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Influence of reservoir geometry and conditions on the seismic response of arch dams

F. García [a,*], J.J. Aznárez [a], H. Cifuentes [b], F. Medina [b], O. Maeso [a]

[a] Instituto Universitario de Sistemas Inteligentes y Aplicaciones Numéricas en Ingeniería (SIANI), Edificio Central del Parque Científico y Tecnológico, Campus Universitario de Tafira, Universidad de Las Palmas de Gran Canaria, 35017 Las Palmas de Gran Canaria, Spain
[b] Grupo de Estructuras, Escuela Técnica Superior de Ingeniería, Universidad de Sevilla, Camino de los Descubrimientos s/n, 41092 Sevilla, Spain

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ABSTRACT

An analysis of the influence that reservoir levels and bottom sediment properties (especially on the degree of saturation) have on the dynamic response of arch dams is carried out. For this purpose, a Boundary Element Model developed by the authors that allows the direct dynamic study of problems that incorporate scalar (dammed up water), viscoelastic (dam and soil site) and poroelastic media (bottom sediments in the reservoir) is used. All of the regions are discretized using boundary elements, later formulating equations of compatibility and equilibrium that allow their interaction to be rigorously established. The seismic excitation consists in plane longitudinal waves (P waves) and shear waves (S waves) impinging the dam site with an angle of vertical incidence. The analysis is carried out in the frequency domain, and the time response is obtained, for synthesized artificial accelerograms defined in terms of the elastic response spectrum taken from Eurocode 8, using a FFT algorithm. The variables used to characterize the response are: Amplitude of the complex-valued frequency-response function, acceleration response spectra and the integral of velocity of points located at the structure. These variables clearly indicate the importance that the factors analyzed have on the dynamic response.

1. Introduction

There are three main factors that affect the seismic response of an arch dam: the effects of soil-structure interaction, the spatial distribution of the seismic excitation, and all those factors that can significantly affect the field of hydrodynamic pressure in the reservoir, and therefore have an impact on the pressures distribution in the upstream face of the dam.

Water compressibility, reservoir geometry, and reservoir level are included in the third group of factors, in addition to the mechanical properties of foundation rock and the possible presence of bottom sediments in the reservoir, all of which modify the effects of the dynamic interaction between the water mass with the foundation rock and with the dam itself. The importance of some of these factors has been analyzed in different studies: [1–19].

This paper focuses on the study of the influence of reservoir levels and the presence of bottom sediment layers in the reservoir on the dynamic behavior of the dam. The reservoir level is subject to seasonal cycles and has a dual impact. First, changes in the reservoir level affect the global mass of the system. Second, these changes alter the reservoir geometry. Thus, the global dynamic behavior of the reservoir, in terms of its natural frequencies and the amplifications of corresponding seismic response, is clearly subject to water height in the reservoir, and this effect can be seen in the results obtained of the seismic response. Previous studies have recognized this effect, however there are only a limited number of them that analyze the role of the reservoir level in cases other than those which considered completely empty or completely full reservoir conditions. Among the many studies that investigate this phenomenon noteworthy are experimental studies by Dabre et al. [20], and Proulx et al. [21] who monitored the dynamic behavior of large arch dams during different months of years under a range of water reservoir levels. These authors conclude that the dynamic behavior of the dam is strongly influenced by reservoir levels. To the extent of the Authors' knowledge, no other study that analyzes the influence of water height in connection with the presence of bottom sediments and their properties has been carried out.

Bottom sediments can reach a degree of consolidation through depth during the sedimentation process. Thus, sediment is a medium with mechanical properties that can change with depth, and are different than those found in reservoir water. On the one hand, the presence of sediments modify the bottom geometry of the reservoir. On the other, they absorb energy from the hydrodynamic waves and therefore increase the damping in the dam–water–sediment–foundation system.

* Corresponding author. Tel.: +34 928 451918.
E-mail addresses: fgarcia@dic.ulpgc.es (F. García), jjaznarez@siani.es (J.J. Aznárez), bulte@us.es (H. Cifuentes), medinaencina@us.es (F. Medina), omaeso@siani.es (O. Maeso).

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Depending of its degree of consolidation, sediment can be modeled as a compressible scalar material with increasing density with the depth (see e.g. [11]), or it can be modeled as a porous elastic saturated material whose skeleton has taken on some type of elastic capacity (the sediment can transmit shear waves). This study follows earlier research [4,6,22–24,11] and assumes that the dynamic behavior of sediment is similar to that of the porous elastic saturated or quasi-saturated material in accordance with the Biot formulation [25]. All of these studies conclude that compressibility plays a role in how bottom sediments can significantly modify global dynamic behavior, especially in the case of partially saturated sediments.

