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SUBESTRUCTURE IRREGULARITY FOR DIFFERENT TYPES OF BRIDGES SUBJECTED TO SEISMIC ACTION

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ABSTRACT

In this paper, to define the influence of the substructure irregularity parametric analyses were accomplished, considering variation in height of piers in a regular system, to form different irregular structures. As a regular model, a simple and symmetrical RC structure was considered, with three hollow cross section piers and a box unicellular girder. Continuous, simple supported and monolithic bridges were considered for regular and irregular systems. All structures were subjected to more than 50 accelerograms database, with magnitudes greater than six, registered in the most hazardous zone of México. Through elastic analyses, the maximum displacements and mechanical elements were defined to obtain the normalized difference between regular and irregular systems. Means, standard deviations and quartiles in the normalized difference were calculated to represent the fragility of each irregularity condition.

Introduction

Bridges are great importance structures for communication and survival in urban centers, and integrate systems of lifelines. Numerous bridges have presented substantial damage as a result of problems like overloads and the natural events impact. Because of these reasons, attention needs to be paid to their preservation and design, to maintain the proper levels of safety and service. In general, maintenance programs can be divided in three stages: preliminary evaluation, detailed evaluation, and designing maintenance strategies. The objective of preliminary evaluation is to detect, in a large group of elements, structures that are in vulnerable conditions. On the other hand, detailed evaluation is based on rigorous analyses that show the systems degradation extension detected in the preliminary evaluation. Then, with the information obtained in the previous stages, decisions are made to design strategies for maintenance, rehabilitation, or rebuilding of structures (Dolce, 1997).

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Parametric analyses, of elastic models that consider one of the most common parameters in preliminary evaluation methods, irregularity of substructure, are presented in this paper. For this purpose, it has been considered three types of bridges (monolithic, continuous, and simple-supported), six irregularity conditions varying from pier height (+75%, +50%, +25%, -75%, -50%, -25%) and 53 seismic movements recorded in México.

Preliminary Evaluation Methods

Preliminary evaluations are used to classify a large number of structures in a simple form, in order to detect elements with different damage degree. There are several methodological approaches used in preliminary evaluation. The methods consist of determining a vulnerability index for each structure, which is obtained by choosing representative parameters for seismic response in bridges, relative weights, and a combination rule. Usually, parameters, respective fragility categories and relative weights are defined subjectively, by means of surveys applied to experts in the field. One of the most common parameters used in preliminary methods include irregularity in piers, in terms of height and bearing conditions or by their typology.

One of the methods proposed in the literature is Kim procedure (Gómez *et al*., 2008), which is a simplified statistical evaluation of the seismic vulnerability in bridges. One of the parameters used is the substructure irregularity, which depends on the height of adjacent piers and whose assigned importance weight is 27.8%, of a total of 100%. This parameter is classified in four categories: 1) structure with no irregularity; 2) bridges with a standardized difference between two piers greater than 1.25; 3) bridges with a standardized difference between two adjacent piers greater than 1.25; and 4) bridges with a standardized difference between adjacent piers greater than 1.5.

Another method was proposed by Pezeshk (Gómez *et al*., 2008). This method considers thirteen parameters grouped in three categories; structural characteristics, foundation and site characteristics, and bridge importance. One of the parameters is used to define substructure irregularity, analyzing the piers height, classified in two categories: piers less than 5 m high, whose relative value is 0, and piers more than 5 m high, with a value of 5.

The method proposed by Kawashima *et al.* (1990) is an inspection method that evaluates the seismic vulnerability of a given number of bridges. There are fifteen parameters to define seismic susceptibility, among them the following primary factors: intensity of ground movement, superstructure and substructure properties, devices to prevent collapse of the superstructure, and site conditions. Irregularity is also evaluated with pier height, with three categories, and a relative weight evaluated based on the interval of seismic damage observed. The categories in which it is divided are: pier height less than 5 m, pier height more than 5 m but less than 10 m, and pier height more than 10 m. The relative weight of substructure irregularity is 28.4%.

