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Earthquake damage estimation of concrete gravity dams using linear analysis and empirical failure criteria

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ABSTRACT

A new methodology is proposed to estimate earthquake damage of gravity dams. In this methodology the static pushover analysis is used to formulate a systematic and rational procedure to estimate the level of damage from the linear seismic analysis results. The tensile cracking of concrete is considered as the main potential damage. Examples of three existing concrete gravity dams are provided to illustrate the methodology and discuss the probable nonlinear response and failure mechanisms. The damage state of the dams under twelve proper earthquake ground motions scaled to increasing intensity levels is estimated using the new proposed criteria and verified using the actual nonlinear time-history analysis. Finally, a damage index is defined to quantitatively predict the earthquake damage of gravity dams.

1. Introduction

Gravity dams are massive concrete hydraulic structures which retain the impounded water relying on their large weight. They are used for flood control, water supply, or electricity generation. The extreme loading combination of gravity dams includes earthquake loading. Various design codes have proposed their own criteria for seismic analysis and design of gravity dams [1–4]. These codes simply utilize a deterministic binary approach (safe/not-safe) to determine the structural state of gravity dams after an earthquake. However, in recent years the approach of performance-based earthquake engineering (PBEE) has been applied in the field of gravity dams. In this approach, the results of actual time-history analysis should be quantitatively interpreted [5].

Seismic analysis of gravity dams is usually started with simplified methods, such as "seismic coefficient method". In this method, the earthquake loading is treated as a lateral force statically applied to the dam structure. The seismic loading is of two types: (a) the inertial force due to the horizontal acceleration of the dam, and (b) the hydrodynamic force resulted from the reaction of the reservoir water against the dam [1]. The simplified methods are not accurate, so they are not used in final design stages; instead, more rigorous and refined methods such as the finite element (FE) or the boundary element (BE) methods are utilized, however, these methods are time-consuming.

As the tensile strength of the mass concrete is less than 10% of its compressive strength, the damage in concrete gravity dams is mainly due to high tensile stresses [6]. During strong ground shaking, the combined static and dynamic tensile stresses usually exceed the tensile strength of the mass concrete. Pacific Earthquake Engineering Research (PEER) center proposes "damage analysis" as one of the main steps in the PBEE approach [7]. The damage will result in loss of stiffness, and change the structural behavior. It can be described qualitatively using damage state, DS, or quantitatively using damage index, DI. Various DIs have been proposed with different applications for framed structures [8–12], but limited studies have tackled to this issue for gravity dams [6,12–16].

Distinct nonlinear constitutive models have been introduced for the mass concrete; the inelastic behavior of concrete dams has been correspondingly investigated using these models [17–30]. The nonlinear analysis of gravity dams demands much more computational cost and time with respect to the linear analysis. In addition, different nonlinear approaches may result in considerably different responses even for the same input modeling parameters. Therefore, in practice, especially in primary design stages, the dynamic response of gravity dams is calculated assuming the linear elastic behavior, and the results of the linear analysis in combination with the engineering judgment are used for the decision making about the structural state of the dam [31,32]. The main question now is that how the results of a linear dynamic analysis can be used to predict the inelastic behavior or damage state of the dam. Seeking this goal, the first methodology,

