INFLUENCE OF THE SUBESTRUCTURE IRREGULARITY IN HIGHWAY BRIDGE SEISMIC BEHAVIOUR

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ABSTRACT :

Most of preliminary evaluation methods to accomplish the seismic vulnerability of bridges consider as an evaluation parameter the substructure irregularity. This parameter is estimated by means of the difference in the length of piers or through the pier typology, but both evaluated by a subjective form. In this paper the evaluation of the influence of substructure irregularity is presented. First, a simple and regular bridge, with three piers of equal length and four spans, is considered as an original structure. Starting from this system, different irregular models were elaborated reducing or incrementing the length of the central or one of the external piers, in percentages of 25%, 50% and 75%. As a seismic action, a database of more than 50 earthquakes, registered in the Mexican Pacific Coast, the most seismic hazardous zone of México, were considered. The selected registers have magnitudes greater than six and important peak ground accelerations. By means of elastic analyses, the variation between regular and irregular maximum responses in displacements and internal forces are determined. Of the obtained responses, statistical values as mean and standard deviation are evaluated. With these values, percentages of difference in the response of irregular bridges were estimated; these percentages could be included as fragility weights of the irregularity degree in more rigorous preliminary methods to evaluate the seismic vulnerability of bridges.

KEYWORDS: Bridges, substructure irregularity, vulnerability, seismic response

1. INTRODUCTION

Recent observed behavior in bridges has shown that the failure of systems with reduced capacity could produce damage and important economic losses. Because of that, the current condition evaluation in existing bridges is a necessary task to define maintenance and rehabilitation programs. The evaluation, in general, is based on preliminary and secondary estimations and on the decision of specific rehabilitation techniques to be used in systems with important degradation. The substructure irregularity as an evaluation parameter is considered in most of the preliminary evaluation methods to accomplish the seismic vulnerability of bridges (Ren and Gaus, 1996, Gómez and Barrera, 2007). This parameter is estimated by means of the difference in length of piers or through the pier typology. The influence of the substructure irregularity degree is evaluated in a subjective form, based on experts opinion or reported damages in past earthquakes.

In general, highway bridges are irregular structures with minor redundancy, because its form depends of the topographical local conditions. Specific studies about the variation in the seismic response of bridges with different substructure irregularities are not found in literature. Most of the studies are focused on the seismic behavior of specific structures, with particular geometrical and structural configuration. The work by Estrada and Reinoso (2005) is an example, where a three-span bridge with different piers lengths was studied, defining the maximum longitudinal displacements when the structure is subjected to earthquake external action.

Thus, to apply simplified and reliable preliminary evaluations of the seismic vulnerability of bridges it is necessary to evaluate, in a more rigorous form, the fragility degrees and importance weights of the parameters with more influence in the seismic behavior of these systems. In this paper an elastic evaluation of the influence of the substructure irregularity is presented. For that, a simple and regular bridge, with three piers of equal length and four spans, is considered as an original and regular structure. For this system, box girder and rectangular hollow cross section of piers are used. Starting from this structure, different irregular models were elaborated, reducing or incrementing the length of the central or one of the external piers in percentages of 25%, 50% and 75%. As a seismic action, a database of more than 50 earthquakes, registered in the Mexican Pacific Coast, the most seismic hazardous zone in México, were considered. By means of elastic analyses, the variation between regular and irregular maximum responses in displacements and internal forces were determined. From the obtained responses, statistical values are evaluated. With these values, variation percentages of the responses of bridges with different piers lengths are presented.

2. REGULAR AND IRREGULAR BRIDGE MODELS

In order to accomplish multiple analyses, simple RC highway bridge models were used in this study. A regular and symmetrical bridge designed by Priestley *et al*. (1996), shows in figure 2.1, is considered. This bridge is composed of four equal spans of 50 m, three piers of 14 m and two abutments. Piers are composed with hollow rectangular cross section and girders are formed by box unicellular sections, with dimensions and geometrical properties represented in figure 2.2 and table 2.1.

