WAVE LOADS ON A NAVIGATION LOCK SLIDING GATE: NON-LINEAR EFFECTS

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The wave loads on a navigation lock gate provided with an opening in the ballast tank are analyzed using a mathematical model based on the linear wave theory and the numerical integration of the Navier-Stokes Equation. The analysis focuses on the evaluation of the non-linear effect influence on the vertical load on the gate. It is shown that the numerical and analytical models agree on the identification of the value of the wave number at which the maximum value of the dimensionless vertical force on the gate is detected. However the analytical model overestimates the peak value of the vertical load with respect to the CFD simulation. To fill this gap, in this paper an easy to use procedure is developed which allows to correct the results of the analytical model.

INTRODUCTION

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

Rolling and sliding gates for navigation locks are usually equipped with ballast tanks, which allow the load on the roller carriages to be reduced in order to improve the manoeuvrability. Wave action is often neglected in the design of these structures as they are usually located in waters characterized by small waves with short periods. However, waves might be important for lock gates located along the coastline of sea or great lakes.

The effects of the force due to wave action on a sliding gate have recently emerged at 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 operative period of the flood control system Mo.S.E. (acronym of 'MOdulo Sperimentale Elettromeccanico' in Italian) (Cavallaro et al., 2017). Such a gate is 50 m wide and 16.6 m high. The mean water depth in front of the gate is 14 m. During a storm in 2015, the seaside gate underwent large vertical swings which resulted in extensive damage due to the action of waves characterized by height and mean period equal to about 1 m and 8 s respectively. In order to reduce these vertical forces, several new designs of the gate were proposed.

An analysis of the wave loads on a lock gate similar to that at the Malamocco inlet was recently performed by Cavallaro et al. (2018), in which the gate was modelled as a totally immersed ballast tank with a vertical wall adjacent to it. It was observed that the vertical forces are mainly due to the difference in pressure between the upper and lower side of the ballast tank. In order to reduce the vertical forces several new designs of the gate were proposed. The gate which appears to cause lower vertical forces on the ballast tank is equipped with a front plate and a large vertical opening which connects the upper and lower side of the ballast tank (see Figure 1).

The loads induced by the waves on a similar structure have not yet been analyzed in detail and in the literature there are no formulas or diagrams available for engineering purposes. Therefore, the forces produced by the waves on these structures could only be assessed through complex physical or numerical models that are not of practical use during the decision-making or pre-design phase of a work. To fill this gap, easy-to-use analytical models and/or empirical approaches should be developed to evaluate optimal design parameters in the first phase of a project (Liu and Li, 2013; Monk et al., 2013).

Cavallaro et al. (2018, 2020) analyzed the wave loads on the original gate and on the new one by means of a linear wave theory and by applying the eigenfunction expansion matching method to solve the governing equations.

This is a classic method to analyse the interaction between waves and structures that has been employed in several studies. Using this approach, Losada et al. (1992) studied the interaction between waves and three different types of vertical thin barriers. Guo et al. (2015) adopted the potential flow approach to study the wave forces acting on semi-submerged bridge decks while Fang et al. (2018) solved the same problem for the case of oblique wave attack. Other problems related to wave-structure interaction analyzed by means of the velocity potential approach are related to elastic floating plates (Wu et al., 1995), a group of submerged

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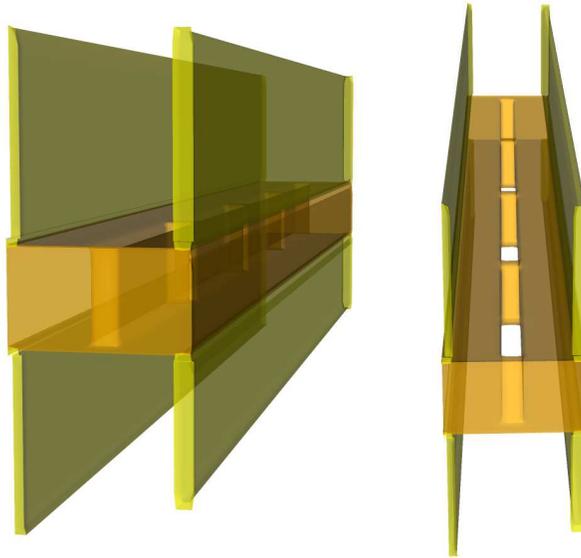
Figure 1: 3D sketches of lock gates with possible vertical openings in the ballast tank. The structural rack is omitted.

horizontal plates (Wang and Shen, 1999), two layers of horizontal thick plates (Liu et al., 2009), and oblique scattering of gravity waves by moored floating membrane (Karmakar and Soares, 2012; Behera et al., 2018; Kundu et al., 2018). This approach has also been used by Malara and Arena (2013) to investigate the performance of a Wave Energy Converter.

