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Comparison of an irregular index and normalized maximum displacements for bridges

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ABSTRACT

The seismic response of irregular bridges could be complex if some irregular conditions were presented in the substructure. To evaluate as a simple form the influence of some irregular conditions, various irregular indices were proposed, considering elastic or inelastic parameters. With these indices, only one number, between 0 and 1, could be used to represent the bridge irregular seismic behavior for design and analyses proposes. However, applying various indices to the same structure could produces different results and it is difficult to define its application in the design procedure.

In this paper, an elastic irregular index is applied to bridges with different irregular substructures, based on the variation of central and extreme piers length. As a regular model, a simple bridge with four spans and three piers of hollow rectangular section was considered, with unicellular box girder. The pier high variations include +25%, +50%, +75%, -25%, -50% and -75% of the original length, so seven irregular models were considered for each regular bridge. Monolithic connection between piers and girder are considered. Regular and irregular models were subjected to a 53 accelerograms database, registered in the most earthquake hazardous zone of Mexico. Through elastic analyses the maximum displacements of piers were defined for each accelerogram and bridge model. A new index is defined as the normalized difference between the maximum displacements of the irregular and regular models. Tendencies of the propose normalized difference and an irregular index available in literature were compared to define the best representation of the irregular condition of bridges.

1. INTRODUCTION

Irregular structures have a more complex behavior than the regular ones and their analysis, design, inspection and maintenance require more attention. For bridges, the

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irregular conditions could be presented in the superstructure or in the substructure. Bridges have an irregular superstructure if they are not straight or are skewed, or if their spans have different lengths, or if there are important variations in the girder sections. On the other side, substructure irregular condition is presented when the piers have variations in length or resistance. Some authors classified bridges as irregulars if their responses have significant contribution of higher modal shapes.

Some analyses, for bridges with irregular substructure, have shown notorious variation in the deformation demands of piers, concentration of shear forces in short piers, variation of ductility demands and more participation of higher modes (Isakovic and Fischinger, 2000 and 2008). Experimental studies indicate that the absorbed energy in an irregular bridge was concentrated in the shorter pier with almost 70% of the entire energy dissipation (Tehrani and Mitchell, 2010).

AASTHO LRFD (2007), Caltrans and Eurocode 8 consider the bridge irregularity in a simple form. AASTHO classifies a bridge as regular when the curvature angle is minor than 30°, or by setting maximum stiffness thresholds between adjacent spans or piers in the same bent. Curved and skew bridges or structures with various levels, not balanced mass or with important variation in piers stiffness are classified as irregular by Caltrans. The Eurocode 8 classifies the bridge irregularity depending only on a ductility factor. In Mexico, the IMT (Mexican Institute of Transport) classifies a bridge as irregular if: it has less than six spans, it is straight or has an alignment with minor curvature, it has a skew angle lower than 15°, it has an irregular distribution of mass and stiffness, and it has a total length not larger than 40 m for the largest span. Then, codes or design recommendations present a simple form to classify bridges as regular or irregular, but in some cases only to suggest the appropriate analysis type.

In recent years, some irregularity indices were proposed to classified bridges. These indices are used to predict if a bridge will behave as it was proposed (Isakovic and Fischinger, 2000). These indices are classified in elastic and inelastic indices, considering that irregularity conditions are displayed by elastic or inelastic modal shapes or displacement values. Ayala and Escamilla (2013) compare different irregular indices for bridges with variation in piers length. Through this comparison, it is observed that irregular indices are not an absolute measure to consider the irregular condition of a bridge; actually different values are obtained with various proposed indices for the same structure. Irregular indices could be an adequate tool to characterize bridges irregularity; however more research is needed to define the practical meaning of some values and indices.

