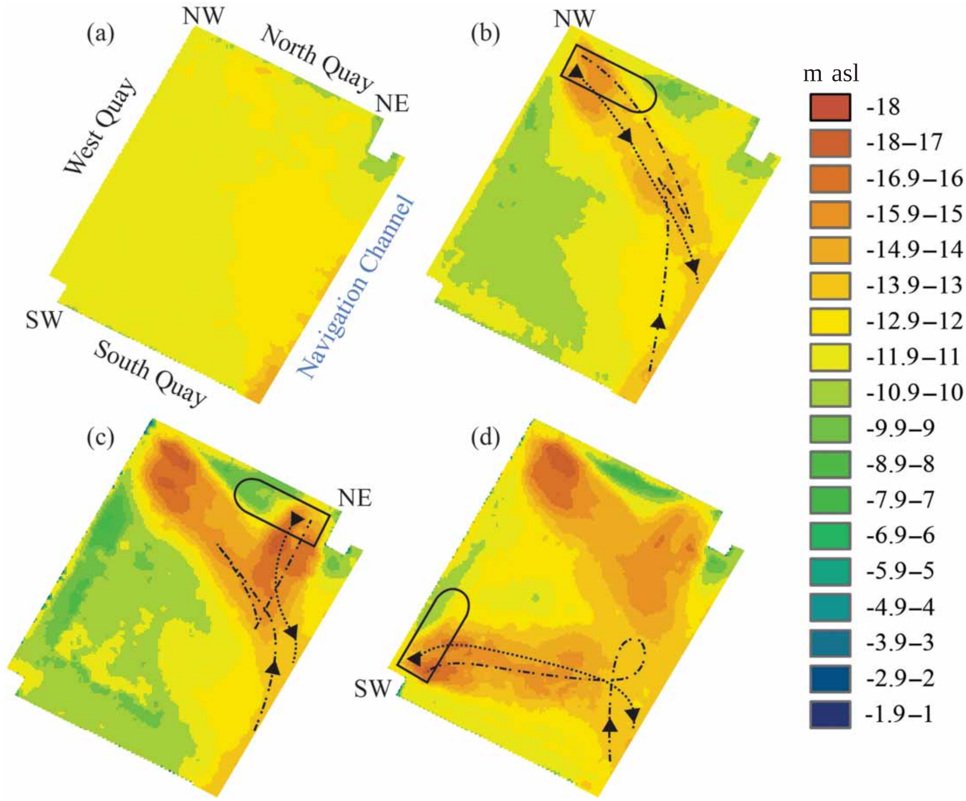

Figure 1 Bathymetric data. (a) November 2007; (b) May 2009, north-west dock; (c) November 2011, north-east dock; (d) June 2014, south-west dock. Point-dashed line indicates docking manoeuvring; point line indicates undocking manoeuvring

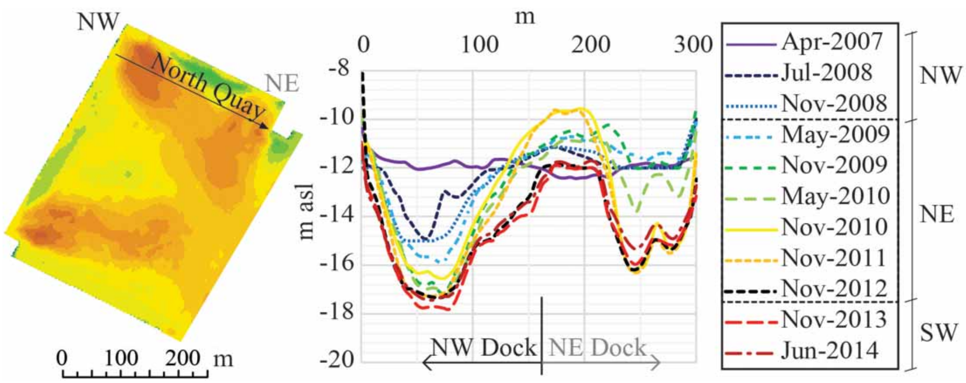

Figure 2 Evolution of the bathymetry along a section parallel to the north quay, from west to east

