Cold Regions Science and Technology 90–91 (2013) 22–32

Contents lists available at SciVerse ScienceDirect

Cold Regions Science and Technology

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

Seismic analysis of rectangular water-containing structures with floating ice blocks

Damien Goulmot, Najib Bouaanani *

Department of Civil, Geological and Mining Engineering, École Polytechnique de Montréal, Montréal, QC, Canada H3C 3A7

ARTICLE INFO

Article history:
Received 20 June 2012
Accepted 17 December 2012

Keywords:
Dynamic response
Water-containing structure
Ice effects
Floating ice blocks
Sloshing ice
Hydrodynamic pressure

ABSTRACT

This paper presents a new formulation to investigate the effects of floating ice blocks on seismically-excited rectangular water-containing structures. The proposed method is based on a sub-structuring approach, where the flexible containing structure and ice-added mass are modeled using finite elements, while hydrodynamic effects are modeled analytically through interaction forces at the water–structure and water–ice interfaces, thus eliminating the need for reservoir finite element discretization. In addition to accounting for the influence of floating ice blocks and container walls' flexibility, the developed frequency- and time-domain techniques also include the effects of container geometrical or material asymmetry as well as the coupling between convective and impulsive components of hydrodynamic pressure. The proposed formulation is illustrated through a numerical example illustrating the dynamic response of symmetric and asymmetric water-containing structures covered with floating ice blocks. Obtained time- and frequency-domain responses are successfully validated against advanced finite element analyses including fluid–structure interaction capabilities. For the water-containing structures studied, the results show that the presence of floating ice blocks affects the frequency content and amplitudes of the dynamic responses corresponding to convective and impulsive modes.

1. Introduction

The dynamic behavior of water-containing structures has been widely studied in the last five decades to predict their response to seismic excitations and prevent heavy damage as observed during the 1960 Chilean Earthquakes (Steinbrugge and Flores, 1963), the 1964 Alaska Earthquake (Hanson, 1973), and more recently the 1994 Northridge Earthquake (Hall, 1995), the 1999 Turkey Earthquake (Steinberg and Cruz, 2004) and the 2003 Tokachi-oki Earthquake (Koketsu et al., 2005).

In earlier analytical work, the containing structure was assumed rigid and the studies mainly focused on the dynamic behavior of the contained liquid (Housner, 1957, 1963; Jacobsen, 1949; Jacobsen and Ayre, 1951; Werner and Sundquit, 1949). Significant observed post-earthquake damage showed that the rigid assumption may lead to the underestimation of the seismic response of such structures, and clearly indicated the necessity of including the flexibility and vibrating response of the containing structure as well as its coupled interaction with the contained liquid.

The work of Chopra (1967, 1968, 1970), Veletsos (1974), Haroun (1980) and many others subsequently (Balendra et al., 1982; Haroun, 1983; Haroun and Housner, 1981a, 1981b; Veletsos and Yang, 1976, 1977), confirmed that structural flexibility affects considerably the coupled dynamic response of water-containing structures. Another phenomenon which attracted the attention of many researchers is the effect of surface gravity waves and corresponding sloshing at the surface of the contained liquid during earthquake excitation. Indeed, it has been evidenced that liquid sloshing was generally a source of most damage observed in the upper part of liquid containing structures (Krausmann et al., 2011). In numerical analyses, dynamic fluid pressures are generally decomposed into (i) a convective component generated by the sloshing of a portion of the fluid near the surface, and (ii) an impulsive component generated by a portion of the fluid accelerating with the containing structure. It has been shown that the coupling between liquid sloshing modes and container vibration modes is generally weak (Haroun, 1980; Haroun and Housner, 1982; Veletsos, 1974). Convective and impulsive pressures can then be first determined separately and their effects combined later to obtain the total dynamic response (Kana, 1979; Malhotra et al., 2000). Several researchers proposed refined analytical and numerical methods to assess sloshing effects in seismically-excited tanks, such as Veletsos and Yang (1976), Gupta and Hutchinson (1990), Fisher and Rammerstorfer (1999), and Ghaemmaghami and Kianoush (2010).