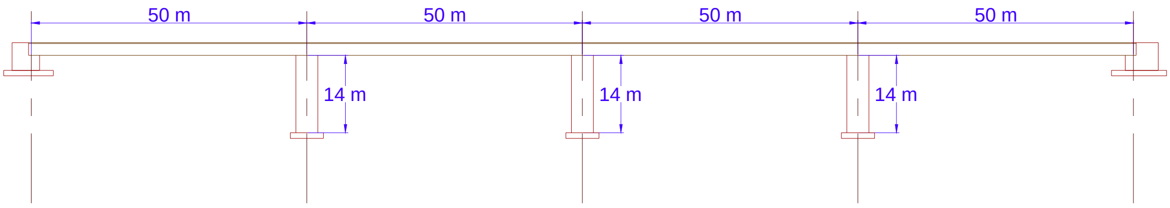


Figure 2.1 Regular bridge

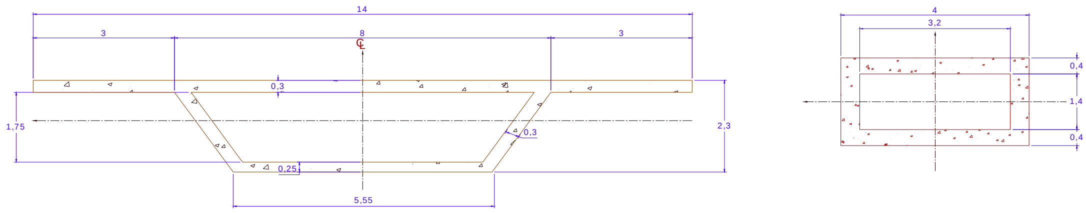


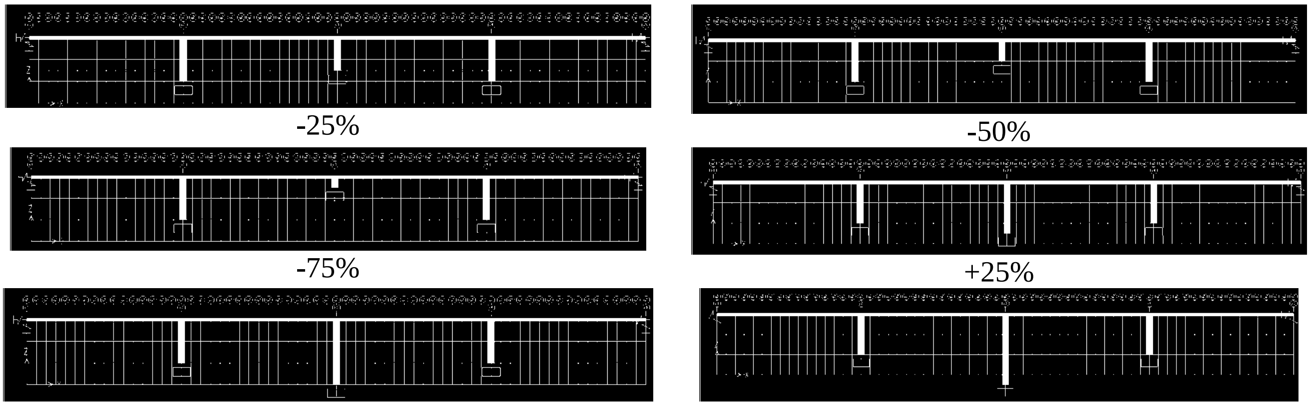
Figure 2.2 Cross section of girder (left) and piers (right)

Table 2. Geometric characteristics of the bridge elements

Characteristic		Girder	Piers
Area	A (m2)	6.8527	4.32
Moment of Inertia	Ix (m4)	85.8023	7.9104
Moment of Inertia	Iy (m4)	4.9577	2.8176
Section module	Sx (m3)	12.2573	3.9552
Section module	Sy (m3)	3.2046	2.5615

Irregular bridge models are created modifying the length of the central and one of the extreme piers, in percentages of -25%, -50%, -75%, +25%, +50% and +75% of the original dimension. A scheme of the irregular bridge models with variations in the length of central pier is shows in figure 2.3.

For all models, longitudinal and transversal stiffness of the abutments were evaluated and introduced by elastic springs, vertical stiffness was considered infinite. The piers are built-in in one extreme (soil-structure interaction effect was not considered) and with displacement connectivity at the girder union, assuming free rotation. In addition, to correctly capture the vertical modes of bridges, the mass of the girder elements was concentrate in several points. The girder nodes were constrained to equal longitudinal displacement.