A bridge management program named SIPUMEX (Gómez and Barrera, 2007) is used in México, which is based on evaluation of highway bridges conducted by the Ministry of Communications and Transport (Spanish acronym SCT). This procedure seeks to opportunely plan strategies to rehabilitate structures that present significant damage. The method is divided in two stages; the first consists of a subjective evaluation based on the quantification of different parameters, among them: abutments, piers, bearings, slabs, and bridge in general. Each of these parameters is graded considering factors such as: average daily traffic, percentage of fracturing, spalling, corrosion and rusting of structural elements, and inclination of substructure elements, assigning grades between zero and five, depending on the degree of attention they require. Irregularity of the substructure is evaluated by recording damage to its elements and its typology.

Methodology

The software program Sap 2000 v11 (2008) was used as calculation tool for the dynamic elastic analyses. A bridge model obtained from the literature (Priestley *et al*., 1996) was made. It is a RC 50 m equal span structure, symmetric, with two abutments and, initially, three piers with constant height of 14 m each. The center pier height was modified, varying its length during the analysis, to obtain the maximum response in displacement for each of the models. The variations considered are: 1) increase of the central pier length 25%, 50% and 75%, and 2) decrease of the central pier length 25%, 50% and 75%. So, the height of the central pier of the six irregular models were 17.5 m, 21.0 m, 24.5 m, 10.5 m, 7.0 m, and 3.5 m, respectively. Similar variations were considered for one of the external piers.

In the proposed models, abutments are considered as infinitely rigid and strong. Piers have identical cross sections, and are equally resistant in terms of lateral strength. The analysis bridge has piers with a hollow rectangular cross section, and the girder is a unicellular box section. To consider the joint between the girder and the piers three models were proposed, monolithic, continuous, and simple-supported. These three models cover the most common highway bridge typologies. In Fig. 1 the bridge geometry and the girder and piers section characteristics, are presented.

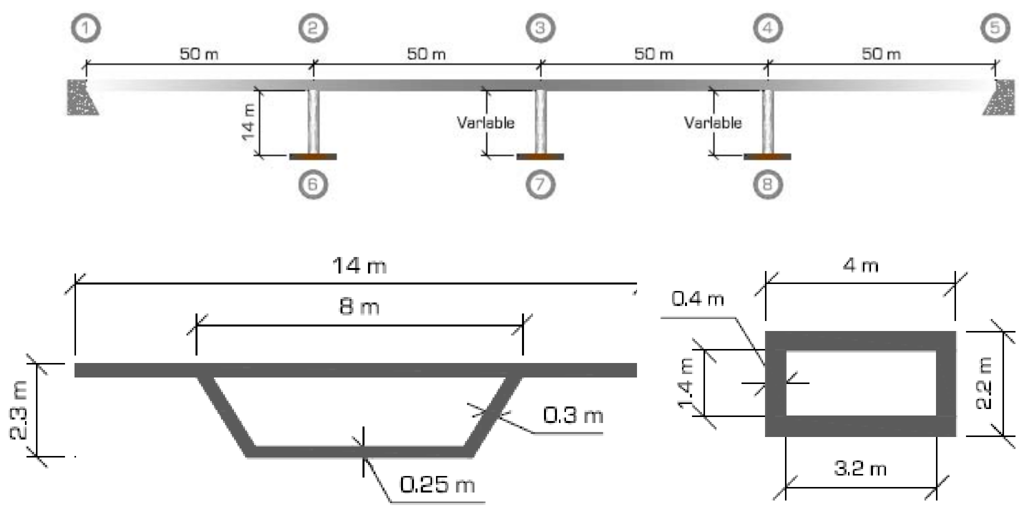

Figure 1 Dimensions of the bridge and girder and piers cross sections

Fundamental periods of the regular and irregular models are show in Table 1. The maximum relation between fundamental periods of regular and irregular monolithic bridges are of 28% and 23%, when central and extreme pier height are modified, respectively, although increase pier length produces more variations. For continuous and simple-supported models fundamental periods are similar, but other periods are different.

Table 1. Fundamental period for all bridge models

Model	Monolithic T(s)		Continuous T(s)		Simple supported T(s)	
	Central	External	Central	External	Central	External
Regular	0.456	0.456	0.581	0.581	0.701	0.701
Irregular, +25%	0.490	0.473	0.581	0.581	0.701	0.581
Irregular, +50%	0.544	0.523	0.581	0.581	0.701	0.581
Irregular, +75%	0.586	0.564	0.581	0.581	0.701	0.581
Irregular, -25%	0.452	0.455	0.581	0.581	0.701	0.701
Irregular, -50%	0.449	0.453	0.581	0.581	0.701	0.701
Irregular, -75%	0.447	0.450	0.581	0.581	0.701	0.701

