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Hydrodynamic pressures in contraction joints including waterstops on seismic response of high arch dams

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ABSTRACT

In the present paper, the effects of hydrodynamic pressures in contraction joints, on seismic response of arch dams are investigated. For this purpose an algorithm for applying the hydrodynamic pressures in open contraction joints is developed. The dam body material is assumed to have linear elastic behavior and all the contraction joints are simulated as reported in as-built drawings. In addition, the reservoir medium is taken to be compressible and the rock foundation is modeled as a mass-less flexible medium. The coupled system of dam-reservoir-foundation is analyzed utilizing simultaneous approach and NEWMARK-β method is used for integration in time domain. The effects of hydrodynamic pressure during seismic excitation on joints opening/sliding, stress distribution patterns within the dam body and on the crest displacement time history are studied. It is found that for a typical high concrete arch dam, the hydrodynamic pressure in the contraction joints are not affected much by in the present of waterstops. Taking these pressures into account leads to significant consequences on the dam behavior; and it must be considered, as the joint opening in high concrete arch dams is a common phenomenon even during low to medium ground shakings.

1. Introduction

Because of the high socio-economic impacts of the concrete dams, the safety of these infrastructures is of paramount importance.

Among the approaches to assess the operation of a dam during earthquake excitation is to utilize numerical modeling. Arch dams are not constructed as a single monolith. They have discontinuities where the contraction joints are present. These contraction joints that separate cantilevers from each other and also the dam body from its concrete saddle (called as pulvino) act as planes of weakness in dams when they are under tensile or shear stresses.

In linear analysis the dam body is idealized as a one-piece monolith and the material behavior is assumed to be linear. The results from linear analysis usually provide tensile stress outputs that the contraction joints cannot withstand. In practice, the contraction joints open and close cyclically during an earthquake and they release the horizontal tensile stresses and redistribute forces. However, the nonlinear dynamic analysis considers the discontinuities in the body caused by the contraction joints and simulates the joints behavior and their effect on the dam stability and dynamic response.

Some researchers have investigated the contraction joints behavior and their effects on the dynamic analyses of concrete dams. Fenves et al. [1] showed that the developed stresses in maximum credible earthquake are significantly affected by opening of contraction joints. Arbitrary joints opening and closing that may happen during an earthquake result in the release of arch tensile stresses and redistribution of stresses between the arch and cantilever actions. They demonstrated that as the number of joints in the dam body increases, arch stress decreases. They also explained that for obtaining a realistic estimation of stresses and displacements not all the joints necessarily needed to be modeled. Ahmadi and Razavi [2] presented a finite element discrete crack modeling of the dam's peripheral and vertical joints. In their study, only the tensile cracks resulting from persistent static loads were taken into consideration. They also developed a method for calculating the failure load, which enables the safety analysis of the structures. In another study, Ahmadi et al. [3] presented a discrete crack model of joints for nonlinear dynamic analysis of concrete arch dams. The results indicated that under severe earthquakes vertical joints usually experience tensile failure; shear failure or both of them, which ultimately lead to redistribution of internal stresses. A nonlinear finite-element analysis for arch dams, that accounts for the gradual opening and closing of vertical contraction joints and horizontal cold joints was presented by Dowling and Hall [4] & Hall and Dowling [5]. In their study, joints represent planes for cracking, but no

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slippage was allowed. In another research, a numerical analysis for assessing the nonlinear seismic behavior of arch dams was developed as the contraction joints open and close by Fenves et al. [6,7]. They developed a nonlinear three-dimensional joint element that only considered the movements perpendicular to the joint plane. Weber et al. [8] investigated the nonlinear seismic response of concrete arch dams when considering the inter-cantilever contraction joints and the joints between the dam body and the foundation. It was assumed that the shear-keys in the joints are strong enough not to break under the earthquake induced seismic shear force; as a result no sliding would occur in the joints. Fenves et al. [7] made some modifications to the "ADAP-88" software to account for relative sliding movements of the contraction joints. Lau et al. [9] studied the effect of linear and nonlinear analyses on the magnitude of horizontal tensile stresses in arch dams. It was observed that as the result of considering the contractions joints in nonlinear analysis, the tensile stress appearing near the joints in linear analysis is decreased. In this study only three contraction joints out of the dam ten joints were modeled. This is justified by the results obtained from the study conducted by Fenves et al. [7] indicating that simulating the three joint out of the several ones is enough for reaching the maximum tensile stress and as the number of joints increase, the tensile stress changes from arch to cantilever form. Chuhan et al. [10] investigated the non-seismic response of Xiaowan and Tujunga arch dams featuring the contraction joints and reinforcements in them. The model presented by Fenves et al. [7] (ADAP-88) was utilized for simulating the contraction joints. Factors such as the critical size of the elements, the number of contraction joints and the need for using reinforcement in joints were studied. The reservoir was assumed to be incompressible, the joints behavior was linear-elastic and the foundation was mass-less. It was observed that the joint opening is most significant in the middle part of the crest length and the magnitude of this opening is greatly affected by the distance of adjacent contraction joints. It was concluded that modeling all the contraction joints located in the mid part of the crest length is essential to obtain acceptable accuracy in joint opening response, whereas modeling the joints close to the abutments have less significant effect for this case.