Both shortcomings, the simple way to assign a weight to the bridge irregularity in design codes, and the reduced reliability of the preliminary inspection methods to reflect the influence of some parameters of the bridge seismic performance, show the importance of further research. Therefore, this paper presents the comparison of two irregular indices, one defined as the normalized difference of maximum displacements between regular and irregular bridges. The other index was taken of the literature; this index defines the bridge irregular condition by comparing the elastic modal shapes of the complete bridge and only the superstructure. Analyzing results it is define the best representation of the bridge irregularity.

2. NORMALIZED DIFFERENCES OF MAXIMUM DISPLACEMENTS

A regular geometry model was proposed to compare its responses with the ones of irregular bridges and identify the influence of some irregular geometrical conditions. The regular model is based on the structure described in a previous research (Priestley *et al.*, 1996). This is a simple four-span bridge (50 m each span) with three piers of 14 m, see Figure 1. The girder is a box unicellular section of reinforced concrete, while piers have box sections. The form and dimensions of girders and piers are shown in Figure 2.

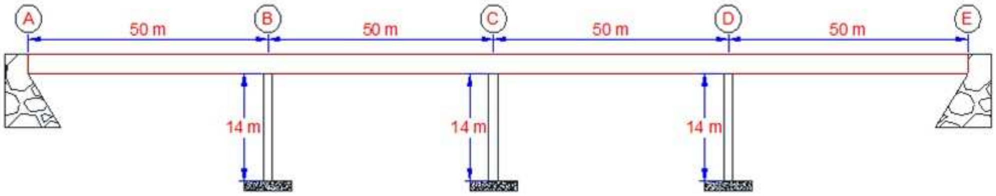


Figure 1. Regular bridge model

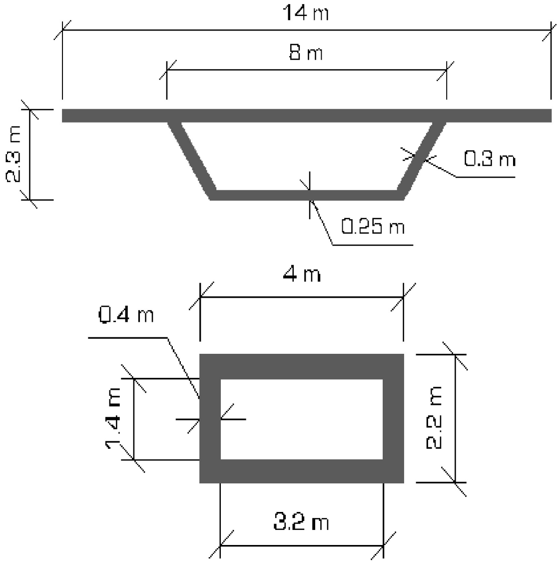


Figure 2. General dimensions of girder and pier elements

To study the influence of irregular substructures, compared to the described regular model, the central and one extreme piers length were modified in percentages of +25%, +50%, +75%, -25%, -50% and -75%. In order to evaluate different pier to girder connection, continuous, monolithic and simple-supported bridges were studied for all models. Monolithic models have rigid connections, while continuous models have only one girder free to longitudinal moment. In simply-supported bridges, there are several girders with fixed and mobile bearings in their extremes. Fixed bearings are restrained against rotation or displacement, and mobile bearings are only longitudinally free to rotation. Detailed analyses of these bridges can be consulted in Gomez and Salas (2012), nevertheless in this paper only the results for monolithic structures are shown.

Regular and irregular bridges were modeled in SAP2000 (v. 14) software, with embedding piers and abutments modeled by elastic springs, for elastic analyses. For the non-linear analyses, a simplified model was considered.

