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ASSESSMENT OF EC8 PROCEDURES FOR THE ASYNCHRONOUS EXCITATION OF BRIDGES BASED ON NUMERICAL ANALYSES AND RECORDED DATA

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Abstract. *The significance of the spatial variability of earthquake ground motion SVEGM is recognized by all modern seismic codes (EC8, AASHTO, ATC, JRA) but it is only EC8 that provides a clear, though simplified, methodology to account for asynchronous motion for design purposes. Currently, two amendments of the EC8 methodology have been proposed by Sextos & Kappos (2009) and Nuti & Vanzi (2009) both aiming to improve the applicability and robustness of the EC8 simplified procedure. In the present study, the above EC8 framework is comparatively assessed in the light of actual, low-amplitude measurements obtained along the Evripos cable stayed bridge. A permanent accelerometer special array of 43 sensors was installed on the bridge in 1994 by the Institute of Engineering Seismology and Earthquake Engineering. Since then, the bridge's behavior to seismic excitations has been continuously monitored. A reliable numerical model was first developed and was updated to match the monitored response given the available free-field recordings. Subsequently, various (synchronous and asynchronous) seismic scenarios were developed to identify the impact of ground motion spatial variation on the action effects of the bridge using the 7/9/1999, Athens earthquake (Ms=5.9) records. The results indicate that spatial variability of earthquake ground motion has generally a favorable effect on the Evripos bridge response, primarily due to the significant flexibility of its deck. It is also concluded that the Eurocode 8 simplified method, being essentially a pseudo-static loading is inable to capture the salient features of dynamic response under multiple-support excitation.*

1 INTRODUCTION

Asynchronous motion, typically referred to as Spatial Variability of Earthquake Ground Motion (SVEGM), denotes the differences in amplitude, phase and frequency content among ground motions recorded over extended areas [1–3]. It is true that the critical question is not whether seismic motion is indeed different along an extended structure; this is almost self-evident [4], physically justified [5] and the sources of spatial and temporal variations of seismic motion have been well identified [6] as: (a) waves that travel at a finite velocity, so that their arrival at each support point is out of phase (b) wave coherency loss in terms of gradual reduction of their statistical dependence with distance and frequency, due to multiple reflections, refractions and superpositioning during propagation and (c) local site effects. As a result of all the above sources, both peak ground acceleration and frequency content of the motion may be significantly different among the various foundation points. Moreover, although often neglected, the potential filtering at the foundation level that results from the relative flexibility of the foundation-soil system components, is an additional source of seismic motion variability [7]. In addition to the above theoretical justification, Spatial Variability of Earthquake Ground Motion (SVEGM) has also been recorded in various densely instrumented arrays all over the world (SMART-1 and LSST-Lotung in Taiwan, Chiba in Tokyo, USGS-Parkfield and Imperial Valley in California, as well as Euroseis-Test in Greece among others), hence the fact that a long structure is expected to be excited with asynchronous and partially uncorrelated seismic forces is evident and well documented.

Although many methods have been proposed during the last 40 years in order to consider the consequences of SVEGM on bridges, asynchronous motion is an aspect not accounted for in the vast majority of the design cases irrespectively of piers' distance and bridge length [8]. This tendency may be attributed to the simplicity of synchronous excitation analysis and to the false perception that SVEGM has a generally favorable effect on bridge dynamic response [4]. However, the potential effects of SVEGM on bridge response cannot be deterministically approached especially in cases where local soil conditions exhibit significant variation with length [4]. Indeed, the uncertainty related to the definition of the appropriate seismic motion at each support and the conditions under which asynchronous motion could be detrimental for a structure is fundamental. Numerous studies have been performed investigating the effects of changes in various parameters regulating the ground motion field as well as the impact of field characteristics on different bridge configuration [7], [9–11]. The results of these studies, though, do not indicate a clear trend regarding the beneficial or detrimental effect of asynchronous excitation on bridge response. It is also recognized that even in cases where the SVEGM effect could be important, the definition of some reasonable input motions and relative motions to resemble the expected ones at bridge supports is by far the most difficult process. Nevertheless, in each case, bridge supports' soil conditions provide an indication about the structure's sensitivity to the phenomenon or not; SVEGM's importance arises when local soil conditions vary significantly with length increasing in this way the probability of failure for even relatively short bridges.

