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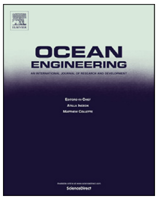

Modeling ship-induced waves in shallow water systems: The Venice experiment

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ABSTRACT

As the size of vessels progressively increases to compete in the global trade, the impact evaluation of navigation in waterways and shallow coastal ecosystems become more important. Therefore, suitable tools to investigate processes are required to support a sustainable management of ship traffic. This work tests a new methodology, based on a numerical model chain, that reproduces the hydrodynamic field close to the ship hull and the ship-induced wave propagation in the surrounding shallow areas. The model chain includes an unstructured hydrodynamic model forced by the near-field estimation of a computational fluid dynamics simulation. The modeling system has been applied to a major navigation channel and surrounding tidal flats in the Venice Lagoon (Italy). Field observations and a theoretical framework were used to characterize the ship waves and to validate the modeling system. Results show that the deeper the initial depression, the larger the dissipation over the tidal flat. In these conditions smaller vessels sailing at higher speed produce smaller waves with low amplitudes compared to larger ships traveling at lower speed. We considered vessels moving at different speeds providing useful information to evaluate impacts and to define criteria for decision support systems for a sustainable management of navigation.

1. Introduction

Shipping is undoubtedly the most efficient way of transporting goods worldwide. However, there are mounting concerns about the impacts of the global traffic on the marine environment both off-shore and on-shore (Zheng et al., 2016). Besides pollution and underwater noise, ship traffic in coastal areas can represent one of the major inputs of energy, in form of disturbance of the hydrodynamic field, which can become a dominant forcing for the morphodynamics of sheltered areas (Soomere, 2005). Moreover, waterways are conveniently located in transitional systems, like estuaries and lagoons, providing a safe access to ports and serving as hubs for inland cities and their industrial and commercial districts. Navigable channels in transitional areas are often the combined result of the anthropic modifications and natural adaptation of the existing morphology to the stress of traffic and they frequently require dredging interventions (Dai et al., 2013; Rosati et al., 2011). The progressive increase in vessel size (Rodrigue, 2013) is a threat for such complex and delicate environments, as large ships moving in channels confined by tidal flats and marshlands (or simply wetlands) can considerably affect the local morphodynamics (Rapaglia et al., 2011, 2015). These issues are of fundamental importance to define criteria for the sustainable management of the ecosystem and minimize the impacts of navigation.

Critical aspects of monitoring and modeling ship waves in shallow water coastal systems are linked with the intrinsic complexity of the process and the variety of morphological features, like natural and artificial channels, tidal flats and salt marshes. When a vessel is moving in a confined channel the wave pattern produced is the result of the interaction between the hydrodynamic field in the proximity of the hull and the geometry of the channel and its margins. When those are constituted by shallow-water areas, three main factors affect the variation of water level: the speed of the ship, the geometry of the hull and the channel cross-section (Sorensen, 1997). The flow field close to the hull is characterized by a pressure increase at the bow and the stern of the hull, whereas the sides experience a rather flat low-pressure region. In the navigation channel, the hydrodynamics is characterized by backward return currents, parallel and opposite to the ship course, a lateral water

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level depression, here called *depression wave* according to Rapaglia et al. (2011), Rodin et al. (2015) and Parnell et al. (2015), and a front wave with positive peaks at bow and stern (Fig. 1). These perturbations represent the so called primary waves. The depression wave follows the ship during its transit along the waterway and has a major component of propagation perpendicularly to the channel main axis. The perturbation approaches the channel sides interacting with the morphology (shoaling) and affects the adjacent tidal flats, determining large sediment resuspension (Gelinas et al., 2013) and morphological changes.

The far-field waves in deep water can be classified as transverse and divergent waves (Fig. 1a). Divergent waves, as free surface inertial waves, originate at the bow and stern, or wherever the ship hull does not show a continuous surface. They propagate, in shallow waters, with an angle from the ship longitudinal axis depending on the ship speed and the water depth in the channel. These waves can combine and produce interferences, with visible peaks. Their amplitude increases with the ship speed and can, locally, deepen the depression wave (primary waves) (PIANC, 1987). For an advancing ship in straight course at constant speed the resulting wave system translates with the ship itself; the included half-angle of the wave pattern is called the Kelvin angle. For a ship advancing in deep water, this angle is fixed and it is equal to 19°28. For a ship advancing in finite depth sea, the Kelvin angle depends on the water depth and the ship speed.

The depth based Froude Number $Fr_h = \frac{V}{\sqrt{gH}}$, where V is the ship speed, g is the gravitational acceleration and H is the water depth (Newman, 1977), can help in distinguishing the different waves propagating from the hull. In shallow channels, like the considered one, the limited navigation speed leads to $Fr_h < 1$. In these conditions the most significant perturbation is connected to the lateral depression waves, while Kelvin waves, usually generated in deep waters, are negligible (Rapaglia et al., 2011). These asymmetric, non-linear V-shaped depression waves propagate on the shallows (Rodin et al., 2015; Parnell et al., 2015).