-25% -50%

-75% +25%

+50% +75%

Figure 2.3 Irregular bridge models with different central pier length

3. ACCELEROGRAMS

To analyze the influence of substructure irregularity in highway bridges an accelerogram database was formed. The selected accelerograms were registered in the Pacific Coast of México, specifically in Michoacán, Guerrero and Colima States, the most earthquake hazardous zone in México. Accelerograms in three orthogonal components are from earthquakes with magnitude greater than six and important peak ground acceleration or displacement (MCSGM, 2000).

Table 3.1 Accelerograms database of Michoacán State

#	Station name	Sampling intervals	PGA (cm/s^2) Channel 1	PGA (cm/s^2) Channel 2	PGA (cm/s^2) Channel 3
1	APAT-01	0.02	50.44 (S00E)	24.81 (+V)	62.22 (N90E)
2	SICC-01	0.02	264.28(N00E)	66.79(+V)	307.22(N90W)
3	APAT-02	0.02	81.57(N00E)	35.58(+V)	96.55(N90W)
4	SICC-02	0.02	265.7(N00E)	0.00(+V)	249.09(N90W)
5	APAT-03	0.02	68.74(S00E)	44.63(+V)	81.28(N90E)
6	CALE-01	0.005	140.68(S90E)	88.45(+V)	139.73(S00E)
7	CALE-02	0.005	50.98(S90E)	25.49(+V)	41.15(S00E)
8	ZACA-01	0.01	147.38(+V)	174.18(N90W)	262.23(S00E)
9	APAT-04	0.02	18.62(S00E)	8.31(+V)	20.80(N90E)
10	ZACA-01	0.01	36.37(+V)	70.82(N90W)	72.73(S00E)
11	APAT-05	0.02	47.78(S00E)	38.37(+V)	52.34(N90E)
12	ARTG-01	0.01	22.53(+V)	20.39(S90W)	27.06 (S00W)
13	CALE-03	0.005	97.17(S90E)	34.42(+V)	76.52(S00E)
14	GUAC-01	0.01	21.94(+V)	31.49(N90W)	55.44 (S00E)
15	ZACA-03	0.01	17.39(+V)	54.27(N90W)	35.89(S00E)
16	CALE-04	0.005	11.62 (S90E)	7.51(+V)	7.42 (S00E)
17	LZ01-01	0.01	68.84(N45E)	38.26(+V)	78.86(N45W)
18	LZ01-02	0.01	10.86(N45E)	4.20(+V)	13.29(N45W)
19	LZ01-03	0.01	22.95(N90E)	11.59(+V)	30.73(N00E)
20	CALE-05	0.005	396.21(S90E)	413.94(+V)	350.27(S00E)
21	LZ01-04	0.01	196.74(N90E)	193.48(+V)	189.75((N00E)
22	RIML-01	0.005	4.95(N00E)	4.06(+V)	6.37(N90E)
23	CALE-06	0.005	4.98(N90W)	2.45(+V)	4.62 (N00W)

