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Investigation of the added mass method for seismic design of lock gates

Loïc Buldgen [a,*], Jean-David Caprace [c], Philippe Rigo [b], Hervé Le Sourne [d]

[a] Haute Ecole Libre Mosane, Quai du Condroz 38, 4000 Liège, Belgium
[b] University of Liège, Quartier Polytech 1, Allée de la découverte 9, 4000 Liège, Belgium
[c] Federal University of Rio de Janeiro, Ilha Fundão, 21941-972 Rio de Janeiro, Brazil
[d] Institut Catholique d'Arts et Métiers, 35 Avenue du champ de Manoeuvres, Nantes, 44470 Carquefou, France

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ABSTRACT

During an earthquake, lock gates are subjected to additional pressure since the water contained in the chamber is put into motion by the earthquake. It is difficult to assess the level of this pressure because the system is affected by a fluid–structure interaction. The gate deformations have an effect on the water pressure, which in turn affects the gate vibrations. A common approach, referred to as the added mass method, consists of simulating the fluid action by distributing lumped masses over the gate. However, this method has been questioned, since the calculation of the lumped masses is usually based on the Westergaard formula, which was derived assuming a perfectly rigid structure. Consequently, fluid–structure interactions may not be captured correctly. This paper proposes to investigate the validity of this approach for such problems and to explain why it might not be conservative. The numerical solutions of an added mass model and a fluid–structure interaction model are confronted. The results indicate that the added mass method may eventually lead to conservative results depending on the type of damping used in the model. Based on these observations, some recommendations are suggested to improve the design of lock gates subjected to earthquakes.

1. Introduction

The design of lock gates requires considering different static and dynamic loads, such as the self-weight, the hydrostatic pressure, the wave induced hydrodynamic pressure, temperature variations, ice action, operational forces, and the impact of vessels. A critical issue to be considered during the design of a lock gates concerns the additional pressure generated by earthquakes. However, it is difficult to assess the level of this pressure because the system is affected by a fluid–structure interaction. Indeed, the hydrodynamic pressure induced by an earthquake is affected by the lock gate vibrations, which themselves depend on the surrounding water.

A way to deal with this issue is to perform numerical simulations where the fluid domain is explicitly depicted by elastic or acoustic finite elements or even through Lagrangian–Eulerian methods. This can be achieved using commercial software.[1] However, numerical models can need a prohibitively large number of finite elements due to the large size of the locks, typically exceeding 50 m in length. Moreover, these simulations are time-consuming to set up and computationally intensive. In order to circumvent these drawbacks, civil engineers commonly avoid modeling the fluid domain, instead developing simplified numerical and analytical approaches. Some investigations have been carried out in this manner, and will be briefly reviewed.

Due to their economic and strategic importance, gravity dams have been quite thoroughly examined regarding seismic action. This problem was first investigated by [1], who derived an analytical solution for the hydrodynamic pressure generated on the upstream vertical face of a dam during a horizontal harmonic ground motion. These developments were later extended by [2] to take into account both horizontal and vertical arbitrary ground accelerations. However, these solutions were established assuming that the lock gate is perfectly rigid, which is obviously not the case in reality. In order to take into account the fluid–structure interaction in the case of short-length gravity dams, [3] used a thick-plate model in which the modal properties of the coupled system were first calculated by the Rayleigh–Ritz method. Based on these results, a forced vibration analysis was carried out by solving the dynamic equilibrium equations.

Besides gravity dams, cylindrical and rectangular containers have also been investigated, in particular for the storage of

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* Corresponding author.

E-mail addresses: l.buldgen@helmo.be (L. Buldgen), jdcaprace@oceanica.ufrj.br (J.-D. Caprace), ph.rigo@ulg.ac.be (P. Rigo), herve.lersourne@icam.fr (H. Le Sourne).
URLs: http://www.helmo.be (L. Buldgen), http://www.oceanica.ufrj.br/labsen/en (J.-D. Caprace), http://www.anast.ulg.ac.be (P. Rigo), http://www.icam.fr/ (H. Le Sourne).

[1] e.g. LS-DYNA, ABAQUS, MSC NASTRAN, ADINA, ANSYS.

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dangerous liquids that might cause severe damages to the environment in the case of failure. In the attempt to include seismic action in the design of such structures, analytical solutions have been developed to assess the hydrodynamic pressure generated by an earthquake. For rigid containers, this has been achieved by [4–9] or [10]. Here again, the structure is assumed to be perfectly rigid, and the fluid–structure interaction is not considered. To take into account this coupling, flexible containers have been examined by [11–13], who postulated a given shape of the vibration modes to calculate the hydrodynamic pressure.

In parallel to these analytical developments, numerical investigations were also carried out by [14], who developed a sequential method to take into account the fluid–structure interaction in the 2D analysis of rectangular flexible tanks. This method was later extended by [15] to take into account free surface motions. In order to investigate more deeply the dynamic response of 3D rectangular containers, [16] gave an extensive presentation of the finite element formulation used to model the fluid domain. These developments were first validated by comparing the results with theoretical solutions known for rigid-wall conditions. From these investigations, it was concluded that the structural vibrations have a limited influence on the convective response. Only a slight increase in the pressure was observed, which tends to corroborate the idea that the free surface motions can be evaluated under a rigidity assumption. Similar conclusions were also addressed by [17], who also developed a similar finite element formulation to take into account the fluid–structure interaction.

