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Application of the endurance time method to the seismic analysis and evaluation of highway bridges considering pounding effects

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ABSTRACT

Seismic-induced pounding between adjacent segments is a complex contact phenomenon in which the dynamic responses of structures, including pounding effects, are strongly related to structural properties and earthquake excitations. This paper explores the effectiveness and accuracy of the endurance time method for predicting the pounding responses of highway bridges with a reduced simulation effort. A three-span highway bridge was selected as the target structure, and the incremental dynamic analysis results were employed as a basis of comparison for the structure under 22 earthquake records. Based on the observations of the validation, the pounding effects analyses were carried out using the ET method. Finally, the analysis results were transferred into a common spectral form to estimate the pounding force and the other pounding responses. The investigation results indicate that the ET method is sufficiently accurate to be implemented for the seismic analysis and evaluation of highway bridges, with the inclusion of pounding effects.

1. Introduction

The seismic-induced pounding of highway bridges, which occurs over an extremely short time, is a complex physical and mechanical phenomenon that includes contact, friction, and the propagation of stress waves [1,2]. In the past decade, bridge damage due to pounding has been widely observed in serious and moderate earthquakes events [3–5]. To mitigate the pounding-induced damage of highway bridges [6], appropriate approaches for predicting pounding responses must be developed beforehand. To date, several impact models based on contact elements have been proposed by researchers to model the pounding phenomenon, including a linear spring model [7], Kelvin model [8], Hertz model [9], Hertz-damp model [10], nonlinear viscoelastic model [11] and phenomenon-based impact model [1].

Based on those pounding models, many researchers have conducted seismic response analyses of highway bridges under earthquake excitations. For example, Ruangrassamee and Kawashima [12] developed a relative displacement response spectra of highway bridges with pounding effects. From the results of an analysis of a two-span highway bridge, it was found that pounding increased the relative displacement between the adjacent structures. Kim and Shinozuka [13] indicated that seismic-induced pounding significantly amplified acceleration and velocity responses, but the ductility demand of the bridge piers was seldom affected by the pounding. Won et al. [14] conducted a time history analysis of a three-span simply supported steel girder bridge with pounding effects. However, it was found that pounding between the adjacent vibration units reduced the pier forces and displacements. From an experimental investigation of a system consisting of a single span and abutments, Li et al. [15] found that the seismic-induced response of the bridge structure relied on the soil conditions, the spatial variation of the ground motions, and the contact stiffness of the abutments. In addition to straight bridges, the seismic responses of skewed bridges with deck-abutment rotational pounding has also been investigated by some researchers [16].

From those results of the pounding analyses of highway bridges in the open literature, it is difficult to obtain a common regulation related to the influence of seismic-induced pounding on the dynamic responses of bridge structures due to the complexity of nonlinear contact during instantaneous pounding. Furthermore, the uncertainty of earthquake excitations and soil-structure interaction (SSI) also significantly affect the pounding responses of the bridges [17,18]. Therefore, case-to-case time history analyses using batches of earthquake records have been the primary approach to this type of problem until now. In fact, incremental dynamic analysis (IDA), which uses several earthquake records and continuously

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increasing intensities [19] for the ground motion inputs, is an appropriate method for analyzing pounding and understanding the effects of pounding on highway bridges. However, the disadvantage of IDA method is its heavy computational burden for time-history analyses of structures and probability analyses of simulation results.

The endurance time (ET) method is an alternate method based on a time-history dynamic procedure for the seismic analysis and design of civil infrastructures [20,21]. The ET method uses artificial accelerograms with continuously increasing amplitudes over time. It has been applied in different areas of seismic engineering such as the quantification of the failure modes of concrete gravity dams [22], the seismic assessment of steel liquid storage tanks [23], estimating the progressive failure sequences of the elements in multistory steel concentrically braced frames [24], and predicting the dynamic response of steel frames [25]. By applying an intensifying accelerogram, many of the structural issues can be readily solved with acceptable precision by the ET method, while significantly reducing the computational demand. However, in the open literature, the ET method has seldom been employed for pounding analyses of highway bridge under earthquake excitations.