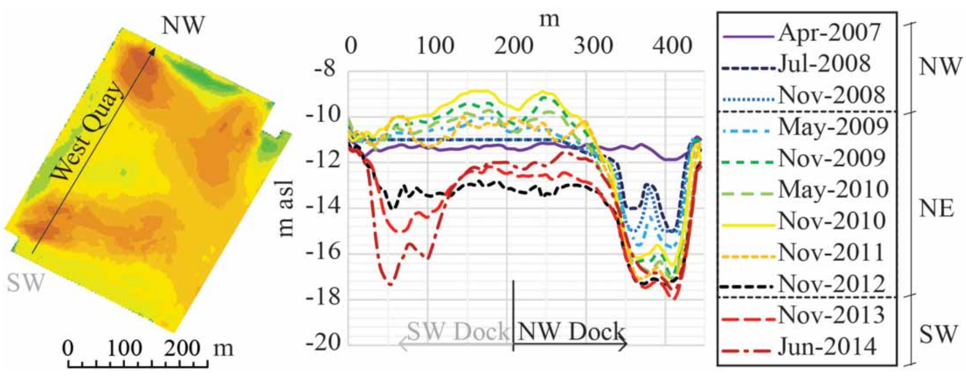

Figure 3 Evolution of the bathymetry along a section parallel to the west quay, from south to north

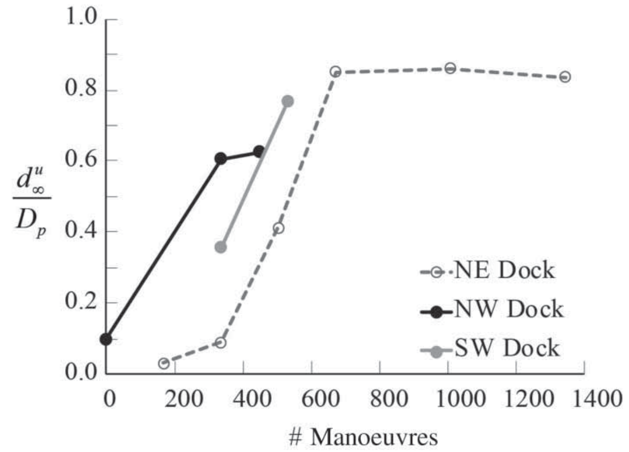

Figure 4 Evolution of the maximum scouring depth with the number of manoeuvres, considering one manoeuvre the sum of the docking and undocking manoeuvres

The effects of twin propellers are clear in all the docking locations. Comparing Figs 2 and 3 with the manoeuvring plotted in Fig. 1, it is clear that the propeller on the port side produces deeper scouring holes, regardless of its location with respect to the wall of the dock. This indicates that the influence of the wall is not as important as the manoeuvring itself.

Figure 4 summarizes the evolution of the scouring rate produced at the three docking locations as a function of the number of manoeuvres, yielding a constant value of 1.2 m every 100 manoeuvres. After 600 manoeuvres, the scouring process reaches a steady state. The final depth at this stage is up to one propeller diameter.

2.2 *Erosion depth formulae*

The erosion caused by propellers during docking and undocking manoeuvring can be addressed from three perspectives. The first, unconfined propeller jets, is related to the consequences produced by a rotating propeller far enough from any blocking object or wall; the second addresses the effects of the same rotating propeller but close to a wall; finally, the third focuses on local jet scouring, approaching the same problem without the rotational effects. The local physics behind the same problem are different for the third case because, as described by Verheij (1983), rotational effects are not considered and there is no suppression zone directly underneath the jet orifice. However, the latter formulations were used in order to increase the options to compute the maximum erosion caused by ship propellers.