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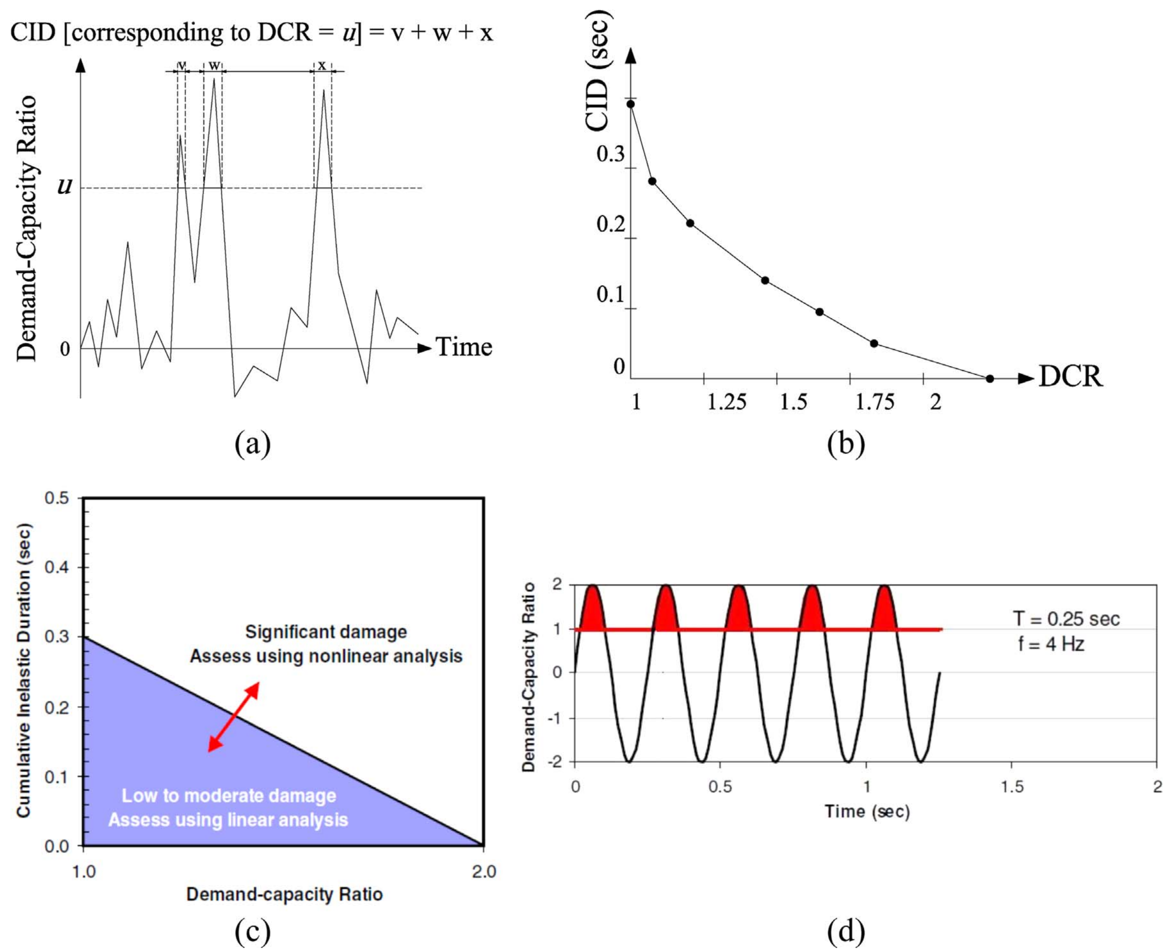

Fig. 1. (a) illustrative example of an actual DCR plot for an element during the time-history analysis along with the calculation of the CID corresponding to specific DCR value (DCR$=u$); (b) illustrative example of an actual CID-DCR response curve for an element; (c) the performance curve proposed for the gravity dams; (c) determination of the CID values for the performance curve [31,33].

which is called “failure modes approach”, was introduced by Ghanaat [33] and adopted afterwards in the USACE guidelines [31]. This methodology will be explained in the next section.

1.1. Failure modes approach (FMA) method

The failure modes approach (FMA) method contains simple criteria for the seismic damage evaluation of concrete dams from the results of the linear seismic analysis. These criteria for 2D gravity dam monoliths employ three main parameters: (1) the demand-capacity ratio DCR, (2) the cumulative inelastic duration CID, and (3) the overstressed area ratio OAR [31]. The DCR for each element of the finite element idealization of the dam is obtained by dividing the time-history of the maximum principal (tensile) stress in that element demanded in an earthquake, to the tensile strength of the mass concrete. Such plot is observed in Fig. 1(a). The CID, corresponding to a specific DCR value, is calculated by adding the durations of principal stress excursions above that DCR value during the time-history analysis (Fig. 1(a)). The CID can be plotted against the DCR for each element. This plot which is called the CID-DCR “response curve” for that element is illustratively shown in Fig. 1(b). Using the envelope contour of the maximum principal stress, the OAR is calculated as the ratio of the tensile overstressed areas to the total area of the 2D dam monolith. Based on the above parameters, three “performance levels” are defined [31,33]:

a. Minor or no damage: if DCR ≤ 1 for all elements during the time-history analysis.
b. Acceptable level of damage: if DCR < 2, OAR $< 15\%$, and the actual CID-DCR response curves fall below the “performance curve” shown as straight line in Fig. 1(c). In this situation, the level of damage is low to moderate; there is no possibility of failure, and the linear analysis of the dam structure is sufficient.
c. Severe damage: if DCR > 2 or the actual CID-DCR response curves fall above the “performance curve”. Therefore, the nonlinear time-history analysis may be required.

The essential advantage of the FMA method is its simplicity. Using these criteria, one can simply decide about the structural state of the dam from the linear analysis results. But there are some ambiguities, for example, how much is the number of elements having $1 <$ DCR < 2 for the acceptable level of damage, and how is their spatial distribution. This number is clearly dependent on the mesh size. In the FMA method, each element has its own response curve, but if more global response parameter such as the crest displacement is utilized, then there is only one response curve for the entire dam body. There is no rational basis for the 15% acceptance ratio of the OAR. The allowable CID values of the straight-line performance curve given in Fig. 1(c) are calculated using the five-harmonic-cycle response history with the amplitude of DCR$=2$ and the oscillation period of 0.25 s (Fig. 1(d)). These parameters, i.e. the number of harmonic cycles and their amplitude and oscillation period, have to be studied. Also, the magnitude of the response excursion in the response history is