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Seismic source effects on the vulnerability of an irregular isolated bridge

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ABSTRACT

The first isolated bridge built in Mexico is part of an important highway that connects central cities of the country to the Pacific Coast. The bridge is located in a geographic zone affected mainly by two types of earthquakes: subduction and deeper inslab seismic sources. The seismic vulnerability studies are frequently conducted by mixing a family of real earthquakes from several seismic sources. Normally, the selection of the seismic records is based on the relative location of the structures to the seismic faults without any distinction among the source type. In this paper, it is analyzed the influence of two earthquake sources with different fault characteristics to assess the seismic vulnerability of an important isolated bridge. The structure demands were determined by using several strong motion movements recorded close to the bridge combined with the results of a probabilistic seismic hazard analysis at the site location. Numerical models were developed to assess the demand and capacity of the structure. The capacity of the piers and cylinders were determined based on their geometrical characteristics and the reinforcing bars of the elements with the use of analytical moment–curvature relationships. Results showed that the effect of the fault type on the seismic vulnerability of the bridge was significant, in spite of the similar pseudo-acceleration response spectra shape of the subduction and deeper inslab seismic records. The expected damage for an equal seismic intensity can be substantially different if the bridge is subjected to accelerograms of one or the other seismic source.

1. Introduction

Evaluating different states of potential damage in relevant bridges for several seismic scenarios is an important issue for rehabilitation decisions and for emergency measures planning. Fragility curves are a valuable tool to assess different damage levels as function of several seismic intensities. These curves relate the probability of reaching or exceeding certain state of damage, as function of a ground motion intensity parameter for a specific structure or group of structures.

Among the existent vulnerability methodologies dedicated to bridge structures, it can be mentioned the studies developed by several authors [1–5]. There are some studies considering just a few random variables in demand and capacity, and others using probability density functions to describe most of the variables involved. Some of these methods have also been proposed to evaluate the expected behavior of retrofitted bridges or bridge elements [6–8].

The bridge capacity is typically assessed by using nonlinear static methods or nonlinear dynamic analysis. When incremental non-linear static procedure is performed, the load pattern is mostly selected according to the first mode shape of the bridge or with a combination of the most important modes. In other cases, more than one load pattern is recommended to conduct the push-over analysis. However, most of the studies make use of load shape patterns that could not be appropriate for irregular isolated bridges [9]. On the other side, more refined models, as nonlinear dynamic approaches, use step by step numerical solutions for assessing the capacity with the computer time-consuming inconvenience.

Despite the large number of studies related to bridge vulnerability assessment, just a few consider more than a single parameter to characterize the expected bridge damages. A more rational analysis can be conducted using damage indices, that involve bridge displacement and energy dissipation demands to assess fragility curves.

Many bridges in the world are located in zones where the seismic hazard is essentially governed by one or two seismic sources. When the potential damage of these sources is significant, it is important to quantify the effect of each one on the bridge seismic vulnerability. Nevertheless, the effect of the fault characteristics have not been assessed in the vulnerability studies reported on the literature. In the Pacific Coast of Mexico, the subduction process of the Cocos and Rivera plates beneath the North American Plate produces intraplate and deeper inslab earthquakes, that have damaged bridges in various sites of the country.

It is well recognized that subduction and deeper inslab earthquakes have independent spatial and temporal occurrence process, and the wave propagation is also different [10]. However, seismic

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records from both faults have been indistinctly used for the seismic assessment of structures. Because of the great importance of the two earthquake sources, this paper determines the seismic source influence on the vulnerability assessment of an important isolated bridge, by analyzing the bridge demands of the structure, subjected to a group of subduction seismic records and a suite of deeper inslab seismic records separately.

2. Earthquake hazard assessment

2.1. Seismic sources

The seismic hazard assessment was conducted identifying initially the more important sources in the country. The central part of Mexico is mainly affected by subduction, deeper inslab and, with minor contribution, local seismic sources. The expected maximum magnitude was determined for each of the faults. The subduction source (from the State of Chiapas to the State of Jalisco) is divided in several sub-zones which can produce earthquakes of magnitudes greater than 8.0 [11]. These earthquakes normally occur at 15–45 km depths. Deeper inslab earthquakes take place inside the continent at depths larger than 50 km, and local sources are related to the Trans-Mexican Volcanic Belt. Based on existing data, an expected maximum magnitude of 8.1 and 7.0 for the deeper inslab and local sources respectively, was assumed [11–13].