In cold climates, water-containing structures such as dams, tanks or navigation locks are generally covered with 1 to 2 m-thick ice sheets for significant periods of time during the year. Increasing exploration of natural resources in northern regions has motivated a variety of research programs which mainly focused on the dynamic response of ice-surrounded offshore platforms to drifting ice action as well as to seismic excitation (Cammaert and Muggeridge, 1988; Croteau, 1983; Kiyokawa and Inada, 1989; Miura et al., 1988; Sun, 1993). Forced vibration tests were carried out on a large gravity dam in Quebec under both

* Corresponding author.
E-mail address: najib.bouaanani@polymtl.ca (N. Bouaanani).

0165-232X/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.coldregions.2012.12.010

summer and severe winter conditions including the presence of an ice cover (Paultre et al., 2002). The experimental results and subsequent numerical studies have shown that the ice cover affects the dynamic response of gravity dams as well as hydrodynamic pressure distribution in the reservoir (Bouaanani et al., 2002). In all previous studies, the ice-covered water domain was assumed infinite, or delimited at a given truncating distance from the structure by a transmitting boundary condition to account for energy radiation at infinity (Bouaanani and Paultre, 2005). However, the dynamic or seismic response of ice-covered water reservoirs of limited extent such as water storages, channels and navigation locks received almost no attention in the literature.

In this paper, we investigate the effect of floating ice blocks on the dynamic characteristics and seismic response of rectangular water-containing structures such as the one illustrated in Fig. 1. The dynamic analysis of such systems, commonly encountered in cold regions, requires the modeling of simultaneous dynamic interactions between floating ice blocks, water and the containing structure. The analytical method developed in this work will address the dynamic and seismic behavior of such systems using a sub-structuring technique where structural and hydrodynamic responses are coupled through interface forces. Finite element modeling is then restricted to the containing structure, while hydrodynamic effects are accounted for analytically, thus eliminating the need for reservoir finite element discretization. In addition to accounting for the influence of floating ice blocks and container walls' flexibility, the developed frequency- and time-domain techniques will also include the effects of possible geometrical or material asymmetry of the containing structure as well as the coupling between convective and impulsive components of hydrodynamic pressure.

2. Mathematical formulation

2.1. General assumptions and governing equations

We consider a rectangular water-containing structure as the one depicted in Fig. 1. We assume that: (i) the longitudinal dimensions of the structure are sufficiently large so that it can be modeled as a two-dimensional plane-strain elasticity problem, (ii) the constitutive material of the containing structure has a linear elastic behavior, (iii) the lateral walls of the containing structure are flexible and have vertical faces at the interfaces with the reservoir, (iv) water is compressible, inviscid, with its motions irrotational and limited to small amplitudes, (v) water surface is covered by floating ice blocks, vibrating vertically without friction, and (iv) the containing-structure can be geometrically or materially asymmetrical.

The reservoir has a length $L_r = 2b_r$ and height H_r as indicated in Fig. 1. We adopt a Cartesian coordinate system with origin at the reservoir bottom, a horizontal axis x and a vertical axis y coincident with the axis of symmetry of the reservoir. As mentioned previously, we will apply a sub-structuring approach as illustrated in Fig. 2, where the flexible containing structure and ice-added mass are modeled using finite elements, while water effects are modeled analytically through interaction forces at the water–structure and water–ice interfaces.

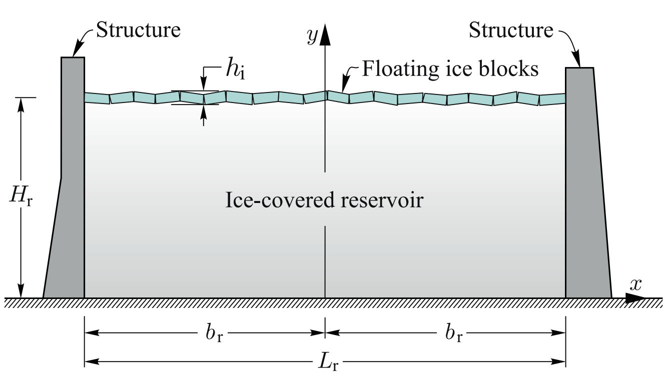

Fig. 1. General geometry of the studied ice–water–structure systems.