The analyses were performed with a 53 earthquakes database obtained from the Mexican Strong Earthquakes Database (BMSF, 2000), of accelerograms recorded on the Pacific Coast, specifically in the states of Michoacán, Colima, and Guerrero, states where there is constant monitoring and significant seismic activity. Each accelerogram is made up by three channels, one vertical and two horizontal, and from the last two the accelerogram of maximum acceleration for excitation in the transverse direction of bridges was taken, because it is the least favorable condition. The earthquakes were filtered and corrected by base line. The choice was based on maximum values for acceleration, velocity or displacement, and magnitude. In Fig. 2 the response spectrums of the stronger component of each earthquake are show. Most of the earthquakes have fundamental periods between 0.1 s and 0.45 s.

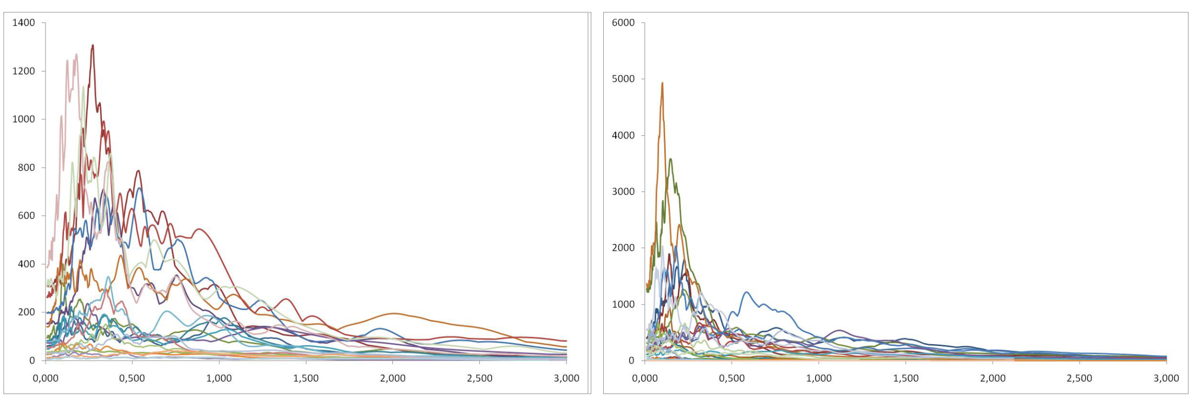

Figure 2. Response spectrums of the earthquakes registered in Michoacán state (left) and Colima and Guerrero states (right)

Data Analysis

An SRSS combination was used, because in prior studies (Acosta and Gómez, 2007) it was found to be one of the combinations with the lowest error rate under rigorous analysis, making the assumption that there is a correlation between the three directions of earthquakes. Five percent damping and step-by-step integration in the time domain analysis were utilized. The analyses were used to define the maximum responses in displacement and mechanical elements at the elements end nodes. Due to no available space, results only for the uppermost node of the center pier, at the joint with the girder, that is node 3 (Fig. 1), are shown.

The difference in response for regular and irregular models is normalized in relation to the regular model, to obtain the variation in response between the regular system and the irregular system, as follows:

$$D_{iff}(\%) = \frac{R_{irr} - R_{reg}}{R_{reg}}(100) \quad (1)$$

where R_{irr} is the dynamic response of the bridge with a certain irregularity, and R_{reg} is the dynamic response of the regular bridge. Also, statistical measurements and deviations from these normalized difference, D_{iff}, are determined to better understand the problem and draw conclusions.

Results

Model 1, Monolithic Bridge

The bridge was analyzed as a rigid frame, to consider the union condition corresponding to a monolithic bridge, incorporating the superstructure and the substructure as an integrated unit. In Fig. 3 normalized difference in percentage and the distribution of results by quartiles are shown for the transverse displacements of node 3, in the monolithic bridge. In the left graph, the earthquake numbers are marked on the horizontal axis and normalized difference is marked on the vertical axis. Horizontal axis on right graph represents accumulated normalized differences.

When a central pier modification is accomplished, the maximum displacement found was 8.3 cm for irregular structures, while for the regular bridge the displacement obtained was 2.7 cm. The maximum displacement for the regular bridge was 5.08 cm. With the same record, the displacement obtained for the bridge with a 50% increase in the center pier was 5.54 cm. As it is concluded from left graph on Fig. 3, there is considerable dispersion in D_{iff} variable. For example, for the bridge model with center pier length increased 75%, a mean of μ=90.54% and standard deviation of σ=73.67, which gives a coefficient of variation of 0.81, are obtained.

