ON THE EXCITATION OF HIGHER MODES OF LONG BRIDGES DUE TO SPATIAL VARIABILITY OF EARTHQUAKE GROUND MOTION

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ABSTRACT: In the present study is investigated the higher modes excitation of long bridges in the case of SVEGM (θ) and it is also made an effort of combining it with its consequences on the response of bridges by conducting a parametric analysis for Lissos' bridge. The results prove a systematic excitation of higher modes and an increase for both the displacements and the moments.

KEY WORDS: Higher modes; Asynchronous motion; SVEGM; Bridge.

1 INTRODUCTION

During the last decades a great progress has been made in the antiseismic design field. The use of more complicated and demanding methods, like non-linear time history analysis, is becoming wider and has already been adopted by the codes. Although this is until now the best available tool for the investigation of the dynamic response of a structure, unavoidably the selection of the input motion is by far the most uncertain factor in the whole process. The problem is even more complex in the cases of structures of great length, like bridges, where input motions may differ among the support points, a phenomenon called spatial variability of earthquake ground motion (SVEGM).

Since '60s, when SVEGM first started to be investigated, scientists were made aware of its causes and many empirical, semi-empirical and analytical methodologies have been proposed to overcome this difficulty. The consequences observed on bridges after important earthquakes forced the code developers to take into account this phenomenon; the problem is dealt with either simplified code-based calculations or indirect measures involving larger seating deck lengths (AASHTO 1996, ATC-32 (ATC 1996), JRA 2002). Only in EC8-part 2 is proposed a complete, simplified set of guidelines for the inclusion of SVEGM and an analytical procedure in the informative annex; the latter is applicable only in elastic analyses [1].

The simplified calculations proposed by EC8 have been compared to other more comprehensive methodologies [2]. Although the proposed procedure is one step forward, one of its disadvantages is that it is not able to predict the location of the most affected by the SVEGM phenomenon piers, something that would be desirable. This is due to its pseudo-static character and the inability to capture the higher modes excitation, which has been observed to occur when asynchronous motion is applied to a bridge [2-4]and it is believed to be one of the key features that SVEGM is found to cause. This is because it is possible in the case of asynchronous motion of a bridge for some of the piers to be affected more, either detrimental or in favor, due to the higher modes excitation. Without doubt this information would be of great importance to the practical engineers during the design of a new bridge.

This paper further investigates through a parametric analysis the excitation of higher modes of a bridge as a mean of defining a simple measure for predicting in advance the favorable or critical effect of asynchronous excitation on the seismic response of long bridges. The results indicate a systematic excitation of higher modes (especially of the first antisymmetric) due to the asynchronous input motion and a subsequent increase of the deck displacements and the pier base flexural seismic demand.

2 METHOD

2.1 The bridge used

For the parametric study is used the Lissos' bridge, a 433m R/C structure along Egnatia Highway in northern Greece (figure 1). It has a continuous deck that rests on 10 piers through elastomeric bearings while at the two ends the deck rests on the two abutments through roller bearings, while there are also expansion joints, whose displacement capacity is ≥330mm. The spans' length and the piers' heights are presented in table 1. Deck's transverse displacement is prevented from being larger than 10cm by stoppers (h=1.20m). The sections of the piers and the deck are presented in figure 2.

The reason for selecting this bridge is dual: its length (which is such that spatial variability of earthquake ground motion is expected to occur), and the number of its piers (so that it can be examined whether some of them are more affected). Moreover, due to the considerable dimension of the bridge (433m) according to the EC8-part 2, a spatial variability analysis should be also performed, regardless of the soil categories on which the piers are founded. It must be noted however that due to the fact that the deck rests on elastomeric bearings, the bridge is not sensitive to statically imposed displacements [2].

2.2 Parametric scheme

A parametric analysis was performed in order to investigate the higher modes excitation. The parameters used are soil category (A, B, C, D according to the EC8) and PGA (0.16g, 0.24g, 0.36g) while for the asynchronous motion only the wave passage effect was taken into account. The properties assumed for the three different soil categories (B, C, D) (simplified one layer for each one) are presented in table 2. As the frequency content of the input motion play an important role in this study, three real records were used for each combination of the above parameters. These records were selected from the PEER strong motion database with the only criteria used being the soil category and the PGA and were applied in each support as displacement time histories.