2.1 Seismic loads

For elastic analyses, a database of 53 accelerograms was utilized, obtained from the Strong Earthquakes Mexican Database (BMSF, for its Spanish abbreviation, 2000). The selected accelerograms were registered at seismic stations located in the Mexican Pacific Coast, one of the most hazardous seismic zones in in México, in the States of Colima, Guerrero and Michoacán. The selection was based on the peak ground accelerations, velocities and displacements and on the earthquake magnitude. For the analyses, only two horizontal components were considered for every record, considering that the highest acceleration component acts in the transverse direction of bridges, for the purpose of evaluating the most unfavorable action. The response spectrums for the highest horizontal component of the 53 signals, with a 5% or critical damping, are shown in Figure 3. Most of the records have fundamental periods shorter than 0.5 s, however an important variety of signals is considered.

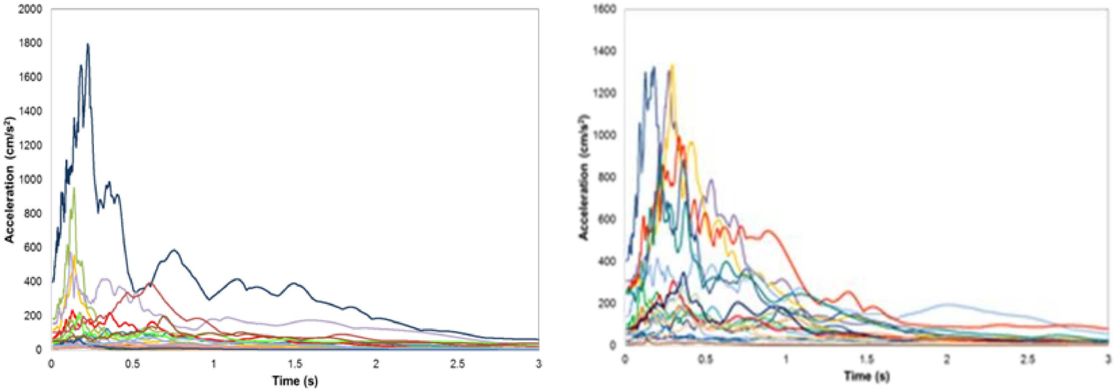


Figure 3. Elastic spectrum of accelerograms for the Guerrero and Colima States (left) and Michoacán State (right)

2.2 Elastic analyses

Models for regular and irregular bridges were analyzed under the selected 53 earthquake signals, to develop elastic analyses. In these analyses, a SRSS rule was

