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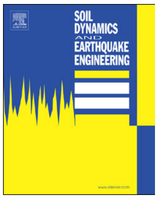

Integrated duration effects on seismic performance of concrete gravity dams using linear and nonlinear evaluation methods

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ABSTRACT

For the assessment of seismic performance of concrete gravity dams, ground motions with horizontal and vertical components are usually selected as seismic excitations. Although various definitions have been proposed to compute strong motion duration from a single component (either horizontal or vertical one) of seismic excitations, duration definitions accounting for the contributions of all components of seismic excitations are still lacking. In order to bridge the gap between duration definitions and multi-component seismic excitations used for simulation, a concept of integrated duration is proposed in this contribution. With the definition of integrated duration, a unified strong motion duration can be calculated for a seismic excitation with multiple components, which facilitates the quantitative evaluation of duration effects. To examine the influence of integrated duration on the seismic performance of concrete gravity dams, both the linear and nonlinear evaluation methods considering the dam-reservoir-foundation interaction are adopted in this study. The linear evaluation method is based on demand capacity ratio, cumulative overstress duration and spatial extent of overstressed regions, whereas the nonlinear seismic analysis of concrete gravity dam-water-foundation systems is on the basis of a Concrete Damaged Plasticity model. 20 real earthquake records with a broad range of durations are selected as seismic excitations to quantify the correlation between the proposed integrated duration and the seismic performance of concrete gravity dams. It is found that the cumulative overstress duration, the accumulative damage and the residual plastic deformation are strongly affected by the integrated duration. Apart from the integrated duration effects, the influence of the vertical component of ground motions is also discussed.

1. Introduction

Dams are critical lifeline infrastructures that serve electricity generation, irrigation, flood control, water supply, recreation and other purposes. In view of the vulnerability of dams to strong earthquakes, seismic performance assessment of high dams is of great significance in dam construction and operation. So far, the knowledge of the dynamic behavior of dams under strong earthquake ground motions is still far from adequate.

Seismic performance of concrete gravity dams can be assessed by linear or nonlinear methods depending on different assumptions on material and loading [1–7]. When a time history analysis is used to evaluate the seismic performance of dams, as-recorded or artificial earthquake ground motions are usually selected as the seismic excitation. As well known, an earthquake ground motion can be characterized by three features, these being amplitude, frequency content and strong motion duration [8]. The importance of frequency content and amplitude in the determination of the damage potential of seismic ground motions has been widely acknowledged. Accordingly, procedures for seismic-resistant design and performance evaluation of structures are typically based on peak parameters of ground motions (e.g. peak ground acceleration (PGA), peak ground velocity and peak ground displacement) and frequency content in major earthquake resistant design codes. In contrast, the influence of strong motion duration has not yet been incorporated in current aseismic design practice.

A seismic accelerogram generally consists of rising, strong motion and decaying phases. Experience from numerous earthquakes showed that a ground motion with a moderate peak and a long strong motion duration may cause severer damage than one with a larger peak but with a shorter duration [9]. Furthermore, numerous studies indicated a possible correlation between strong motion duration and structural seismic responses [10–14]. Thus,

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duration of the strong motion portion of a seismic excitation is also one of the key parameters affecting the seismic performance of structures. Very recently, Zhang et al. [15] conducted investigations related to the effects of strong motion duration on the accumulated damage of concrete gravity dams. Wang et al. [16] discussed the correlation between three definitions of strong motion duration (i.e. significant, bracketed and uniform durations) and damage measures of concrete gravity dams. In these works, a positive correlation between strong motion duration and damage indices of concrete gravity dams was observed. But this finding is only valid for cases where the horizontal component of ground motion records is selected as the seismic excitation.

For seismic response analyzes of structures, one component (i.e. one horizontal excitation) or two components (i.e. one horizontal component together with the vertical component) of ground motions are usually selected as the seismic input for two dimensional problems. However, the available duration definitions [17–19] can only calculate strong motion duration based on one component of ground motions, either horizontal seismic excitation or vertical one. To bridge the gap between duration definitions and multi-component seismic excitations used for simulation, we propose a concept of integrated duration in this study to account for the duration contributions of all components of a seismic input. The proposed definition of integrated duration is on the basis of the concept of significant duration [20], considering that the significant duration can reasonably represent the duration of the most significant ground shaking through a relative criterion.