The main question therefore, is how the designer may produce 'reasonable' spatially varying suites of ground motion, what the response of a structure would be under such an asynchronous excitation, whether the final response is detrimental compared to the prediction made assuming a structure uniformly excited in the time domain, and especially whether it can be indeed predictable in advance during the design process. The answer to this question is difficult not only due to the complexity in predicting incoherency patterns but also, due to the significant coupling between earthquake input, dynamic characteristics of the soil-structure system (particularly in terms of foundation compliance and energy dissipation) at the soil-foundation interface. To deal with this problem, modern seismic codes (such as the US Standard Specifications for Highways and Transportation Bridges, ATC-32, Japanese Design Specifications for Highway Bridges) prescribe increased seating lengths for the deck.

A more practically-oriented approach is prescribed in EC8, currently the only seismic code worldwide providing a clear and detailed framework for considering the effect of SVEGM in bridge design, through a simplified and an analytical methodology, the latter in the form of an informative annex. An improvement to EC8 simplified methodology has also been proposed by Sextos & Kappos [12] and Nuti & Vanzi [2], [13].

However, with the exception of the latter studies [2], [13], neither the EC8 simplified method nor the numerically-derived suggested improvements have been compared or calibrated to free-field or on-structure recordings. In this context, a comparative assessment between analytical solutions, numerical predictions and actual recordings has been undertaken for the case of Evripos cable-stayed bridge in Greece, a cable-stayed structure that has been permanently monitored by an accelerometer network since 1994. A valuable set of motions is provided, recorded both in bridge vicinity and on specific locations on the structure and its foundation. Based on these data, an effort is made to:

(a) develop a reliable finite element model after appropriate system identification and model updating procedures and
(b) assess the bridge sensitivity to SVEGM effects using the free field (asynchronopus) ground motion excitations in the light of the aforementioned EC8 suggested amendments.

A brief description of the bridge structure, its monitoring system and the recorded response under various asynchronous ground motion cases is provided in the following.

2 SIMPLIFIED METHODOLOGIES EXAMINED

2.1 EC8-part2 provisions

EC8-Part 2 recognizes the importance of multi-support excitation in case that (a) soil properties along the bridge vary in such a way that the soil at the various supports may be considered to belong to more than one category (as specified in Eurocode 8-Part 1), or (b) soil properties along the bridge are approximately uniform, but the length of the continuous deck exceeds a pre-specified limit, L_{lim}. The recommended value of L_{lim} equals $L_g/1.5$, where L_g is given in Table1 as a function of ground conditions and corresponds to the distance beyond which, motions may be regarded as completely uncorrelated.

For the general case, the potential maximum values of the considered seismic action effect (i.e. member force or deformation) can be estimated through an adequate (albeit simplified) procedure. This method should be followed, unless a more accurate analysis is carried out. To this end, the more detailed procedure for the assessment of the asynchronous motion effects in the frequency domain [6] is proposed in an informative annex to the Code, while guidance on the generation of artificial spatially variable ground motions is also provided. The idea (put forward by the EC8-2 drafting panel) to compute in a simplified way the necessary stress or displacement increase due to SVEGM effects is simple, practical, and physically-motivated: Since motion is different between support points, the various bridge supports are subjected to different values of (location-dependent) earthquake accelerations, which are partially correlated; as a result, pseudo-static internal forces develop [14], [15]. From the numerous possible combinations of relative support vibration, two cases are identified as the most critical: a) all piers are subjected to ground displacements of the same sign (but varying magnitude) and b) the two piers in each pair of two successive piers are displaced in opposite directions. More details about this methodology are presented in **Figure 1**.