Table 3.2 Accelerograms database of Colima and Guerrero States

#	Station name	Sampling intervals	PGA (cm/s^2) Channel 1	PGA (cm/s^2) Channel 2	PGA (cm/s^2) Channel 3
Colima					
24	MZ – 01	0.01	387.62(N00W)	302.86(+V)	387.13(N90W)
25	MZ – 02	0.01	9.25(N00E)	2.55(+V)	8.93(N90E)
26	MZ – 03	0.01	7(N00E)	3(+V)	4.92(N90E)
27	MZ – 04	0.01	9.28(N00E)	3.77(+V)	10.18(N90E)
28	MZ – 05	0.01	111.67(N00E)	45.49(+V)	117.75(N90E)
29	MZ – 06	0.01	106.34(N00E)	67.02(+V)	183.21(N90E)
Guerrero					
30	AZIH – 01	0.01	4.47(+V)	8.25(N90W)	6.12(S00E)
31	PAPN	0.01	13.13(+V)	16.55(S90W)	15.51(S00W)
32	CHI – 01	0.02	21.88(N00E)	12.81(+V)	13.47(N90W)
33	CPDR – 01	0.01	11.01(+V)	14.07(S90W)	10.93(S00W)
34	FICA	0.01	8.1(N00E)	7.27(+V)	11.9(N90W)
35	MSAS	0.005	43.51(S90E)	19.94(+V)	31.38(S00E)
36	OCTT	0.01	8.14(V)	14.06(N90E)	12.82(N00E)
37	ACAJ – 01	0.01	7.05(N00E)	8.33(N90E)	5.98(+V)
38	CHIL – 01	0.01	10.5(N00E)	7.97(N90E)	6.74(+V)
39	COYC – 01	0.01	4.79(V)	6.7(N90E)	8.61(N00E)
40	CPDR – 02	0.01	10.53(V)	12.44(N90E)	13.4(N00E)
41	MEZC	0.01	4.25(N00E)	6.84(N90E)	5.13(+V)
42	CHI – 02	0.02	43.14(N00E)	21.36(+V)	29.32(N90E)
43	ACAJ – 02	0.01	13.76(N00E)	13.28(N90E)	11.6(+V)
44	ATYC – 01	0.005	6.8(S90E)	5.1(V)	8.75(S00E)
45	CHIL – 02	0.01	26.31(N00E)	19.1(N90E)	18.55(+V)
46	COPL – 01	0.01	46.42(V)	68.91(N90E)	77.04(N00E)
47	COPL – 02	0.01	9.75(V)	25.84(N90E)	21.53(N00E)
48	ATYC – 02	0.005	59.96(S90E)	59.7(V)	53.04(S00E)
49	AZIH – 02	0.01	100.09(+V)	153.93(S90W)	98.62(S00W)
50	COYC – 02	0.01	18.84(+V)	35.69(N90W)	42.04(S00E)
51	CPDR – 03	0.01	12.3(+V)	15.3(S90W)	25.78(S00W)
52	SUCH	0.01	49.62(+V)	81.45(S90W)	103.12(S00W)
53	TEAC	0.01	24.73(S90E)	27.14(+V)	51.3(S00E)

In table 3.1 the general characteristics of the selected registers from Michoacán State are shown. The signal number, station name, sampling interval and peak ground acceleration in three orthogonal components are shown in columns one to six, respectively. These values are presented in table 3.2 for signals registered in stations located on Colima and Guerrero States. Accelerograms of table 3.1 and 3.2 were registered on rigid soils.

In order to eliminate erroneous frequencies and bad register procedures in used accelerograms, they were modified applying a normal filter and a baseline correction. Signals with incomplete or incorrect register procedure were eliminated in the database. For the filtered signals response spectrums were defined.

4. RESULTS

The bridges models described on section two were subjected to all the accelerograms described on tables 3.1 and 3.2, in three orthogonal directions. Then, more than 400 modal spectral analyses were accomplished to obtain maximum responses in form of displacements and internal forces in the extreme node of piers, the ones schematized in figure 4.1. In these analyses, the strong horizontal component of the signal is applied in the transversal direction of the structure, to consider the worst setting.

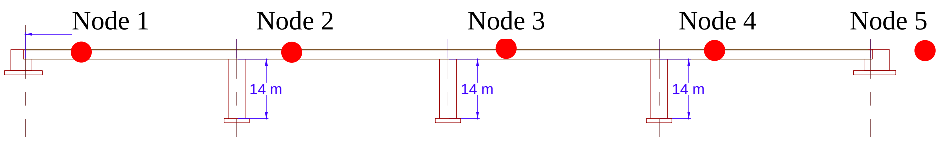


Figure 4.1 Nodes where seismic responses were evaluated

Maximum responses in displacements and internal forces in three directions were combined by means of the SRSS rule, to obtain the total maximum responses in each node. The regular model responses were compared with the ones of irregular structures, to obtain percentages of normalized difference, that is

$$D_{if} = \frac{R_r - R_{ir}}{R_r}(100) \tag{4.1}$$

where: D_{if} is the percentage of normalized difference between the regular and irregular responses of bridge models, R_r is the response of the regular bridge and R_{ir} is the response of irregular systems.

The values of D_{if} parameter were obtained for each of the five nodes of figure 4.1, signals and degree of substructure irregularity. Also, mean and standard deviation values of this parameter for each node were defined. Because of space limitations, only a few results were presented in this paper, specifically the responses in the node three (central) of figure 4.1. Variations in the parameter of equation 1 for the transversal displacement and for reductions or increments of the central pier length are presented in figures 4.2 and 4.3. Similar values for the longitudinal displacement in the node three can be observed in figures 4.4 and 4.5.

