Seismic Soil-Structure Interaction Effects in Instrumented Bridges

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SUMMARY:
This paper presents preliminary results from a major study of the seismic response of bridges, based on acceleration records from instrumented bridges. A database on instrumented bridges is being assembled which currently contains records from ten bridges which have been subjected to multiple earthquakes and aftershocks. The first objective of the study is to investigate soil structure interaction (SSI) and how it has affected the responses of the bridges and especially the input motions to the bridges. The effects of SSI are demonstrated by comparing the acceleration spectra of the free field motions with the spectra of the bridge motions recorded at the foundation slabs or on the pile caps. It is generally accepted that SSI de-amplifies the foundation motions and FEMA outlines a procedure for calculating the spectral reduction for shallow or embedded footings. The present study shows clearly that the free field motions are not always deamplified. It has also been found that this inconsistency in response is not due only to differences in bridge structure or site conditions. Whether the same site and bridge will result in amplification or de-amplification varies from one earthquake to another. The paper will provide a detailed exposition of SSI effects on the instrumented bridges and clarify mechanisms leading to the observed phenomena.

Keywords: bridges, soil-structure interaction, seismic records

1. INTRODUCTION

Soil-structure interaction (SSI) can significantly affect the dynamic properties of certain structures. The characteristics of the structure, foundation soil and earthquake input play a role on this [Sextos(2009)]. There are two main physical phenomena that constitute the soil-structure interaction mechanism [Stewart et al (1999)]: 1) the effect of inertia developed in the structure affecting foundation system (called Inertial Interaction), that raises base shear and moment and cause additional displacements of the foundation related to free field, and 2) the difference in stiffness of foundation system and soil, the embedment of the foundation, and the averaging effect of seismic waves passing through the foundation (called Kinematic Interaction). The most sophisticated approaches used to model the effect of SSI include kinematic or inertial interaction separately, but are unable to consider the combined effect of both phenomena, as it happens in real cases. This supports the need of a better understanding of such effect in order to establish a better SSI modelling technique.

In this paper, a method to determine how significant are the SSI effects from the analysis of records obtained from instrumented bridges is presented. The first stage of the proposed method is intended to provide an insight of the dynamic properties of the structure via System Identification methods. Those properties are then used to evaluate the spectral responses, focusing on the difference between free field and column base records, where the displacement spectra are particularly useful considering their sensitivity to the inertial interaction phenomenom [Finn(2010)]. Fourier spectra are also analyzed to evaluate the signals characteristics.

2. EVALUATION METHOD

2.1. Structural System Identification

The first step is to determine fundamental dynamic properties –i.e. natural period and damping ratio– corresponding to the transverse direction for each bridge. The analysis is based on the seismic records provided by the instruments located on bridge's pier base and deck. The software ArteMis Extractor 4.1 has been used to obtain the required dynamic properties. The Enhanced Frequency Domain Decomposition (EFFD) technique was used for this purpose [Ventura et al (2011)]. The fundamental mode and estimated damping ratio in the transverse direction are obtained based on the Singular Value Decomposition charts, by identifying prominent peaks and evaluating their corresponding modal shapes.

2.2. Response Spectra and Directionality

In this step, the response spectra from records obtained from instruments located on the free field, base of bridge piers and deck are computed first. This first stage includes obtaining the response spectra for acceleration, velocity and displacement for each signal, and to conduct a graphical comparison of the computed spectra; this is complemented with a plot of the spectral ratio of column base vs. free field. The frequency content of all signals is determined by reference to Fourier spectra plots. The ground motion directionality characteristics are also presented in order to provide a further insight of how the input signal "attacked" the bridge.

2.3. Results Analysis

The last step is the evaluation of the results to identify trends that may be used for assess the significance of SSI effects.

3. BRIDGES AND GROUND MOTION DESCRIPTIONS

This study included ten bridges instrumented by the California Geological Survey, which basic data and records are available online in the Center for Engineering Strong Motion Data (CESMD) website. All bridges have straight longitudinal axis and accelerometers located at column base, deck and free field. The overall structural characteristics, instrumentation and retrofitting information for all the analyzed bridges are summarized as follows.