In order to establish a trend in bridges vulnerability with certain irregularity, these results were used to plot graphs in which the values are grouped by quartiles, Q_1, Q_2, Q_3, Q_4, which represent 25, 50, 75, and 100% of the data, respectively. It is shown in the right graph on Fig. 3, on increasing center pier height the variation between displacements of irregular systems compared with the regular bridge is greater. Also, reducing pier height leads to a reduction in displacements, which would mean less damage and degradation of structural elements. Seeking to define a trend line that could be applied to a preliminary evaluation method, this graph may help showing that the variation in displacement is not linear with the variation in center pier height, but approaches a quadratic polynomial function. This means, in principle, that a structure is more vulnerable when the difference between their piers is greater, although increasing the length produces greater dispersion than reducing it, which is not considered in the preliminary evaluation methods.

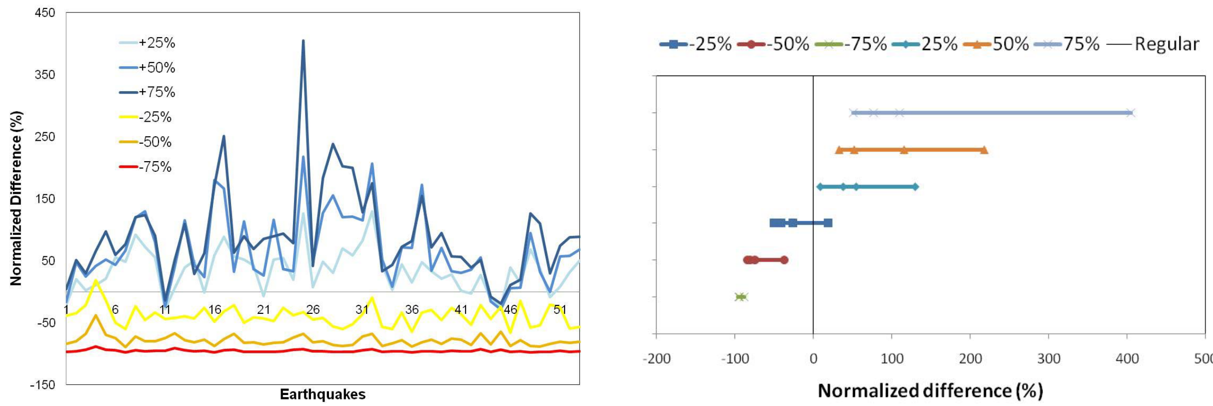

Figure 3. Normalized difference and quartiles for transverse displacements of monolithic bridge. Variation of the central pier height

Normalized differences and distribution of the results by quartiles for transverse displacements of node 3, with variations of extreme pier heights, are represented in Fig. 4. Comparing Figs. 3 and 4, more dispersion was obtained when central pier height is modified. As a result, for monolithic bridges, increase 75% the extreme pier height is equivalent in maximum displacement that increase the length of central pier 25%. Therefore, is more vulnerable a bridge with variations of the lengths of central piers, than other with variations of piers nears the abutments. Finally, decrease the height of central and extreme pier produce similar maximum displacements.

Model 2, Continuous Bridge

In this type of bridge, the results were registered in maximum displacements from the reference node, when the central pier height was modified. The maximum displacement found was 8.2 cm, when the central pier length was increased 50%. For the regular bridge, the displacement obtained with the same record was 2.6 cm. The mean displacement was μ=93.49%, the standard deviation σ=72.28, and the resulting coefficient of variation was 0.77, similar to the one obtained for the monolithic bridge. Results obtained for models with height variations in the extreme pier show that the maximum displacement of the irregular model was 5.02 cm, while the value for the regular model was 2.6 cm. For example, for a 75% increment in height of the extreme pier, the mean and standard deviation were μ=24.55% and σ=22.87, respectively, with a variation coefficient of 0.93.

In Fig. 5, graphs with the distribution displacements for quartiles are presented. These distributions are similar to those obtained from monolithic bridges with variations in the central and the extreme piers, respectively. In addition, the trends observed are similar to those of the monolithic bridge.

