Comparison of the seismic fragility of common Mexican simple-supported highway bridges

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SUMMARY:
Fragility curves and damage probability matrices of common Mexican highway bridges are presented in this work, defined by a simulation process. To do that, different typologies of bridges, located at the most seismic hazardous zone of México were selected. For these structures, dynamic characteristics were defined by experimental procedures, which results were used to calibrate mathematical models. Uncertain of mechanical properties of materials were considered. Also, seismic hazard at the bridge location area was defined using artificial records for various scenarios. No linear responses were defined, in form of local and global damage indices. Changes in fragility curves were evaluated when some damage levels are presented in bridge piers. Results show the differences of damage probability in various types of bridges.

Keywords: Bridges vulnerability, fragility curves, seismic analysis

1. ANTECEDENTS

Bridges are structures with long functional life, so seismic vulnerability evaluations should be periodically applied to define adequate inspection, maintenance and rehabilitation procedures. There are different methodologies to evaluate the seismic vulnerability of structural systems, one of them is through the estimation of damage probability matrices or fragility curves. These evaluation tools are normally applied to diverse structural configurations, structural typologies, and in different structural life moments, to reflect real conditions. With these evaluations, structures could be classified in order to differentiate their fragility to external action. Fragility curves can also be used to define some actions in structure analysis, modifications of design codes or as tools of decision in replacement programs.

In general, fragility curves are graphic expressions of the ratio between damage and its probability of occurrence, for each type of external action. Diverse researches define fragility curves for bridges subjected to various external actions. For example, seismic fragility curves for all types of bridges in the coterminous of United States were defined by the ATC-25 (1997) based on expert opinion. Other curves for bridges in China (Shinozuka, 1998) were proposed starting from a statistical damage data. Recently, Jara *et al*. (2009) proposed some fragility curves for specific bridges at Michoacán State in México, evaluating possible damage conditions by means of rotational values in the extreme of piers. These last curves were defined with a deterministic procedure, so the uncertainty of external loads and structure parameters need to be considered. Other examples of evaluations of fragility curves are the works of Colombi *et al*. (2008), Karim and Yamazaki (2007), Nasserasadi and Ghafory (2009), Nielson and DesRoches (2007), Padgett and DesRoches (2008) and Shinozuka (2003).

2. BRIDGE MODELS

To define fragility curves, three types of highway bridges typologies in México were selected. The studied bridges are:

a) *Motín de Oro Bridge.* This is a continuous box unicellular girder with single bend and circular section piers. This bridge has three-single RC piers of different length, between 4.11 m y 4.46 m, as it is shown in figure 1. Also, the bridge has a total length of 109.85 m, divided in four spans. The pretressed girder has a 10 m transversal and a 1.8 m vertical dimension. Bridge is classified as irregular due to the variation of piers and girder lengths. The bridge had been repair in 1994 using external and longitudinal pretressed cables, as figure 1 shows, but the fragility curves were evaluate with the original conditions.
b) *Second Bridge.* This bridge has a simple-supported deck with AASTHO girders and multiple-bent circular piers. The girders are simple-supported over bearings, placed above two transversal girders with a length of 9.9 m. The total length of the bridge is 102.4 m, divided in five spans of 20.5 m each one, as it is presented in figure 2 The substructure has four bents, with six piers by bent with a height of 5 m, a diameter of 1.2 m and 2.32 m of transversal dimension between elements.
c) *Despeñadero Bridge.* This is a simple supported bridge, with three spans of 22.56 m, 26.1 and 25.9 m, with a total length of 77.56 m (see figure 3). The superstructure consists of a concrete slab of 11.86 m cross section, supported over six AASTHO IV girders. Girders are sustained in neoprene bearings of 20 x 40 cm, with a height of 4.1 cm for fixed bearings and 5.7 cm for movable bearings. Piers are of frame type, with rectangular-section columns of 160 x 123 cm, and 13 m of height. Columns are transversal strength with RC horizontal girders of 130 x 130 cm, located almost in the central part of columns. There are diaphragms in the superstructure, located in the extreme and each 1/3 of the lengths.