Presented results are then used to analyze the sensitivity of dam response against the reservoir level, the presence of sediments and its degree of saturation, with the aim of emphasizing important differences in the dynamic response. Three different variables have been chosen to characterize the response in different points of the rock foundation and the dam crest: the amplitude of the acceleration frequency-response functions, the acceleration response spectra, and the integral of velocity.

2. Boundary Element Model of the dam–water–sediment–foundation system

The Morrow Point dam (located in Black Canyon National Park, Gunnison River, Colorado, USA) has been chosen for the analysis proposed in this paper since it is well known from previous works ([2,5,8,10,24,26]). The model assumes that the dam and foundation rock are linear, isotropic, viscoelastic materials with internal damping according to hysteretic damping model, being the latter a boundless domain when compared to the dam dimensions. The dammed up water is modeled as an inviscid, compressible fluid. The sediment is a poroelastic material that is partially saturated by water, whose dynamic behavior is represented by Biot's theory as previously noted.

Different reservoir levels have been studied with and without bottom sediments. If the height of the dam is labeled by H, a porous bottom sediment layer with a depth equal to $H/5$ is considered in this analysis in conjunction with multiple reservoir levels given in $H/5$ increments. The study covers all eleven combinations, including the cases of full and empty reservoir conditions (Fig. 1).

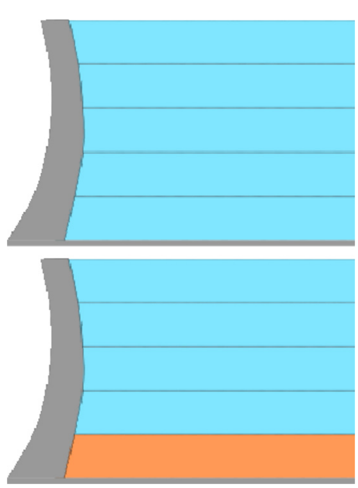
Table 1 show the properties of the regions involved in the model. Bottom sediment is a two-phase porous material and has the same properties used by Bougacha and Tassoulas [6] and Domínguez et al. [22] in their two-dimensional studies of seismic response of gravity dams and adopted by Maeso et al. [24] in their three dimensional studies of arch dams. The dissipation constant b corresponds to a hydraulic conductivity $\kappa = 10^{-3}$ m/s.

The bulk modulus, when sediment is partially saturated, has been calculated by using the following equation presented by Verruijt [27]:

$$\frac{1}{K_f'} = \frac{1}{K_f} + \frac{1-s}{p_0} \quad (1)$$

where K_f' is the pore fluid compressibility under partially saturated conditions for a degree of saturation s, and p_0 is the hydrostatic pressure. Hydrostatic pressure depends on the reservoir level, and in this paper it is calculated as the mean depth of the bottom sediment layer. Based on this data, Biot's constants are easily obtained from the expressions $Q' = (1-\phi)K_f'$ and $R' = \phi K_f'$. A summary of the K_f' values are given in Table 2 for the five degrees of saturation (99.8%, 99.6%, 99.4, 99.2%, and 99.0%) and reservoir levels under study. Full saturation ($s = 100\%$) is not studied because earlier works (see Maeso et al. [24]) showed that differences in the dam response are negligible with respect to cases where sediments are absent. On the contrary, partially saturated conditions ($s < 100\%$) of sediment have a significant impact on the dynamic behavior of the system. The high level of uncertainty regarding the actual degree of saturation adopted by the bottom sediments of the reservoir justifies the study of a saturation range with the aim of understanding how this factor influences the behavior of the boundary. The 99.0 % to 99.8 % range was chosen for two reasons. First, it is consistent with experimental studies on the degree of saturation of sediment in real settings (Cheng [4]). Second, the greatest variability of P1 wave velocity in the sediment occurs in this range (Fig. 2).

A sketch of the problem under study is given in Fig. 3 (the view includes a longitudinal section through the model to show in greater detail the regions involved). To address it, a numerical model based on the Boundary Element Method is used. This model is described by the authors in previous studies, such as in [11] or [24]. All the regions of the dam–reservoir–sediment–foundation system are represented by boundary integral equations discretized into boundary elements, taking into account their specific



	Reservoir level
No sediments	5H/5 (full)
	4H/5
	3H/5
	2H/5
	H/5
	0 (empty)
With sediments of thickness H/5	5H/5 (full)
	4H/5
	3H/5
	2H/5
	H/5 (empty)

Fig. 1. Problems under study with respect to presence of sediments and reservoir water level (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)