The maximum scouring depth, defined as the maximum scour in time produced by a propeller, is expressed as a function of the efflux velocity (described as the velocity behind the propeller); the propeller diameter; the distance between the propeller and the bottom of the harbour basin; and the size of the sediment settled at the bottom of the harbour basin. Apart from the influence of the previous variables, other authors have suggested the need to include rudder influence (Verheij, 1983), the use of more than one propeller (Berg & Magnusson, 1987), and the influence of the propeller characteristics (i.e. Hamill, 1988; Hamill et al., 1999; Hashmi, 2007; Lam, Hamill, Robinson, & Raghunathan, 2012).

Some of the following equations estimate the maximum scouring depth as a function of time, but restricted to an experimental time in which a steady state, also named asymptotic state, is reached. Results obtained with the formulations below can be compared to the aforementioned field data, since the maximum scouring depth has already been reached in at least one of the three docking positions.

One of the most important variables used in the formulas described in the literature is the efflux velocity, V_0. This velocity can be estimated with two theoretical approaches that are based on the idealized behaviour of a single propeller. The first expression is based on the momentum equation of an actuator disk with negligible thickness and infinite number of blades:

$$V_0 = C_1 n D_p \sqrt{K_T} \tag{1}$$

where C_1 is the coefficient shown in Table 1. When this coefficient is unknown, the second theoretical expression, developed after the mass continuity equation, gives another result for the efflux velocity:

$$V_0 = C_2 \left(\frac{f_p P_p}{\rho_w D_p^2} \right)^{1/3} \tag{2}$$

where C_2 is the coefficient shown in Table 2, f_p is the percentage of installed engine power during the docking and undocking manoeuvring, which is 0.15 according to PIANC (2015) and 0.4 according to Puertos del Estado (2012).

Mujal-Colilles, Gironella, Jaquet, Gomez-Gesteira, and Sanchez-Arcilla (2015) conclude that the results obtained using both expressions are overestimating real efflux velocity, particularly for the case of Eq. (1). However, in the cases where

Table 1 Expressions and values for C_1 coefficient in Eq. (1). In the table, p is the pitch ratio, β is the blade area ratio, and D_h is the hub diameter

	C_1
Theoretical	1.59
Hamill (1987)	1.33
Stewart (1992)	$D_p^{-0.0686} p^{1.519} \beta^{-0.323}$
Hashmi (1993)	$\left(\frac{D_p}{D_h}\right)^{-0.403} K_T^{-1.79} \beta^{0.744}$

Table 2 Values for C_2 coefficient in Eq. (2)