The approach proposed by Cavallaro et al. (2018, 2020) has allowed to analyze numerous gate configurations and wave conditions with small computational effort. The results carried out on the new configuration of the gate show that the peak values of the dimensionless vertical forces and the value of the wave number at which such peak occurs are mainly dependent on the ratio between the width of the opening trough the ballast tank and the water depth and on the ratio between the height of the ballast tank and the water depth.

However, the configuration of the new gate can produce significant non-linear effects. In order to evaluate such effects, the results of the model proposed by Cavallaro et al. (2020) were compared with those obtained by the numerical integration of the Navier-Stokes Equations.

FORMULATION OF THE PROBLEM

The cross section of the navigation lock is shown in Figure 2. The geometric parameters that characterize the flow around the structure are: (i) the water depth above the ballast tank a; (ii) the width of the gate b; (iii) the width of the vertical connection through the ballast tank c; (iv) the height of the gap at the bottom of the frontal panel d; (v) the height of the ballast tank s; (vi) the water depth in front of the gate h; (vii) the thickness s_1 of the front plate. In addition, the hydrodynamic parameters involved in the analysis are the incident wave height H and the wavelength L. It is assumed that the waves and the gate have constant geometrical characteristics along the y axis of the reference system so that the flow can be assumed as two-dimensional.

In order to evaluate the influence of the non-linearity, four gate configurations were analyzed. In this preliminary analysis we focused our attention on the effects produced by the width of the vertical opening c and the high of the ballast tank s. Table 1 shows the main geometrical parameters of the analyzed configurations. The thickness s_1 does not appears in 1 as previous analysis showed that its effect can be neglected.
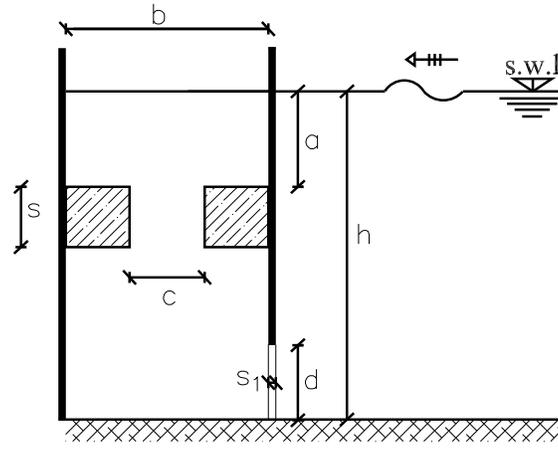
Figure 2: Transverse section of the lock gate. Water depth above the ballast tank a**; width of the lock gate** b**; width of the vertical opening in the ballast tank** c**; height of the bottom opening** d**; height of the ballast tank** s**; thickness of the front plate** s_1**; water depth** h**.**

Configuration	1	2	3	4
a [m]	2.50	2.50	2.50	2.50
b [m]	3.00	3.00	3.00	3.00
c [m]	0.80	0.40	0.80	0.40
d [m]	1.00	1.00	1.00	1.00
s [m]	2.00	2.00	3.00	3.00
h [m]	7.00	7.00	7.00	7.00

Table 1: Geometrical parameter of the analysed configurations

NUMERICAL MODEL

In this section, the numerical model used for simulating the force induced by waves on the gate is summarised. Subsequently, the computational domain is presented together with the grid characteristics. The last part of this section is dedicated to discussing the adopted boundary conditions.

Numerical modelling of wave interaction with a navigation lock sliding gate has been performed by means of CFD simulations based on OpenFoam, which solves the Navier-Stokes equations for free surface flows using a volume of fluid (VOF) method.

The two-phase fluid solver uses the incompressible Navier-Stokes (NS) equations to express the motion of the two fluids (i.e., water and air). The NS equations consist of a mass conservation equation and a momentum conservation equation, which, using the Einstein summation, can be written as:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_j u_i}{\partial x_j} - \frac{\partial}{\partial x_j}\left[\mu_{eff}\frac{\partial u_i}{\partial x_j}\right] = -\frac{\partial p*}{\partial x_i} + F_{b,i} \tag{2}$$

where t is the time, $u_i(i = 1, 2, 3)$ are the Cartesian components of the fluid velocity, ρ is the fluid density, μ_{eff} is the effective dynamic viscosity, $p*$ is the pressure in excess of the hydrostatic, F_b is an external body force (including gravity) which is defined as:

$$F_{b,i} = -g_i x_i \frac{\partial \rho}{\partial x_i} \tag{3}$$

in which $\mathbf{g} = [0; 0; -9.81]m/s^2$ is the gravitational acceleration vector and $\mathbf{x} = [x_1, x_2, x_3]$ is the position vector.