Table 1. Analyzed Bridges and their basic instrumentation information (from CESMD website)

Station No.	Location	Bridge Name	Bents Angle	Structure / Foundation Characteristics	Instrumentation
01336	El Centro, Highway 8	Meloland Overpass	Perpendicular	2 spans. Concrete box girder connected monolithically to the abutments. Reinforced concrete central pier with one column. Timber piles as foundation system for a square concrete footing under central pier and also for abutments.	Instrumented in 1978. Upgraded in 1991.
13795	Capistrano Beach, I5	Via California	Perpendicular	6 spans. 6-cell concrete box girder. Cantilever abutments. Reinforced concrete columns, 2 columns per bent. Spread footings.	Instrumented in 1999.
24706	Palmdale, Highway 14	Barrel Springs	Skewed	5 spans. Concrete box girders. Open end diaphragm abutments. 2 Rectangular concrete columns per bent. Spread footings support all bents and abutments. Bridge was retrofitted.	Instrumented in 1994.

Station No.	Location	Bridge Name	Bents Angle	Structure / Foundation Characteristics	Instrumen-tation
47315	San Juan Bautista, Highway 101	156 Overpass	Skewed	6 spans. Welded steel girders with concrete diaphragms supported by rocker bearings. Seat abutments with catcher beams and integral wing walls. Concrete bents with 2 rectangular columns. Spread footings. Retrofitted by adding concrete diaphragm to girders and infill walls between the columns.	First instrumented in 1977. Re-instrumented in 2002.
54730	Lake Crowley	Highway 395 Bridge	Skewed	2 spans. Continuous concrete box girder. Diaphragm abutments. Bents with 2 circular concrete columns. Spread footing foundations.	Instrumented in 1995.
57748	Santa Clara, Highway 237	Alviso Overpass (Bridge K)	Skewed (variable angle)	6 spans. Continuous concrete box girder without intermediate hinges. Seat abutments with elastomeric bearings. One rectangular concrete column per bent with flares in the upper portion. Prestressed concrete piles.	Instrumented in 1995.
57748	Santa Clara, Highway 237	Alviso Overpass (Bridge L)	Skewed (variable angle)	6 spans. Continuous concrete box girder without intermediate hinges. Seat abutments with elastomeric bearings. 2 rectangular concrete columns per bent with flares in the upper portion. Prestressed concrete piles.	Instrumented in 1995.
68717	Rohnert Park, Highway 101	Rohnert Park Bridge	Perpen-dicular	2 spans. Continuous concrete box girder. Sliding diaphragm abutments with elastomeric bearings and shear keys. Two semicircular concrete columns per bent, with flares in the upper portion. Concrete piles as foundation system for abutments bents.	Instrumented in 1995.
89324	Rio Dell, Highway 101	Painter St Overpass	Skewed	2 spans. Continuous concrete box girder. Diaphragm abutments. Two circular concrete columns per bent. Concrete piles.	Instrumented in 1977.
89708	Arcata, Highway 101	Murray Road Bridge	Perpen-dicular	4 spans. 6 concrete T-beams supported on open end cantilever abutments and concrete bents. Abutments with rocker bearings. 2 rectangular concrete columns per bent. Spread footings.	Instrumented in 1995.

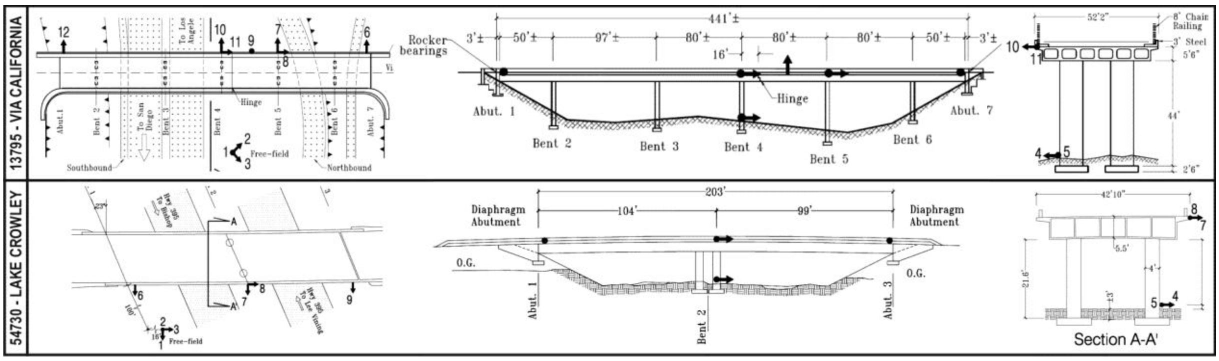


Figure 1. Summarized drawings of Via California and Lake Crowley Hwy 395 bridges

The analysis included 24 ground motions recorded by the instruments on the assessed bridges and free field locations. The basic characteristics of all the ground motions are summarized following table.