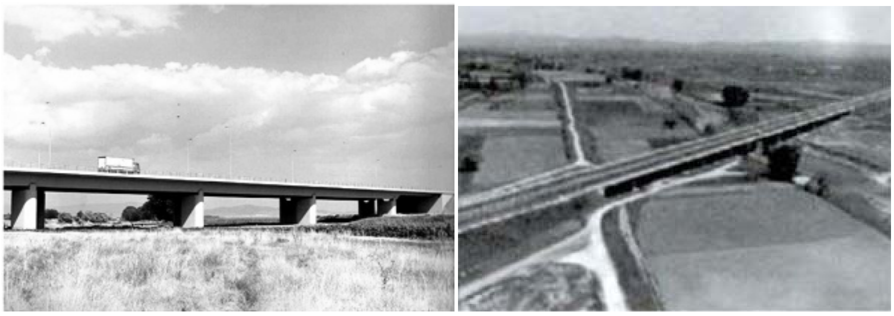

Figure 1. The Lissos' bridge along Egnatia Highway in northern Greece.

Table 1. The heights of the piers [m] and the distances [m] among them.

A1	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	A2
	5.50	5.83	6.12	6.40	10.24	10.58	7.92	8.26	8.60	4.40	
29.56	37.05	37.05	37.05	44.35	44.35	44.35	44.35	44.35	44.35	26.50	

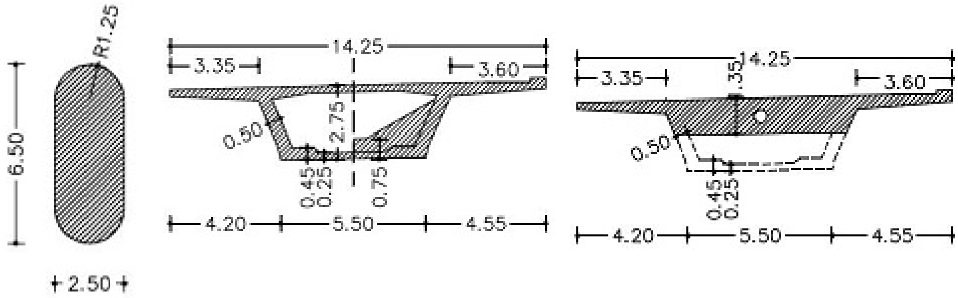

Figure 2. Left: The section of the piers. Middle: The section of the deck at the spans and over the piers. Right: The section of the deck at the last span.

In order for the dynamic SSI to be taken into account, the foundations of the bridge were designed (EC7 and EC8) for each combination of the above soils and PGA. In the case of soil A the bridge's supports were assumed to be fixed. Due to the fact that the deck rests on the piers through elastomeric bearings, piers were assumed to remain the same. The procedure for the partially embedded foundations proposed by Mylonakis et. al. and the respective one for piles foundation were followed in order for the footing impedances to be calculated [5,6].

Table 2. Soil properties selected for the parametric study. As for category A is rock and the supports of the bridge assumed to be fixed.

Category	V_s[m/sec]	N_{spt}	φ[°]	c [kPa]	γ [kN/m³]	v	β [%]	G [MPa]
B	500	60	43	0	22	0.4	3	550
C	250	30	36	15	19	0.4	3.5	118.75
D	100	10	30	8	16	0.4	4	16

2.3 Bridge's model

All the analyses were performed using the computer program SAP2000v.10. Beam elements were used to model the piers, the deck and the stoppers while the bearings, the gaps, the dashpots (for the SSI) and the expected plastic hinges at the bases of the stoppers were simulated by NNLink elements. Bearings were assumed to have linear behavior. The footing impedances were modeled through springs (6 and 5 components in the case of spread and piles foundation respectively) and dashpots at the piers' bases (figure 3) while at the abutments were assumed to be only springs in transverse (10^6 kN/m) and vertical direction ($1.5*10^6$ kN/m).

As the scope of this study is the investigation of the higher modes excitation, the geometric non-linearities appearing were neglected by rendering all stoppers inoperative so that the dynamic characteristics of the bridge would not change. However, because the results of the analyses prove that the stoppers would have been activated in 12 cases, it was decided to perform a second series of analyses. In these 12 analyses are examined only the consequences of the asynchronous input motion on the response of the bridge.

2.4 Criteria set for higher modes excitation

In order to examine the higher modes excitation, and try to associate it with the change in deck's displacements and the piers' moments, the Fourier spectra of the accelerations were plotted at the deck's point over each pier. As explained before, due to the fact that these analyses are linear elastic the frequencies where the peaks of the Fourier spectra are observed coincide with the eigen-frequencies of the structure. However, it is important to set some criteria in order for a mode to be considered excited. These are summarized in the following expression:

$$a\ mode\ is\ excited\ when \begin{cases} FA_{asyn}(T) > 0.2 \cdot maxFA_{syn} \\ FA_{asyn}(T) > FA_{asyn}(T) \\ \frac{\varphi_T^T \cdot \boldsymbol{M} \cdot \varphi_T}{\Sigma(\varphi_i^T \cdot \boldsymbol{M} \cdot \varphi_i)} > 5\% \end{cases} \quad (1)$$

in other words:

- the Fourier amplitude at an eigen-period T under asynchronous motion ($FA_{asyn}(T)$) should be 20% larger than the maximum Fourier amplitude at either eigen-period when the bridge is excited uniformly (maxFA_{syn}).

