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Wave load on a navigation lock sliding gate

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A R T I C L E I N F O

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A B S T R A C T

The wave load on a navigation lock sliding gate equipped with a ballast tank is investigated assuming the linear wave theory is valid and using the eigenfunction expansion matching method to solve the governing equations. The correctness and the limits of the solution have been checked by comparing the results with those of a numerical code which solve the full non linear Navier-Stokes equations. The results relating to the effect of the geometrical parameters and wave characteristics on the load acting on the gate are presented and discussed.

The ballast tank is found to increase the complexity of the phenomenon in relation to the wave interaction with the gate. The results indicate that the peak value of the vertical force occurs for wave numbers mostly dependent on the tank length and on the tank position along the depth, while the thickness has a smaller influence. The ballast tank has also a significant effect on the horizontal dynamic force acting on the gate, which vanishes when the wave number takes particular values. Finally, the moment applied to the gate shows a dependency on the geometrical and hydrodynamic parameters similar to that of the forces.

1. Introduction

Lock gates are essential parts of a navigation lock, since they allow for the retention of water and the locking of vessels to a higher or lower level. Several types of lock gates are used around the world: mitre gates, single pivot gates, standing tainter gates, rolling gates, sliding gates, lift gates, etc.

Rolling and sliding gate for navigation locks are usually equipped with a ballast tank, which allows the load on the roller carriages to be reduced in order to improve the maneuverability. The presence of this element may produce some disadvantages, among which is the increase of vertical force due to waves which may have negative effects especially during the gate movement. Such a problem recently occurred in the seaside gate of the navigation lock realized at the Malamocco inlet of the Venice lagoon which was designed to allow the access to the Port of Venice during the operational period of the flood control system Mo.S.E. This sliding gate is characterized by a vertical plate on the lagoon side and a rack with a ballast tank on the sea side. During a storm in 2015 the gate swung vertically due to the action of waves, characterized by an incident wave height and mean period approximately equal to 1 m and 8 s respectively. Ignoring the presence of the rack, as it provides only a small contribution to the hydrodynamic forces, this gate may be schematized as a totally immersed parallelepiped and a vertical wall adjacent to it. The actions that waves exert on a similar structure were not already analyzed in detail and no formulas or diagrams had been provided that could be used for engineering purposes.

The vertical force induced by waves on horizontal deck has been widely investigated but only for the case in which the horizontal deck is not immersed. Kaplan and Silbert (1976), Kaplan (1992) and Kaplan et al. (1995) investigated the wave forces acting on flat decks and horizontal beams on offshore platforms. They developed a semi-analytic model for the evaluation of time history wave loads on horizontal decks. Shih and Anastasiou (1992) and Toumazis et al. (1989) analyzed wave-induced forces and pressures on horizontal platform decks at small scales. Bea et al. (2001) proposed a semi-empirical method which accounts for the dynamic amplification of slamming due to dynamic response of structural elements. Tirindelli et al. (2002) and McConnell et al. (2003, 2004) measured the wave loads on deck and beam elements in a series of 2-dimensional physical model tests. These measurements were carried out to explore the process of wave loading, with the aim of developing improved predictions. Cuomo et al. (2003) and Cuomo (2005) developed a new method for the analysis of non-stationary time-history loads which is based on wavelet transform.

The influence of a vertical wall next to a deck near the coastline was recently investigated by Kisacik et al. (2012a, 2012b, 2014) who analyzed the load conditions due to wave impacts on a vertical structure with an overhanging horizontal cantilever slab.

Recently, Guo et al. (2015) analyzed the wave force acting on a

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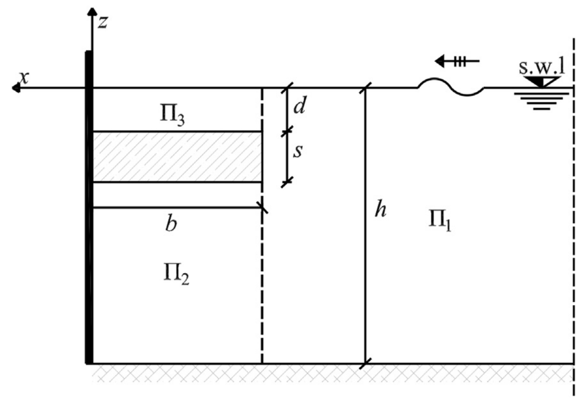

Fig. 1. Sketch of the problem.