Table 2. Analyzed ground motion records basic information

No.	Station	Bridge	Epicenter Location / Date	Epicentral Dist (Km)	PGA	PGV	PGD
					(g)	(cm/s)	(cm)
1	01336	Meloland Overpass	BorregoSprings 07Jul2010	120.2	0.012	1.050	0.137
2	01336	Meloland Overpass	Calexico 20Nov2008	50.4	0.017	0.610	0.158
3	01336	Meloland Overpass	Calexico 22May2010	35.2	0.031	0.670	0.068
4	01336	Meloland Overpass	Calexico 30Dec2009	41.2	0.174	16.610	3.899
5	01336	Meloland Overpass	Calexico 04Apr2010	58.9	0.213	19.050	13.928
6	13795	I5 / Via California	Borrego Springs 17-07-2010	110.1	0.006	0.600	0.140
7	13795	I5 / Via California	Calexico 04-04-2010	337.1	0.020	4.000	2.350
8	13795	I5 / Via California	Chinohillls 29-07-2008	52.1	0.023	1.140	0.280
9	24706	Barrel Springs Bridge	BigBearCity 22022003	120.6	0.009	0.270	0.043
10	24706	Barrel Springs Bridge	Chinohills 29072008	73.6	0.027	0.970	0.063
11	47315	156 Overpass	SanJuanBautista 12012011	12.4	0.016	0.470	0.036
12	47315	156 Overpass	AlumRock 30102007	65.7	0.021	1.500	0.121
13	47315	156 Overpass	Aromas 02072007	4.5	0.073	2.900	0.198
14	54730	Hwy 395	QualeysCamp 18-09-2004	48.7	0.014	0.390	0.070
15	54730	Hwy 395	Toms Place 26-11-2006	16.1	0.015	0.250	0.010
16	54730	Hwy 395	Mammoth Lakes 12-06-2007	12.8	0.051	0.830	0.100
17	57748	Alviso Overpass (K)	Gilroy 13052002	60.0	0.077	0.660	0.074
18	57748	Alviso Overpass (K)	Gilroy 13052002	60.0	0.077	0.660	0.074
19	68717	Hwy 101 Bridge	Bolinas 1999	49.0	0.009	1.150	0.121
20	89324	Painter St Overpass	CapeMendocino 21111986	29.9	0.146	18.380	1.530
21	89324	Painter St Overpass	PetroliaAftershock2 26041992	40.8	0.198	33.440	8.419
22	89324	Painter St Overpass	PetroliaAftershock1 26041992	40.3	0.515	45.620	6.248
23	89324	Painter St Overpass	Petrolia 25041992	17.6	0.541	44.700	17.800
24	89708	Murray Road Bridge	Ferndale 09012010	64.7	0.077	13.120	3.149

4. EVALUATION METHOD RESULTS

The analysis method was applied to all the assessed structural systems. The following section include a detailed explanation of the results for two cases –Via California Bridge (Station No. 13795) and Lake Crowley Hwy 395 (Station No. 54730)– intended to provide a better insight into the application of the evaluation method. The last apart includes a summary of the findings for the other cases.

4.1. Detailed results for Via California Bridge and Painter Street Overpass

4.1.1. System Identification Results

The experimental model of the Via California and Lake Crowley Hwy 395 Bridge were based on the instrumented points that have transverse direction measurements, including channels at the instrumented pier base and on deck. The resulting modal parameters obtained based on each ground motion records are shown below.

Table 3. Transverse fundamental modal parameters identified for both bridges

Bridge	GM No.	Ground Motion	Frequency (Hz)	Damping Ratio (%)
Via California	06	Borrego Springs 07-Jul-2010	2.688	0.834
	07	Calexico 04-Apr-2010	2.518	2.524
	08	Chino Hills 29-Jul-2008	2.623	1.753
Lake Crowley Hwy 395	14	Qualeys Camp 18-09-2004	5.379	0.558
	15	Toms Place 26-11-2006	5.202	0.539
	16	Mammoth Lakes 12-06-2007	5.342	0.356

The results show consistent values, and the variability for natural frequency in both structures is very similar. The estimated damping ratios show agreement for Lake Crowley Bridge, but a variation of about 50% for the Via California Bridge is observed.