- the Fourier amplitude at an eigen-period T under asynchronous motion ($FA_{asyn}(T)$) should be larger than the respective one when the motion applied synchronously($FA_{syn}(T)$).
- the mode corresponding to eigen-period T (Φ_T) should activate >5% of the mass in the transverse direction or around the z-axis.

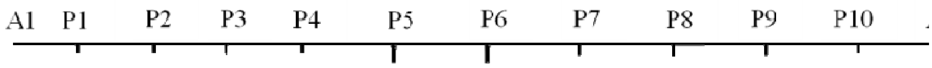

Figure 3. The model of the bridge and the support conditions at each pier.

3 RESULTS

3.1 Elastic analyses

The amplitudes of deck's displacements in transverse direction over each pier and piers' moments have been examined for synchronous and asynchronous input motion. The effect of the SVEGM is revealed through the ratio of maximum displacements or bending moments in time for asynchronous to synchronous excitation. The results presented in figure 4 and the brief statistical analysis summarized in tables 3 and 4 prove that both the displacements and the moments were increased in an important percentage of the cases examined, although on average the ratios were smaller than 1 at the first 6 piers.
As for the higher modes excitation, the cases in which it has been observed are presented in figure 4 using filled squares. It is obvious from tables 3 and 4 that higher modes are systematically excited especially at the edge piers (44%-69% of the cases for P1 to P4 and 75% to 94% for P7 to P10). Also it's, worth mentioning that an important percentage of the cases where higher modes were excited resulted in an increase of both the displacements (11% for P6 to 89% for P9) and the moments (6% for P5 to 94% for P7) while, as presented in the 6^{th} row of tables 3 and 4 in most cases where asynchronous motion was detrimental, the increase was verified by the higher modes excitation with the exception of the P5 and P6 which were not significantly affected by SVEGM. As presented in table 5 in most cases the 1^{st} antisymmetric mode was excited.

3.2 Non-linear analyses

In the twelve analyses where the non-linearities were taken into account, only the consequences of the SVEGM were examined. The statistical analysis of these is presented in table 6 where analogous to the aforementioned changes were observed. It was also investigated the influence of asynchronous motion on the closure of the gaps. Piers 1, 6 and 10 remain unaffected as presented in figure 5. Despite the fact that modal frequencies cannot be identified in non-linear systems, it is hinted by the results in figure 5 that the detrimental effect of SVEGM is associated with the excitation of the antisymmetric mode.

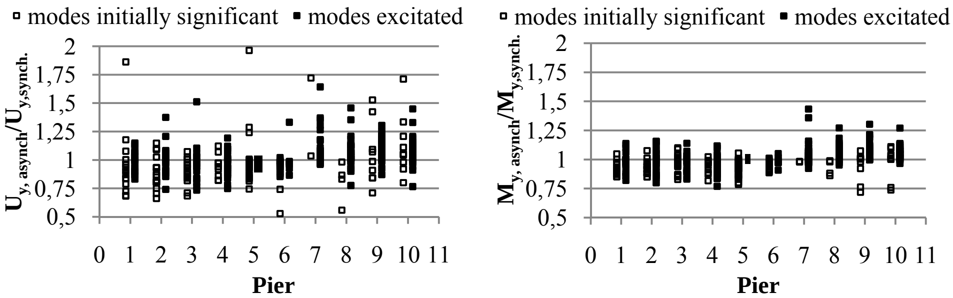

Figure 4. Comparison of the maximum displacements of the deck (left) and of the maximum moments at each pier (right) in the case of asynchronous and synchronous excitation (36 cases). Filled squares represent the cases in which higher modes were excited.

Table 3. Statistical analysis of the results obtained from the comparison of asynchronous to synchronous excitation for the displacements of the deck (36 cases).

	Piers:	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
1	% of cases $U_{asyn.}>U_{syn.}$	38.9	38.9	25.0	33.3	13.9	8.3	80.6	72.2	77.8	75.0
2	Average of $U_{asyn.}/U_{syn.}$	0.98	0.95	0.93	0.96	0.98	0.94	1.11	1.04	1.08	1.09
3	σ of $U_{asyn.}/U_{syn.}$	0.19	0.15	0.14	0.10	0.19	0.11	0.17	0.15	0.15	0.17
4	% of cases where h. m. are excited	55.6	52.8	44.4	69.4	5.6	25.0	94.4	88.9	75.0	75.0
5	% of cases where excited modes lead to critical response	55.0	52.6	31.3	40.0	50.0	11.1	79.4	81.3	88.9	77.8
6	% of 1 where h. m. are excited	71.4	71.4	55.6	83.3	20.0	33.3	93.1	100.0	85.7	77.8

Table 4. Statistical analysis of the results obtained from the comparison of asynchronous to synchronous excitation for the moments of the piers (36 cases).