2.2. Magnitude distribution

The annual magnitude exceedance rate $\lambda(m)$ is defined for magnitudes in the range of m_0 and m_u. It was considered as a relevant minimum magnitude m_0 = 4.5 and m_u was the maximum expected magnitude at a fault. λ_0 is the m_0 exceedance rate and β is the slope of the initial part of the curve. The magnitude exceedance rate is defined as,

$$\lambda(m) = \lambda_0 \frac{e^{-\beta m} - e^{-\beta m_u}}{e^{-\beta m_0} - e^{-\beta m_u}} \tag{1}$$

The parameters λ_0, m_0, and β, defined for each subzone of the seismic sources, were determined using Mexico earthquake catalogs and other studies [14,15]. Hence, the magnitude probability density function $f_M(m)$, is,

$$f_M(m) = \frac{\beta e^{-\beta m}}{e^{-\beta m_0} - e^{-\beta m_u}} \tag{2}$$

2.3. Earthquake occurrence models

The analysis of the seismicity data in Mexico shows that strong earthquakes tend to occur nearly periodically, invalidating the common assumption of Poisson process [16]. In contrast, other earthquakes arriving from several independent sources can be modeled as a Poisson process; then, two models of the occurrence process were adopted namely: Poisson and characteristic earthquake processes. Deeper inslab events, local seismic sources and subduction earthquakes with a maximum magnitude of 7.0 were modeled as a Poisson process. On the other hand, the characteristic earthquakes (subduction earthquakes with magnitude larger than 7.0) were assumed to be lognormally distributed. This function was adopted based on a previous study, where several probability density functions were analyzed to better describe the distribution of inter-occurrence times in subduction zones [16]. The parameters of the time density function (m_T = 40.7 and $\sigma_{\ln T}$ = 0.40) were assessed, using historical data of the region, with the maximum likelihood method [15].

The characteristic earthquake model, also assumes that the probability of a large characteristic earthquake is dependent upon the time since the occurrence of the previous characteristic earthquake. Using the catalog earthquake subduction data in Mexico and performing a regression analysis of the magnitude vs. characteristic interoccurrence times, the following equation is obtained,

$$E(m|t) = \max(7.5, 4.71 + 0.757 \ln t) \tag{3}$$

where t is the elapsed time since the last characteristic event.

2.4. Attenuation laws

Empirical attenuation relationships were adopted for each of the seismic sources. For local earthquakes the Abrahamson proposal was used [17], the deeper inslab source mechanism was specifically studied for Mexican faults [10] and the use of seismic catalogs allow proposing an attenuation law for the subduction zone [15].

The attenuation law for deeper inslab earthquakes was determined with a data set of 16 earthquakes recorded in Mexico [10]. After conducting a regression analysis and using the maximum likelihood method the PGA was assessed by Eq. (5).

$$\log \mathrm{PGA} = -0.2 + 0.59M_w - 0.0039R - \log R + 0.008H \tag{4}$$

where M_w is the moment magnitude, R is the closest distance to the fault surface and H is the focal depth.

Considering seismic catalogs of the subduction earthquakes in Mexico and with the analysis of more than 1000 seismic records, an empirical equation for the attenuation law of this source was determined (Eq. (5)). The proposed equation is valid for distances between 70 km and 300 km.

$$\log \mathrm{PGA} = 0.444M_s - 2.454 \log R + 4.06 \tag{5}$$

where M_s is the surface wave magnitude and R is the closest distance to the fault.

2.5. Seismic hazard assessment

The seismic hazard assessment included all the seismic sources contributing to the site location, namely: local faults, deeper inslab faults and subduction faults. These seismic sources were discretized in several subzones, aimed at properly evaluating the distance between epicenter and the bridge place during the seismic hazard process. As an example of this division, the subduction and the inslab sources are presented in Fig. 1. In the left map, the star symbol shows the bridge location.

The seismic hazard at the bridge location was calculated by determining the annual acceleration exceedance rate (Eq. (6)), for all the discretized zones (j) of the analyses.

$$v(A) = \sum_j v_j(A) \tag{6}$$

where

$$v_j(A) = \sum_k W_{jk} P(A_0 > A) \tag{7}$$

W_{jk} is a weighting parameter to consider the size of each j element in the source k. This parameter was evaluated as $W_{jk} = A_j/\sum A_j$, where A_j is the subzone area j of the source k. Finally, the probability that A_0 exceeds A can be quantified by using the theorem of total probability as,

$$P(A_0 > A) = \prod_i^m \int_i f_i d_i \tag{8}$$

where A is the peak ground acceleration, f_i are the probability density functions of all the random variables used in the analysis (e.g. acceleration, magnitude, time between earthquake occurrences,