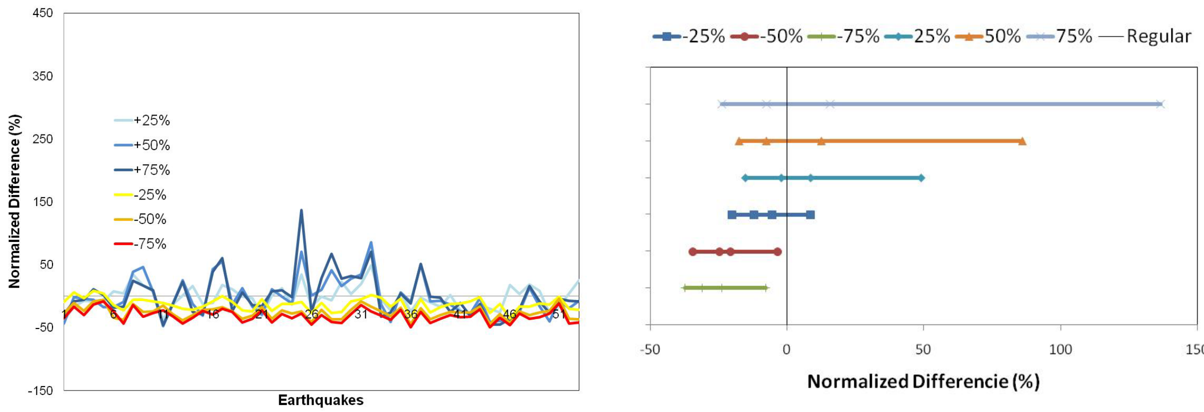

Figure 4. Normalized difference and quartiles for transverse displacements of monolithic bridge. Variation of the extreme pier height

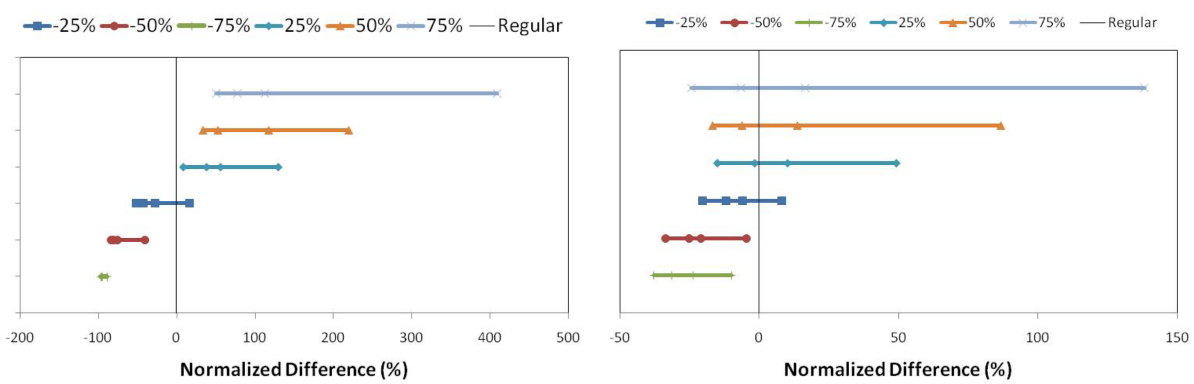

Figure 5. Quartiles for transverse displacements of continuous bridge. Variation of the central and extreme pier height

Model 3, Simple-Supported Bridge

The results in distribution by quartiles, in simple-supported models with variation of the central and the extreme piers, are graphed for the reference node in Fig. 6. The models with variations of the central pier, the maximum displacement found was 7.82 cm when the pier height was increased 75% in the irregular model, and 2.91 cm for the regular model. In particular, for the former irregular model, the statistics were: μ=108.40%, σ=76.68% and the coefficient of variation = 0.71, only below of those obtained for the previous bridge typologies. When a length variation of the extreme pier is considered, the maximum displacements for irregular and regular models were 4.68 cm and 2.91 cm, respectively. For example, the irregular model with a variation of 75% in the extreme pier length, μ=23.59%, σ=23.43% and the coefficient of variation = 0.99. Trends for simple-supported models are similar to other typologies.

Table 2 presents a summary of statistics for the normalized difference (equation 1) between regular and irregular models, with values of mean (μ), standard deviation (σ), and coefficient of variation (CV); for the three models and variations in the central pier length. The results are similar for both, monolithic and continuous bridges; although the responses of the simple-supported bridge are not so different.