The modal shapes have an expected behaviour, noticing a rigid axis rotation in the Lake Crowley Bridge modal shapes, which may be related to the skewed condition of that structure. The variability in identified damping ratio values for Via California Bridge can be originated from several factors, such as soil condition, integrity of the structural elements, and energy-dissipation mechanism acting after the structural retrofitting process carried out in 1999.

4.1.2. Response Spectra and Directionality

The following images show the Response Spectra plots for both analyzed bridges, followed by the discussion of results corresponding to each case.

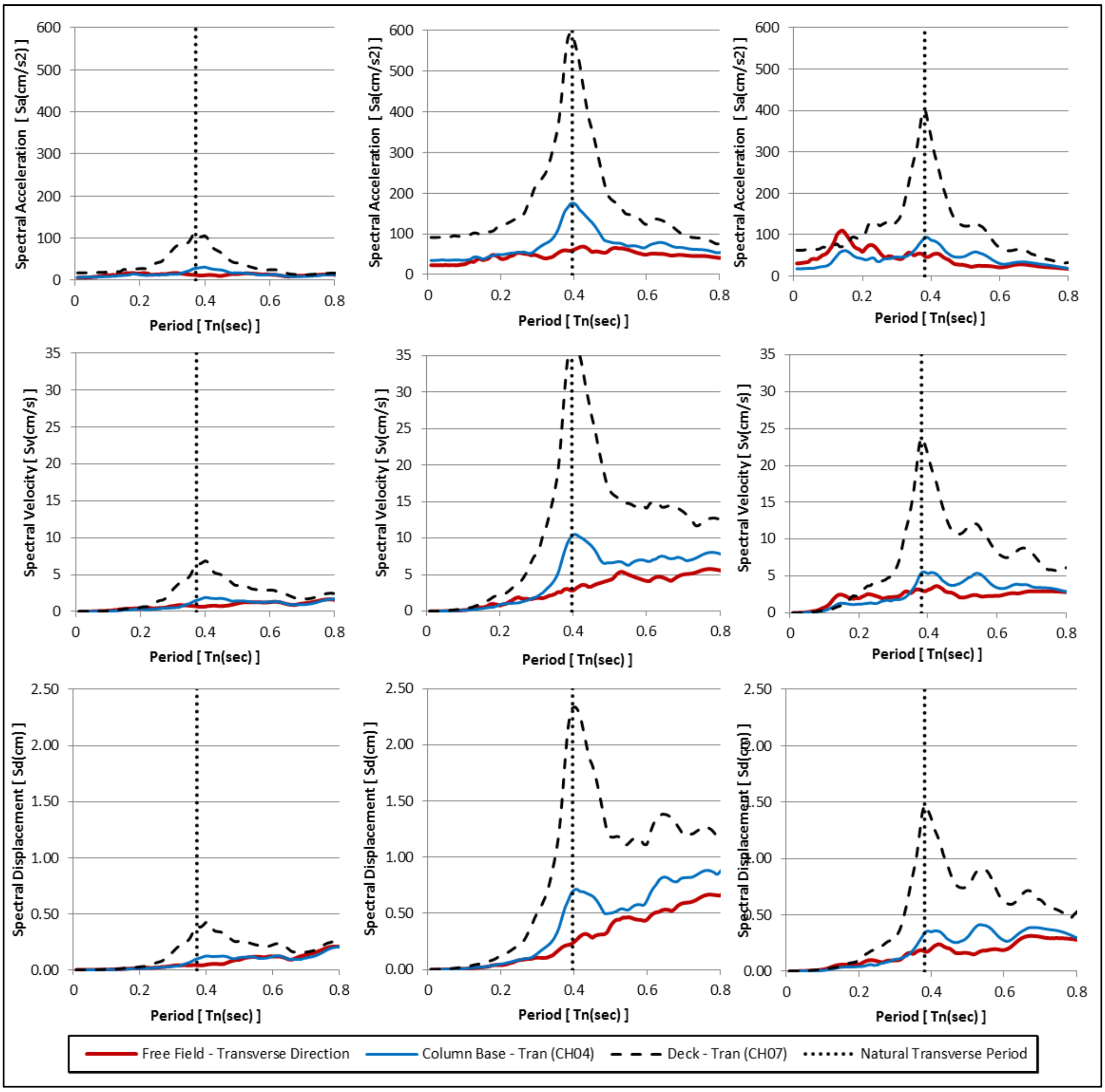


Figure 2. Response spectra for Via California Bridge corresponding to ground motions No. 06 (left), No. 07 (center) and No. 08 (right).