This paper explores the possibility of using the ET method to achieve a fast and accuracy analysis of the pounding responses of highway bridges. The contributions of this study include the following. (1) The effectiveness and accuracy of the ET method for predicting the pounding responses were validated using the results of the IDA of a simply supported bridge. (2) The seismic-induced pounding effects on this bridge were analyzed using the ET method. (3) The ET analysis was transferred to a spectral form so that this method can be more easily employed to the estimation of pounding forces and other pounding responses by engineers. The main contents of this paper are organized into four parts. First, the ET and IDA methods' concepts are briefly introduced. The bridge information and the finite element model of the prototype structure are then given. Then, the endurance time accelerograms and earthquake records used for the ET and IDA analyses are presented, respectively. Based on the IDA of this bridge, with 22 earthquake records, the effectiveness and accuracy of the ET method, the pounding effect analysis and pounding force estimation method are finally analyzed and discussed.

2. Brief introduction of ET and IDA methods

In this study, the analysis results of the IDA were selected as a basis of comparison for the validation of the effectiveness and accuracy of the ET method for predicting the pounding responses of highway bridges under seismic excitations. Therefore, the concepts of the ET and IDA methods are now briefly introduced.

2.1. ET method

The basic concept of the ET method is the analysis of the dynamic responses of structures by applying artificial accelerograms in which the amplitude is continuously increased with time as the ground motion. If a finite element model of the structure is built, the endurance time analysis (ETA) of the structure is similar to a traditional time-history analysis. Compared to the high computation burden of IDA, this method is advantageously capable of determining the increased dynamic performance of structures using a few pre-designed intensifying accelerograms. Previous studies have indicated that an ETA using a few ET accelerograms can capture the seismic performance of structures [21,23–25]. This greatly improved the efficiency of the structural dynamic analysis.

However, the pitfall of the ET method is that the pre-designed accelerograms are not real earthquake records. For the ET method, the performance of the structures is judged based on the time interval when the damage of the structure exceeds the limit state. The ET method has three major issues that should be addressed: (1) generating appropriate intensifying accelerograms; (2) establishing a finite element model of the structure; and (3) appropriately interpreting the analysis results.

2.2. IDA method

Similar to the ET method, IDA is also based on time-history analysis to investigate the seismic performance of the structures. However, this method uses a batch of real earthquake records to consider the uncertainty of the ground motion. Furthermore, each earthquake record is scaled to different intensity levels according to specific principals. From a suite of nonlinear dynamic analyses of the structure under different earthquake records and various intensity levels, structural responses ranging from elastic to global dynamic instability stage responses are observed. From a statistical analysis of the simulation results of the seismic responses, the relationship between the engineering demand parameter (EDP) and the seismic intensity measure (IM) can be established in the form of IDA curves to understand the evolution process of the seismic damage to structures under earthquake excitation [26]. Although IDA is a high-precision computational procedure for estimating seismic demand and seismic capacity corresponding to different limit states, it should be noted that the IDA method has an inevitable shortcoming because the large number of nonlinear dynamic analyses of a structure is time-consuming, especially for complicated structures [27].

3. Bridge structure and finite element model

3.1. Bridge information

To validate the effectiveness of the ET method for pounding analyses, a simply supported reinforced concrete bridge was adopted for the numerical simulation of this study [28]. As shown in Fig. 1, the three-span bridge had a total length of 48 m and a width of 15 m, with spans of 12, 24 and 12 m. The superstructure of the bridge was comprised of decks and eight type-I girders. Each bridge bent was comprised of three circular columns supported by reinforced concrete (RC) footing and piles, as shown in Fig. 1(b). The clearance height of the column was 4.6 m, and the diameter was 0.9 m, with a concrete cover thickness of 50 mm. Each column had 12 #28 longitudinal steel bars and a circular stirrup with a volume percentage of 0.5%. As depicted in Fig. 1(a), fixed bearings and expansion bearings were installed alternately along the longitudinal direction of the bridge. The gap sizes of the A and D expansion joints (between the deck and the abutment) and B and C expansion joints (between the neighboring decks) were set to 20 mm and 36 mm, respectively.

3.2. Finite element model

A finite element model of the bridge, which is shown in Fig. 1(c), was built using the OpenSees software package to perform the dynamic analysis [29]. In that model, a nonlinear beam-column fiber element was adopted to model the nonlinear behavior of the columns. The Concrete01 material model, which was developed based on the uniaxial Kent-Scott-Park model, was used for the concrete of the columns, with compressive strengths of 27.6 and 29.1 MPa and associated strains of 0.002 and 2.018×10^3 for the unconfined and confined concrete, respectively [30]. The reinforcing steel was modeled with uniaxial bilinear steel material of Steel01. The yield strength, elastic modulus and strain-hardening

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