As it is observed in figure 4.2, if the length of the central pier is diminished, more variations of the D_{if} parameter in maximum displacement are obtained, compared with values defined when the length of the central pier is incremented. In general, to larger or shorter length of the piers, greater displacements are obtained. D_{if} parameter of equation 1 has similar variations in transversal and longitudinal displacements of the node three. High values in this parameter in the right graphic of figures 4.3 and 4.5 are due to very small displacement values in regular and irregular bridges.

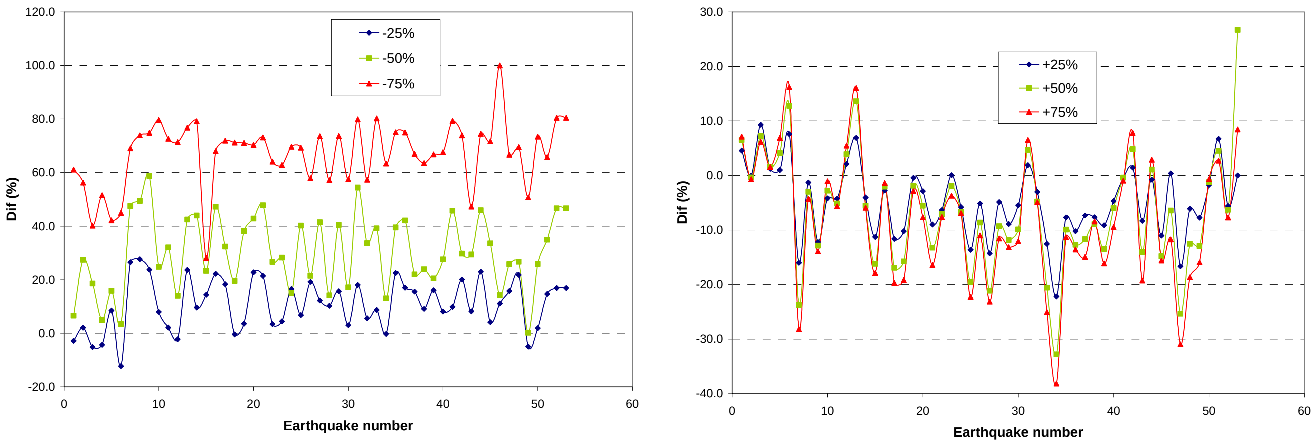


Figure 4.2 Transversal displacements in the node three. Modification of the central pier length

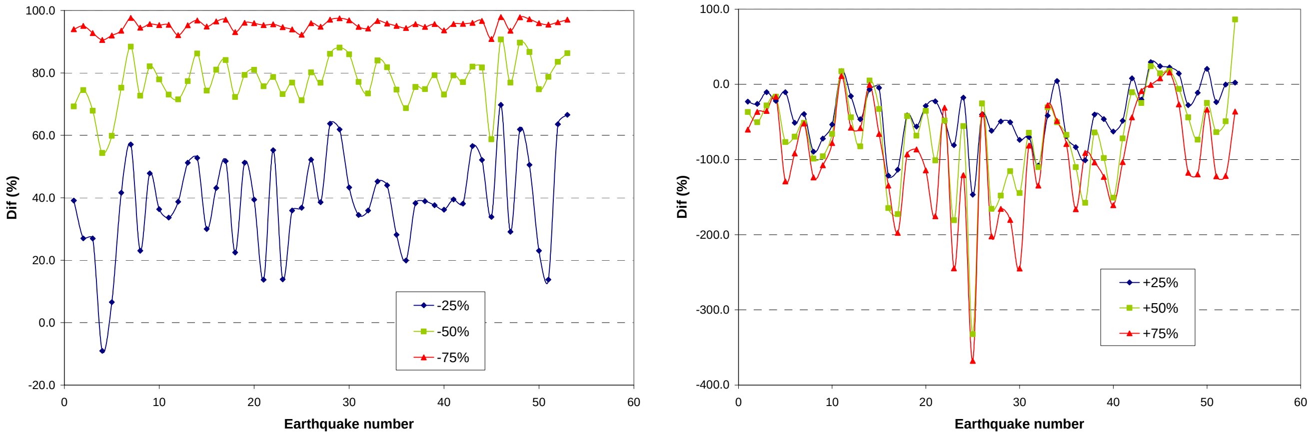


Figure 4.3 Longitudinal displacements in the node three. Modification of the central pier length

