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Effects of fluid–structure interaction modeling assumptions on seismic floor acceleration demands within gravity dams

Najib Bouaanani *, Sylvain Renaud

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

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ABSTRACT

This paper presents an original investigation of the sensitivity of floor acceleration demands in gravity dams to various modeling assumptions of the impounded reservoir. Such floor acceleration demands are crucial for the assessment of the seismic performance or vulnerability of dam-supported appurtenant structures. Two approaches are proposed to obtain floor acceleration demands: analytical and coupled dam–reservoir finite element models. Both techniques are applied to typical dam–reservoir systems with different geometries. The dam–reservoir systems are subjected to ground motions with various frequency contents and the resulting floor acceleration demands are examined to investigate the effects of reservoir geometry, water compressibility, reservoir bottom wave absorption and dam higher vibration modes. A new approach based on proposed floor frequency response functions is also developed to assess floor acceleration demands at the stage of preliminary seismic design or safety evaluation of dam-supported appurtenant structures. Examples are given to illustrate how the proposed approach can be effectively used to compare floor acceleration demands within different dams or within the same dam considering various modeling assumptions of the reservoir.

1. Introduction

Floor response spectra define maximum responses of light mass equipments or other secondary structures supported at various locations of a more massive primary structure. These spectra are commonly used to investigate the dynamic response of secondary structures when interaction with the primary structure can be neglected. Floor response spectra were extensively studied in the contexts of nuclear facilities and multi-storey buildings [1–5]. Floor response spectra can also be used to assess the dynamic response of safety-critical piping, power supply units, and other electrical or mechanical equipment anchored within dam galleries as well as appurtenant facilities such as bridges, control unit buildings, spillway support structures, gates, hoist bridges and lifting equipment generally located near dam crest where ground motions can be significantly amplified from dam base. For example, seismic records at three dam sites in Quebec during the Saguenay earthquake showed motion amplifications of 7 to 15 times from rock to dam crest [6].

Assessment of maximum floor acceleration demands along the height of hydraulic structures is crucial for the design and safety evaluation of appurtenant systems. Indeed, amplification of seismic demands in dams may cause significant damage as was documented in several cases, such as the 103 m-high Koyna dam (India) after the 1967 M6.3 reservoir induced earthquake, the 105 m-high Hsingfengkiang buttress dam (China) under the effect of a 1962 M6.1 reservoir induced earthquake, and the 106 m-high Sefid-Rud buttress dam (Iran) following a 1990 M7.3 earthquake [7–9]. In other events, if damage to the dam itself remained marginal, supported equipment and appurtenant structures were severely affected by amplified ground motions which induced offset or cracking of elements such as walls, parapets, or bridge girders [10,11]. Amplifications of seismic demands in dams were also evidenced by shake table tests [12–14]. Therefore, modern guidelines dealing with the earthquake response of dams, such as ICOLD [15], clearly specify that seismic input at the support of equipments or at the base of appurtenant structures should take account of ground motion amplifications. Such practice has not been always uniformly observed however, especially for older dams and appurtenant structures with initial designs that may fail to meet modern safety criteria.

Weiland and Malla [16] performed 3D dynamic analysis of a 45 m-high arch-gravity dam assuming that water in the reservoir is incompressible. They found an acceleration amplification factor with respect to the PGA of 3.8 at the upper gallery, and about 8

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

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at dam crest. They also used the floor response spectrum at a given level to generate artificial spectrum-compatible accelerograms used to conduct stability analyses of an upper cracked portion of the dam [16,17]. Ben Ftima and Léger [18] investigated the possibility to compute floor response spectra at the base of cracked sections of a gravity dam and the use of these spectra to define compatible accelerograms to perform transient rigid body sliding/rocking response analyses along dam's height. They used Westergaard's added masses to represent hydrodynamic loads from the reservoir.

It is now widely accepted that the accurate evaluation of reservoir loading on a dam upstream face is an important ingredient of its seismic safety assessment. Significant research has been devoted to study this type of loading since the pioneering work of Westergaard [19]. Several advanced analytical and numerical frequency-domain and time-domain approaches were also proposed to account for dam deformability, water compressibility, radiation of outgoing waves towards far reservoir upstream, and reservoir bottom wave absorption in the seismic response of dam–reservoir systems, such as described for example by Chopra [20], Fenves and Chopra [21], Humar and Jablonski [22], and Bouanani and Lu [23]. To the authors knowledge however, no published work has addressed the sensitivity of floor acceleration demands to modeling assumptions commonly adopted for hydraulic structures such as gravity dams, namely those related to hydrodynamic loading. These assumptions may range from simplified added mass approach to more advanced treatment of frequency-dependent dam–reservoir interaction, including water compressibility, reservoir bottom wave absorption and energy dissipation at far reservoir upstream. Dam engineering analysts are usually left to select the most appropriate of these assumptions for a particular project without having sense or prior knowledge of the relative impacts on the design or safety evaluation of appurtenant infrastructure. Informed choices are however crucial considering the critical importance and seismic vulnerability that may be associated with dam-supported appurtenant structures. This paper's main objective is to feed such informed choices as analytical and coupled dam–reservoir finite element models are proposed and used to thoroughly investigate the effects of various assumptions on floor acceleration demands within typical dam–reservoir systems with different geometries.