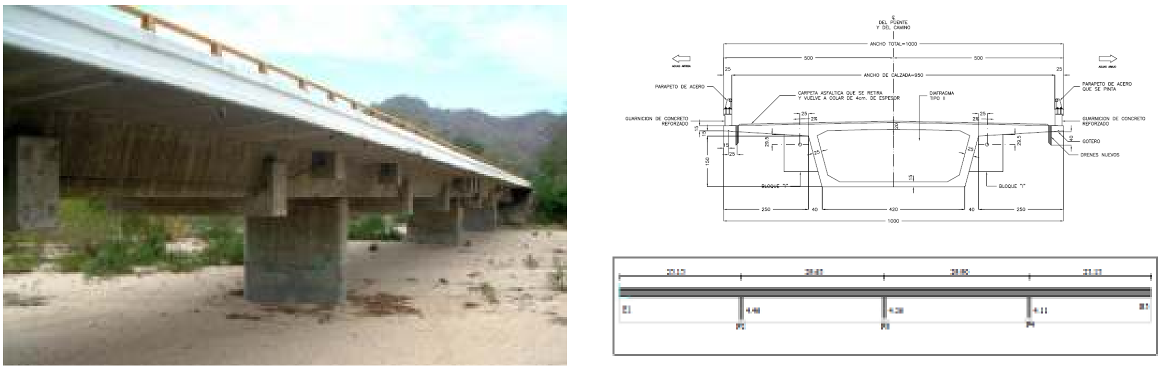

Figure 1. Photograph and general dimensions of Motín de Oro Bridge

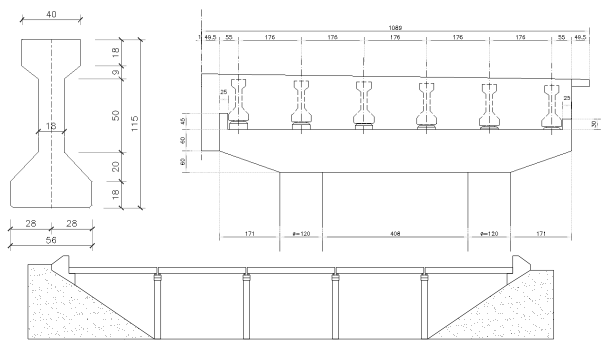

Figure 2. General dimensions of Second Bridge

Bridges were modelled with the SAP 2000 program (SAP 2000) to define dynamic characteristics. This program was used because offers more tools to modelled bridge structures, like the ones to define bearings elements. The SAP models of the selected structures can be shown in figure 4.

Figure 3. Despeñadero Bridge

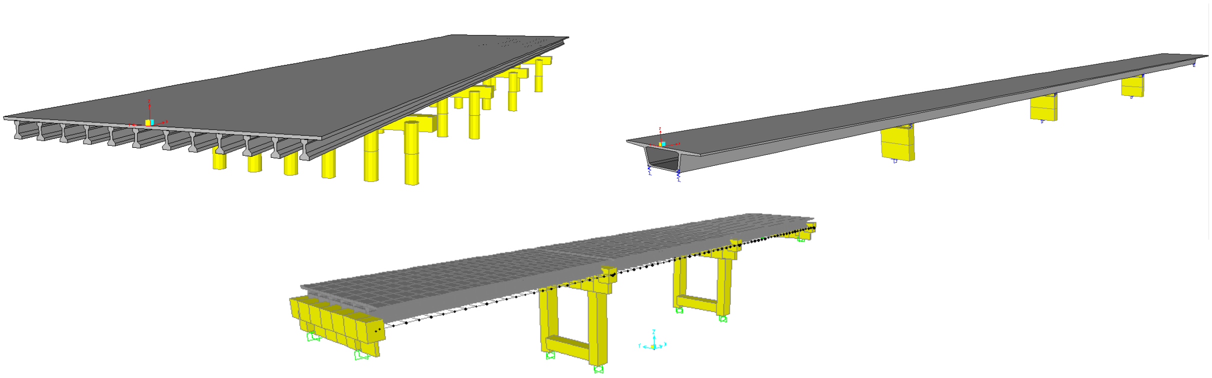

Figure 4. SAP models of bridges

SAP models were calibrated using experimental campaigns (Jara *et al*., 2010). The first periods of the bridges are presented in table 1, where it is observed that the more flexible structure is the Despeñadero Bridge.