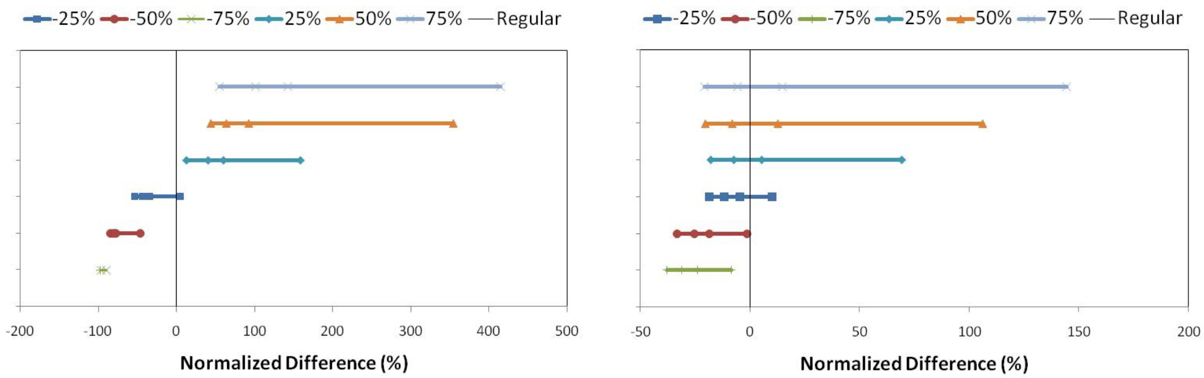

Figure 6. Quartiles for transverse displacements of continuous bridge. Variation of the central and extreme pier height

Table 2. Statistics of the models when central pier height is modified

Variable	Monolithic bridge	Continuous bridge	Simple-supported bridge
+25%			
μ	34.99	35.99	40.61
Σ	33.94	34.09	40.26
CV	0.97	0.95	0.99
+50%			
μ	62.27	68.59	78.80
Σ	57.22	57.89	64.14
CV	0.86	0.84	0.81
+75%			
μ	90.54	93.49	108.16
Σ	73.67	72.28	76.68
CV	0.81	0.77	0.71
-25%			
μ	-39.09	-39.85	-42.91
Σ	16.15	15.79	14.10
CV	0.41	0.40	0.33
-50%			
μ	-78.30	-78.74	-80.16
Σ	8.68	8.19	7.25
CV	0.11	0.10	0.09
-75%			
μ	-95.41	-95.51	-96.15
Σ	1.76	1.68	1.53
CV	0.02	0.02	0.02

Nonlinear analysis

Piers in simple-supported bridges were designed for the hazardous seismic zone in Mexico, considering the same resistance for all piers and equal height variations of the central pier. Regular and irregular structures were analyzed with a simplified algorithm that evaluates the damage in the piers by seismic action, using a continuous mechanic formulation. This algorithm only considers the degree of freedom at the upper part of piers, and flexural deformation.

Bridges were submitted to the earthquake database described in Fig. 2. Distributions of the pier damage and normalized differences between regular and irregular models were obtained using equation 1. In Fig. 7 the maximum displacement of the central pier in a regular elastic model (discontinuous line) and the damage index of a regular nonlinear model (continuous line) are compared. In this figure, it is observed that values for displacement and damage are different, but tendencies are similar; that is, greater displacements are related to greater damage index and when the damage index is small or null, displacements are also small. Quartiles distributions of normalized differences of damage index are similar to quartiles distributions of maximum displacements. These results validate elastic displacements as representative of the general normalized different between regular and irregular bridges.

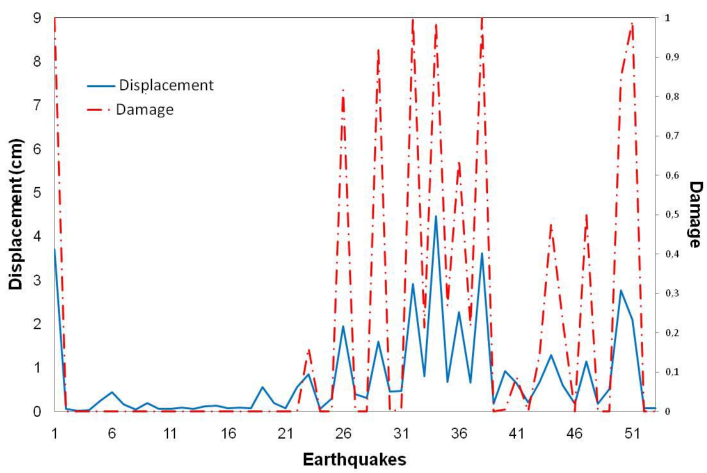

Figure 7. Tendencies of normalized differences for maximum displacement and damage index

