SEISMIC STUDY OF THE URBAN BRIDGES OF THE CITY OF ENSENADA, BAJA CALIFORNIA, MEXICO

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ABSTRACT :

The coastal city of Ensenada Mexico (300 km south of Los Angeles, California), lies in an area close to the San Andres fault system, hence, seismic risk studies aimed to prevent the disaster that an eventual fail of the infrastructure (particularly the 29 city's urban bridges) might cause, are required. The objective of this research is to characterize those bridges in a Geographic Information System (GIS) according to their vulnerability. To achieve this goal, the study has been integrated in three stages: microtremors' measurement, to determine the bridge's fundamental periods; seismic vulnerability computation with Maldonado method (fuzzy sets) and correlation with the structural models of finite-element of some bridges; and the GIS construction. With this information, a GIS showing the seismic vulnerability for each bridge is available to be harness by the local emergency management agency.

KEYWORDS: Bridges, seismic research, seismic vulnerability, microtremors, fuzzy sets

1. BRIEF BRIDGES DESCRIPTION

Table 1. Bridges main data: structural type, plan dimensions, span number and crossing stream.

Bridge	Structural type	Length	Width	Span Number	Stream
Calle Segunda	Reinforced concrete with simply supported over piers prestressed beams	54.70	15.40	3	Ensenada Stream
Villabonita	Reinforced concrete with simply supported over piers prestressed beams	32.00	10.60	1	El Gallo Stream
El Gallo	Reinforced concrete caisson supported over the abutments	18.00	18.50	1	El Gallo Stream
Calle Nueve	Reinforced concrete with simply supported over piers prestressed beams	43.30	17.60	3	Ensenada Stream

Four of twenty nine bridges of Ensenada City (Table 1) were subjected to measurements of microtremors. The bridges, with 2 or 4 circulation tracks, were erected with reinforced concrete, three of them with prestressed simple-supported over piers beams and one, with a caisson system supported over the abutments (Figure 1).

Figure 1 One of the 29 Ensenada urban bridges: Calle 9.

2. EQUIPMENT SPECIFICATIONS

2.1. Sensors

Four EpiSensor FBA ES-T accelerometers that use piezoelectric elements to detect the three orthogonal components of the microtremors were used. Their specifications are shown in the table 2.

Table 2. Triaxial EpiSensor FBA ES-T accelerometer specifications

Bandwidth	DC-200 Hz
Cross-axis sensitivity:	< 1% (including misalignment)
Full-scale range:	User selectable at ± 0.25g
Outputs:	User selectable at: ± 2.5V single-ended; ± 10V single-ended; ± 5 V differential; ± 20 V differential

2.2. Event recorder

To record the waves, a Kinemetrics SSR-1 six channels recorder was used (Table 3). A laptop is used to set the recording parameters: the computer is plugged to the recorder and using a communication protocol, the parameters to start the record are defined. When a wave is registered by the accelerometer, enters to the recorder, where according to the way the sign should be registered, the number of channels, sample velocity, gain, and filter type is selected.

Table 3. Kinemetrics SSR-1 recorder specifications

Storage type	Solid state memory
Available channels	6
Analogic-digital converter	16 bits
Filters type	6 poles Butterworth and Bessel
Filter’s crop frequency	5, 15 ó 50 Hz
Gain	1, 10, 100 ó 1000
Sample frequency	50, 100 o 200 samples/s

3. PROCEDURE

3.1. Excitation source

Microtremors –consisting in low energy waves and periods between 0.1 and 10 s–, are the excitation source used to measure the structure's response. Microtremors are mainly generated by human activity, industrial machinery performance and vehicular traffic. Also, contains wind-produced vibrations induced into the soil by trees, buildings or by their impact on the relief. This source is not associated to earthquakes and some researchers regard that microtremors (natural or cultural noise) is formed by superficial waves generated at ocean-continent interaction zones, by planet's fundamental vibration modes, by atmospheric pressure changes and by internal volcanic activity, as well as by artificial sources previously quoted (Espinoza, 1999). As an advantage, this excitation source is non-destructive –does not cause damage to the structure– because of its low acceleration, in order of 10^{-3} cm/s^2.

3.2. Sensor's arrays

To measure the microtremors and according to the geometric characteristics of each bridge, different arrays of sensors were disposed on the structure. For each array, all three orthogonal directions of movement were registered, assigning always the *x*, *y* and *z*, axis to longitudinal, transversal and vertical directions, respectively. For instance, to measure the longitudinal (in the direction of the traffic of vehicles), transversal (in the direction of the flow of the stream), and vertical components, the sensors were placed in the corners of the El Gallo bridge and free field as shown in Figure 2.