Table 2.1. Fundamentals periods of the selected bridges

Bridge	First period (s)	Second period (s)
Motín de Oro	0.292 (longitudinal)	0.277 (transversal)
Second	0.213 (longitudinal)	0.113 (transversal)
Despeñadero	0.800 (longitudinal)	0.450 (transversal)

Bridges were also modelled using Ruaumoko 3D program (Ruaumoko, 2004) in order to evaluate damage indices to elaborate fragility curves. Interaction diagrams and moment curvature diagrams for piers, needed as input for the Ruaumoko program, were defined with external routines. In this work, Takeda model was applied to define constitutive laws of elements. In all the models, superstructure elements were assumed elastic, so damage could be produced only in piers. Ruaumoko models for selected bridges are presented in figure 5.

3. EXTERNAL ACTION

To define the external action, real accelerograms were selected to simulate artificial records. As bridges are located in one of the most hazardous region of Mexico, the Pacific Coast, real signals were selected of close seismic stations. In figure 6 are indicate the physical location of Motín de Oro Bridge and the position of six selected stations, Colima, Manzanillo, Caleta de Campos, Scartsa, and Arteaga.

From these stations, four earthquakes were chosen in function of PGA and duration values; these earthquakes represent the four seismic scenarios for with fragility curves were evaluated. Selected accelerograms were:

- First seismic scenario (1), defined by the accelerograms registered the January 11^{th}, 1997, with a PGA of 396 cm/s^2. This is the seismic scenario with grater PGA
- Second seismic scenario (2), defined by the accelerograms registered the October 12^{th}, 1995, with a PGA of 227 cm/s^2.
- Third seismic scenario (3), defined by the accelerograms registered the April 30^{th}, 1986, with a PGA of 69.2 cm/s^2. This is the scenario with the smaller PGA
- Four seismic scenario (4), defined by the accelerograms registered the September 19^{th}, 1985, with a PGA of 140 cm/s^2. This is the record with greater duration of the intense phase.

Accelerograms were taken from the Mexican Database of Strong Earthquakes (BMSF, 2000). The elastic spectrums of the four accelerograms, for a 5% of critical damping and for the horizontal signal with greater PGA, are shown in figure 7. As it is observed in this figure, the fundamental period of the selected accelerograms are less than 0.5 s. So, the fundamental periods of two of the selected structures are located in the zone of greater amplitude of the spectrum.

4. EVALUATION OF UNCERTAINS

Considering the variability of the structure properties and external action, different structures with the same typology were considered. In addition, starting from the selected accelerograms (figure 7) artificial signals were defined to consider the uncertain nature of earthquake loads.