The response spectra in the previous figure show a general agreement in terms of coincidence between peak response and natural period response. The Chino Hills ground motion (No. 08) show a peak acceleration response in free field for periods near 0.15 sec. Although the column base spectrum seems to be affected by this, the agreement corresponding to the peak at natural period remains in all cases.

The response spectra corresponding to Lake Crowley Bridge case –included in the next figure– show a consistent peak for Free Field records at periods near 0.1 seconds, which could be related to dynamic properties of the foundation soil; this condition seems to influence the column base response spectra increasing spectral values near that period. However, there is a fair agreement for having peak spectral values corresponding to the natural period in all cases.

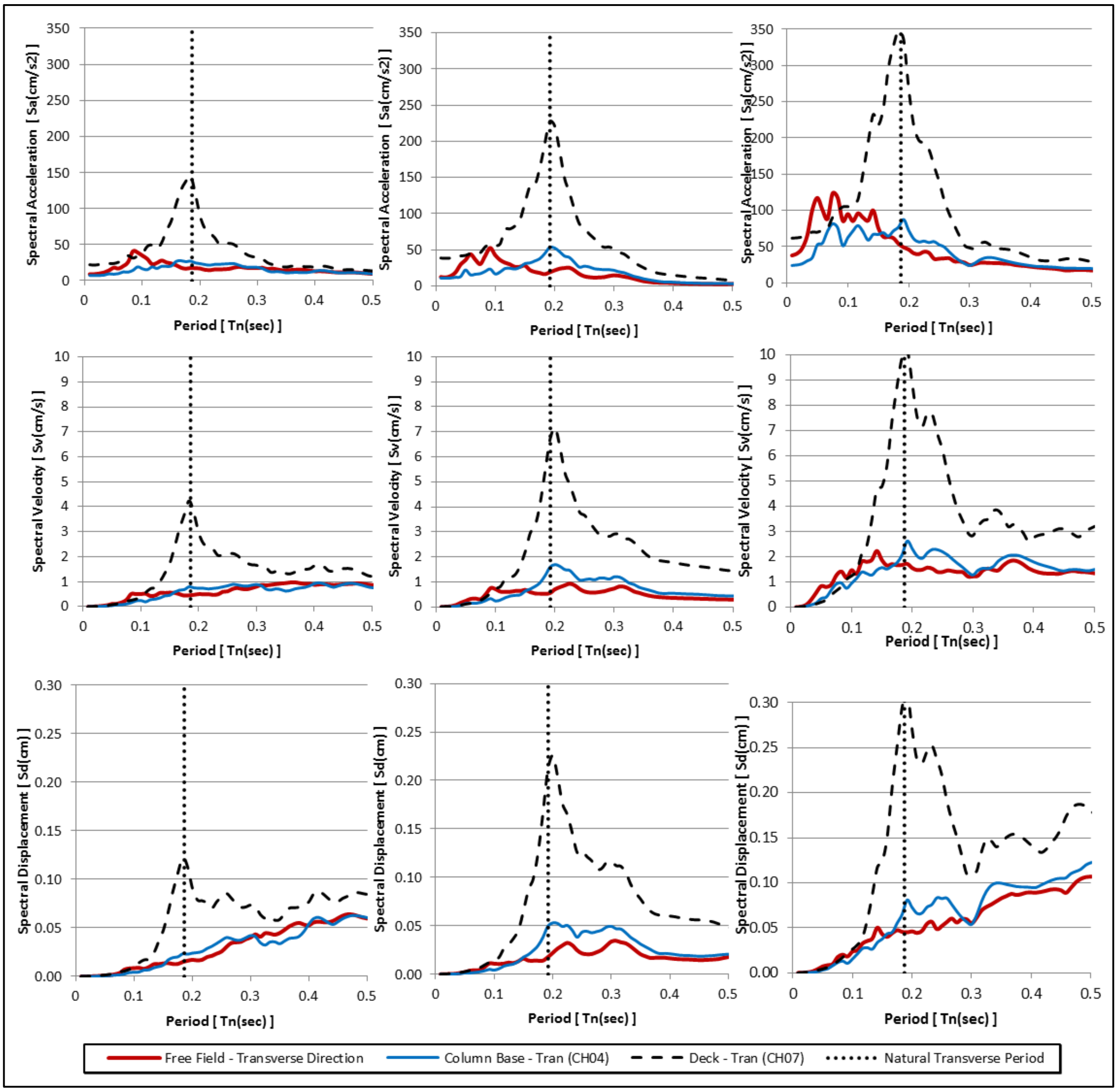
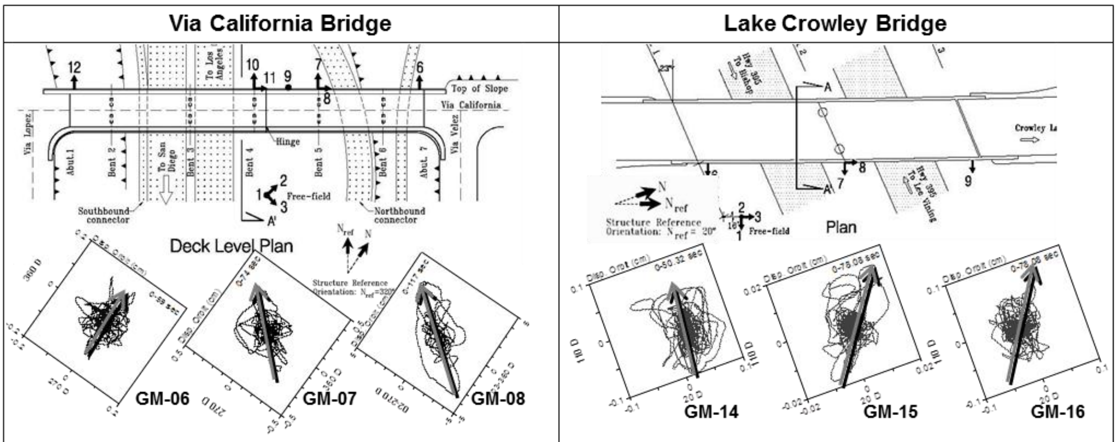