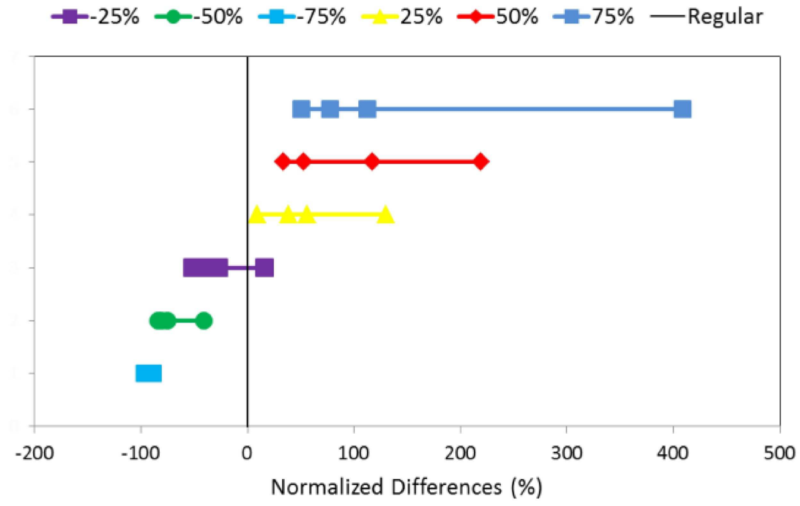


Figure 4. Normalized differences when the central pier length is modified

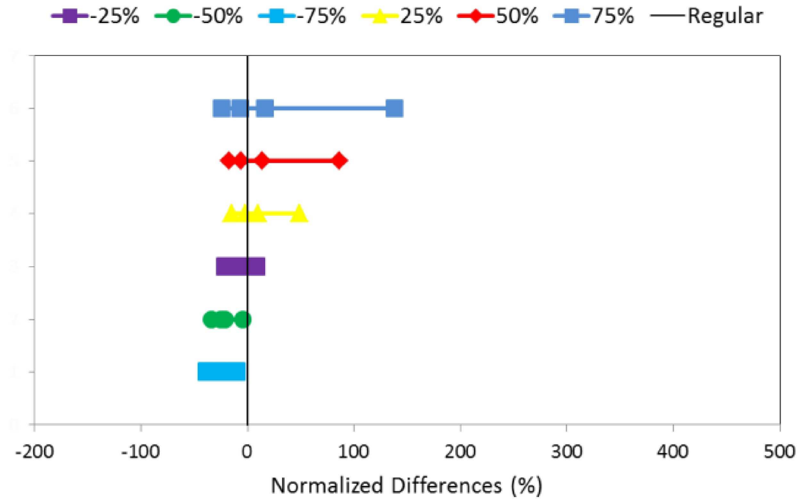


Figure 5. Normalized differences when the extreme pier length is modified

used to combine the maximum responses for displacements and forces at the upper nodes of piers. In order to assess the influence of different irregular conditions, compared to regular bridge performance, the normalized difference was assessed. This normalized difference, D_n, is defined by

$$D_n = \frac{R_{IR} - R_R}{R_R}, \qquad (1)$$

where R_{IR} and R_R are the maximum responses obtained from irregular and regular bridge models, respectively. Mean, standard deviations, quartiles and the probabilistic distributions of D_n were obtained for all bridge models. In this paper the responses are only represented by the maximum displacement.

The variation of the maximum normalized differences for each selected accelerogram does not indicate the influence of different irregular conditions. Then, to define the influence of different irregular substructure conditions in a bridge, the normalized differences were grouped by quartiles, classifying the results and registering the values related to the 25%, 50%, 75% and 100% of the data. Figure 4 shows the normalized differences by quartiles of the maximum displacement for the central node, when the central pier length is varied for continuous bridges. It is observed, that the increment of the central pier length produces more variations than the reductions on this dimension. The effect of changes on the length is larger for the central pier as compared to the ones on the adjacent pier. For example, when the length of the central pier is 75% shorter than the length of the extreme pier, the normalized difference on responses is similar for all accelerograms. However, when this length is 75% larger than the one of the extreme pier, the normalized differences have variations between 50% and 450%.

The normalized differences for variations on the extreme pier length are compared to the ones due to variations on the central pier. In Figures 4 and 5, it is observed that the variation trends are similar. However, when the central pier length is modified, wider variations are registered than when the extreme pier length was changed. For example, when the central pier length is incremented 25% (Figure 4), the normalized difference is similar to the one determined when the length of the extreme pier is incremented 75% (Figure 5). By analyzing Figures 4 and 5, it is to conclude that a bridge is more vulnerable to seismic load when there are variations in the length of the central pier, as compared to bridges having the same variations on the length of a pier close to the abutments.

Trends of the ratio between normalized difference in displacement, I_d, and the variation percent of the central pier length, v_p, for the percent 100 are defined. These ratios are shown in Table 1, for the three types of bridges. It is observed that the equations are similar for all types of bridges in the table.

Table 1 Relations for bridges with changes in the length of central pier

	Change the length of central pier
Continuous	$I_d = 0.022\ v_p^2 + 3.04\ v_p + 37$
	Change the length of extreme pier
Continuous	$I_d = 0.009\ v_p^2 + 0.95\ v_p + 16$
Id = normalized difference (%), vp = variation in the length of the pier (%)	

3. IRREGULAR INDICES

In recent years, some irregular indices were proposed to classify bridges in function of their substructure irregular condition. The proposed indices were grouped as elastic and inelastic irregular indices, considering that elastic and inelastic responses characterize the seismic behavior of the structures.