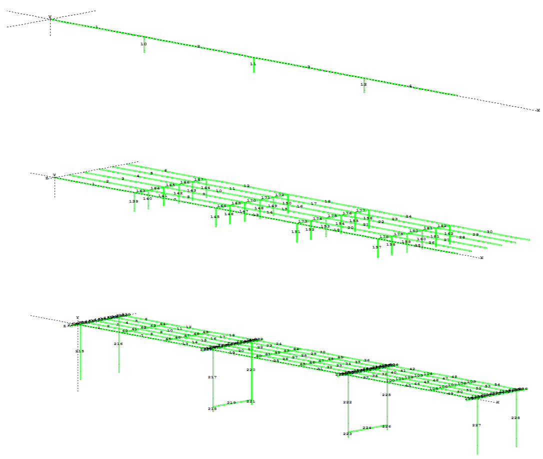

Figure 5. Ruaumoko mathematical models for the bridges

Figure 6. Location of Motín de Oro Bridge and seismic stations

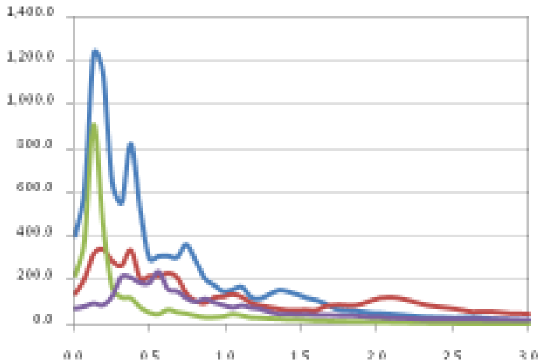

Figure 7. Elastic spectrums of selected earthquakes

4.1. Earthquake load

To generate artificial records, SIMQKE program, part of Ruaumoko 3D code (Ruaumoko, 2004) was used. With SIMQKE, artificial accelerograms, compatibles with a response spectrum, were generated. For each response spectrum an infinite number of different records can be generated, although with similar characteristics, being of the same family of records. A total of 300 artificial accelerograms were produced considered that the phase angle is uniformly distribute between 0 and 2π.

4.2. Structural parameters

The uncertain of structural parameters was considered assuming some of them as random variables. The selected parameters were the mechanical properties of materials. Geometric parameters were assumed deterministic variables because their uncertain normally is low. The probabilistic characteristics of the assumed random variables were taken from the available literature (Gómez, 2002). The probabilistic characteristics are presented in table 4.1.

Table 4.1. Probabilistic characteristics of the mechanical parameters

Variable	Mean	VC	Distribution	Description
f'_c (kPa)	28890	0.064	Normal	Simple compressive strength of concrete
E_c (kPa)	22000000	0.077	Lognormal	Elastic modulus of concrete
W_c (kN/m3)	24	0.04	Normal	Specific weight of concrete
f_y (kPa)	412020	0.064	Normal	Yield strength of steel
f_u (KPa)	618030	0.064	Normal	Ultimate strength of steel
E_s (kPa)	210000000	0.08	Lognormal	Elastic modulus of steel
W_s (kN/m3)	77	0.01	Normal	Specific weight of steel

5. FRAGILITY CURVES

Using Monte Carlo simulation, 300 different Ruaumoko models of the bridges described in section 2 were elaborated. These structures were subjected to artificial records defined in section 4. A total of 300 local and global damage indices, proposed by Park and collaborates (Datta and Ghosh, 2008 and Wen *et al.*, 1998), were the results of the analyses. Although the Ruaumoko program evaluates other damage indices, the proposed formulation of Park *et al.* is one of the most used. The formulation of Park *et al.* for local (element) index is

$$ID = \frac{\delta_m}{\delta_u} + \frac{\beta}{F_y\,\delta_u}\int dE \qquad (5.1)$$

where δ_m and δ_u are the maximum and ultimate deformation of the elements subjected to static monotonic load, respectively; β is a parameter that represent the resistance loss, usually β=0.15; E is the hysteretic energy and F_y is the fluency force.

Park *et al*. propose a global (system) index that considers a weight factor proportional to the element index (equation 1). The global index, ID_G, is expressed as

$$ID_G = \frac{\sum_i ID_i^2}{\sum_i ID_i} \tag{5.2}$$

The histograms of the result damage indices were adjusted to theoretical models of distribution probability functions, using Kolmogorov and Chi-square test. In follow sections, the obtained fragility curves of selected bridges, with no linear analyses though, will be described. In all next figures, horizontal axe represent damage indices and vertical axe cumulative probability.

The seismic scenario 3 was no considered to calculate the fragility curves of bridges, because most of the damage indices calculated are minor than 0.1, no registered for Ruaumoko program. Also, the obtained histograms of the damage indices with this seismic scenario have a high-frequency class, compared with the frequencies of other class, so it is no possible to adjust a theoretical model of a probability density function.

5.1. Motín de Oro Bridge

In figure 8, the fragility curves of the three piers of Motín de Oro Bridge are depicted for the first seismic scenario. This figure shows that the element with higher cumulative probability of damage was the left pier (element 10), being a damage index minor or equal to certain level. For example, the cumulative probability of left, central and right piers (figure 1), being a damage minor or equal to 0.4, are 0.46, 0.64 and 0.83, respectively. The most susceptibility element to suffer damage greater than a certain threshold was the right pier.

For each pier of the bridge, fragility curves for the three seismic scenarios were compared. These fragility curves are presented in figure 9 for the left pier. In this figure, it is observed that for damage minor or equal to 0.25, the cumulative probabilities are 0.19, 0.6 and 1 (secure event) for seismic scenarios 1, 4 and 2, respectively. So, the seismic scenario 1 produces the most hazardous condition.