Figure 3. Response spectra for Lake Crowley Bridge corresponding to ground motions No. 14 (left), No. 15 (center) and No. 16 (right).

For both analyzed structures, the response spectra in all cases shows a point –corresponding to a period lower and close to the fundamental– before which free field spectral response values are higher than column base values. After that point the spectral response based on column base signal is predominantly higher that free field.

The directionality of each ground motion is analysed based on the particle orbit plot made from the free field records. In the Via California Bridge case, the ground shaking seems to be oriented predominantly in the bridge’s transverse direction for ground motions 07 and 08. The No. 06 case does not show a clear orientation, which can be defined with similar longitudinal and transverse components related to the bridge axis.

Regarding the Lake Crowley Bridge case, the second and third ground motions orientations seems to have important components perpendicular to the skewed bent direction, whereas the first analysed event seems to have more important components parallel to the skewed angle. The graphics are shown in the following figure.



GM No.	06	07	08
Location	Borrego Springs	Calexico	Chino Hills
PGA (g)	0.006	0.02	0.023

GM No.	14	15	16
Location	Qualeys Camp	Toms Place	Mammoth Lakes
PGA (g)	0.014	0.015	0.051

Figure 4. Estimated directionality of ground shakings and incidence to analyzed bridges.

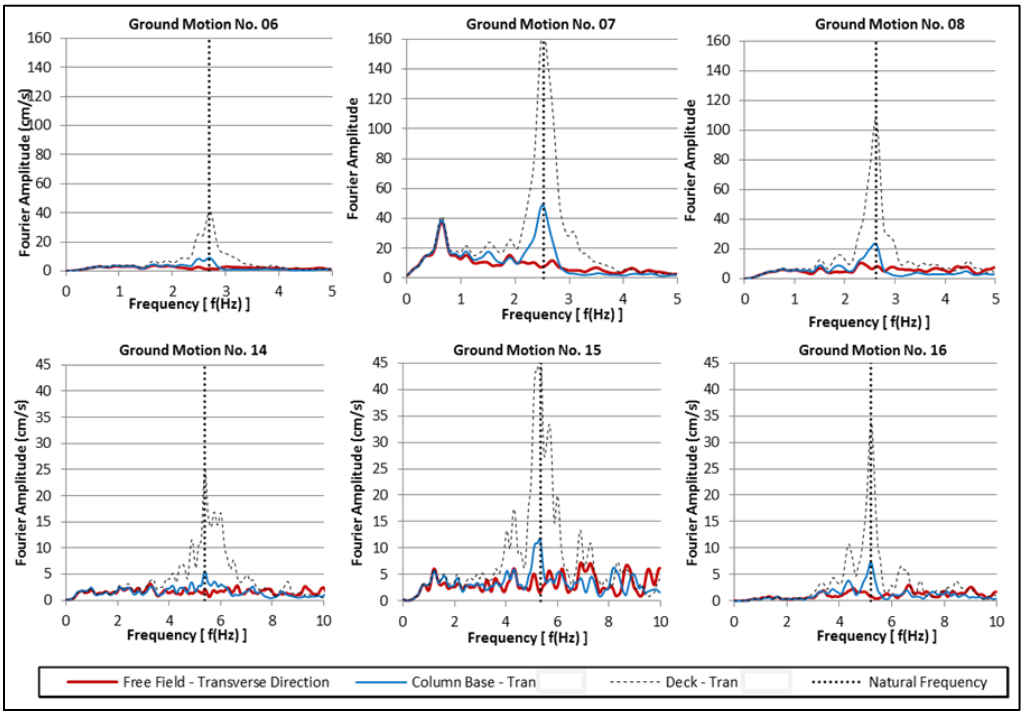


Figure 5. Fourier Spectra corresponding to each ground motion for Via California bridge (top) and Lake Crowley bridge (bottom).

The Fourier Amplitude spectra for Via California Bridge case show strong agreement between free field, column base and deck for frequencies below 1Hz in all cases. Frequencies higher that 1Hz for the column base signal show amplitudes higher than free field, until they pass the amplification range that surrounds the natural frequency and amplitudes become lower in column base compared to free field. The Lake Crowley Bridge case shows a similar behaviour, with a threshold frequency of approximately 2.5Hz for amplitude agreement between signals.

4.1.3. Results Analysis