	C_2
Free propellers	1.48
Ducted propellers	1.17

Table 3 Equations used to compute the maximum scouring depth

	Authors	Equation	
Unconfined propeller jets	Hamill (1987)	$d_{\infty}^{u} = 45.04 \cdot 10^{-3}\Gamma^{-6.98}(\ln(t_{\infty}))^{\Gamma}$ $\Gamma = 4.1135\left(\frac{c}{d_{50}}\right)^{0.742}\left(\frac{D_p}{d_{50}}\right)^{-0.522}\mathsf{F}_0^{-0.682}$	(5)
	Hamill et al. (1999)	$d_{\infty}^{u} = 38.97 \cdot 10^{-3}\Gamma^{-6.38}(\ln(t_{\infty}))^{\Gamma}$ $\Gamma = 4.1135\left(\frac{c}{d_{50}}\right)^{0.94}\left(\frac{D_p}{d_{50}}\right)^{-0.48}\mathsf{F}_0^{-0.53}$	(6)
	Hong et al. (2013)	$\frac{d_{\infty}^{u}}{D_p} = k_1\left(\log_{10}\left(\frac{V_0 t}{D_p}\right) - k_2\right)^{k_3}$ $k_1 = 0.014\mathsf{F}_0^{1.12}\left(\frac{h_p}{D_p}\right)^{-1.74}\left(\frac{h_p}{d_{50}}\right)^{-0.17}$ $k_2 = 1.882\mathsf{F}_0^{-0.009}\left(\frac{h_p}{D_p}\right)^{2.302}\left(\frac{h_p}{d_{50}}\right)^{-0.441}$ $k_3 = 2.477\mathsf{F}_0^{-0.073}\left(\frac{h_p}{D_p}\right)^{0.53}\left(\frac{h_p}{d_{50}}\right)^{-0.045}$	(7)
	Puertos del Estado (2012)	$d_{\infty}^{u} = \frac{h_p}{250}\left(\frac{\mathsf{F}_0 D_p}{h_p}\right)^{2.9}$	(8)
Confined propeller jets	Hamill et al. (1999)	$\left(\frac{d_{\infty}^{c} - d_{\infty}^{u}}{d_{\infty}^{u} + h_p}\right) + 1 = 1.18\left(\frac{X_w}{X_m^u}\right)^{-0.2}$ $X_m^u = c\mathsf{F}_0^{0.94}$	(9)
Jet local scouring	Hong et al. (2012)	$\frac{d_{\infty j}^{u}}{D_p} = 1.171\left(\frac{h_p}{D_p}\right)^{-0.761}\left(\frac{d_{50}}{D_p}\right)^{0.34}\mathsf{F}_0^{0.872}$	(10)
	Chiew and Lim (1996)	$\frac{d_{\infty j}^{u}}{D_p} = 0.21\mathsf{F}_0$	(11)
	Canepa and Hager (2003)	$\frac{d_{\infty j}^{u}}{D_p} = 0.37\mathsf{F}_0$	(12)
	Chiew, Hong, Susanto, and Cheng (2012)	$\frac{d_{\infty j}^{u}}{D_p} = 0.265\left(\mathsf{F}_0 - \left(4.114\frac{h_p}{D_p}\right)\right)^{0.955}\left(\frac{h_p}{D_p}\right)^{-0.022}$	(13)

experimental values of efflux velocity were used to compute the maximum scouring depth, both Eqs (1) and (2) will be used to compare results. The percentage of installed engine power will be set to $f_p = 0.15$.

Table 3 describes the existing equations in the literature. The notation is standardized throughout the manuscript where the Froude densimetric number is defined as:

$$\mathsf{F}_0 = \frac{V_0}{\sqrt{g d_{50}((\rho_s/\rho_w) - 1)}} \tag{3}$$

and the relation between the offset height and the clearance is:

$$h_p = c + \frac{D_p}{2} \tag{4}$$

Table 4 summarizes the constraining variables for all the equations in Table 3, used only in laboratory experiments.

Table 4 Constraints of the study case and the experimental expressions of Section 2

	F_0	d_{50} (mm)	$\frac{d_{50}}{D_p}$	$\frac{h_p}{D_p}$
Study case	35–170	0.3	0.0001	1.3
Eq. (5)	4.5–150	0.75–1.5	0.005–0.025	–
Eq. (6)	< 20	–	–	1–3
Eq. (7)	5.5–11.1	–	–	0.5–3
Eq. (8)	–	100–300	–	–
Eq. (9)	5.5–18.7	–	0.005–0.05	–
Eq. (10)	4.5–150	0.7–1.5		0.5–1.5
Eq. (11)	4.8–85.3	–	0.01–0.15	–
Eq. (12)	2.5–15	–	–	–
Eq. (13)	–	–	–	> 0.5

3 Results and discussion

The data described in the previous section were used as a reference to assess the equations presented in the previous section. The clearance height between the harbour basin bottom and the propeller tip is 5 m and the wall distance is assumed to be around 2 m.

Constraining values for the expressions above are only given for laboratory results and will not be considered, initially, to obtain the total erosion depth in the real case. The first hypothesis is that the real data correspond to an asymptotic state, at least in the NE dock where the ship docked daily for more than two years. The maximum scouring depth in this area is around 5 m, as seen in Fig. 4. These data are important as some of the proposed equations detailed in Table 3 use time as a predictor variable. However, both Hamill et al. (1999), Hamill (1987) and Hong, Chiew, Susanto, and Cheng (2012) define an experimental time for the asymptotic state. Therefore, the asymptotic state reached in the real data are compared to results yielded by Eqs (5–8), using their reference time scale with a 1/25 geometric scale.