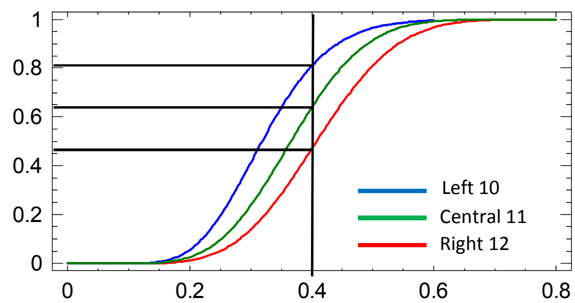

Figure 8. Fragility curves of piers of Motín de Oro Bridge. Seismic scenario 1

5.2. Second Bridge

Similar fragility curves were defined for the Second Bridge. The fragility curves of the piers of this bridge were classified, for similitude values, in three groups: external, intermediate and central piers, in transversal direction. In figure 10, fragility curves of the pier groups are presented, where it is observed that the higher probability of damage is determined for central piers. Fragility curves for different seismic scenarios of central pier group are shown in figure 11. In this figure it is observed that the obtained probabilities are similar for the two bridges, when they are subjected to seismic scenario 1. However, for the other seismic scenarios, the probabilities obtained in Second Bridge are lesser, having a minor or equal damage level.

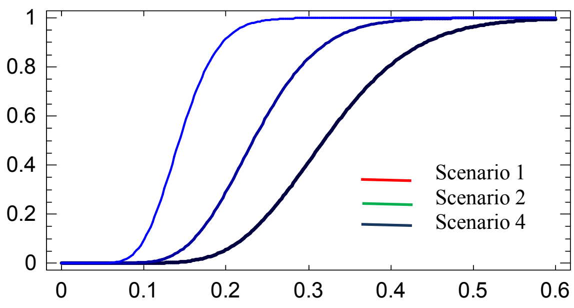

Figure 9. Fragility curve of the left pier of Motín de Oro Bridge. Seismic scenarios 1,2 and 4

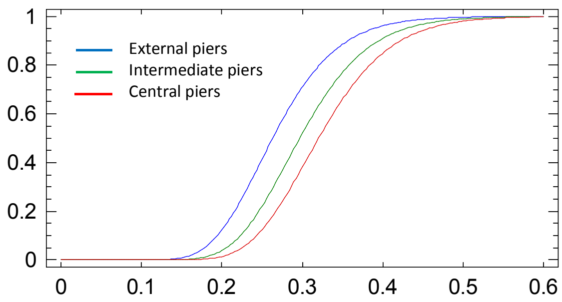

Figure 10. Fragility curve of piers groups of Second Bridge. Seismic scenarios 1

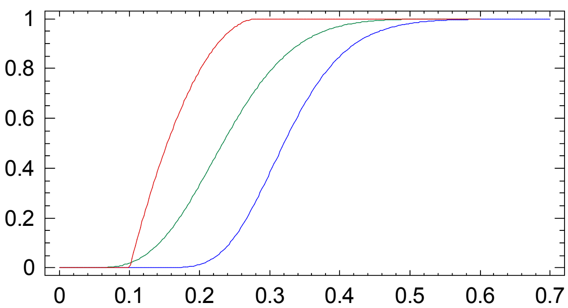

Figure 11. Fragility curves of central piers of Second Bridge. Seismic scenarios 1, 2 and 4

5.3. Despeñadero Bridge

Despeñadero Bridge does not suffer damage due to anyone of the four seismic scenarios, so it is not possible to evaluate global or local damage indices or fragility curves. This is attributed to the bridge dimensions and its dynamic characteristics, in comparison with the other structures. However, analysing elastic responses of the structure, it is observed that the mechanical elements are comparable in the four piers of the bridge. Then, for earthquakes with greater PGA the subestructure elements will have similar probabilities of damage.