An effective way of evaluating soil-structure interaction effects in the structural behaviour is the comparison of spectral responses based on free field records with column base records. The table below summarizes the ratio of spectral values corresponding to column base vs. free field for each record.

Table 4. Spectral response ratio for both bridges corresponding to the fundamental transverse period.

No.	Station	Bridge	Record	PGA (g)	Ts (sec)	Sa_{BASE} / Sa_{FF}	Sv_{BASE} / Sv_{FF}	Sd_{BASE} / Sd_{FF}
6	13795	I5 / Via California	Borrego Springs 17-07-2010	0.006	0.372	2.35	2.13	2.36
7		I5 / Via California	Calexico 04-04-2010	0.020	0.396	2.93	3.56	2.93
8		I5 / Via California	Chinohillls 29-07-2008	0.023	0.381	1.92	1.75	1.92
14	54730	Hwy 395	QualeysCamp 18-09-2004	0.014	0.186	1.51	1.70	1.51
15		Hwy 395	Toms Place 26-11-2006	0.015	0.192	2.76	2.82	2.76
16		Hwy 395	Mammoth Lakes 12-06-2007	0.051	0.187	1.59	1.37	1.60

The following remarks can be stated based on the information provided by the previous results reports and information analysis:

- The modal analysis results show consistency in the identified fundamental frequency for both bridges and in damping ratio values for Lake Crowley Bridge.
- The spectral response ratios Column Base vs. Free Field corresponding to the fundamental period show a good agreement for each ground motion in both analyzed bridges, indicating clear amplification condition in all cases, which is the opposite effect that would be expected due to the soil-structure interaction effect.
- The ground motion No. 2 for Via California Bridge has an important increment in that ratio compared to the other motions; considering the previously discussed variability in the identified damping ratios, this could be possibly related to the energy dissipation mechanisms acting in the structure during the event.
- The evaluation of response spectra plots indicate that this amplification effect is noticed in different magnitudes for periods higher than a threshold value, which is always near and below the natural period of the structure. On the other hand, there is a de-amplification of the spectral response for periods smaller than the threshold value.

4.2. Summary of analysis results for all bridges

The analysis procedure detailed above was applied to the remaining group of eight bridges. The following table summarizes the results of all cases, including the peak ground acceleration, identified fundamental transverse period and spectral response ratios for each ground motion.