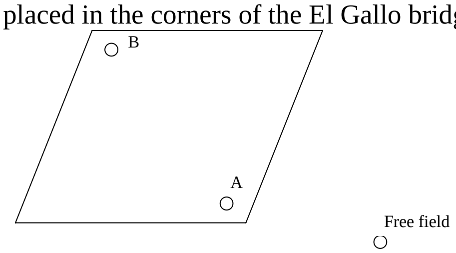

Figure 2 Outline of El Gallo bridge and measured points

3.3. Data recording.

Collected time series range was between 10 and 20 minutes and sample frequency was 50 Hz, for all cases. Registered microtremors waves were processed at the frequencies domain to obtain transfer functions using as input the signal measured at free field and as output the signal at the bridge's deck.

4. MALDONADO METHOD AND CALCULATION OF VULNERABILITY INDEX

In this work the fuzzy sets are used to quantify the vulnerability index relating the qualifications of each parameter and its respective values of importance (Cervantes, 2007). The traditional method of combination of several pieces of information, with unequal importance or weights is used to calculate the seismic vulnerability index of the Ensenada urban bridges. The vulnerability index is expressed in the following formula (Eqn. 4.1):

$$IV = \frac{\sum_{i=1}^{19} W_i K_i}{\sum_{i=1}^{19} W_i} \tag{4.1}$$

where *IV* is the seismic vulnerability index of the bridge, K_i is a measurement of the degree of vulnerability of the category of parameter *i*. The W_i values (weights) are the measurement of the opinion of the importance associated to parameter *i* with respect to the other parameters. The values K_i and W_i are fuzzy numbers. Regarded the most relevant and influential on the bridge behavior under a seismic action, those parameters were determined by Maldonado (2000) and are used to calculate the vulnerability index *IV*.

Table 4. Maldonado Method uses 19 parameters that were determined based in studies realized on behavior seismic of bridges, postearthquake experiences, studies of existing models and opinions of experts.

Parameter of the model	
Symbol	**Description**
K_1	Year of project and construction of the bridge
K_2	Type of superstructure
K_3	Shape of the superstructure
K_4	Existence of internal joints
K_5	Material of the superstructure
K_6	Type of pile
K_7	Type of foundation
K_8	Material of pile
K_9	Longitudinal irregularity in geometry or stiffness
K_{10}	Length of stirrup
K_{11}	Soil type
K_{12}	Type of stirrup
K_{13}	Length of abutment
K_{14}	Type of support
K_{15}	Conservation condition
K_{16}	Constructive procedure
K_{17}	Constructive procedure of the piles (concrete)
K_{18}	Liquefaction potential
K_{19}	Nonstructural elements

5. FINITE ELEMENT MODEL

A three-dimensional finite element modeling technique for slab-on-girder bridges was used to verify the experimental tests. Figure 3 shows a model of the standard single span of the so-called El Gallo bridge (Espinoza et al, 2004).

For the bridge's analyses, the live loads were considered using the criterions of the regulation of the AASHTO (1992); while the accidental loads were considered the criterions of the manual of civil works of the Electrical Federal Commission (1993); at last the different elements of concrete reinforced were design in agreement with the Regulation of the Constructions of Concrete Reinforced ACI-318-95.

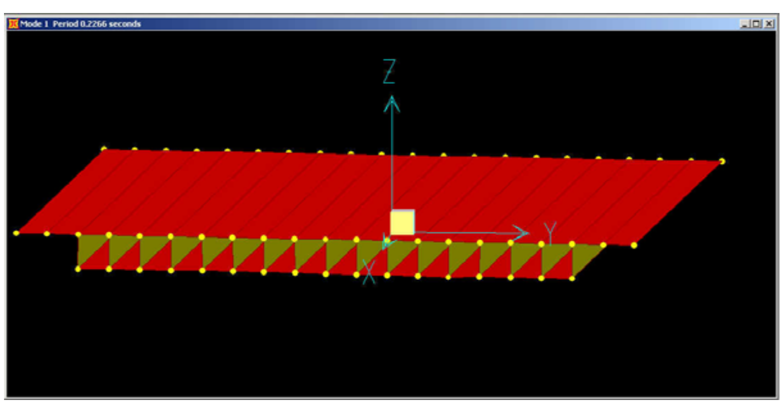

Figure 3. Lateral view of El Gallo Bridge.