5.4. Global damage

Once the damage indices were defined, the global evaluation of structures is accomplished using equation 2. With this global damage index, fragility curves of bridges were defined. Figure 12 presents the fragility curves of the Motín de Oro Bridge (blue line) and Second Bridge (red line) for the seismic scenario 1. In this figure, it is observed that the Motín de Oro Bridge is more vulnerable to this seismic scenario. For these structures, the probabilities of $ID_G \leq 0.25$ is 100%, so at less they have a minor damage for a seismic action similar to the one considered. The Motín de Oro Bridge has a probability of 0.38 to have Severe damage ($ID_G \geq 0.4$), while the other structure has a probability of 0.08 for the same scenario.

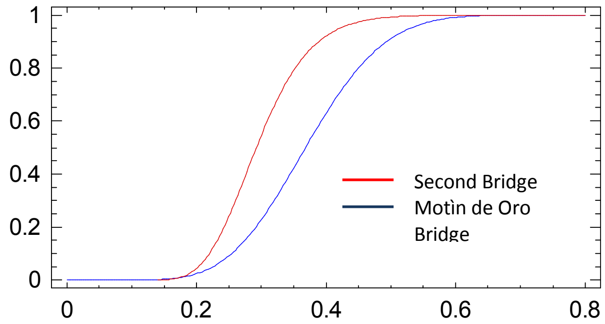

Figure 12. Fragility curves of bridges. Seismic scenario 1

5.5. Damaged structures

Fragility curves of Motín de Oro Bridge and Second Bridge were defined when damage is presented in an element or group of elements. For the right pier of Motín de Oro Bridge and central piers of Second Bridge a strength degradation of 50% was assumed, without changes in the resistance. Fragility curves of bridge elements are presented in figure 13. Fragility curves for central piers of Second Bridge are no presented (right figure) because for the most variations damage indices are lesser than 0.1, so it is impossible to adjust a theoretical probability distribution function. Global fragility curves of the two bridges with damaged elements are presented in figure 14.

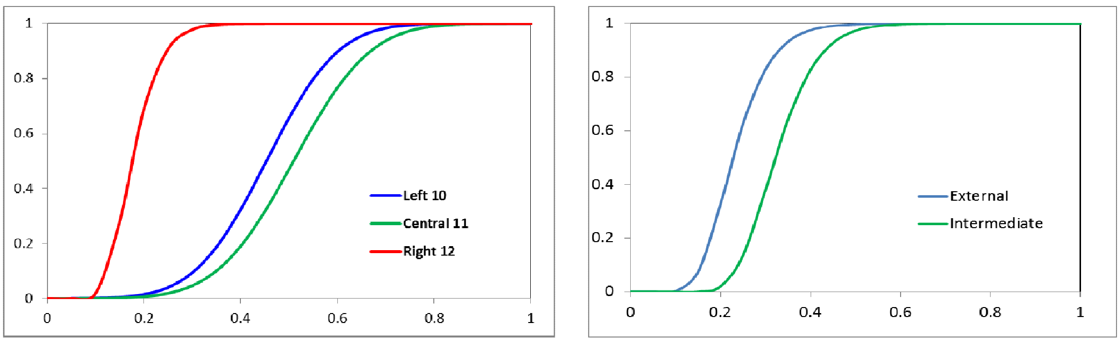

Figure 13. Fragility curves of elements of bridges with previous damage. Seismic scenario 1

Comparing fragility curves for elements with or without previous damage, it is observed that the elements with strength degradation sustain lesser damage, so other more resistant elements assumed the load and have more damage, as it is expected. For Motín de Oro Bridge (left curves in figure 13), for a minor or equal damage of 0.4 the cumulative probability were of 0.46, 0.64 and 0.83 when damage is not presented, while this probabilities were of 1.0, 0.19 and 0.32 of when a previous damage is considered. For the Second Bridge similar results were obtained. Then, pier probabilities of have damage greater than a certain value are more possible to happen in bridges with a previous damage.

Changes in cumulative probabilities, for damage greater than 0.4, are up to 44% and 59% for Motín de Oro and Second bridges, respectively. However, the collapse of one pier in the Motín de Oro Bridge could represent the collapse of the structure. Global fragility curves have similar values when previous damage are or are not present, although global damage index is only an average of element damage.