	Piers:	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
1	% of cases $M_{asyn.}>M_{syn.}$	33.3	27.8	33.3	25.0	11.1	11.1	66.7	75.0	77.8	86.1
2	Average of $M_{asyn.}/M_{syn.}$	0.95	0.96	0.96	0.95	0.93	0.96	1.04	1.05	1.05	1.04
3	σ of $M_{asyn.}/M_{syn.}$	0.08	0.09	0.08	0.08	0.06	0.04	0.10	0.08	0.11	0.09
4	% of cases where h. m. are excited	55.6	52.8	44.4	69.4	5.6	25.0	94.4	88.9	75.0	75.0
5	% of cases where excited modes lead to critical response	40.0	31.6	25.0	28.0	50.0	11.1	67.6	81.3	81.5	77.8
6	% of 1 where h. m. are excited	66.7	60.0	33.3	77.8	25.0	25.0	100.0	96.3	78.6	67.7

Table 5. The rates of the modes' shapes which were excited at each pier.

Mode's shape	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
	4.1	0.0	0.0	0.0	0.0	11.1	18.8	41.2	45.4	51.4
 1st antisymmetric	79.2	95.0	88.9	33.3	50.0	88.9	46.4	54.9	50.0	17.1
	0.0	0.0	0.0	63.3	0.0	0.0	34.8	2.0	2.3	25.7
other shapes	17.7	5.0	11.1	3.3	50.0	0.0	0.0	2.0	2.3	257

Table 6. Statistical analysis of the results obtained from the comparison of asynchronous to synchronous excitation (12 non-linear cases).

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Displacements										
% of cases $U_{asynch.}>U_{synch.}$	33.3	25.0	33.3	25.0	8.3	16.7	83.3	75.0	50.0	75.0
Average of $U_{asynch.}/U_{synch.}$	0.91	0.95	0.98	1.00	0.92	0.96	1.05	1.04	0.99	1.03
σ of $U_{asynch.}/U_{synch.}$	0.12	0.13	0.15	0.14	0.06	0.04	0.06	0.11	0.15	0.12
Moments										
% of cases $M_{asynch.}>M_{synch.}$	25.0	33.3	33.3	25.0	8.3	0.0	83.3	83.3	66.7	75.0
Average of $M_{asynch.}/M_{synch.}$	0.92	0.94	1.03	0.91	0.88	0.94	1.03	1.13	1.12	1.03
σ of $M_{asynch.}/M_{synch.}$	0.07	0.13	0.22	0.13	0.09	0.04	0.05	0.17	0.26	0.20

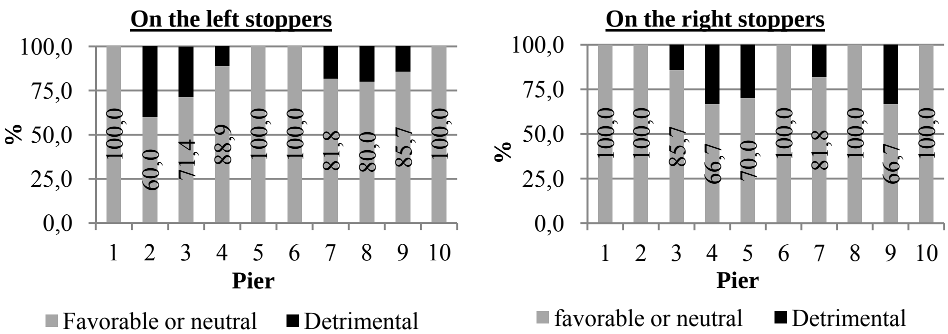

Figure 5. The effect of the asynchronous motion on the closure of the gaps at each pier. (12 cases).

4 CONCLUSIONS

The basic scope of this study was to investigate the higher modes excitation and to try to combine these observations with the consequences of SVEGM on the displacements and the bending moments. The results indicate that:

- Higher modes (especially the 1st antisymmetric) are systematically excited due to asynchronous (θ) input motion (on average: 55% at piers 1, 2, 3 and 4, 18% at piers 5 and 6 and 83% at piers 7, 8, 9 and 10).
- Displacements and bending moments are increased especially at the edge piers (on average 32% at piers 1, 2, 3, 4 and 76% at piers 7, 8, 9, 10) but on average the ratio of asynchronous displacements (or moments) to the synchronous ones is smaller than 1 at the first 6 piers.
- On average 56.7% of the cases where higher modes were excited led to a critical response for the displacements and 49.4% for the bending moments.
- The closure of the gaps at the piers is increased due to asynchronous motion and its detrimental effect is associated with the excitation of the antisymmetric mode.

It is believed that the excitation of higher modes due to SVEGM is a key factor and it is worth being further investigated.

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