Engineering Structures 100 (2015) 522–534

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

A simplified analytical method to evaluate the seismic pressure on plane lock gates

Loïc Buldgen [a,*], Philippe Rigo [a], Hervé Le Sourne [b]

[a] University of Liège, ANAST, 1 Chemin des Chevreuils, 4000 Liège, Belgium
[b] ICAM Nantes, 35 Avenue du champ de Manœuvres, 44470 Carquefou, France

ARTICLE INFO

Article history:
Received 12 February 2015
Revised 10 June 2015
Accepted 16 June 2015
Available online 2 July 2015

Keywords:
Earthquake engineering
Lock gate
Meshless method
Analytical formulation
Rayleigh–Ritz method
Fluid–structure interaction
Added-mass method

ABSTRACT

This paper presents a meshless method to perform the seismic analysis of a plane lock gate. The approach is based on the analytical derivation of the total hydrodynamic pressure, with due consideration for the gate flexibility. In particular, the flexibility of the gate and the fluid–structure interaction are taken into account in the calculation of the equivalent force that has to be applied on the gate to model the action of the water. To reach this goal, the Rayleigh–Ritz method is first used to determine the modal properties of the dry structure. This is achieved by using mode shapes extracted from the beam theory as generating functions. The results obtained in this way are validated by comparison with numerical solutions. The second step consists in performing the dynamic analysis of the gate by deriving a weak form of the equilibrium equation. Based on the Galerkin method, a matrix formulation is derived and the Newmark integration scheme is used for the evaluation of the pressure during the earthquake. Here again, non-linear finite element simulations including water modeling are carried out to corroborate the analytical developments. In addition, the lumped-mass method is also investigated and a criteria is proposed to check its applicability. Finally, some concluding remarks are given to perform more easily the seismic analysis of lock gates.

1. Introduction

Amongst all the loads that have to be considered to design lock gates, the seismic action has to be treated carefully because it may drastically increase the total pressure acting on such structures. This is particularly true in regions that are frequently submitted to earthquakes. Nevertheless, dealing properly with the seismic action is not straightforward because of the interaction that may appear between the structure and the water.

Indeed, it is well-known that the vibrations of the lock gate have an influence on the water pressure, but this latter has also an effect on the structural behavior. In other words, the fluid and solid domains are coupled, which implies that the dynamic response of the gate has to be determined with due consideration for the surrounding water. One of the most appropriate method to account for this interaction is to perform finite element simulations in which the fluid domain is extensively modeled. However, doing so requires a sufficient knowledge to correctly model both the water (elastic or acoustic elements, arbitrary Lagrangian–Eulerian methods...) and the contact between the water and the structure. Furthermore, building the model and running the simulations may be time demanding, particularly for locks where the chamber length commonly exceeds 50 m. Consequently, to circumvent these difficulties, the idea is to develop a new meshless method, in which the fluid domain does not have to be modeled anymore. The aim of this paper is therefore to help engineers by developing a simplified analytical procedure to quickly approximate the total hydrodynamic pressure acting on a lock gate during an earthquake.

In the literature, some references dealing with the seismic design of hydraulic structures are already available. Amongst them, the case of gravity dams has been quite largely investigated. This problem was first solved by Westergaard [1], who theoretically derived the hydrodynamic pressure acting on the upstream vertical face of a dam submitted to horizontal harmonic ground motion. For this calculation, only a harmonic horizontal acceleration was considered and the reservoir was supposed to be of infinite length. These developments were later extended by Chopra [2] to the case of a similar dam submitted to a horizontal or a vertical arbitrary ground acceleration. Nevertheless, one of the main

* Corresponding author at: University of Liège, Faculty of Applied Sciences, ANAST, 1 Chemin des Chevreuils, 4000 Liège, Belgium. Tel.: +32 (0)4 366 48 59, mobile: +32 (0)478 50 21 88; fax: +32 (0)4 366 91 33.

E-mail addresses: L.Buldgen@ulg.ac.be (L. Buldgen), ph.rigo@ulg.ac.be (P. Rigo), herve.lesourne@icam.fr (H. Le Sourne).

http://dx.doi.org/10.1016/j.engstruct.2015.06.030
0141-0296/

hypothesis in the work performed by the previous authors is that the structure was assumed to be perfectly rigid, which means that the pressures are the same as if a body of water was forced to move in unison with the dam. In order to investigate the fluid–structure interaction, an analytical approach was suggested by Rashed and Iwan [3] for short-length gravity dams. In this study, the structure was modeled as a thick plate. The modal properties of the coupled system were first obtained by applying the Rayleigh–Ritz method and a forced vibration analysis was performed by solving the equilibrium equations.

Apart gravity dams, rectangular storage tanks have also been investigated in the literature, which could be of direct interest in the present situation as a lock chamber may be seen as a very large reservoir. The case of rigid containers submitted to horizontal ground accelerations was treated by Epstein [4], Housner [5] or Graham and Rodriguez [6] amongst others. These developments were later extended by Haroun [7] to concrete reservoirs simultaneously submitted to horizontal and vertical seismic accelerations. Nevertheless, in the references mentioned previously, the fluid–structure interaction was neglected as the tank walls were supposed to be perfectly rigid. In order to investigate this phenomenon, Kim et al. [8] proposed an analytical method based on the Rayleigh–Ritz method, where the vibration modes of simply supported or cantilever beams were used as admissible functions. Their approach was validated by comparisons with numerical results and it was clearly pointed out that the hydrodynamic pressure tends to be amplified and that its distribution largely differs from the one obtained for a rigid configuration. Of course, such a conclusion is particularly valuable for lock gates.