Elastic indices consider that only elastic parameters are sufficient to represent the response of irregular bridges. One of the elastic indices is the one proposed by Calvi and Elnashai in1994 (Ayala and Escamilla, 2013), to define the analyses methodology to design and to classify the irregular condition of bridges. This index, I_R, combines the mode shapes of the deck with the mode shapes of the entire bridge, as:

$$I_R = \sqrt{\frac{\sum_{i=1}^{n}\left(\frac{\Phi_i^B}{\Phi_i^B M \Phi_i^B} M \frac{\Phi_i^D}{\Phi_i^D M \Phi_i^D}\right)^2}{n}}, \tag{2}$$

where Φ^B and Φ^D are the modal shapes of the entire bridge and for the deck, respectively, M is the mass matrix of the structure and n is the number of modes uses in the modal spectral analyses. I_R index varies from 0, for irregular bridge, to 1.0 for the regular system.

Calvi and Elnashai index was evaluated by the same regular and irregular bridges analyzed in above section, when the central and extreme piers length is changed in percentages of +25%, +50%, +75%, -25%, -50% and -75%.

First, the indices of Eq. 2 were defined using a 2D model of the structures, as it can be observed in Figure 1 for the regular bridge, with hinges in the girder extremes and piers built-in in one extreme and continues in the other. This model have only 13 degree of freedom (horizontal and vertical displacements and a rotation in the plane for nodes without restriction) and complement the 90% of the effective mass, as it is indicated by codes, to the dynamic analyses. For this type of model, for regular and irregular bridges, the Calvi and Elnashai index was defined; its values when the central pier length is changed are shown in Table 2. For this model the transversal shapes are not considered.

In addition, irregular index I_R was determined for a more elaborated model,

Table 2 I_R index for the 2D bridge models

Model	**Change of length of central pier**
-75%	0.621
-50%	0.838
-25%	0.968
Regular	1.0000
+25%	0.895
+50%	0.798
+75%	0.735

length is changed. The values of the normalized differences in this figure are determined using the mean value (50% percentage) of the 53 accelerograms, as the representative of the variation of this parameter. In horizontal axes of Figure 8 are the percentages of variation of the pier length; while in vertical are the values of the respective indices.

As it can be observed in Figure 8, there are differences between the values of the two indices. Irregular index (Equation 2) has minor variation when the length of piers changes, maybe because it is bounded between 0 and 1; normalized difference index has not bounded values. If a curve is adjusted to the values obtained, the best fit for I_R index is a straight line, whereas for the normalized difference is a quadratic function (represented by the equations of Table 1.

In figure 9 it is shown the comparison of the two indices when the 100% percentage is used for the normalized differences, as a maximum value representation. In this figure it is observed that tendencies are similar as commented by figure 8, but the differences among the values of two indices are greater.

6. FINNAL COMENTARIES

In this paper are presented the comparison of two indices to represent the irregularity condition of the substructure of bridges. Fist index is the normalized differences of the maximum transversal displacement obtained by elastic analyses. The second index was proposes by Calvi and Elnashai in 1994, based on the changes of the mode shapes of a complete bridge and only the deck system.