As far as the modeling is concerned, previous studies address the investigation of ship hydrodynamics from different perspectives and with different aims. Most of the works are focused on the near-field analysis (i.e. a region around the vessels of the order of one ship length). Applications considering vessels operating in open sea (as for example Visonneau et al., 2016, Carrica et al., 2016, Broglia et al., 2015, Dubbioso et al., 2017 and Hirdaris et al., 2016), interacting with the surrounding background field (e.g. Mousaviraad et al., 2015; Volpi et al., 2016; Carrica et al., 2008; Shibata et al., 2012), and advancing in confined channels (e.g. Rodin et al., 2015; Eloot and Vantorre, 2011; Dam et al., 2008; Fleit et al., 2016; Torsvik et al., 2009) can be mentioned. Both Experimental Fluid Dynamics (EFD) tests and Computational Fluid Dynamics (CFD) models are commonly used. For an overview of the state of the art on this topic, the interested reader can refer to the latest workshops on marine hydrodynamics and related topics (Salvatore et al., 2015; Larsson et al., 2013; Simonsen et al., 2014). These studies are mainly focused on local, small scale interaction between the hull and the surrounding water and rarely does the investigation involve far-field hydrodynamics. The main advantage of these models is the high resolution and the capability to reproduce small scale and turbulent processes close to the hull as well as wave pattern, providing a useful indication for ship maneuverability, sea keeping and, in general, naval hydrodynamics related problems. Navigation in confined water (either shallow or restricted waterways) and hydrodynamic interactions due to the passage of multiple ships are also interesting research topics. Different numerical approaches are commonly used, ranging from the Boussinesq 2D models (e.g., Nascimento et al., 2011; Dam et al., 2008) to 3D models (e.g., Yuan et al., 2016; Yao and Dong, 2016) and CFD based tools (e.g., Mousaviraad et al., 2016a), as well as combined EFD studies and CFD implementations (e.g., Eloot and Vantorre, 2011; Fleit et al., 2016; Mousaviraad et al., 2016b).

However, due to the high computational resources required, CFD tools cannot be deemed as the most suitable and efficient approach for the investigation of the propagation of the ship generated waves in the far field. Rather, the use of simplified models has to be considered. The existing literature provides several examples of these models, which consider the channel borders investigating the effects of the ship passage on the surrounding shallow areas, generally adopting idealized and synthetically produced characteristic wave crest (e.g., Torsvik et al., 2009; Dam et al., 2008; Rodrigues et al., 2015). Modeling applications

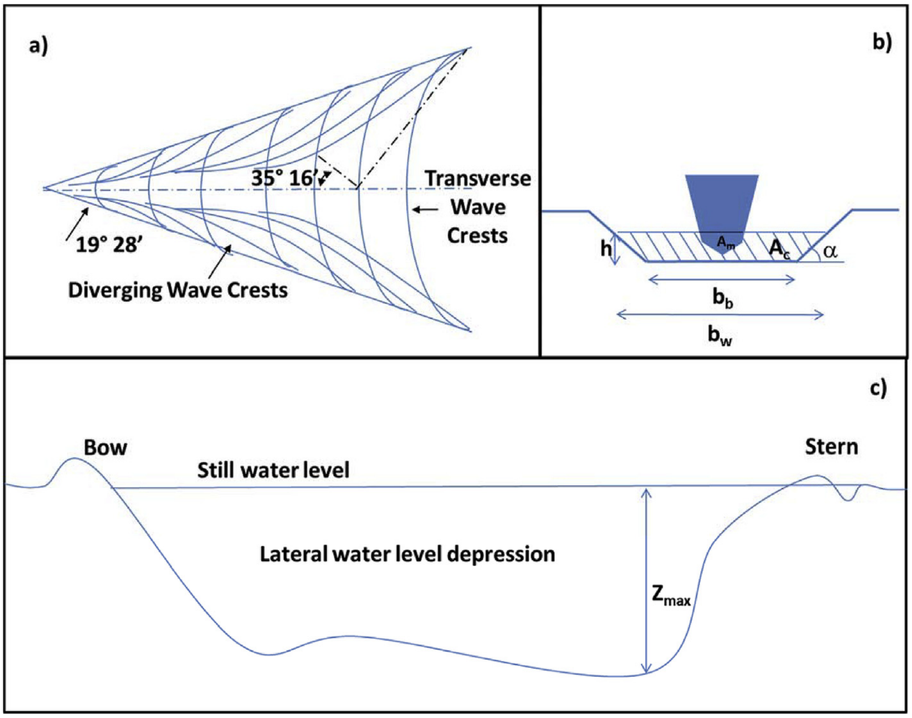

Fig. 1. a) Ship Wave pattern around a moving vessel in deep water (Newman, 1977); b) cross sectional scheme of a navigable channel, with h still water level, A_m wetted area of ship at mid length, A_c wetted area of cross channel section, b_w width of the channel at the surface, b_b width of the channel at the bottom; c) depression wave on a longitudinal section parallel to the main ship axis. The maximum value of the depression wave is hereinafter called Z_{max}. b) and c) schemes are reproduced from (PIANC, 1987).