Ground Type	A	B	C	D	E
L_g (m)	600	500	400	300	500
L_{lim} (m)	400	333	266	200	333

Table 1: Limiting length to consider spatial variability effects, as a function of ground type

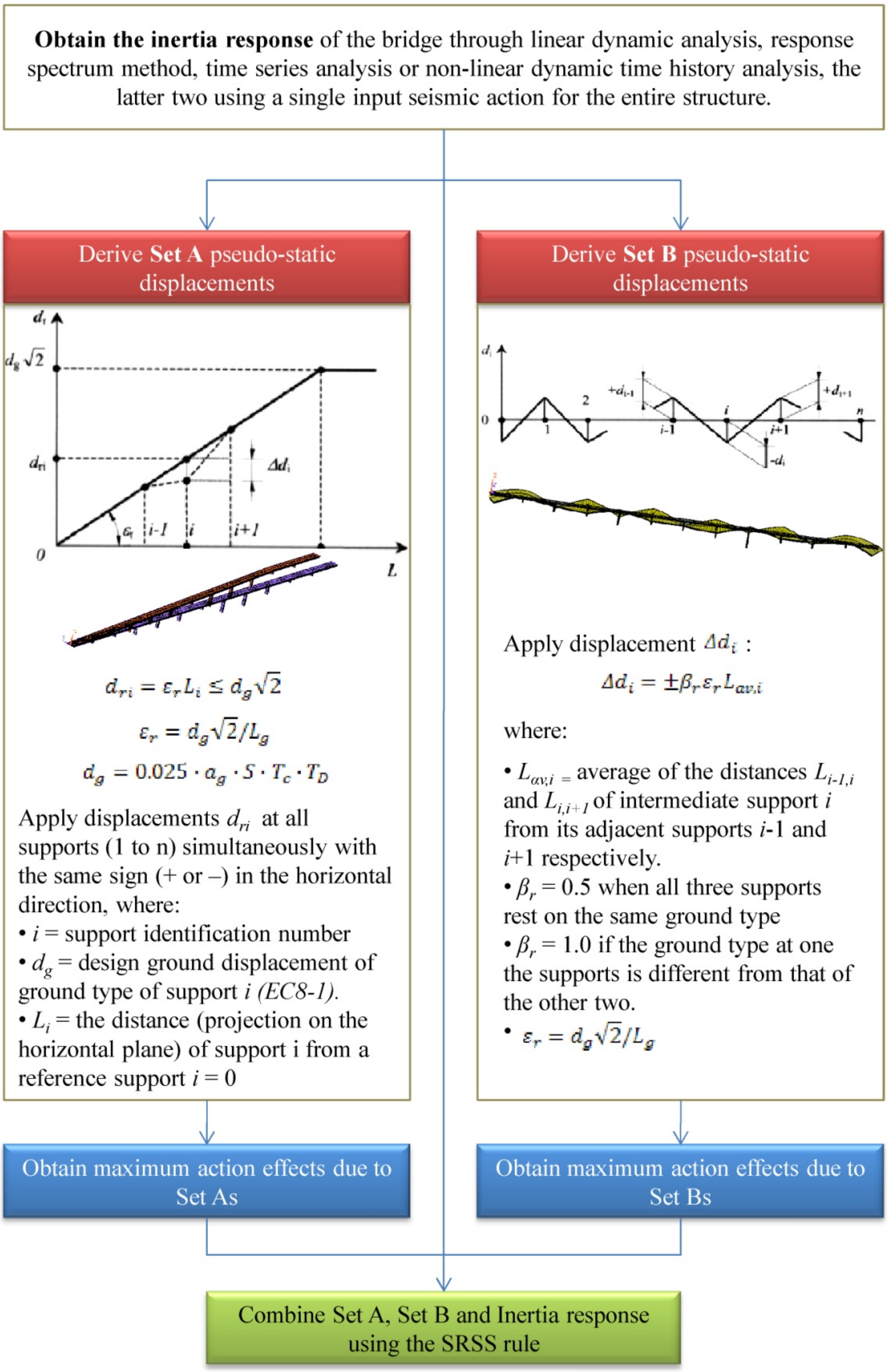

Figure 1: The simplified methodology proposed by EC8 to account for SVEGM effects [12].