2. Basic notation and types of analyses

2.1. Floor acceleration demands

We consider a gravity dam monolith, of height H_d, subjected to a horizontal ground acceleration $\ddot{u}_g$ at the base as illustrated in Fig. 1. Floor seismic demands at a given point P of the dam are defined by studying the dynamic response of SDOF systems with various vibration frequencies f_s, attached to point P, while the dam is excited by a ground acceleration $\ddot{u}_g$ applied at its base. These SDOF systems, may represent dam-supported appurtenant secondary structures, with mass m_s, stiffness k_s and viscous damping c_s. We assume that the mass of the appurtenant secondary SDOF system is too light so that its dynamic response does not affect that of the primary system, i.e. the dam monolith. The equation of motion of the appurtenant SDOF can be written as

$$m_s\ddot{u}_s + c_s\dot{u}_s + k_s u_s = -m_s(\ddot{u}_P + \ddot{u}_g) \quad (1)$$

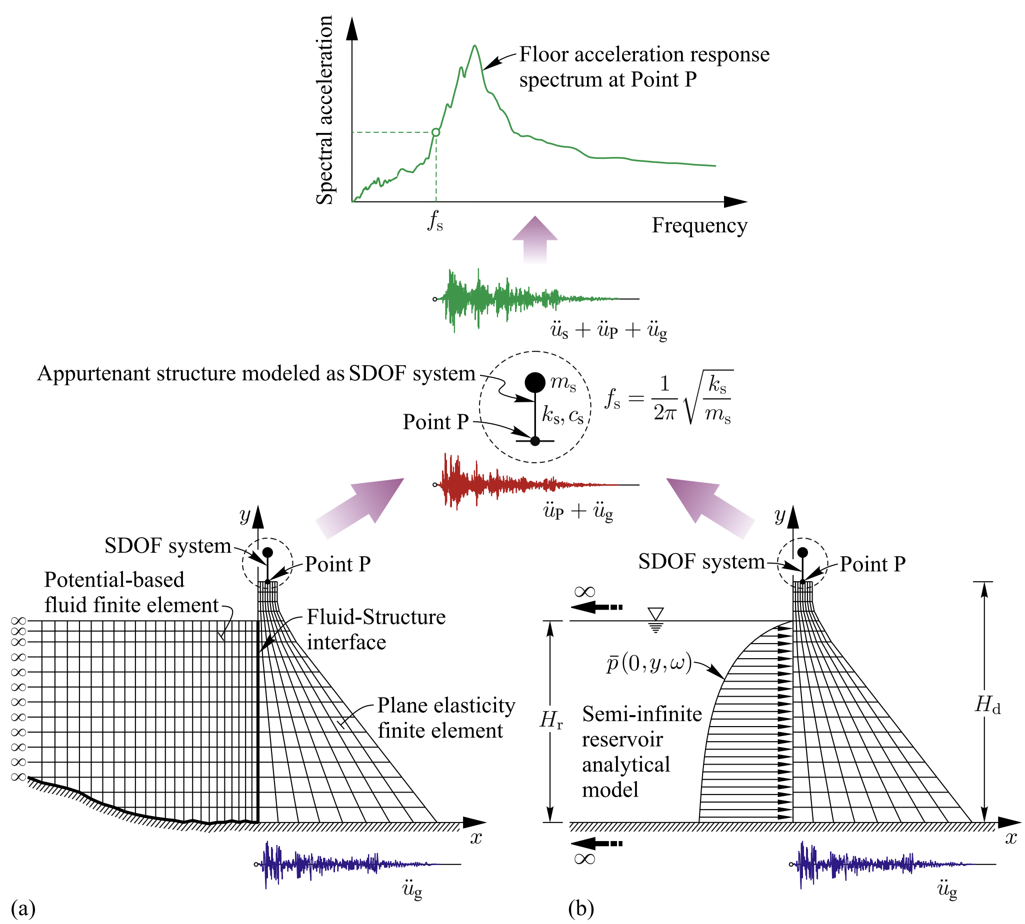

Fig. 1. Illustration of the computation of floor acceleration spectra at a given point P of a gravity dam: (a) using a coupled dam–reservoir finite element model and (b) using a semi-infinite reservoir analytical model.