Final Commentaries

Some preliminary evaluation methods proposed consider that the substructure irregularity is a relevant parameter. To determine the influence of different irregularity conditions in bridge substructures, parametric analyses of monolithic, continuous, and simple-supported linear elastic models were conducted. In these models, irregularity was considered varying the center pier length in a simple system, the variation percentages were +25%, +50%, +75%, -25%, -50% and -75%. These variations are considered allowable, except -75%, but it is utilized in order to define the tendency in the accumulated normalized differences. Bridges were subjected to a database of 53 earthquakes recorded in one of greatest seismic activity zones in Mexico. The analyses were used to record maximum displacements and mechanical elements, with them the normalized difference in percentage, between regular and irregular structures, was obtained.

Based on the results, graphs were plotted showing the normalized difference values between regular and irregular models and quartiles Q1, Q2, Q3, Q4, which represent 25, 50, 75, and 100% of the data, respectively. The results show that increasing the central pier height increases the variation between displacements for the irregular models, compared with the regular bridge. That is, bridges are more vulnerable when the difference between their piers height is greater, although increasing the length produces greater dispersion, than reducing it. It is also shown that the displacements variation is not linear with the variation in the central or the extreme pier height, but approaches to a quadratic polynomial function. It is possible to say that a bridge with variations in central piers height is more vulnerable, than other with variations in piers nears the abutments. Trends are similar for monolithic, continuous and simple-supported bridges, so the bridges typologies do not have influence in the substructure irregularity. Nonlinear analyses show that distribution by quartiles of damage index have similar tendencies to the distributions for displacements of elastic structures. So, results in the elastic models are considered representative to define normalized differences.

For a preliminary prioritizing method of bridges subjected to earthquakes, it is considered that the substructure irregularity should be a parameter. Based on the results of this work, for this parameter, the vulnerable categories are: 1) bridges without piers, 2) bridges with 25% more length in the extreme piers, 3) bridges with 25% more length in the central piers, 4) bridges with 50% more length in the extreme piers, 5) bridges with 50% more length in the central piers, 6) bridges with 75% more length in the extreme piers, and 7) bridges with 75% more length in the central piers. Former category is the most vulnerable. The vulnerable values could be assigned in function of the quadratic lines adjusted to the distributions by quartiles, which are similar for monolithic, continuous and simple-supported bridges. However, to define these vulnerable values, results of more complex models will be obtained.

References

Acosta-Zambrano A. and C. Gómez-Soberón, 2007, Participation factors of the three earthquake components in the seismic response of regular bridges. *9th Canadian Conference on Earthquake Engineering*. 1309, Ottawa.

BMSF. *National Database of Strong earthquakes 1960-1993* Sociedad Mexicana de Ingeniería Sísmica, A.C., México.

Dolce, M (1997). "Seismic vulnerability evaluation and damage scenarios". Tech. Report NCEER-97-0003. NCEE. Proceedings for the US-Italian workshop on Seism. Evaluation and Retrofit.

Gómez-Soberón, C. and L. A. Barrera, 2007, Modification of the preliminary bridge evaluation by the Communication and Transportation Secretary of México to define maintenance politics for seismic action. *IABSE Symp. Improving infrastructure bringing people closer Worldwide*.

Gómez-Soberón, C., J. M. Alonso and J. M Gómez, 2008, Influence of the substructure irregularity in highway bridges behavior. *14th World Conference on Earthquake Engineering*. Paper 05-02-0068, China

Kawashima, K. and S. Unjoh, 1990, An inspection method of seismic vulnerability of existing highway bridges, *Structural Engineering and Earthquake Engineering, Proceedings JSCE, 416/I-13*, 1, 155-161, Tokio, Japan.

Priestley, M. N., F. Seible and G. M. Calvi, 1996, *Seismic design and retrofit of bridges*, Wiley, USA.

SAP2000, 11, 2008. Computers and Structures, Inc.