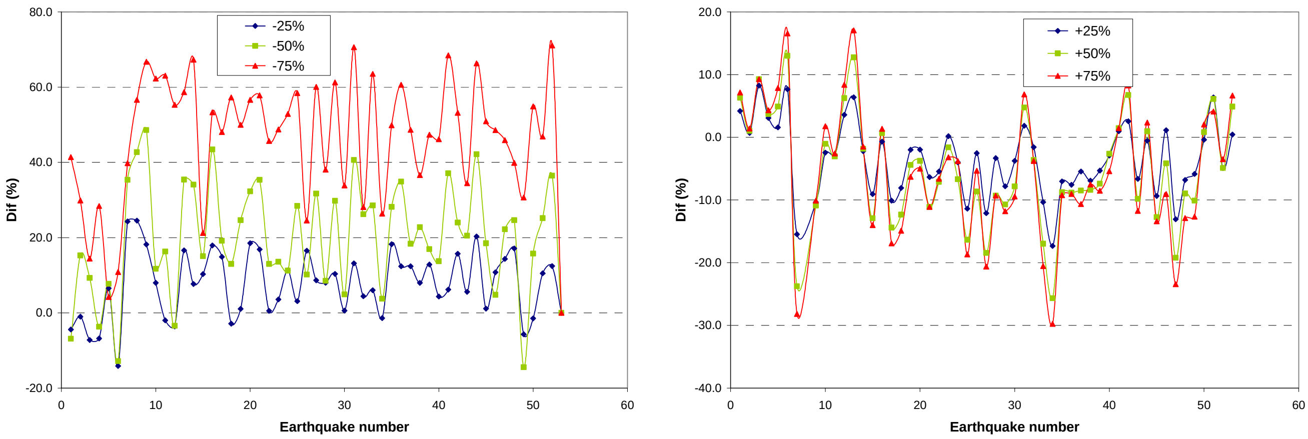


Figure 4.4 Transversal displacements in the node three. Modification of the extreme pier length

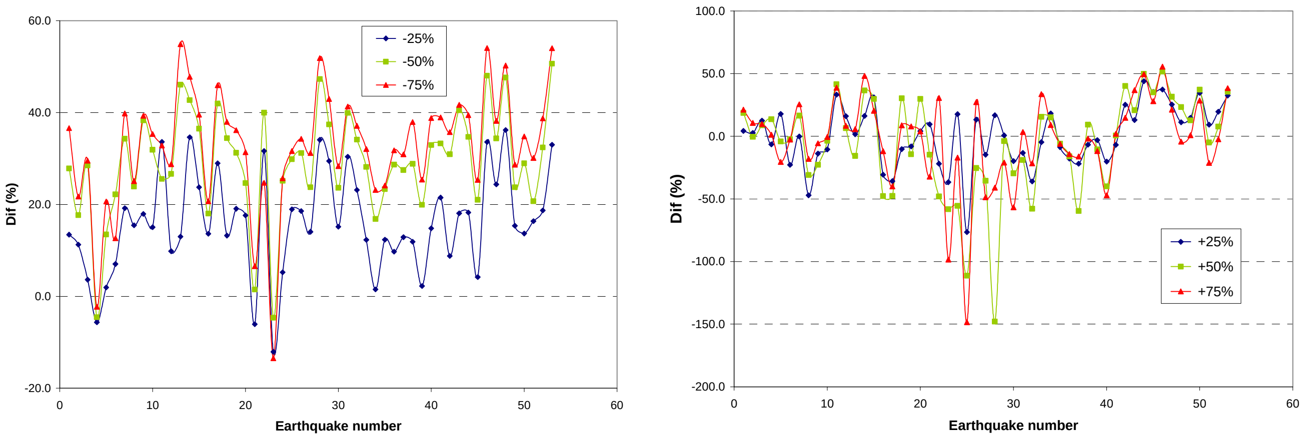


Figure 4.5 Longitudinal displacements in the node three. Modification of the extreme pier length

Means and standard deviations of D_{if} parameter for transversal and longitudinal displacements in the node three are shown in table 4.1. In this table it is observed that the mean values are greater when the length of the central pier is reduced, although the standard deviations are similar. In addition, differences between regular and irregular displacements in the node three are greater for transversal than longitudinal directions, because longitudinal displacements are lesser. When the length of extreme pier is modified, lesser means and standard deviations are obtained. The means and standard deviations can be used as fragility weights of the irregularity degree in the substructure of bridges. Then, for example, a 25% of difference in the length of adjacent piers can produce variations of transversal displacements of 3.5% to 10.5%. These comments are preliminary, because it is necessary to accomplish non-linear analyses to relate irregularity degrees with expected damages.