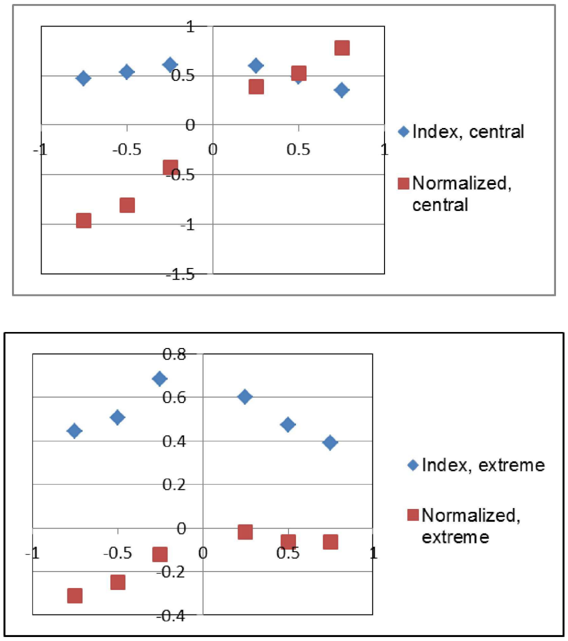
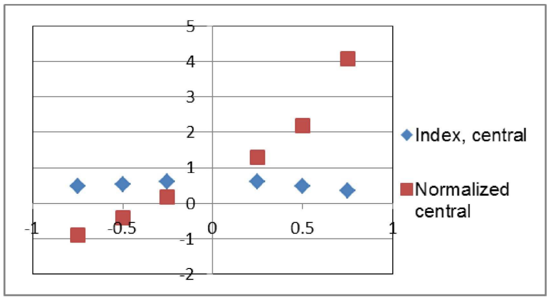


Figure 8. Comparison of the two indices when the length of the central (upper) and extreme (bottom) piers change. Mean values of the normalized differences



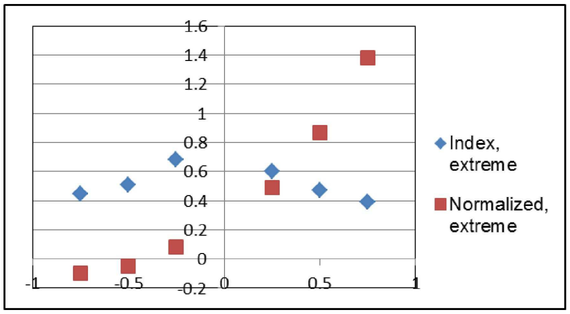


Figure 9. Comparison of the two indices when the length of the central (upper) and extreme (bottom) piers change. Maximum value of the normalized differences

To make the comparison, elastic models of bridges when the length of central and extreme piers change were elaborated in SAP program. The percentages of variation of the length of piers were +25%, +50%, +75%, -25%, -50%, and -75%. A database of 53 accelerograms were considered to define the normalized differences of maximum displacements, and from results mean and the four quartiles were determined and tendencies function were adjusted to them.

From the obtained results, conclusions are:

- It is difficult to compare both indices because one is bounded and the other not. However the two indices are used to represent the irregular condition of the same structures.
- The irregular index I_R is evaluated by means of a modal elastic analyses. So it is not very difficult that practise engineers could obtain it. To define a correct values of this index it is necessary a 3D model with sufficient degree of freedom to a better characterization of the modal shapes. The use of the 90% of the effective mass could be a reasonable definition of the necessary number of modal shapes to define this index.
- Normalized difference of the maximum displacement index is defined by means of an elastic modal-spectral analysis. Then, its evaluation is a little complex than the I_R index, however the analyses can be conducted and trends were defined to use only, as representatives of this index, the adjusted functions, for example, the ones expressed in Table 1. To a better representation is necessary to define if 53 accelerograms are sufficient to denote the variation of seismic load. Then a reliable analysis could be conducted.

- The trend of the I_R index is a straight line for the considered variations of the lengths of piers. Most of the inspection methods that use substructure irregularity as an influence parameter consider linear variation to define vulnerability categories for this parameter.
- For the normalized difference of maximum displacement index, the best adjust function of the obtained values are a quadratic function. This index have different variations when the central or pier length is changed, indicating different vulnerability of the systems when the shorter pier is close to the abutments. It conclusion is verified by studies of other researches, whose specified that the effect of geometrical irregularities depends on the position of the strongest pier.

More studies are necessary with other proposes indices and models with other irregular conditions, to evaluated in a reliable and simple form a bridge irregularity. This final index could be included in design codes.

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