Based on the previous studies, seismic excitation of a concrete arch dam leads to joints opening and closing during the earthquake; meanwhile, cracks may also appear within the dam body. Transient opening of these cracks and joints during earthquake allows water to exert hydrodynamic pressure in the joints and cracks. By applying external forces on the walls of the cracks and joints, the hydrodynamic pressure contributes to crack propagation and may jeopardize the global force equilibrium required to keep the structure stable. Assessment of the proper uplift pressure value in cracks to use in the static and dynamic analyses of concrete dams has attracted the attention of many researchers. In a study conducted by Hall [11], ADAP-88 software for smeared crack analysis of arch dam was developed. The transient uplift pressure in the cracks and joints of the dam was taken into account. The hydrodynamic uplift pressure resulting from the interaction between the dam and reservoir was considered to act at the cracks' (joints') openings on the upstream face of the dam. The pressure along the crack band was assumed to vary linearly through the dam cross section. Independence of the water pressure in the cracks from the relative movements of the cracks wall was another assumption made in their research. They observed that the hydrodynamic water pressure in the cracks changed the computed cracking pattern and crack opening and sliding responses. These results manifested a need for further development of a model for seismic water-crack interaction. Slowik and Saouma [12] carried out an experiment to measure the development of water pressure along a crack in a dynamic wedge splitting test. They also developed a numerical model for simulating the results of the experiment. In this theoretical model only the initial crack propagating phase during seismic excitation is considered and the crack opening and closing is not taken into account. On the other hand, this model was not applied for investigating the propagation of cracks under seismic excitation and stability of concrete dams. Javanmardi [13] & Javanmardi et al. [14] investigated the seismic water-crack interaction theoretically and experimentally. Reinhardt et al. [15] concluded that the cracks that open more than 0.03 mm have more permeability than uncracked concrete. For cracks with smaller openings the penetration behavior is similar to that of uncracked concrete.

It's worthy to note that many researchers have investigated the development of hydrodynamic pressures in cracks and its effect on the crack propagation and dam behavior. What seems to have been left out and given much less attention than what it deserved is the effect of hydrodynamic pressure in contraction joints of the dam during seismic excitation.

Contraction joints are present in almost all parts of the dam body and they exist at the interface between the dam body and the concrete saddle. Being prone to opening during earthquake, the joints experience water penetration and the accompanied transient hydrodynamic pressure in them while they are open.

In the present study, seismic behavior of a typical high and thin concrete arch dam considering the nonlinearity due to presence of contraction joints is studied as the hydrodynamic pressure is present in the joints when they open. All of the contraction joints in the dam body between the cantilevers and the joint between the dam body and its concrete saddle are taken into consideration. The assumptions made in this study are as follows:

- Water-stops are installed at the upstream end of the joint so the water flows into the joint if the joint open bigger than the allowable limit.
- The joint is filled immediately with water when the water-stops are broken, no matter how short the opening time is.
- The joint is emptied immediately of water when it closes, no matter how short the opening time is.
- When the joint closes, all the water in it flows out as a result no water gets trapped in the joint, so there is no residual water pressure in the joint after its closure.
- When the joint is closed the closure is complete and no water is allowed in when the joint is closed, consequently there is no water pressure in the closed joint.
- The hydrodynamic pressure distribution in the open joint is uniform as we move through the dam thickness.

2. Numerical model of a typical high arch dam

Dez double curvature arch dam in Iran is selected as the case study. Crest length is 240 m and thickness at the crest level is 4.5 m (Fig. 1). ANSYS commercial software is used for making the finite element model of the dam-reservoir-foundation coupled problem. Finite element model developed for the dam, foundation rock and reservoir is displayed in Fig. 1, which consists of 792 8-node solid elements for modeling the dam body and concrete saddle, 3770 8-node solid elements for simulation of the foundation rock and 3660 8-node Eulerian fluid elements in the reservoir domain. In addition, 956 node-to-node contact elements are used to model vertical and peripheral joints of the dam. Fig. 2 shows the surfaces on which the contact elements are located.

Node-to-node contact element employed for modeling the joints is defined by two nodes attached to the two opposite surfaces, which may maintain or break physical contact and may slide relative to each other (Fig. 3). The element is capable of supporting only compression in the direction normal to the surfaces and shear (Coulomb friction) in the tangential direction and has three degrees of freedom at each node; translations in the nodal x, y, and z directions. K_n is the stiffness of the surfaces in contact acting in the normal direction and K_t represents the tangential stiffness acting in tangential direction when the gap is closed and not sliding. In the provided finite element model, K_n and K_t are taken as 240 GPa/m and 24 GPa/m, respectively. Based on sensitivity