Although there is a great deal of literature related to the effect of seismic loads on dams and storage tanks, not much has been devoted to lock gates subjected to ground motions. In a recent paper, [18] presented a semi-analytical approach to evaluate the seismic hydrodynamic pressure on a lock gate considering the fluid–structure interaction. In this approach, the modal properties of the dry structure were first derived by applying the Rayleigh–Ritz method. The eigenmodes were then used with the principle of virtual work to perform the dynamic analysis.

The added mass method recently applied by [19] to design the entrance lock of the Rosyth Royal Dockyard has become popular due to its simplicity. The validity of this method has been under discussion for many years. For example, the question has been raised during the design of the new Panama lock gates, and no consensus has been reached between the specialists. More specifically, engineers are still wondering whether working with lumped mass leads to conservative results. Moreover, the experts [20] do not really explain the origin of the divergences observed between the added mass method and other more elaborate approaches.

In a previous publication, [18] demonstrated that the hydrodynamic pressure might not necessarily be conservative. The purpose of the present paper is to go one step further, by explaining the origin of the observed discrepancies. As far as the knowledge of the authors extends, this has never been done before. Finally, the rational arguments exposited in this paper might be useful to change the current engineering practice of lock gate design.

This paper is structured as follows. Section 2 describes the lock gate structure used in the discussion. Theoretical and numerical background related to added mass method is then presented in Section 3. The numerical results of an added mass model and a fluid–structure interaction model are compared and discussed in Section 4. Finally, recommendations and conclusions are provided in Section 5.

2. Description of the lock structure

To illustrate the discussion of the reliability of the added mass method, the present paper focuses on the gate depicted in Fig. 1. The gate is made of a single plating, having a thickness of 0.012 m, a total height h (along the y axis) and a total width l (along the z axis) both equal to 13.1 m. The plating is reinforced by 5 horizontal girders with T-shaped cross-sections (Fig. 1), irregularly placed along the y axis. Six vertical frames are also regularly located along the z axis. Finally, the plating is also reinforced by small horizontal stiffeners with rectangular cross-sections that are distributed between the girders. Their role is mainly to prevent the panels from having buckling instabilities due to compressive stresses. All the cross-sectional dimensions, h_w, t_w, h_f, and t_f, are listed in Table 1.

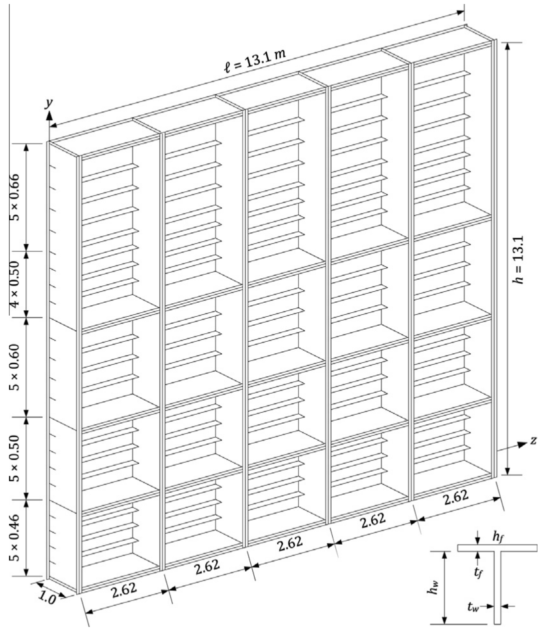

Fig. 1. Dimensions of the lock gate (m).

Table 1
Cross-sectional properties.

Property		Girders (m)	Frames (m)	Stiffeners (m)
Web height	h_w	1.000	1.000	0.210
Web thickness	t_w	0.020	0.020	0.006
Flange width	h_f	0.400	0.400	N/A
Flange thickness	t_f	0.025	0.025	N/A

Regarding the material properties, it is assumed that all the parts of the gate are built using mild steel, with a Young modulus E of 210 GPa, a Poisson ratio ν of 0.3 and a mass density ρ equal to 7850 kg/m^3.

The lock chamber has a total length L equal to 100 m (Fig. 2). When it is totally filled, the water level h_s is equal to 8 m, so that about 60% of the plating surface is in contact with the fluid. Concerning the boundary conditions, the gate is supposed to move freely at the bottom of the chamber, which means that it is not resting against a sill when it is closed. At the lock walls, the leftmost and rightmost vertical frames are placed in a recess that provides contact through a sealing device (Fig. 3): due to the water pressure, the gate is simply pushed against the walls, which produces a deformation of the seal and ensures watertightness. As some space is left between the frames and the lock walls, they do not move exactly synchronously. In this study, this steel–concrete interaction will be neglected in order to avoid a difficult modeling of the contact conditions at the gate boundaries. Consequently, the vertical edges located at $z = 0$ and $z = l$ are simply

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