In addition to these purely analytical developments, flexible rectangular containers were also analyzed with help of numerical techniques. For example, Chen and Kianoush [9], Kianoush et al. [10], Ghaemmaghami and Kianoush [11] or Mitra and Sinhamahapatra [12] derived their own finite element formulations to account for the coupling between the walls and the fluid contained in the reservoir. Of course, this could also be achieved by using commercial software such as LS-DYNA, ABAQUS, MSC NASTRAN, ADINA, and ANSYS.

In order to close this introduction, it should be mentioned that the seismic analysis of lock gates is practically not reported in the literature. One study is due to Forsyth and Porteous [13] who applied the added mass method in conjunction with response spectra to realize the seismic design of the entrance lock at the Rosyth Royal Dockyard in the United Kingdom. However, as discussed later in this paper, such an approach has to be carefully used, in particular for flexible gates. It is therefore the aim of this article to propose another solution.

2. Description of the structure

The gate considered in this paper is made of a simple plating having a total height h, a total width ℓ and an average thickness t_p. It is reinforced by an orthogonal stiffening system (Fig. 1a). The n_v vertical elements (parallel to the y axis) are called the frames and are placed at different horizontal locations z_n. Usually, they are regularly spaced along the width of the gate, but this is not necessarily the case. The plating is also reinforced by n_h horizontal girders (parallel to the z axis) located at various vertical positions y_n. In addition to this basic system, some supplementary horizontal and/or vertical smaller stiffeners may be added to prevent the buckling of the plating. All these reinforcing elements are assumed to have a T-shaped cross-section, as depicted in Fig. 1c. The web height and thickness are denoted by h_w and t_w respectively, while the flange width and thickness are designated by h_f and t_f.

The lock chamber configuration is depicted in Fig. 1b. Its length and width are denoted by L and ℓ respectively, while the water level is equal to h_s. As a matter of simplification, it is supposed that the upstream and downstream lock gates are strictly identical, but this hypothesis will be later investigated in more details (see Section 7).

Regarding the boundary conditions, the gate is simply supported along the edges ① and ③ corresponding to the lock walls (Fig. 1a), but this is also the case for edge ② if the structure is resting against a sill at the bottom (Fig. 1d). During the earthquake, it is assumed that a longitudinal seismic acceleration $\ddot{X}(t)$ is imposed at these three boundaries (Fig. 1b).

3. Derivation of the hydrodynamic pressure

The total pressure $p(y,z,t)$ acting on the gate during the earthquake may be obtained by summing up three different contributions:

$$p(y,z,t) = \rho g(h_s - y) + p_r(y,t) + p_f(y,z,t) \tag{1}$$

where the first term may be recognized as the hydrostatic pressure. The two remaining ones are known as the rigid and flexible impulsive pressures and are designated by $p_r(y,t)$ and $p_f(y,z,t)$. It is worth mentioning that an additional term may eventually be added in Eq. (1) to account for the convective pressure that is associated to the sloshing of the free surface. Nevertheless, in the present situation, this phenomenon is expected to have little influence as the parameters L and ℓ are usually quite large for classical lock chambers. Furthermore, according to the European Standards [14], the sloshing effect does not predominantly affect the fluid–structure interaction, which is an additional reason to neglect it. As a consequence, the evaluation of $p(y,z,t)$ only requires the derivation of $p_r(y,t)$ and $p_f(y,z,t)$. This can be achieved by applying the potential theory and solving the Laplace equation. As mentioned by Kim et al. [8], these two contributions may be evaluated as follows:

$$p_r(y,t) = -\rho_f \left(\sum_{n=1}^{+\infty} \frac{4}{\beta_n^2 L} \frac{\cosh(\beta_n y)}{\cosh(\beta_n h_s)} - \frac{L}{2} \right) \ddot{X}(t) \tag{2}$$

$$p_f(y,z,t) = -\sum_{n=1}^{+\infty}\sum_{m=0}^{+\infty} c_{mn} \cos(\alpha_n y)\cos(\bar{\gamma}_m z) \int_0^{h_s}\int_0^{l} \ddot{u}(y,z,t) \times \cos(\alpha_n y)\cos(\bar{\gamma}_m z)\,dy\,dz \tag{3}$$

where ρ_f is the fluid mass density, $\beta_n = (2n-1)\pi/L$ and the other parameters involved in Eq. (3) have the following definitions:

$$c_{mn} = 2\rho_f \frac{1-\cosh(\xi_{mn}L)}{h_s \ell_m \xi_{mn} \sinh(\xi_{mn}L)} \quad \bar{\gamma}_m = \frac{m\pi}{\ell}$$
$$\alpha_n = \frac{(2n-1)\pi}{2h_s} \quad \xi_{mn} = \sqrt{\alpha_n^2 + \bar{\gamma}_m^2} \tag{4}$$

in which $\ell_m = \ell$ if $m = 0$ and $\ell_m = \ell/2$ if $m > 0$. From Eqs. (2) and (3), it can be observed that the rigid contribution is directly related to $\ddot{X}(t)$, while the flexible one is influenced by the gate accelerations $\ddot{u}(y,z,t)$. Consequently, the fluid–structure interaction is entirely included in $p_f(y,z,t)$ and the evaluation of the total hydrodynamic pressure has to account for this coupling.

4. Free vibration analysis of a dry gate

From the previous observations, the first step to perform the seismic analysis is to better characterize the modal properties of the dry gate (i.e. without considering the surrounding water). Of course, such characteristics may be obtained by finite element software, but in the purpose of developing a simplified method, it is