2.2 EC8-Part 2 suggested amendments

Numerous parametric analyses have been performed assessing the effect of asynchronous input motion on different bridge types and configurations based on the simplified EC8 method. It is concluded [12] that provisions adopted by EC8-2 are clearly a step forward not only compared to the previous version of the code, but also with respect to modern seismic codes worldwide. The limits for considering asynchronous excitation (i.e., 400m to 200m for ground categories A to D according to EC8 classification) are in line with other research findings [16] while SVEGM effects should be considered even for shorter bridges in cases wherein ground conditions vary significantly among supports, a fact that is verified in the literature as well [17–19]. On the other hand, the simplified approach proposed by Eurocode 8 systematically leads to negligible seismic demand increase even in cases where the effect of multiple-support excitation is apparent. Furthermore, it has been shown that the pseudo-static nature of the EC8 simplified method is inevitably unable to capture dynamic effects triggered by multiple-support earthquake input, such as excitation of higher modes of vibration. In case that the application of the simplified method is the only available option, an amendment has been proposed [12] that results in higher values of Set A and Set B imposed displacements as a means to implicitly compensate for the increased structural demand. In particular, displacements are calculated from the following modified EC8 expressions:

$$d_{ri} = e_r L_i < 8d_g \tag{1}$$

where

$$e_r = 8d_g / L_g \tag{2}$$

Application of both the original and the amended Set A and Set B imposed support displacement profile for the case of Evripos bridge is illustrated in Figure 2 for a PGA equal to 0.24g and different soil classes.

