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Nonlinear dynamic response of concrete gravity dams considering the deconvolution process

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ABSTRACT

In order to model any physical system, including concrete dams, one needs to apply simplifications to the real system to make the modeling feasible. To study the dynamic response of concrete dams, relevant assumptions are made regarding foundation modeling, input motion mechanism, dam-reservoir interaction, and material behavior. Some of these simplifications may lead to more conservative and uneconomical outcomes. In this paper, nonlinear time-domain dynamic analyses are conducted to evaluate the effect of the input motion mechanism on the concrete gravity dam response. An ideal model of a dam-reservoir-foundation system, considering the inertia of the foundation, appropriate boundary conditions and precise deconvolved base motions, is selected as the reference model. The process of deconvolution of seismic waves through the frequency- and time-domain approaches is discussed, and suggestions for the selection of an appropriate damping model for the rock foundation are presented. The results are compared to those of the standard model of a massless foundation system as recommended by the US Army Corps of Engineers. The numerical results indicate that, generally, the nonlinear response of the two dam models follow similar patterns, but with a larger amplitude for the massless system. It is noted that the consequence of neglecting the dynamic effect of the foundation can be significant. Additionally, the results demonstrate that the degree of overestimation varies dramatically for the various seismic excitations. The average overestimation of the massless system for the crest displacement, crest acceleration, and the contact opening and sliding are 57%, 45%, 152%, and 90%, respectively. It is further shown that the use of the deconvolved input excitation at the base of the finite foundation derived from the frequency-domain approach can yield discrepancies between the target and convolved surface ground motions, which can also have a considerable effect on the dam response.

1. Introduction

The seismic safety assessment of concrete dams is a very significant issue with great impact on society. The linear and nonlinear behavior of concrete dams have been widely studied by many researchers over the past decades. However, due to the computational cost and complexity of concrete dam modeling, some simplifications and assumptions are usually made to make the numerical modeling more tractable. In the numerical analysis of the dam-foundation-reservoir systems, relevant assumptions are made regarding foundation modeling, input motion mechanism, and material behavior. Each simplification and assumption impose uncertainties on the results.

Concrete gravity dams are usually built on rock foundations. The simplest and most-commonly used approach to model a rock foundation in finite element method (FEM) codes is by means of the massless foundation system shown in Fig. 1a. The main reasons for the use of such an approach are: (1) the reflection of seismic waves at the fixed boundary is eliminated; (2) a deconvolution analysis is not required, and (3) the free-field motion can be applied directly at the base of the rock foundation [1].

In order to properly consider the SSI effect in the seismic safety evaluation and design of dams, the rock foundation needs to be modeled as accurately as possible. Suitable boundary conditions between the finite and infinite foundation domain should be utilized to absorb the outgoing seismic waves (Fig. 1b). For a realistic time history analysis, the input motions need to be applied at the base of the finite rock foundation. Generally, it is considered that the free-field motions are recorded at the ground surface of the rock, and are, commonly, termed "target surface ground motion" or "design surface ground motion". The base motions should then be determined by performing a deconvolution analysis of the target surface ground motion. Frequency- [2] and time-domain [3,4,6] approaches can be used to evaluate the seismic motions at depth. Alternatively, in order to avoid the deconvolution process when the foundation inertia is taken into account, i.e. for a "massed"

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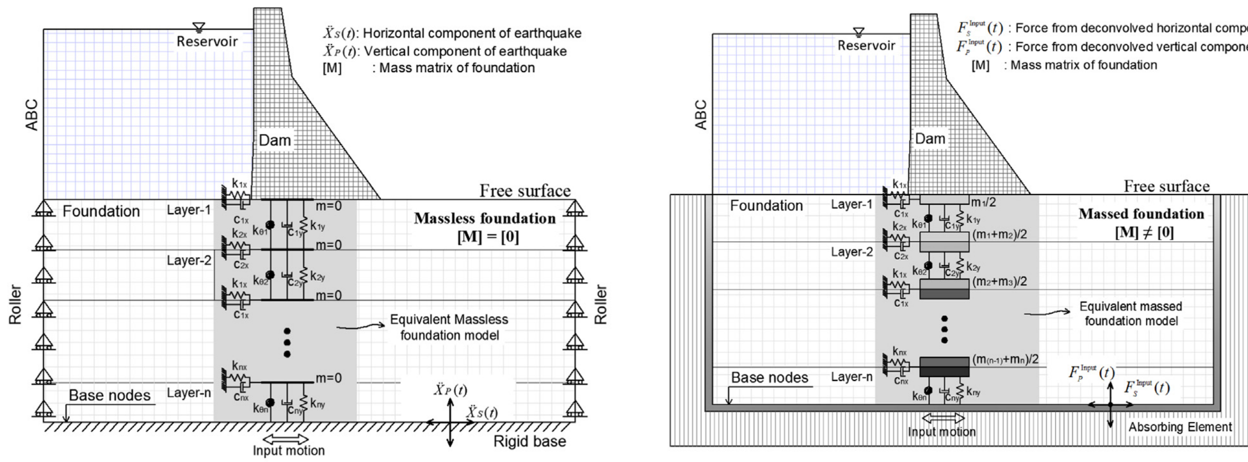

(a) Standard model of dam-reservoir-foundation system (massless foundation system) [27]

(b) Ideal model of dam-reservoir-foundation system (massed foundation system)

Fig. 1. Finite element models of the concrete gravity dam.

foundation system, the recorded free-field earthquake acceleration is specified at the dam-foundation interface [7,8].