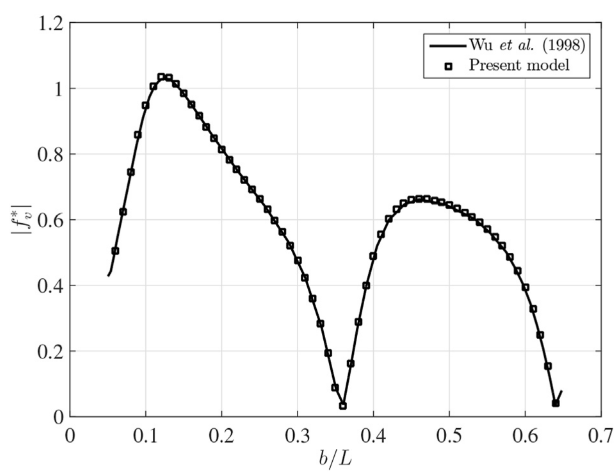

Fig. 2. Comparison between the dimensionless amplitude of the vertical force reported by Wu et al. (1998) and that computed by the present model for $d/h = 0.2$, $h/L = 0.25$ and $s/h = 0$.

semi-submerged deck by using the potential flow approach. Such an approach is a classic method to analyze the wave properties and wave force for structures under gravity waves, such as elastic floating plates (Wu et al., 1995), a group of submerged horizontal plates (Wang and Shen, 1999), and two layers of horizontal thick plates (Liu et al., 2009). The approach has also been used by Mei and Black (1969) and Black et al. (1971) to investigate the scattering phenomenon and the wave force acting on submerged rectangular objects.

A configuration similar to the one considered in this paper was analyzed by Wu et al. (1998) and Liu et al. (2007) in order to evaluate the performance of a breakwater equipped with a submerged horizontal porous plate. However, such studies were focused on the wave reflection of the breakwater and only a thin plate was considered.

In the present paper the wave load acting on a navigation lock gate, equipped with a prism-shaped tank connected to it at a certain height from the bottom, is studied by means of an analytical solution of the wave field obtained assuming the linear wave theory is valid and using the eigenfunction expansion method to solve the boundary value problem. Since the solution is based on the linear wave theory it cannot reproduce the nonlinear effect of wave propagation. Therefore, in order to evaluate the correctness and the limits of the theoretical model when the non-linearities may be important, the results have been compared with those obtained by means of the numerical integration of the Navier-Stokes Equations (NSE). In section 2 the mathematical formulation of the boundary value problem is illustrated and the eigenfunction expansion method is used to determine the analytical solution. In section 3 a validation of the model is presented along with a discussion about its limitations. In section 4 the analytical solution is used to analyze the wave force induced on the gate for different geometrical configurations and hydrodynamic conditions. Finally, in section 5 the conclusions are drawn.

2. Formulation of the problem and analytical solution

The flow generated by a progressive water wave propagating towards a navigation lock is here considered. Fig. 1 shows a sketch of the problem.

The origin of the reference system is placed at the intersection between the still water level and the vertical wall. The x axis points in the direction of the incoming waves, while the z axis points upwards. It is assumed that the waves propagate in the direction orthogonal to the gate and that the latter have constant geometrical characteristics along the y axis of the reference system. Therefore, considering a structure infinitely extended in the y direction, the flow is two dimensional. It is assumed that the incoming wave is characterized by an amplitude $H/2$ much smaller than the wavelength L such that the linear potential wave theory can be applied (Mei et al., 2005). Denoting the velocity potential by the symbol Φ, the mathematical problem is posed by the Laplace equation plus appropriate boundary condition as reported below:

$$\frac{\partial^2\Phi}{\partial x^2} + \frac{\partial^2\Phi}{\partial z^2} = 0, \tag{1}$$

$$\frac{\partial\Phi}{\partial \mathbf{n}} = 0 \quad \text{at the rigid boundaries,} \tag{2}$$

$$\frac{\partial^2\Phi}{\partial t^2} + g\frac{\partial\Phi}{\partial z} = 0 \quad \text{at z} = 0, \tag{3}$$

where g is the gravity acceleration, t is the time and $\mathbf{n}$ is the unit vector orthogonal to the boundary. Assuming that the incoming wave is

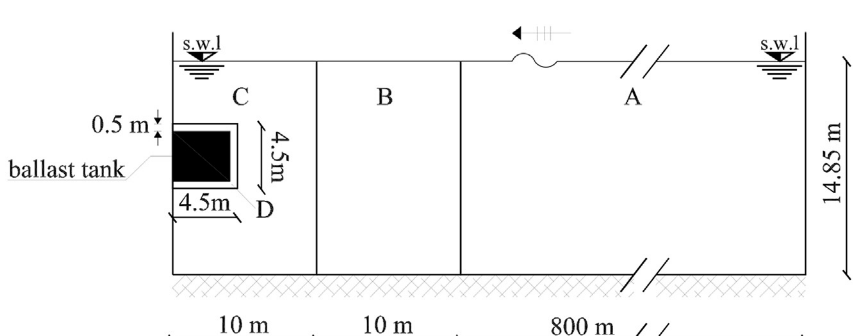

Fig. 3. Sketch of domain adopted for CFD computation.