Configuration	1	2	3	4
$T_{resonance}$ [s]	8.6	10.5	9.3	11.7
T [m]	6.0-13.6	6.5-13.5	6.3-12.3	9.7-14.7

Table 2: Resonance period and range of the analyzed wave period

The interface between water and air is obtained by the Volume of Fluid (VoF) method using a compression term. The method is based on a volume fraction α which is 0 for a completely dry cell and 1 for a completely wet cell and in between 0 and 1 for an interface cell containing both water and air.

The effective dynamic viscosity μ_{eff} is obtained by the sum of a weighted value based on the volume faction α:

$$\mu_{eff} = \alpha\mu_{water} + (1 - \alpha)\mu_{air} \tag{4}$$

where μ_{water} and μ_{air} are the dynamic viscosity of water and air respectively.

The numerical wave tank is characterized by a length equal to three times the wavelength. Grid points distributions are determined on the basis of the following aspects:

- no less than 20 grid points in the vertical direction between the trough and the crest;

- no less than 80 grid points per wavelength in the horizontal direction where the free surface is expected.

In order to reproduce adequately the hydrodynamics processes close to the gate, the grid resolution gradually increases from the flume inlet to the gate model.

More in details, inside the flume the vertical grid resolution was set equal to 0.812 cm except in a strip straddling the still water level with an height of $2.6 \cdot H$ where the vertical resolution was assumed equal to 0.406 cm.

Inside the gate the horizontal grid resolution was set equal to 1.25 cm except in the above describe strip straddling the still water level where the horizontal resolution was assumed equal to 0.625 cm.

The simulations were performed using the solver IHFOAM which is a part of the official release by OpenFoam. IHFOAM handles wave generation and active absorption at the boundaries. At the seaside regular waves were generated with a wave height equal to $H = 0.20m$ and a variable wave period, around the resonance period. The resonance period was evaluated trough a special simulation, in which at time the water level inside the gate was set 0.2 m above the still water level. Table 2 shows the evaluated resonance period and the range of the adopted wave period for the 4 tested configuration.

ANALYSIS OF RESULTS

Figure 3 shows the comparison of the results obtained with the linear analytical model proposed by Cavallaro et al. (2020) and the CFD simulations.

The numerical results show that both models agree on the identification of the value of the wave number kh at which the maximum value of the dimensionless vertical force on the gate is detected ($F* = \frac{F_v}{\rho g H(b-c)}$), which corresponds to the resonance condition. However, the analytical model provides a higher value of this force with respect to the CFD simulation. Such an overestimation is due to non-linear effects, which are not included in the analytical model. Figure 4 shows the relative difference between the forces provided by the two models versus the ratio between the wave period T and the resonance period of the gate Tr. It can be observed that all the considered configurations follow trends close to each other.

The expression for the correction factor of the analytical model results can be obtained by fitting to the data reported in Figure 4 a polynomial rational curve:

$$\frac{F_{an} - F_{CFD}}{F_{an}} = \frac{p_1\left(\frac{T}{T_r}\right)^2 + p_2\frac{T}{T_r} + p_3}{\left(\frac{T}{T_r}\right)^2 + q_1\frac{T}{T_r} + q_2} \tag{5}$$

