

Ship-induced solitary Riemann waves of depression in Venice Lagoon



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ARTICLE INFO

Article history:

Received 17 September 2014

Received in revised form 30 October 2014

Accepted 3 December 2014

Available online 8 December 2014

Communicated by F. Porcelli

Keywords:

Ship wakes

Bernoulli wake

Nonlinear waves

Shallow-water waves

Riemann wave

Bore formation

ABSTRACT

We demonstrate that ships of moderate size, sailing at low depth Froude numbers (0.37–0.5) in a navigation channel surrounded by shallow banks, produce depressions with depths up to 2.5 m. These depressions (Bernoulli wakes) propagate as long-living strongly nonlinear solitary Riemann waves of depression substantial distances into Venice Lagoon. They gradually become strongly asymmetric with the rear of the depression becoming extremely steep, similar to a bore. As they are dynamically similar, air pressure fluctuations moving over variable-depth coastal areas could generate meteorological tsunamis with a leading depression wave followed by a devastating bore-like feature.

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1. Introduction

The wakes of ships range from the classical Kelvin wave groups [1,2] at low Froude numbers, to intricate nonlinear mechanisms at transcritical speeds [3], and to Mach-type systems at supercritical speeds [4,5]. It is commonly believed that the largest environmental impacts come from long and long-crested almost non-dispersive wave groups of significant amplitude [6,7]. Another recognized hazard is caused by solitonic waves that may result in high water velocities [8], elevate water levels at the shore [9] or build rogue waves [10]. The motion of a ship at finite depths also produces a depression region frequently called Bernoulli wake [11,12]. It is at times present at fairly low Froude numbers (down to 0.13 [13]) but is much more pronounced at moderate and high depth Froude numbers. It becomes often evident as a region of depression of nearly uniform depth [14–16], causes the draw-down effect (squat [17–22]) usually restricted to the navigation channel and may form structures similar to undular bore [23–25].

If the channel has adjacent harbor areas or wide banks, the depressions may cause extensive dropdown in the harbor water level [26], spread far away from the channel [27], or play the largest role in sediment resuspension [27–29]. They may penetrate to a distance of many hundreds of meters from the navigation channel [27,30]. The resulting events have a characteristic dominant, leading trough, followed by small crests [28].

The core new feature of our analysis is the description of striking features of ship wakes in a fairly realistic situation where a navigation channel is surrounded by wide but very shallow banks. The existing studies [15] suggest that in such situations the usual definition of the (depth-based) Froude number may lead to inconsistent results and unexpectedly high waves of elevation may occur at relatively modest Froude numbers.

The purpose of this paper is to provide evidence about unprecedentedly deep depression waves in this geometry and get some insight into how the resulting depression wave can be replicated, how far it can propagate and which are (fairly unexpected) implications from the described phenomenon for adjacent fields of wave science. The resulting long-living waves of depression obviously cannot be treated as linear or weakly nonlinear. We make an attempt to describe such events using fully nonlinear theory of shallow-water waves in terms of simple or Riemann waves [31,32].

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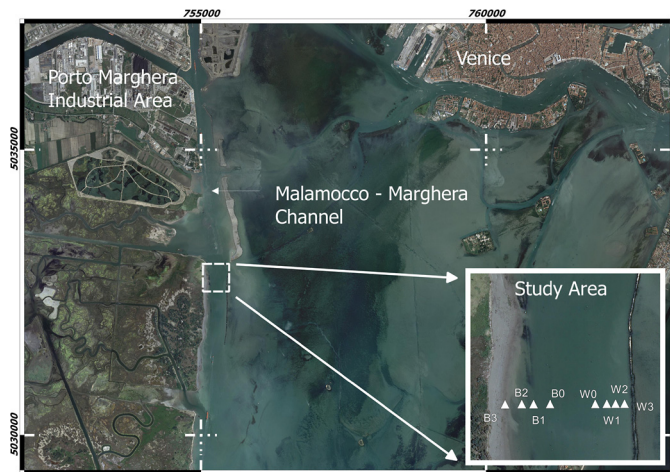


Fig. 1. The study area in the Malamocco–Marghera industrial channel. White triangles in the inset indicate the locations of pressure sensors in Fig. 2.

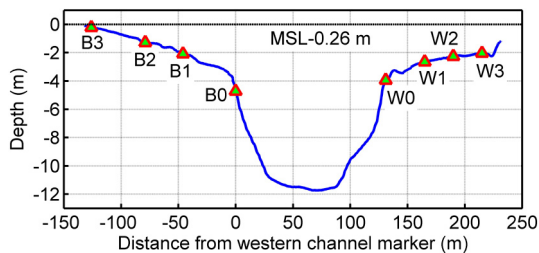


Fig. 2. Cross-section of the channel at the measurement site showing the location of pressure sensors (B0–B3, W0–W3). Distance is referenced to the western channel marker, and the depth is referenced to the local tidal datum (0.26 m below mean sea level (MSL)).