A structural analysis program (SAP2000) was used to perform analyses. As shown in Figure 3, the model includes shell elements for the superstructure. The bridge members properties were fy = 4200 kg/cm^2 for steel and f'c = 250 kg/cm^2 for concrete. The total dead load was 1470 kg/m^2 and the live load was 2903 kg/m^2. Furthermore, a concentrated load of 3132 kg was considered in agreement of AASHTO code. Fundamental period obtained using modal analyses is 0.23s.

From analysis of the time series (Figure 4) we obtained Fourier spectra (Figure 5) and identify frequencies and fundamental periods (table 6). The stiffest bridge is El Gallo, with around 0.2 s in its three components, and the most flexible, Calle Nueve bridge with 1.7 s at longitudinal direction. Soils periods vary from 0.3 to 0.8 s.

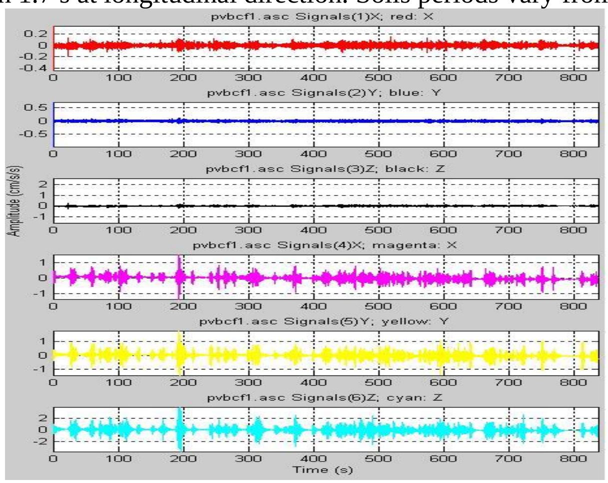

Figure 4 Accelerations measured in two sensors with 3 channels (*x = longitudinal*, *y = transversal and z = vertical*) in up to down order. Upper signals belong to free field and the bottom ones to deck of Villabonita bridge.

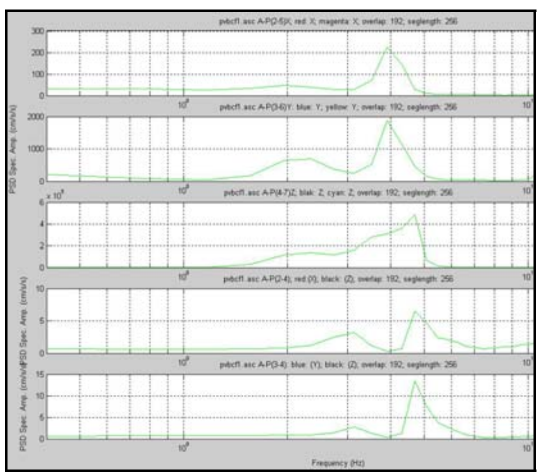

Figure 5. Power Spectral density of signals measured at Villabonita bridge. The upper graps correspond to x,y and z component and bottom graphs represent transfer function in x and y component.

Table 6 Vibration fundamental mode frequencies (Hz) of the four bridges. Inside parenthesis, periods in seconds are shown. Associated value with the X component of Calle Segunda bridge was not identified.

Bridge	**X**	**Y**	**Z**	**Soil**	
	Longitudinal	**Transversal**	**Vertical**	**X**	**Y**
Calle Segunda	1.4 (0.7)	6.5 (0.2)	8.8 (0.1)	-	1.2 (0.8)
Villabonita	3.8 (0.3)	3.8 (0.3)	4.6 (0.2)	3.2 (0.3)	3.2 (0.3)
El Gallo	4.3 (0.2)	5.6(0.2)	4.3 (0.2)	1.2 (0.8)	1.4 (0.7)
Calle Nueve	0.6 (1.7)	4.4 (0.2)	0.7 (1.4)	1.6 (0.6)	1.4 (0.7)

6. GEOGRAPHIC INFORMATION SYSTEM (GIS)

GIS is a relatively recent tool assisting seismic risk researches. It eases analysis method implementation, data management and in particular, results visualization thanks to its georeferencial capacity, which permits to model geographic elements in the research zone in a more realistic way. In addition, database support on which SIG data is built, ease data managements in a simple and quick way (Mena, 2002).

To generate the web based GIS, Bridges' geographic coordinates, the IV and other columns are lumped. The SIG is built with ArcView and its execution runs on ArcExplorer. The first application permits to visualize and to edit the map and the second one permits to visualize the map on the web. Vectorial data format is Shapefile (.shp) and raster image format is Joint Photographic Experts Group (.jpeg). Once finished, this tool brings support in the generation and disposition of seismic risk maps and in the determination of contingency plans on emergency cases (Juarez et al, 2007).