where: p_1=-0.5215; p_2=1.017; p_3=-0.474; q_1=-2.018; q_2=1.061.
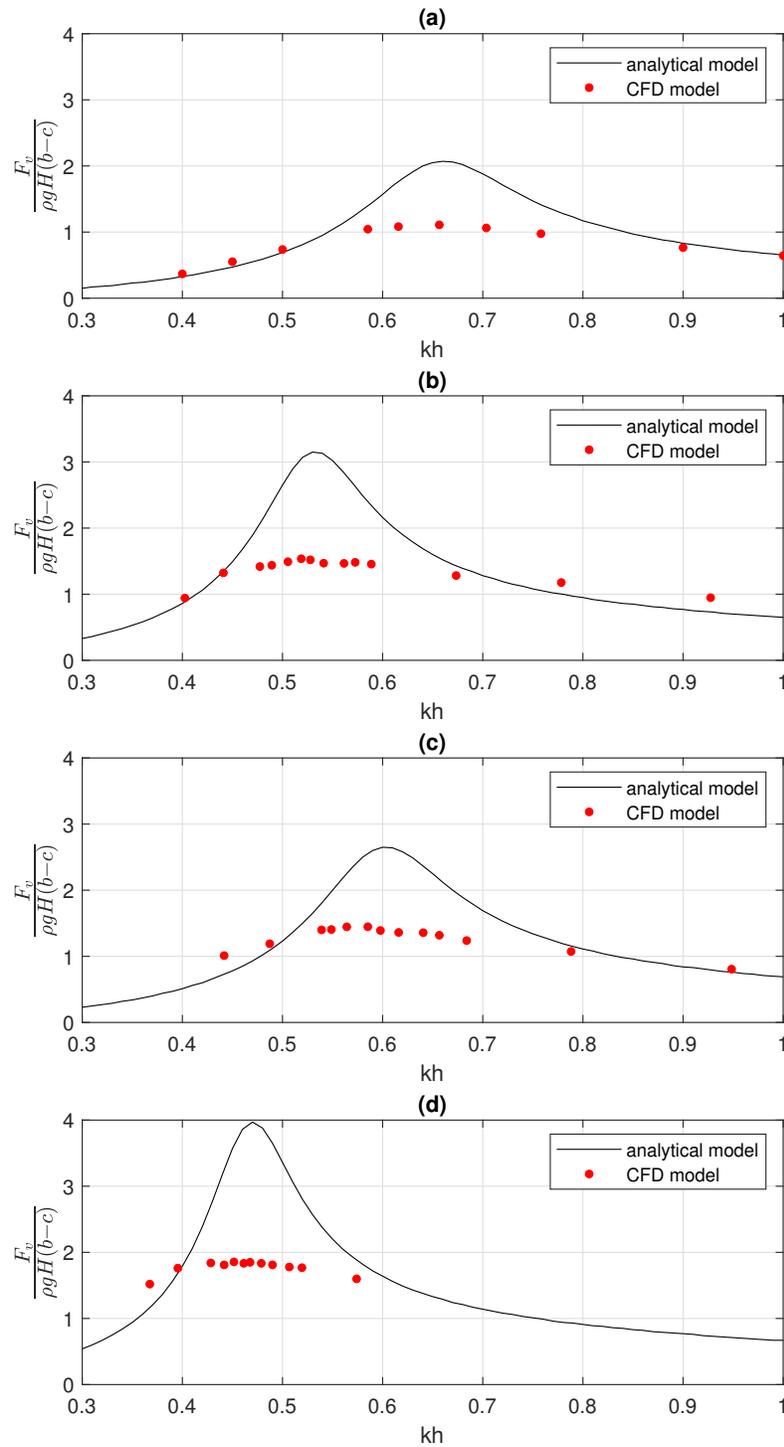
Figure 3: Non dimensional vertical force on the gate: (a) configuration 1; (b) configuration 2; (c) configuration 3; (d) configuration 3.

CONCLUSION

The wave load on a navigation lock sliding gate provided with a vertical front plate and an opening through the ballast tank has been analysed by means of an analytical model based on the linear wave theory. However, this analytical model does not include the energy dissipation and the damping of the oscillatory
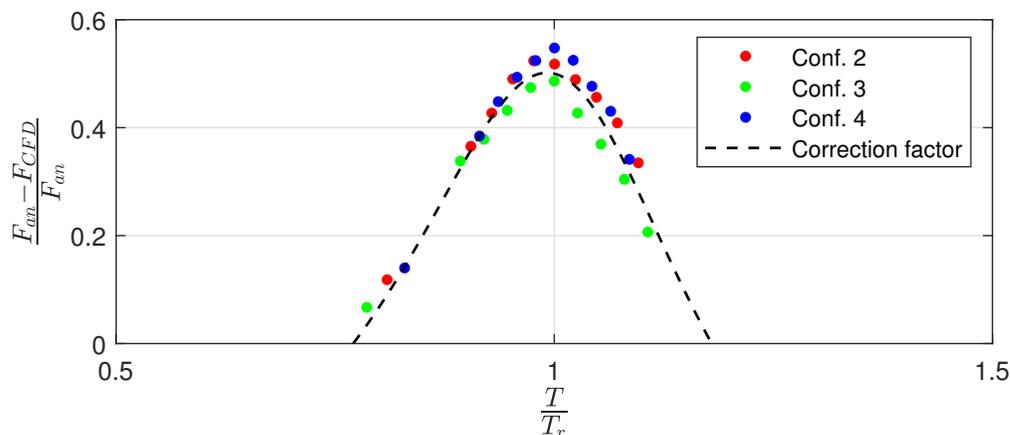
Figure 4: Dimensionless period T/Tr versus relative difference of the vertical forces evaluated with the two models.

flow.

In order to evaluate these non-linear effects, the wave load on the the gate were evaluated by means of the numerical integration of the Navier-Stokes equations.

The results of the present analysis show that the analytical model proposed by Cavallaro et al. (2020) can be usefully adopted for the preliminary design of a navigation lock sliding gate. More in details, the analytical model allows to evaluate the value of kh at which the peak of the vertical force is detected but overestimates the value of such vertical force. However, trough a comparison between the results of the analytical model and those obtained by means of the numerical integration of the Navier-Stokes Equations, it was possible to develop a procedure to correct the output of the analytical model, which result in a reliable and expeditious method for the evaluation of wave loads acting on the gate.

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