2. Ship-driven depressions

Venice Lagoon, the largest Italian lagoon ($>500 \text{ km}^2$), is extremely shallow (with an average depth of 0.8 m, the tidal range between 0.3 and 1.1 m) and crossed by numerous tidal channels and artificial waterways, as deep as 10 m or more. It underwent severe erosion after the construction of the Malamocco–Marghera industrial channel [33]. The channel (Fig. 1) is orientated almost north–south, 11–12 m deep and 60 m wide bottom with relatively steep slopes ($\sim 10\%$) that rise from this depth to about 4 m deep water (Fig. 2). On the western side of the channel, the water shoals at a constant slope ($\sim 3\%$) to a shoreline. The eastern side of the channel has a smaller slope of $\sim 2\%$ and is bordered by a permeable rock wall, the base of which is 90 m from the edge of the channel, at water depth $\sim 2 \text{ m}$.

The measurements were performed using self-recording pressure sensors incorporated in various instruments (four InterOcean S4 current meters, one RBR Virtuoso wave gauge, one Ocean Seven CTD, two Esterline pressure sensors) at eight locations (Fig. 2). The InterOcean S4 instruments were fully time-synchronized while there may be some small error ($\pm 10 \text{ s}$) for other instruments. Sensors at the edges of the channel were suspended from the channel markers, and all other sensors were mounted on the seabed. Data were collected at either 2 Hz or 5 Hz over four sampling periods of 2 to 6 days in March–April 2014. The data for three ships (Table 1) are selected out of about 90 recorded examples to illustrate the range of appearances of the wakes for ships with similar parameters.

Water level records (Fig. 3) are presented as actual water depths at the time of ship passage. The ships did not produce any substantial transient sign-variable wave groups or solitary waves of elevation evidently because of relatively low speeds (7.7–10.4 knots,

$Fr_d \sim 0.37\text{--}0.5$). The dominant feature of the ship passage was a deep depression. The typical duration of an event from still water level preceding to still water level following was $\sim 400 \text{ s}$, with the characteristic solitary trough (V-shaped wave of depression) lasting typically $\sim 80 \text{ s}$. The characteristics of the depression produced by different vessels varied significantly. The maximum water level drop recorded (2.52 m from still water level at the shoreline side of the channel) was for *Abu Dhabi Star*, an unremarkable ship in terms of both its size and speed (Table 1).

A characteristic feature of the deepest depressions was the disparity of their maximum depths at the opposite margins of the channel. The maximum depth of the above depression by *Abu Dhabi Star* was only about 1.6 m on the lagoon side. *Domenico Ioveli* produced a depression of 1.6 m on the lagoon side of the channel, but only 0.6 m on the shoreline side. The significant differences observed between the sides of the channel may reflect the position of the ship in the channel. Another reason may be the impact of the shape of the hulls. These depressions are, however, much larger than those previously reported [27,29,34].

The depressions were almost perfectly symmetric in time with respect to their deepest point at the margins of the navigational channel (locations B0 and W0 in Fig. 3). None of the recorded depressions had an elongated almost horizontal trough that is suggested by weakly nonlinear simulations [15,16]. This suggests that the depressions had strongly nonlinear nature.

The timing of the disturbance at subsequent sites (Fig. 3) indicates that the wave front moved obliquely with respect to the channel margin. Therefore, the subsequent recordings reflect the different parts of the wave crest. As around the measurement site the channel is essentially straight, its banks are almost homogeneous and the ship was moving at practically constant speed and direction, it is acceptable to assume that the properties of each depression only depend on the distance from the border of the channel.

The depression becomes gradually asymmetric with the distance from the channel margin. Its amplitude was usually smaller on the shoals compared to the channel edges but did not change significantly from one device to another (except at site B3, located in very shallow water where an increase in height was observed). The predominant process was an increase in the front/rear asymmetry of the wave profile. Its front slope became gradually less steep while the rear slope rapidly became steeper with the water surface exceeding the undisturbed level for a short period at the end of some of the depression events. The asymmetry (defined as the ratio of typical values of the rear and front slopes) is usually well below 1.5 at sites W0 and B0 and increases to the level of 2–3 at sites B1 and B2, and to ~ 10 at sites W3 and B3. The overall appearance of the depression at sites B1–B3 and W1–W3 is a strongly skewed V-like shape. In most occasions an extremely steep section of the rear slope develops at the eastern (lagoon) side of the channel. Interestingly, virtually all records on the shoals demonstrate the development of a step, or a sequence of smaller steps on the rear slope of the depression wave.

3. Riemann waves

Based on the above arguments, we employ fully nonlinear 1D shallow-water equations for the description of the depression waves [31]:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + g \frac{\partial \eta}{\partial x} = 0, \quad \frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x}[(h + \eta)u] = 0. \quad (1)$$

Here h is the unperturbed water depth, η is the water surface displacement, $u(x, t)$ is the depth-averaged horizontal velocity, g is

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