With the concept of integrated duration, we first investigate the influence of integrated duration on the seismic performance of Koyna gravity dam-reservoir-foundation system using the linear performance evaluation method presented in Ref. [1], which is based on demand capacity ratio (DCR), cumulative overstress duration and spatial extent of overstressed regions. Later, a nonlinear dynamic analysis is also carried out by using the concrete damage plasticity (CDP) model [21,22]. With the linear and nonlinear analyzes results, the effects of integrated duration on the linear cumulative overstress duration as well as the nonlinear dynamic response and cracking pattern of concrete gravity dams are discussed. In order to further quantify the effects of integrated duration, correlations between the integrated duration and the seismic performance (cumulative overstress duration, accumulated damage and damage dissipation energy) are studied based on 20 real earthquake records with a broad range of durations. Besides, we also investigate the influence of the vertical acceleration on the seismic performance of concrete gravity dams.

2. Integrated duration definition

Various definitions for strong motion duration have been proposed to characterize the strong motion phase of earthquake ground shakings [23–26]. For a comprehensive review of more than 30 different strong motion duration definitions, the interested reader is referred to [9] . Among these widely differing definitions, there is no clear consensus as to which definition should be preferred. This probably reflects the fact that different definitions of strong motion duration may be more or less suitable for different applications. In general, the available definitions of strong motion duration can be classified into four categories: (a) bracketed duration [27,28], (b) uniform duration [26], (c) effective duration [9], (d) significant duration [20]. Note that all the aforementioned definitions of strong motion duration can only compute the duration of each component of a seismic input. That is to say, if both the horizontal and vertical components of an earthquake record are selected as the seismic excitation, the aforementioned duration definitions could give two durations (horizontal and vertical ones) for the selected record. Apparently, the presence of two individual durations for a multi-component seismic input brings about inconvenience for the quantitative evaluation of duration effects. In order to obtain a unified duration from a multi-component seismic input, we introduce in this section the concept of integrated duration, which takes into account the duration contributions of all components of an earthquake record.

In this study, significant duration [20], defined as the time interval between two given percentages of Arias intensity [29], is selected to obtain the strong motion duration of a single component of ground motions. Such a choice is based on the consideration that the significant duration reasonably represents the duration of the most significant shaking through a relative criterion. This favorable feature enables the significant duration to be one of the most frequently used definitions by seismologists and earthquake engineers.

As well known, the destructiveness of a ground motion can be characterized by several intensity parameters. The Arias intensity I_0 is an energy-related seismic index reflecting the total energy content of a ground motion, which is defined by [29]

$$I_0 = \frac{\pi}{2g}\int_0^{T_0} a^2(t)\mathrm{d}t \tag{1}$$

where T_0 is the total duration of the earthquake accelerogram, a is the acceleration of the ground motion, and g is the gravitational acceleration.

According to the significant duration definition, the Husid diagram [30] is used in this study. The Husid diagram is defined to be the time history of the seismic energy content scaled to the total energy content, given by the following relation

$$H(t) = \frac{\frac{\pi}{2g}\int_0^t a^2(t)\mathrm{d}t}{I_0} \tag{2}$$

where $H(t)$ is the Husid diagram given as a function of time t.

There are two definitions of significant duration $T_{90\%}$ [20] and $T_{70\%}$ [31] which are based on different lengths of interval between two moments of the Arias intensity. In this work, the significant duration $T_{70\%}$ (15%–85%) [31], defined as the time interval between 15% and 85% of the Arias intensity, is selected to measure the durations of ground motions:

$$T_{70\%} = T_2 - T_1 \tag{3}$$

with T_1 and T_2 the time instances when 15% and 85% of the Husid diagram are reached, respectively. This choice is made because the significant duration $T_{70\%}$ (15%–85%) shows a slightly higher correlation with the damage measure than the significant duration $T_{90\%}$ does [32]. It should be noticed that the significant duration $T_{70\%}$ can also be defined as the time interval between 5% and 75% of the Arias intensity [20]. Regarding the two definitions of the significant duration $T_{70\%}$, there is no study showing which one is better.

When seismic performance of structures is evaluated, two components (i.e., both the horizontal and vertical components) of ground motions are usually selected as the seismic excitation for two-dimensional problems. However, from Eq. (2), a unified duration for both the horizontal and vertical seismic excitations cannot be obtained. To overcome this shortcoming, an integrated Husid diagram $H^{\mathrm{I}}(t)$ considering two components of ground motions is presented as follows:

$$H^{\mathrm{I}}(t) = \frac{\frac{\pi}{2g}\int_0^t {a_1}^2(t)\mathrm{d}t + \frac{\pi}{2g}\int_0^t {a_2}^2(t)\mathrm{d}t}{I_{01}+I_{02}} \tag{4}$$

where I_{01} and I_{02} are the Arias intensities of horizontal and vertical components, respectively; a_1 and a_2 are the ground accelerations of horizontal and vertical seismic excitations, respectively; After introducing the integrated Husid diagram $H^{\mathrm{I}}(t)$, an integrated