Table 5. Summary of analysis results for the remaining group of bridges.

No.	Station	Bridge	Record	PGA (g)	Ts (sec)	Sa_{BASE} / Sa_{FF}	Sv_{BASE} / Sv_{FF}	Sd_{BASE} / Sd_{FF}
1	01336	Meloland Overpass	BorregoSprings 07Jul2010	0.012	0.269	0.75	0.77	0.74
2		Meloland Overpass	Calexico 20Nov2008	0.017	0.297	0.84	0.73	0.84
3		Meloland Overpass	Calexico 22May2010	0.031	0.259	0.87	0.85	0.86
4		Meloland Overpass	Calexico 30Dec2009	0.174	0.288	0.66	0.61	0.66
5		Meloland Overpass	Calexico 04Apr2010	0.213	0.273	0.71	0.66	0.71
9	24706	Barrel Springs Bridge	BigBearCity 22022003	0.009	0.203	1.47	1.47	1.48
10		Barrel Springs Bridge	Chinohills 29072008	0.027	0.239	0.98	0.94	0.98
11	47315	156 Overpass	SanJuanBautista 12012011	0.016	0.190	1.03	1.13	1.04
12		156 Overpass	AlumRock 30102007	0.021	0.202	0.54	0.52	0.54
13		156 Overpass	Aromas 02072007	0.073	0.172	1.02	0.94	1.03
17	57748	Alviso Overpass (K)	Gilroy 13052002	0.077	0.611	1.46	1.50	1.46
18		Alviso Overpass (L)	Gilroy 13052002	0.077	0.389	3.16	3.21	3.16
19	68717	Hwy 101 Bridge	Bolinas 1999	0.009	0.269	2.48	2.41	2.48
20	89324	Painter St Overpass	CapeMendocino 21111986	0.146	0.281	0.60	0.58	0.60
21		Painter St Overpass	PetroliaAftershock2 26041992	0.198	0.241	0.61	0.41	0.62
22		Painter St Overpass	PetroliaAftershock1 26041992	0.515	0.243	0.67	0.65	0.67
23		Painter St Overpass	Petrolia 25041992	0.541	0.247	0.91	1.02	0.89
24	89708	Murray Road Bridge	Ferndale 09012010	0.077	0.152	0.94	0.82	0.95

The evaluation of all cases leads to several remarks, based on the identification of possible trends and their relation with the expected structural behaviour. The following list summarizes the findings:

- The Meloland Overpass bridge shows de-amplification for all cases comparing spectral response at the column base with free field records. The identified fundamental periods show low variability and no clear trend with respect to PGA values. The de-amplification behaviour may be related to the condition of integral bridge and the medium/high intensity of the ground motions.
- The results corresponding to the Painter Overpass also show de-amplification of spectral response for all cases, with similar values for all cases of PGA. The identified fundamental periods in this case indicate general agreement.
- The Barrel Spring bridge results indicate amplification for a very low intensity ground motion, reducing the spectral ratio to near unity when the PGA is triplicated compared to the first one, but still considered as low intensity motion. The identified periods are fairly similar.
- The 156 Overpass shows de-amplification of spectral response in all cases, with no clear trend if compared with PGA values. The identified periods show consistency in the results.
- The Alviso Overpass bridges share location and have similar plan geometry, with one column bents in Bridge K and two columns in Bridge L. For the same ground motion, in both cases the response is amplified, but the bridge with stiffer bents shows more than two times larger amplification if compared with the neighbour structure.
- The Highway 101 Bridge in Rohnert Park shows spectral response amplification for a very low intensity ground motion.
- The Murray Road bridge analysis results indicate similar spectral response in column base and free field, with slight de-amplification of the response at the column.

- There seems to be a general consensus among the analysed data of showing amplification of the spectral response only for low level of shaking, whereas the de-amplification can be found in both low and high intensity motions. Further research should be conducted in order to gain a better understanding of this phenomenon.

5. CONCLUSIONS

The previously developed methodology highlights several aspects that can be related to the soil-structure interaction condition of the bridges, focusing on the information provided by signals at free field, column base and deck, and mainly investigating the difference between parameters obtained from free field and column base records.

This method of analysing recorded motions from bridges will be implemented by the authors to process the records from a database of recorded motions obtained from instrumented bridges around the world. The results from this investigation will be used to develop guidelines to evaluate the effects of soil-structure interaction on the seismic response of bridges.

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