The hydrodynamic pressure $p(x,y,t)$ within the reservoir is governed by the classical wave equation

$$\nabla^2 p = \frac{1}{C_r^2}\frac{\partial^2 p}{\partial t^2} \tag{1}$$

where ∇^2 is the Laplace differential operator, t the time variable, ρ_r the mass density of water and C_r the compression wave velocity. We consider harmonic ground accelerations $\ddot{u}_g(t) = a_g e^{i\omega t}$ where ω denotes the exciting frequency. Hydrodynamic pressure in the reservoir can then be expressed in frequency domain as $\overline{p}(x,y,t) = \overline{p}(x,y,\omega)e^{i\omega t}$, where $\overline{p}(x,y,\omega)$ is a complex-valued frequency response function (FRF). Eq. (1) becomes then the classical Helmholtz equation

$$\nabla^2 \overline{p} + \frac{\omega^2}{C_r^2}\overline{p} = 0. \tag{2}$$

Using a modal superposition analysis, the FRFs for structural displacements and accelerations can be expressed as

$$\overline{u}(x,y,\omega) = \sum_{j=1}^{m_s}\psi_j^{(x)}(x,y)\overline{Z}_j(\omega); \qquad \overline{v}(x,y,\omega) = \sum_{j=1}^{m_s}\psi_j^{(y)}(x,y)\overline{Z}_j(\omega) \tag{3}$$

$$\overline{\ddot{u}}(x,y,\omega) = -\omega^2\sum_{j=1}^{m_s}\psi_j^{(x)}(x,y)\overline{Z}_j(\omega); \quad \overline{\ddot{v}}(x,y,\omega) = -\omega^2\sum_{j=1}^{m_s}\psi_j^{(y)}(x,y)\overline{Z}_j(\omega) \tag{4}$$

where $\overline{u}$ and $\overline{v}$ denote the horizontal and vertical displacements, respectively, $\overline{\ddot{u}}$ and $\overline{\ddot{v}}$ the horizontal and vertical accelerations, respectively, $\psi_j^{(x)}$ and $\psi_j^{(y)}$ the x- and y-components of the jth structural mode shape, respectively, $\overline{Z}_j$ the generalized coordinate, and m_s the

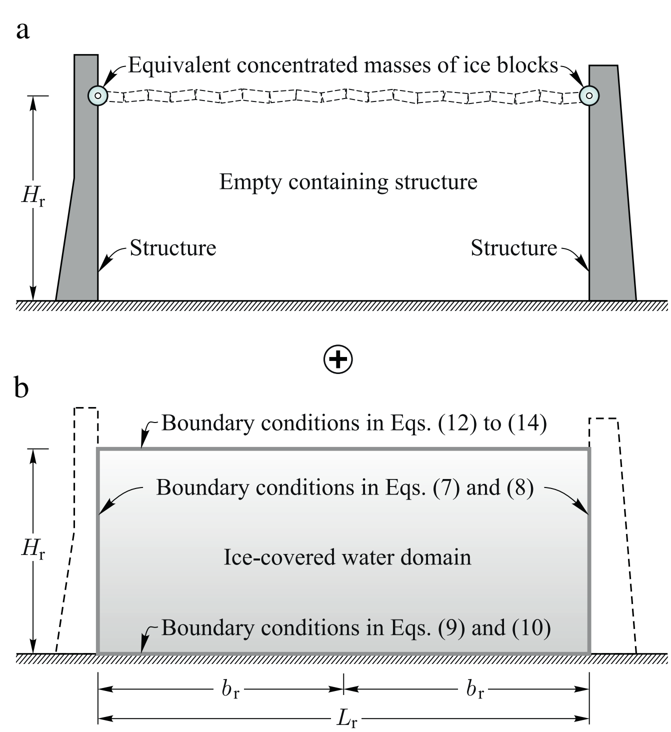

Fig. 2. Sub-structuring approach: (a) containing structure and ice-added mass; and (b) reservoir model.