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Seismic evaluation of existing arch dams and massed foundation effects

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Abstract

In the present paper, the effects of a massed foundation on the nonlinear seismic response of an existing arch dam are investigated. A co-axial rotating smeared crack approach was used to model the nonlinear behavior of the mass concrete in a 3D space which is able to model cracking/crushing under static and dynamic conditions. The analysis also considered the opening/slipping of joints. The reservoir was assumed to be compressible and was modeled using the finite element method with the appropriate boundary conditions. The Dez arch dam was selected for the case study and excited by a maximum credible earthquake. It was found that assuming a massless foundation leads to the overestimation of the stresses within the dam body and causes many more crack profiles than the massed foundation model. As a result, in the case of a massed foundation, no numerical instability was found to exist during the analysis.

Keywords: Arch dams; Dam–reservoir–foundation interaction; Massed foundation; Seismic analysis; Smeared crack model

1. Introduction

Estimating the structural response of existing dams is a major task in dam engineering. To evaluate the seismic safety of arch dams, a 3D dynamic analysis of a dam–reservoir–foundation system, that can consider the following phenomena, is required: (1) dam–foundation interaction, (2) nonlinearities originating from the opening/slipping of the vertical contraction joints and the cracking/crushing of the mass concrete, (3) application of boundary conditions as close as possible to those of the real ones, and (4) application of eligible earthquake records for analyzing the arch dam located in a region with significant seismicity. Several researchers have studied the linear response of arch dams by ignoring the foundation inertia (Lau et al., 1998; Mojtahedi and Fenves, 2000; USACE, 2003; Alves, 2004). Hall (1998) proposed a simple smeared crack model to simulate the contraction and construction joints in the dynamic analysis of arch dams by assuming the flexibility of the foundation rock. At the same time, USBR (1998) evaluated the seismic safety of the Hoover Dam, a high curved arch gravity dam, by assuming a massless foundation. Due to the overestimated results of the conducted analysis, however, an investigation considering the dam–foundation interaction was conducted (USBR, 2002). The results showed that for the model with only foundation-rock flexibility, the stresses were overestimated three times in comparison to those obtained from the model with the massed foundation.

The EACD-3D computer program, originally developed by Fok et al. (1986), employs an analytical procedure for the three-dimensional seismic analysis of concrete dams including the effects of the dam–water interaction and the flexibility of

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the foundation rock. In EACD-3D-96, the seismic analysis procedure is extended to include the inertia effect and radiation damping arising from the mass of the foundation rock (Tan and Chopra, 1996). The analytical procedure underlying the program just considers the linear behavior of the dam body and the surrounding rock. Thus, the potential for concrete cracking/crushing and for the opening/slipping of the contraction joints during vibrations are not considered. In Wang and Chopra (2008), the analysis procedure of the earlier EACD-3D-96 is extended to consider the spatially varying excitation phenomenon along the dam–foundation rock interface.

Sevim et al. (2012) studied the earthquake behavior of an arch dam using vibration test results assuming a massless foundation. According to the results, very small damping ratio values with the massless foundation model in a seismic analysis lead to an upper-bound estimation of seismically induced stresses. Chopra (2012) investigated the appropriate procedures by studying the factors necessary for estimating the seismic demands on concrete arch dams.

Other researchers have studied the effects of foundation interaction on the seismic response of concrete dams (Mirzabozorg et al., 2003a, 2010a; Noorzad et al., 2007). Ghaemian et al. (2005) studied the effects of foundation shape and mass on the linear seismic response of arch dams using the finite element method including the structure–reservoir interaction. Mirzabozorg et al. (2007) studied the seismic analysis of concrete dams in a 3D space using the smeared crack approach. Wang et al. (2012) investigated the nonlinear seismic behavior of a high arch dam–water–foundation rock system. Hariri-Ardebili and Mirzabozorg (2012) considered the seismic evaluation of concrete arch dams by assuming a massless foundation. They modeled the joints and material nonlinearly and separately. However, not much work has been conducted that considers the effects of massed foundations and the nonlinearities that originate from the contraction/perimetral joints and the mass concrete on the seismic response of arch dams.

Mirzabozorg et al. (2010b) studied the nonlinear seismic response of arch dams considering the massed foundation effect. Berrabah et al. (2012) addressed the effect of the surrounding soil on the linear seismic response of a concrete gravity-arch dam and found that modeling the massed foundation leads to more conservative results. Nevertheless, based on the authors' experience, the conclusions presented in that work are questionable. Hariri-Ardebili and Saouma (2013b) investigated the effects of near-fault vs. far-field ground motions on the linear seismic behavior of a concrete arch dam and found that modeling the massed foundation leads to lower stress levels within the dam body in each case.

Mirzabozorg et al. (2012) considered the linear and nonlinear behaviors of the coupled system of a reservoir–dam–foundation in a 3D space under various conditions of the foundation. They found that a massless foundation overestimates the response of the system. Hariri-Ardebili and Mirzabozorg (2013a) presented a comprehensive study on the seismic behavior of a high arch dam including a massed foundation, the application of infinite elements, and absorbing boundaries on the far-end nodes of the foundation. In that work, the nonlinear behavior was simulated using the proposed smeared crack approach by the first author. It was found that a massed foundation leads to fewer cracks through the dam body. However, joint nonlinearity and compression crushing were not considered in that study.

In the present paper, the effects of a massed foundation on the nonlinear seismic response of an existing arch dam in a 3D space are investigated. The reservoir–structure interaction is taken into account by the finite element method. The nonlinearity originating from the mass concrete is modeled with a co-axial smeared crack approach. The reservoir is assumed to be compressible, and the opening/slipping of the vertical and perimetral contraction joints is included in the analysis. Finally, the viscous condition at the far-end boundary of the foundation is used to model the radiation effect. It is worth mentioning that the main novelty of the present investigation, with respect to previous works by the same authors, is that it takes into account the effects of a massed foundation in addition to both the joint and the material nonlinearity, which have an important impact on the structural response of high slender arch dams. As is known in the field of dam engineering, the common approach to designing new dams or to evaluating existing ones is to assume the massless condition of the foundation rock surrounding the dam due to the conservative results and because of some uncertainties encountered when taking into account the mass effect of the rock. However, having mass effects can lead to lower stress levels, and consequently, lower costs for the required retrofitting works on the dams which are infra-structures with significant impacts on socio-economical aspects. In the present study, it is shown that assuming a massed foundation, which is the real state in nature, leads to more realistic results in a seismic safety evaluation, which is in contrast to the conclusion drawn from the traditional assumption in which foundation flexibility is considered.

2. Foundation interaction and wave propagation

The equations governing P and S wave propagations within the massed foundation rock are

$$\frac{\partial^2 u}{\partial t^2} = V_p^2 \nabla^2 u \tag{1}$$

$$\frac{\partial^2 v}{\partial t^2} = V_s^2 \nabla^2 v \tag{2}$$

$$\frac{\partial^2 w}{\partial t^2} = V_s^2 \nabla^2 w \tag{3}$$

in which, u, v, and w are displacements in the direction of the wave propagation and the other two orthogonal directions, respectively, and V_p and V_s are primary and secondary wave propagation velocities within the rock medium, respectively, derived as