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Procedure for selecting and modifying earthquake motions to multiple intensity measures

Richard J. Armstrong

California State University, Sacramento, United States

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ABSTRACT

A new ground motion selection and modification procedure is presented that selects a set of ground motions to capture multiple intensity measure targets. The ground motion selection and modification procedure involves selecting a set of candidate ground motions scaled to a conditioning intensity measure that is subsequently trimmed down using a semi-automated selection process to reach a final set that satisfies statistical considerations. The new procedure is relatively straightforward to implement using common tools and knowledge yet is still based on the principles of conditioning and on aspects of previously-developed selection and modification procedures. A single example is provided to demonstrate the use of these concepts to ground motion development.

1. Introduction

The seismic evaluation of civil infrastructure is critical to the evaluation of the structures' safety and resilience. A key step for many of these seismic evaluations is the development of ground motions to represent the anticipated seismic loading on the structure. As an example, consider ground motion development for a zoned embankment dam underlain by potentially liquefiable alluvium (Fig. 1). To develop ground motions for this structure, the ground motion characteristics or intensity measures that play a key role in the response (e.g., deformations) must be identified. In the identification process, it is often advantageous to select multiple intensity measures to accurately characterize the ground motion that most directly relates to the response of the structure. Once these important intensity measures have been identified, ground motion prediction equations are used to calculate median and standard deviation predictions. The specific value of these intensity measures for design are then determined based on a specified hazard level.

When developing ground motions to capture multiple intensity measures, challenges in practice occur: (1) in quantifying the value of multiple ground motion intensity measure targets at a specified hazard value, and (2) in modifying ground motions to these intensity measure targets. The challenge of quantifying the value of multiple ground motion intensity measure targets, although not routinely done in dam engineering practice, can be addressed by using the principles of conditional probability where the various intensity measures are conditioned based on the value of a specific intensity measure in which the hazard is developed (e.g., Baker [1] and Bradley [2]). Solutions to the second listed challenge have been developed for spectral acceleration – for example, by Kottke and Rathje [3], Jayaram et al. [4], and Wang [5] – and for multiple intensity measures by Bradley [6].

This paper presents a new ground motion selection and modification (GMSM) procedure that is relatively straightforward to implement, is based on the principles of conditional probability, and incorporates aspects of previously developed selection and modification procedures. Although the focus of this paper is on the development of ground motions for embankments and slopes, this work can be applied to other structures by replacing the intensity measures considered in this paper with those more applicable to the structure being analyzed. The paper will begin with a review of the key concepts of conditional probability and the conditioning intensity measure as it pertains to the development of intensity measure targets, followed by a description of the key stages of the ground motion selection and modification procedure. Throughout the paper, a single example of ground motion development is provided to demonstrate the concepts and uses of this procedure.

2. Development of intensity measure targets

Ground motion characteristics or intensity measures that play a key role in the response (e.g., deformations) must be identified. The selection of the appropriate intensity measures depends on

E-mail address: richard.armstrong@csus.edu

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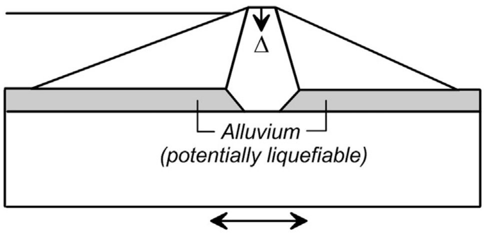

Fig. 1. Structure such as an embankment dam in which ground motions may be developed.

many factors, such as the structure and the analysis method used. Multiple structures could be chosen to demonstrate the use of the ground motion selection and modification procedure, but this paper focuses on ground motion development for slopes or embankment dams, which are structures frequently evaluated by the California Division of Safety of Dams.

Common intensity measures identified as important to slope or embankment deformations ([7–10]) are spectral acceleration (*SA*), peak ground velocity (*PGV*), Arias Intensity (*AI*, [11]), Cumulative Absolute Velocity (*CAV*, [12]), and significant duration between 5% and 95% of Arias Intensity (*D*595, [13]). Arias Intensity and Cumulative Absolute Velocity are similar time-integrated intensity measures (square versus absolute value in integral) with a correlation coefficient of 0.923 (Campbell and Bozorgnia [14]). Historically, the California Division of Safety of Dams has used *AI* as an important intensity measure for ground motion development to analyze embankment dams [15], so this paper focuses on the use of *AI* instead of *CAV*. This leads to *SA*, *PGV*, *AI*, and *D*595 as intensity measures applicable to ground motion development for slopes.

Of these several intensity measures, the one that best describes structure performance – and for which the hazard has been developed – is often called the conditioning intensity measure (see Bradley [2]). Bradley identified the conditioning intensity measure as IM_j, where j functioned as a subscript in common index notation. In this work, the conditioning intensity measure will be identified as IM^*, where the star superscript highlights the importance of this intensity measure. (A list of all variables mentioned in this paper is provided at the end of the paper.) For concrete dams, it has been commonly seen that *SA* at the period of interest T_s is of key importance to the response of the structure, and so $IM^*=SA(T_s)$. For embankment dams founded on liquefiable alluvium, Beaty and Pelea [9] suggested that *AI*, *CAV*, and $\sqrt{AI\bullet D595}$ are promising predictors of embankment deformation; therefore, one of these would be equal to IM^*. Given the use of *AI* by the California Division of Safety of Dams, *AI* will be used as the conditioning intensity measure for embankment dams with the possibility of foundation liquefaction.