7 RESULTS

Database and web-based GIS are shown in figures 6 and 7, respectively. As a result, a GIS containing the vulnerability index for all bridges in the urban zone of Ensenada, is available to be harness by the local emergency management agency.

Table 7 SIG's generatrix table; first column: identification number; second: road name; third and fourth: geographical coordinates obtained from a Garmin GPS device; fifth: negotiated hurdle by the bridge; sixth to eight: bridge's length, width and span number; ninth and tenth: vulnerability index and its interpretation, respectively.

1	Blvd. General Lázaro Cárdenas	31°51'33.5"N	116°37'11.7"W	Ensenada Stream	61.50	2 tranches of 15.5m	4	2.3	Low vulnerability
2	Calle Segunda	31°51'40.6"N	116°37'4.3"W	Ensenada Stream	54.70	15.5	3	3.4	Low vulnerability
3	Av. Juárez	31°51'51.7"N	116°36'58.9"W	Ensenada Stream	61.70	16.7	8	3.2	Low vulnerability
4	Calle Novena	31°52'7.30"N	116°36'54.3"W	Ensenada Stream	43.30	17.6	3	4.5	Moderate vulnerability
5	Calle Once	31°56'16.6"N	116°36'52.9"W	Ensenada Stream	50.00	20	2	4.1	Low vulnerability
6	Alisos	31°52'40.9"N	116°36'44.4"W	Ensenada Stream	43.00	9.5	3	2.8	Low vulnerability
7	Av. Ambar	31°52'57.7"N	116°36'38"W	Ensenada Stream	18.00	21	1	3.1	Low vulnerability
8	Av. Reforma	31°53'0.3"N	116°36'37.8"W	Ensenada Stream	24.50	10	5	4.7	Moderate vulnerability
9	Av. Espinoza	31°52'9.3"N	116°36'47.2"W	El Aguajito Stream	20.60	10	1	3.5	Low vulnerability
10	Calle Once (Xochicalco)	31°52'8.1"N	116°36'36.1"W	Ensenada Stream	18.10	16.8	1	3.6	Low vulnerability
11	Av. Reforma (Mision)	31°52'19.30"N	116°36'29.4"W	Ensenada Stream	28.10	19.8	1	3.3	Low vulnerability
12	I. Allende	31°52'30.5"N	116°35'48.2"W	Doña Petra Stream	14.00	8.4	3	3.8	Moderate vulnerability
13	Calle Bronce	31°52'33.8"N	116°35'35.2"W	Doña Petra Stream	15.00	10.7	1	4.1	Moderate vulnerability

14	Av. Riveroll	31°52'49.9"N	116°36'50.7"W	Doña Petra Stream	21.60	14.5	1	3.3	Low vulnerability
15	Calle Agaves	31°53'8.3"N	116°36'57.8"W	El Gallo Stream	8.30	8.7	1	3.3	Low vulnerability
16	Calle Puebla	31°53'16.9"N	116°37'1.1"W	El Gallo Stream	11.70	14.6	1	3.8	Low vulnerability
17	Puente Nuevo	31°50'49.7"N	116°34'21.5"W	El Gallo Stream	21.80	2 tranches of 12.30m	1	2.8	Low vulnerability
18	Av. Pedro Loyola	31°50'46.00"N	116°36'28.2"W	El Gallo Stream	19.25	23.5	1	3.1	Low vulnerability
19	Av. Reforma	31°50'45.8"N	116°36'10.8"W	El Gallo Stream	62.65	26	5	3.7	Low vulnerability
20	Av. Mexico	31°50'43.20"N	116°35'24.3"W	El Gallo Stream	18.00	18.5	1	3.3	Low vulnerability
21	Access to Villa Bonita	31°50'49.2"N	116°34'21.8"W	Tijuana-Ensenada Road	32.00	10.6	1	2.7	Low vulnerability
22	Access to Ensenada by Recinto Portuario	31°59'29.10"N	116°38'7.4"W	Tijuana-Ensenada Road	30.50	36	1	3.8	Low vulnerability
23	Marina Coral	31°52'0.2"N	116°39'40.4"W	Tijuana-Ensenada Road	30.00	14	1	3.8	Low vulnerability
24	Access to UABC	31°51'59.9"N	116°40'1.7"W	Tijuana-Ensenada Road	32.00	13	2	3.7	Low vulnerability
25	Access to Ensenada from Tecate	31°53'55.00"N	116°42'17.7"W	Tijuana-Ensenada Road	28.15	9	2	4.0	Moderate vulnerability
26	Access to Cibolas del mar from Tijuana	31°54'13.13"N	116°43'21.00"W	Tijuana-Ensenada Road	25.70	22.6	3	2.8	Low vulnerability
27	Access to Carretera libre from Tiuana	31°54'13.00"N	116°43'39.8"W	Tijuana-Ensenada Road	25.80	9	2	3.0	Low vulnerability
28	San Miguel			Riverbed unidentified	82.00	10	4	3.9	Moderate vulnerability
29	Carretera Transpeninsular (San Carlos)	31°46'16.5"N	116°35'17.00"W	Riverbed unidentified	38.00	17.5	3	3.8	Moderate vulnerability