6. FINAL COMENTARIES

Fragility curves for three common Mexican highway bridges were evaluated. The selected structures were: a) Motín de Oro Bridge, a continuous structure with unicellular-box section for the superstructure and single pier bents, b) Second Bridge, a simple-supported system with pretressed girders and multiple circular piers by bent, and c) Despeñadero Bridge, a system with frame substructure and AASTHO girders. The first bridge has irregularities because of the differences in the piers height and the length of the central spans; meanwhile the other structures are almost regular. It was defined, as external actions, four seismic scenarios, considering seismological stations close to the bridges location. Basing on the four scenarios, families of artificial records were generated (supposing that their spectrum were compatible with the spectrum of the original records). The technique to generate artificial records contemplates that accelerograms are represented by a sum of harmonic functions with phase angles evaluated as a random variables, with uniform distribution between 0 and 2π. A total of 300 models were elaborated from the original bridges, considering as random variables some structural parameters. The bridges were modelled with SAP and Ruaumoko programs. No linear analyses were accomplished with the bridge models and the families of accelerograms to define damage indices, as well as fragility evaluation of the structures subject to earthquake action.

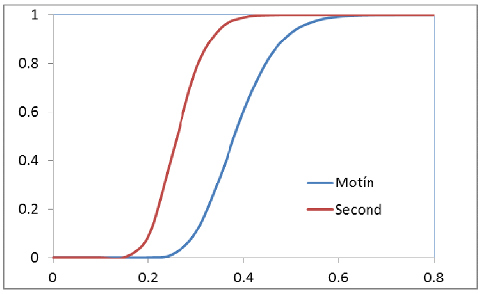

Figure 14. Fragility curves of bridges with previous damage. Seismic scenario 1

Fragility curves were defined for local (for elements) and global (for the structure) damage indices. The local damage was obtained using the Park *et al*. damage index, while the global damage was obtained by the weight sum of the local elements damage. In both bridges, the superstructure elements were elastic, so damage was only presented at piers.

In the Motín de Oro Bridge, the most and less earthquake-vulnerable piers were the extreme elements. For example, for the most hazardous seismic scenario, the cumulative probabilities of DI $\leq$ 0.4 were 0.46, 0.64 and 0.83 for the left, central and right piers. The left pier is the element with small length. For example, the probabilities to define ID$\leq$0.25 were of 0.19, 0.6 and 1.0 (secure event) for seismic scenarios 1, 4 and 2, respectively. So, for the seismic scenario 2 it is certain that the element will not have damage indices greater than 0.25 in all variations.

Similar fragility curves for the Second Bridge were defined. These curves were grouped in extreme, intermediate and central piers (transversal direction), since the determined damage indices are similar. In the defined fragility curves, it was observed that the central piers had more susceptibility to earthquake action. For example, external piers had a probability of 0.15 to suffer ID$\geq$ 0.3, while this value for central piers was of 0.6 approximately. Fragility curves for central piers were compared for different seismic scenarios. As it was previously observed in Motín de Oro Bridge, in the Second Bridge the most hazardous seismic scenario was the one with greater PGA. Despeñadero Bridge has elastic behaviour for the four seismic scenarios, due to its dimensions and dynamic characteristics.

Fragility curves for global damage indices were defined. From these curves, it was concluded that, to the most hazardous seismic scenario, the Motín de Oro Bridge is more vulnerable than the Second

Bridge. For example, the Motín de Oro Bridge had a probability of 0.38 to present Severe damage (IDG≥0.4), while the other structure had a probability of 0.08 for the same damage level.

When one pier or group of piers has previous strength degradation, these elements support lesser load but the other substructure elements have more probability of damage. In Second Bridge the percentage of damage probability in one element is greater than in Motín de Oro Bridge, but a collapse in a pier of the former bridge type could be the structure collapse. Fragility curves of the systems are similar with or without previous damage, although global indices are only an average of element damage indices.

Fragility curves, as those described in this work, can be used as a decision tool to define inspections programs. So, more vulnerable structures could be candidates to inspection more frequently than others, in order to capture the beginning and propagation of damage. Also, fragility curves could be used to define maintenance, rehabilitation and reposition of structures, principally when the economic resources are limited.

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