The example of the use of the proposed GMSM procedure for ground motion development is for the embankment dam illustrated in Fig. 1. This example problem involves a zoned embankment dam with a predominant period of approximately 0.4 s. Both shells are underlain by potentially liquefiable alluvium. Embankment deformations (e.g., settlement) will likely be driven by liquefaction of the alluvium; thus, the conditioning intensity measure was selected as *AI*, because it relates well with liquefaction. The other intensity measures considered in the ground motion development will be *SA* at $N_p=42$ spectral ordinates between 0.1 and 1.0 s, *PGV*, and *D*595. *AI* is used as the conditioning intensity measure. Spectral accelerations were considered beyond the predominant period of around 0.4 s because of the inherent uncertainty in estimating this value and to account for the potential lengthening of the spectral period of the embankment due to softening of the embankment material and liquefaction in the alluvium below. This leads to $N_{IM}=45$ intensity measures portioned into $\boldsymbol{IM}=\left\{SA(T_1), SA(T_2),\ldots,SA\left(T_{N_p}\right), PGV, D595\right\}$ of size $N_{IM}-1=44$ and $IM^* = AI$.

Each intensity measure is a random variable with a distribution that is typically lognormal and determined from ground motion prediction equations. Using the variable *IM* to denote any of these intensity measures, the predictive equations provide estimates in the form:

$$\ln IM = \mu_{\ln IM} + \varepsilon\sigma_{\ln IM} \tag{1}$$

with $\mu_{\ln IM}$ equal to the mean of $\ln IM$, $\sigma_{\ln IM}$ equal to the standard deviation of the *IM*, and ε as the standard normal random variable with mean equal to 0 and standard deviation equal to 1 (see [1]). Eq. (1) is a function of the earthquake's moment magnitude (M_w), rupture distance (R), style of faulting, and other parameters.

Distributions of the intensity measures for the example embankment dam shown in Fig. 1 were determined for an earthquake scenario typical of many dams in California: strike-slip fault with $M_w=7.5$, $R=5$, shear wave velocity in the upper 30 m, and V_{s30}=600 m/s. The results are shown in Fig. 2a, where the prediction for *SA* and *PGV* are from Campbell and Bozorgnia [16], *AI* is from Campbell and Bozorgnia [14], and *D*595 is from Bommer et al. [13]. Other predictive equations or a combination of several predictive models for a single intensity measure could have been used. Note that for plotting purposes, *SA* was calculated from 0.01 to 4.0 s; however, the GMSM procedure will only be used for N_p ordinates between 0.1 and 1.0 s

The predictive equations of the intensity measures above provide the anticipated distribution. The hazard is defined for the conditioning intensity measure, IM^*, based on results from deterministic or probabilistic seismic hazard analysis that are a certain number of standard deviations from the mean prediction. The specific value of the conditioning intensity measure at the specified hazard level is denoted here as im^*. For the example problem, the value im^* would be defined for a specific value of Arias intensity, ai, from a deterministic or probabilistic seismic hazard analysis. For simplicity in the example problem, the value of Arias intensity will be 1 standard deviation above the mean prediction calculated from Campbell and Bozorgnia [14] and shown in Fig. 2b. This results in a numerical value of $im^*=ai$=3.1 m/s.

According to Baker [1], knowledge of im^* results in a modification of the mean and standard deviation of the other intensity measures. In particular, the mean and standard deviation of the i^{th} intensity measure, IM_i, given or conditioned on IM^* is $\mu_{\ln IM_i|\ln IM^*}$ and $\sigma_{\ln IM_i|\ln IM^*}$, respectively. Values of $\mu_{\ln IM_i|\ln IM^*}$ and $\sigma_{\ln IM_i|\ln IM^*}$ for the i^{th} intensity measure IM_i are determined according to

$$\mu_{\ln IM_i|\ln IM^*} = \mu_{\ln IM_i} + \sigma_{\ln IM_i}\rho_{IM_i,IM^*}\left(\frac{\ln im^* - \mu_{\ln IM^*}}{\sigma_{\ln IM^*}}\right) \tag{2}$$

$$\sigma_{\ln IIM_i|\ln IM^*} = \sigma_{\ln IM_i}\sqrt{1-\rho_{IM_i,IM^*}^{\;2}} \tag{3}$$

where ρ_{IM,IM^*} is the correlation coefficient between the i^{th} intensity measure, IM_i, and IM^*. The value of ρ_{IM_i,IM^*} for many *IM*s has been determined empirically, and a summary is presented in [6].

Based on equations (2) and (3), calculated distributions of the $N_{IM}-1$ intensity measures are shown in Fig. 2b for the example problem conditioned on $IM^*=AI$. Note that for plotting purposes, the *SA* conditioned on $IM^*=AI$ was calculated from 0.01 to 4.0 s; however, the proposed GMSM procedure will only be used for N_p ordinates between 0.1 and 1.0 s. In calculating these distributions, the correlation coefficient between *SA* and *AI* ($\rho_{SA|AI}$) and *PGV* and *AI* ($\rho_{PGV|AI}$) is from Campbell and Bozorgnia [14], and the