Results of the predicted maximum erosion depth due to propeller effects are shown in Fig. 5. For unconfined jets, the formula proposed by Hamill (1987), Eq. (5), underestimates the real case study values whereas all the other expressions clearly overestimate the measured values. Moreover, the use of Eq. (6) to compute the maximum scouring depth for confined jets is also out of a realistic range, although it was proposed to correct Eq. (5). However, a detailed sensitivity analysis performed on Eq. (6) suggests that only higher values of d_{50} will yield results closer to the expected eroded depth. In terms of applicability of the proposed equations, only Eqs (9) and (5) provide a sensitive result, including a safety factor, although none of the constraining conditions are fulfilled.

A physical model, with scaling geometric variables with a ratio 1/25, is used to check the applicability of the same

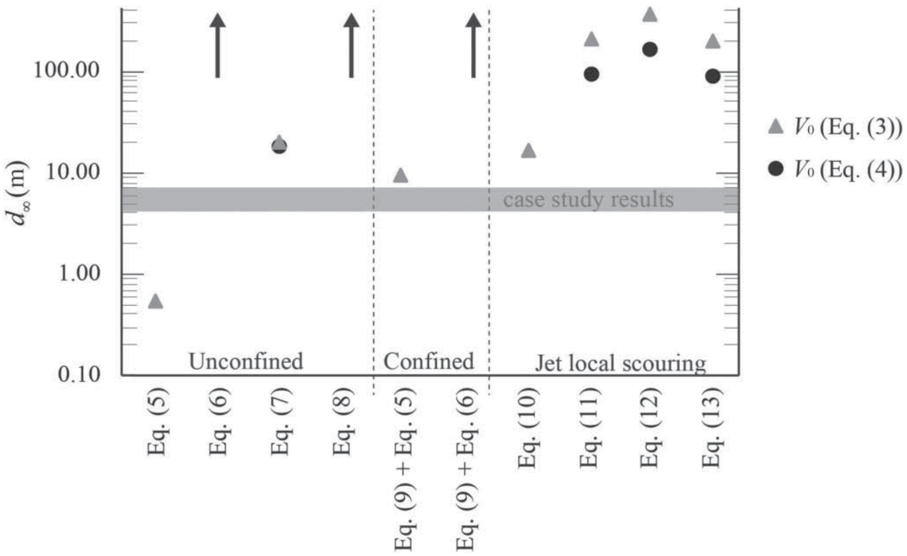

Figure 5 Results obtained using empirical equations to predict the maximum scouring depth, d_∞, at the example harbour basin

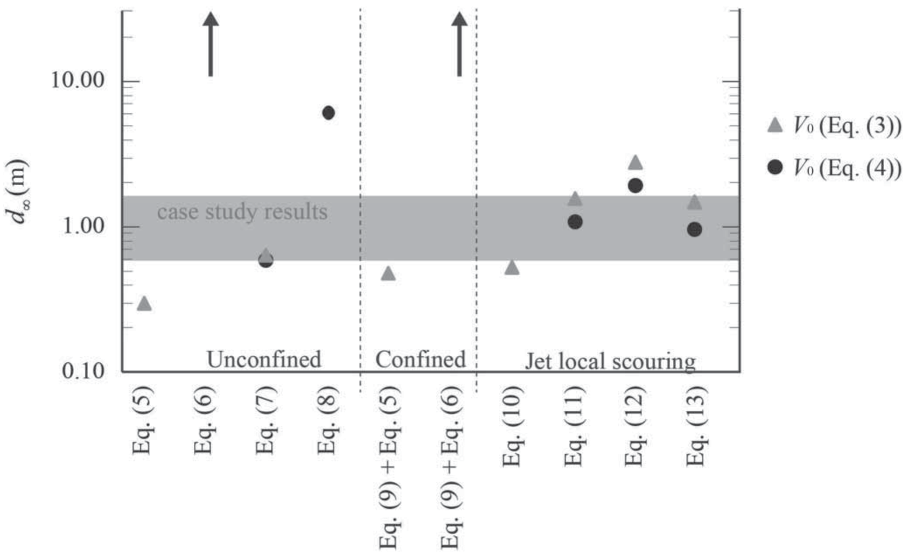

Figure 6 Results obtained using empirical equations to predict the maximum scouring depth, d_∞, at a scaled physical model using the case-study real data