For simplicity, the use of the massed foundation system with deconvolved base motion is usually avoided in the dynamic analyses of concrete gravity dams, as illustrated in the references provided in Table 1. Although this massed-foundation model has been used in a few studies ([7,9,10]), the accuracy of the deconvolution process and its effect on the dam response has not been studied adequately. Chopra [10], in a numerical study of the linear dynamic response of a concrete arch dam, showed that the massless foundation system can increase the stress and crest displacement in the dam by a factor of 2–3, and the overestimation increases as the ratio of the elastic moduli of the foundation rock and the dam concrete decreases. Chuhan et al. [11], in their study of an arch dam, reached similar conclusions, and suggested the use of damping values higher than 10% for a massless foundation system.

This paper investigates the effect of the rock foundation domain on the seismic response of concrete gravity dams. A series of nonlinear dynamic analyses are performed on a concrete gravity dam using the FEM. Two models of the rock foundation and the input motion mechanism are considered, i.e., (1) a standard simplified model and (2) an ideal model with deconvolved base excitation. The key features of the deconvolution approaches in the frequency and time domain are illustrated. In addition, some recommendations for the selection of the damping model and its target ratio for the rock foundation are presented.

2. Deconvolution of seismic waves for seismic analysis of concrete dams

Consider a 2-D model of a dam-foundation-reservoir system (Fig. 2), and assume that there is a recorded time series at the ground surface, the so-called “target surface ground motion”, that needs to be deconvolved to the base of the finite rock profile, i.e., the interface between the finite and infinite ground domains in the FEM model. It is assumed that the horizontal ground motion component consists primarily of

Table 1
Foundation modeling.

No	Publication		Foundation model	Location of input motion	Dam type	Deconvolution process
1	Reimer (1973)	[3]	Massed foundation	Base of foundation	Concrete arch dam	Time-domain approach
2	Clough et al. (1985)	[1]	Massless & massed foundation	Base of foundation	Concrete arch dam	Frequency-domain approach (SHAKE)
3	Leger and Boughoufalah (1989)	[7]	Massed foundation	Base of foundation	Concrete gravity dam	Frequency-domain approach (SHAKE)
4	Bayraktar et al. (2005)	[9]	Massed-foundation	Base of foundation (NI)	Concrete gravity dam	Frequency-domain approach (SHAKE)
5	Long et al. (2009)	[12]	Massless foundation	Base of foundation	Concrete gravity dam	No deconvolution process
6	Bayraktar et al. (2009)	[13]	Massless foundation		Concrete gravity dam	No deconvolution process
7	Akköse and Şimşek (2010)	[14]	Massless foundation	Base of foundation (NI)	Concrete gravity dam	No deconvolution process
8	Bayraktar et al. (2010)	[15]	Massless foundation	–	Concrete gravity dam	No deconvolution process
9	Sevim et al. (2011)	[16]	Massless	Base of foundation	Concrete arch dam	No deconvolution process
10	Wang et al. (2012)	[17]	Massless foundation	Base of foundation	Concrete gravity dam	No deconvolution process
11	Seyedpoor et al. (2012)	[18]	Massless foundation	Base of foundation	Concrete arch dam	No deconvolution process
12	Ardebili et al. (2012)	[19]	Massless foundation		Concrete arch dam	No deconvolution process
13	Zhang and Wang (2013)	[20]	Massless foundation	–	Concrete gravity dam	No deconvolution process
14	Pan et al. (2014)	[21]	Massless foundation	Base of foundation	Concrete gravity dam	No deconvolution process
15	Lee et al. (2014)	[22]	Massed foundation	Base of foundation	Concrete gravity dam	No deconvolution process
16	Huang and Zerva (2014)	[8]	Massed foundation	Top of foundation	Concrete gravity dam	No deconvolution process
17	Arici et al. (2014)	[23]	Massless foundation	–	Concrete gravity dam	No deconvolution process
18	Chopra (2014)	[10]	Massless & massed foundation	–	Concrete arch dam	–
19	Wang et al. (2015)	[24]	Massless foundation	Base of foundation	Concrete gravity dam	No deconvolution process
20	Amina et al. (2015)	[25]	Massless & massed	–	Concrete arch dam	No deconvolution process
21	Hariri-Ardebili et al. (2016)	[26]	Massless & massed foundation	Base of foundation	Concrete gravity dam	No deconvolution process
22	Wang et al. (2016)	[27]	Massless foundation	Base of foundation	Concrete gravity dam	No deconvolution process
23	Løkke and Chopra (2017)	[28]	Massed foundation	Base of foundation	Concrete gravity dam	–