Similar tendencies were observed in displacement results of other nodes. For internal forces (momentum, shear and axial loads) the commented tendencies are also similar, however the variations due to decreasing and increment of length of the piers are lesser.

Table 4.1 Means and standard deviations in the node three

	Transversal displacement Dif (%)		Longitudinal displacement Dif (%)	
	$\bar{x}$	s	$\bar{x}$	S
Modifying the central pier length				
-25%	10.59	9.51	39.3	15.99
-50%	29.04	15.46	37.42	7.44
-75%	65.39	16.66	95.17	1.17
+25%	-4.8	6.55	-38.36	39.74
+50%	-6.12	12.08	-68.92	67.06
+75%	-8.14	11.61	-94.87	74.38
Modifying the extreme pier length				
-25%	7.56	8.77	16.02	10.87
-50%	19.46	15.7	29.13	11.66
-75%	45.44	20.38	32.67	12.83
+25%	-3.49	5.77	0.44	24.02
+50%	-4.98	8.71	-5.95	39.23
+75%	-5.37	10.33	-2.27	35.67

5 FINNAL COMMENTS

Most of preliminary methods to estimate the seismic vulnerability of bridges use, as an evaluation parameter, the substructure irregularity, obtained by means of subjective assignation of the irregularity degree. In order to consider more rigorous evaluations in the substructure irregularity parameter, regular and irregular models of a simple bridge were subjected to more than 50 accelerograms in three orthogonal components. The substructure irregularity was evaluated changing the length of the central pier or one of the extreme piers in percentages of -25%, -50%, -75%, +25%, +50% and +75%. Using modal spectral analyses the maximum responses in displacement and internal forces were defined for the extreme node of each pier, irregularity degree and earthquake signal. Statistical means and standard deviations were obtained for each node.

Analyzing the obtained results the follow commentaries were considered:

- Differences between the regular and irregular bridges responses are due to the variation of the pier lengths. When the dimension of the central pier changes, important variations of maximum displacements are obtained. Minor variations are obtained in internal forces.
- In general, more variations in the pier lengths are related with greater differences of responses of regular and irregular models. But, for some earthquakes, this tendency is not observed. This is attributed to bridge and earthquakes dynamic characteristics.
- Means and standard deviations of the normalized difference parameter indicate vulnerability weighs for various substructure irregularity degrees.

- Mean and standard deviation values are greater when the length of the pier is reduced, compared with greater length of the pier.

It is necessary to evaluate the influence of substructure irregularity with earthquakes of different characteristics. For example, with signals registered in soft soil. For irregular models, equal capacity was considered for all piers, however they could be different. Bridges irregularity not only includes the substructure irregularity, so no regular conditions in the superstructure will be considered. It is important to estimate the influence of different substructure irregularity with expected damage of the system, so non-linear analyses should be accomplished.

REFERENCES

MCSGM (2000). Mexican Catalog of Strong Ground Motions. CD-ROOM. Seismic Engineering Society of México

Estrada Ruiz, L. and Reinoso-Angulo, E. (2005). Desplazamientos relativos longitudinales en pilas de puentes. *Revista de Ingeniería Sísmica*, SMIS, México, **1:72**, 25-44

Gómez-Soberón, C. and Barrera-Bautista, L.A. (2007). Preliminary estimation of seismic vulnerability of a database of bridges located at the Mexican Pacific Coast. *Proceedings of the IABSE Symposium Improving Infrastructure Worldwide* CD ROOM. Paper number A-0707.

Priestley M.J.N., Seible, F. and Calvi, G.M. (1996). Seismic Design and Retrofit of Bridges. John Wiley and Sons, Inc.

Ren, S. and Gaus, M. P. (1996). Gis tools for regional bridge seismic risk assessment. *Technical report GIS-2*. Department of Civil Engineering, State University of NY at Buffalo