equations (Fig. 6). The sediment diameter in the laboratory is not scaled following the geometric scale due to the experimental limitations and finally a sediment grain size of $d_{50} = 0.25 \times 10^{-4}$ m was used in the experiments presented herein. Results are all closer to the expected maximum erosion depth, between 0.8 and 2 m, except Eq. (8) from Puertos del Estado (2012). In this case, the constraining conditions are mostly satisfied for Eqs (5), (9), (10) and (13). Again, as for the field results, Eq. (6) yields values that do not reflect the reality of the situation. A more detailed study of this equation shows high sensitivity to the clearance distance and the sediment grain size, compared to other equations.

4 Conclusions

The detailed study of real bathymetric data allowed trend lines to be obtained for the behaviour of a daily berthing vessel. If the docking frequency is constant, the scouring rate is also constant, representing 1.2 m every 100 docking and undocking manoeuvres. The maximum scouring, reached after almost two years of daily berthing and 600 manoeuvres, is of the order of the propeller diameter.

The influence of quay walls, studied throughout confined jets, was revealed to be less significant than pitch and rudder effects when the bathymetries were correlated with manoeuvring trajectories.

For harbour authorities to prevent and correct the scouring action of vessels during docking and undocking manoeuvring, only three of the formulas described in the literature are recommended. Most of the empirical and theoretical expressions described herein are useful for physical model studies but are clearly influenced by a scaling factor and are, therefore, not useful for real cases. The formulas that harbour authorities can use, keeping in mind that they already include a security factor, are:

- equations for unconfined propeller jets: Hong et al. (2013) with Eq. (7);
- equations for confined propeller jets: Hamill et al. (1999) with Eq. (9), but using the first expression described by Hamill (1987) to compute the scouring action of an unconfined propeller jet, Eq. (5);
- equations for local scouring of a jet: Hong et al. (2012) with Eq. (10).

Finally, further research is clearly needed on the scouring effect of vessels during docking and undocking manoeuvring, using field data instead of the physical model data. However, due to limitations of field data, physical models should be used in addition to field measurements, but always adding a scaling factor to the expressions stated for experimental data. The use of numerical models may be restricted due to limited knowledge of the initial conditions; that is, the detailed knowledge of the efflux velocity including the rotational aspects of the flow produced by the propellers. Composite models may also be useful in order to study real cases and reduce the costs of the field data acquisition.

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Notation

c = clearance distance (m)
d_∞^u = maximum depth erosion for unconfined jets (m)
$d_{\infty j}^u$ = maximum depth erosion for local jets (m)
d_∞^c = maximum depth erosion for confined jets (m)
d_{50} = sediment size (m)
D_p = propeller diameter (m)
D_h = propeller hub diameter (m)
F_0 = Froude number (–)
g = gravity acceleration (m s^{-2})
h_w = water depth (m)
K_T = thrust coefficient (–)
n = rotation speed (rpm)
p = pitch ratio (–)
P_p = maximum engine power (W)
t_∞ = asymptotic time (s)
V_0 = efflux velocity (m s^{-1})
X_w = distance from the propeller plane to the wall (m)
X_w^u = distance from the propeller plane to the maximum asymptotic scour depth (m)
β = blade projected area (–)
ρ_w = water density (kg m^{-3})
ρ_s = sediment density (kg m^{-3})

ORCID

Anna Mujal-Colilles http://orcid.org/0000-0003-0139-3849
Xavier Gironella http://orcid.org/0000-0002-8862-5704
Agustín Sanchez-Arcilla http://orcid.org/0000-0002-3450-6697
Carol Puig Polo http://orcid.org/0000-0002-8820-6446
Manuel Garcia-Leon http://orcid.org/0000-0001-6498-1440

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