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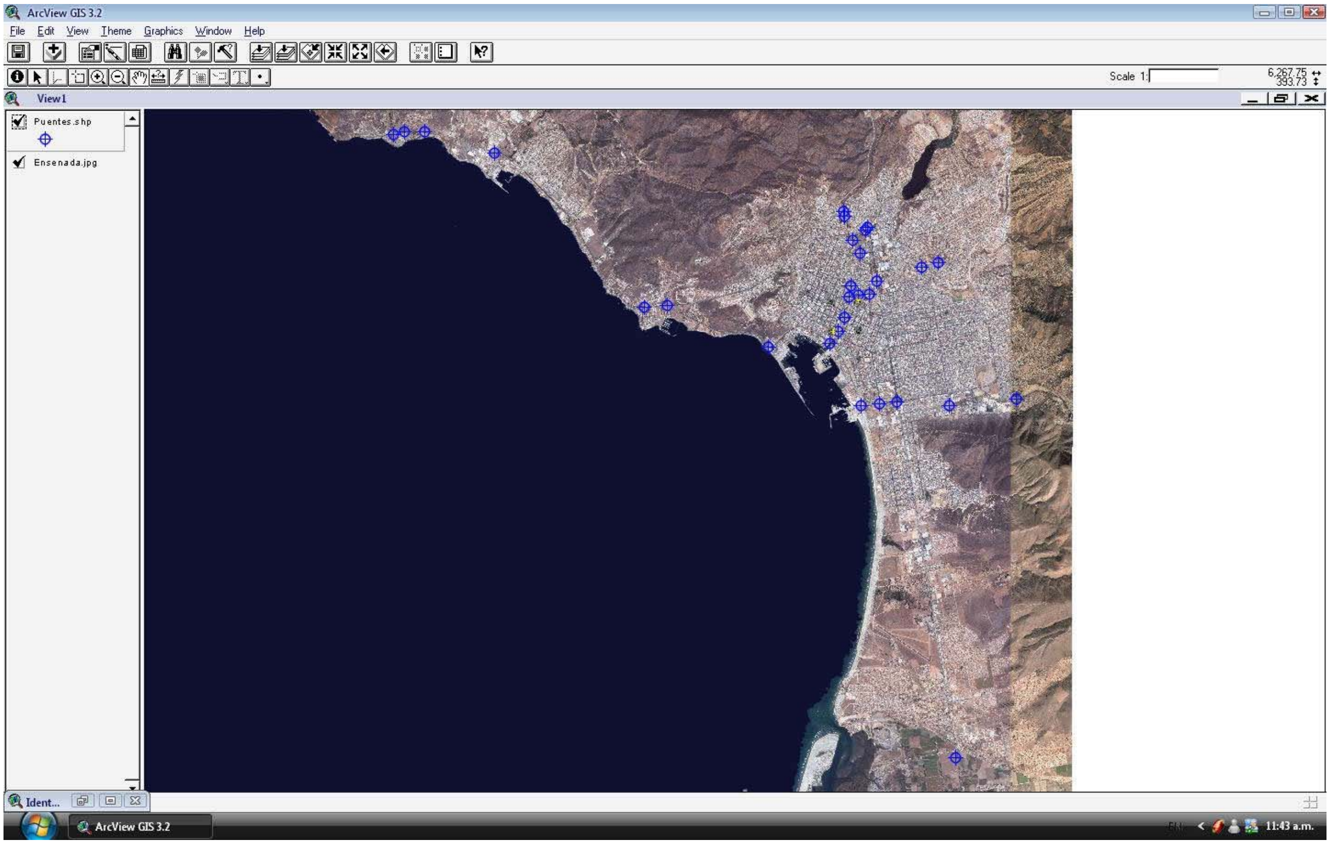

Figure 6. Map's visualization with ArcView, showing all bridges constructed in the urban zone of Ensenada, Baja California Mexico.

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