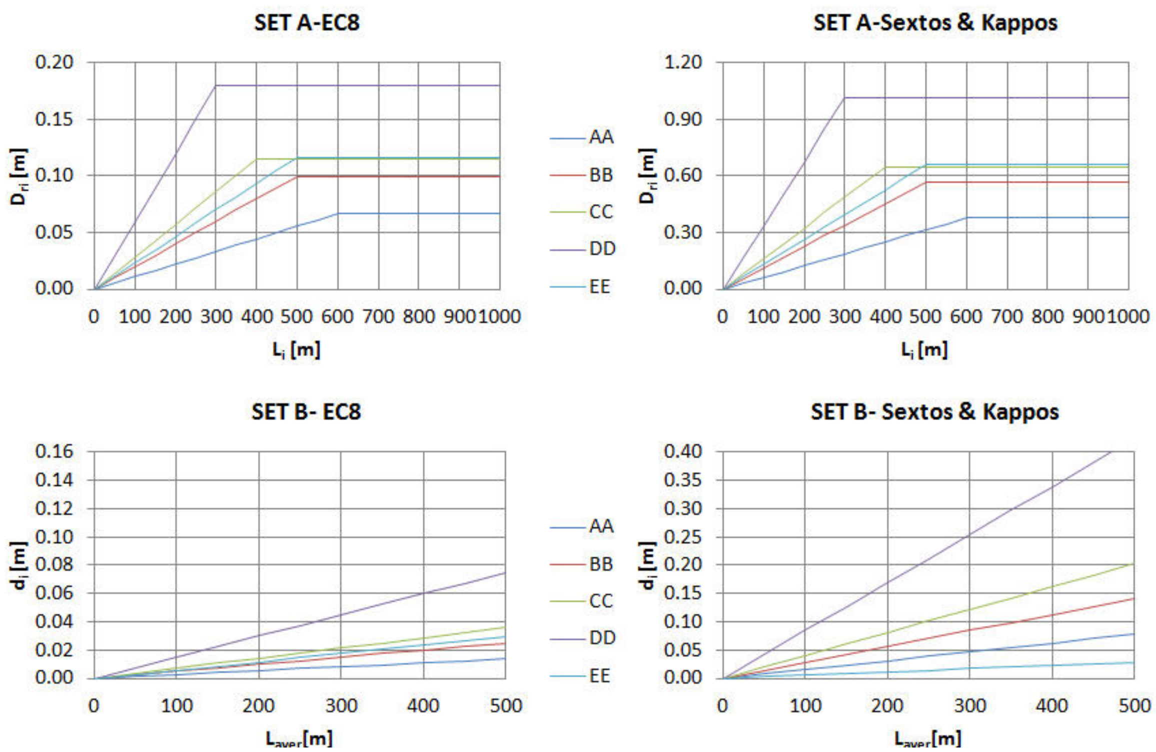

Figure 2: Comparison between the pseudo-static displacements imposed at the supports of the structure according to the EC8 provisions (left) and the suggested approach of Sextos and Kappos [12].

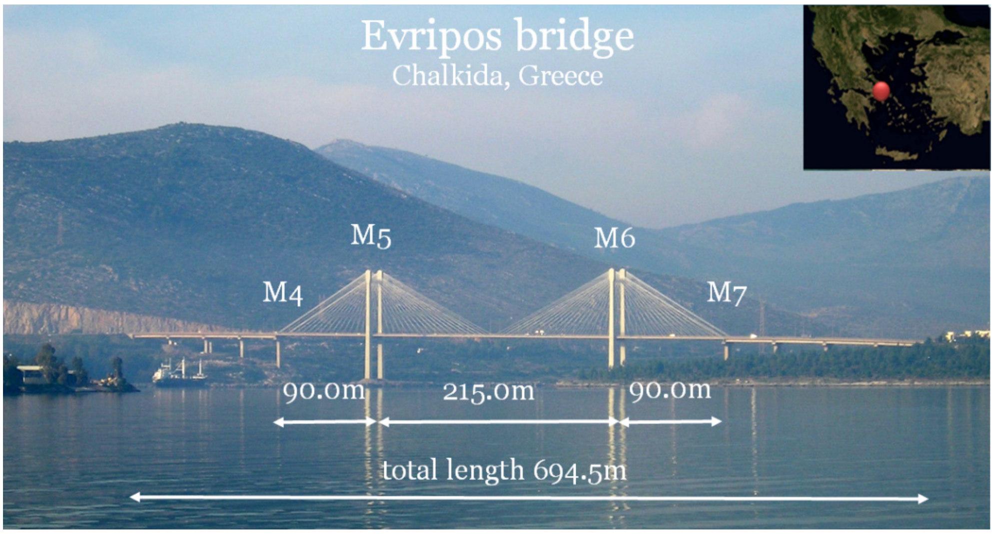

Figure 3: The Evripos cable stayed bridge in the central Greece.

2.3 Italian Seismic code

The same critical rationale lies behind the work of Nuti and Vanzi [20], [21], later reported in the new Italian Seismic Code [22], aiming at improving the simplified EC8 method by inducing a modified set of differential displacements d_{ij} between successive support points after appropriate consideration of soil conditions:

$$d_{ij}(x) = 1.25\left|d_{gi} - d_{gj}\right| + 1.25\left(\sqrt{d_{gi}^2 + d_{gj}^2} - \left|d_{gi} - d_{gj}\right|\right)\left[1 - e^{-1.25\left(x/v_s\right)^{0.7}}\right] \tag{3}$$

where v_s is the velocity of shear waves, d_{gi} and d_{gj} are the maximum design ground displacements at the supports i and j, respectively, x is the distance between these two successive piers. It is also noted that the relative displacement between the adjacent pairs (i-1, i) and (i, i+1) is taken equal to $d_{ij}/2$, while d_{ij} is assumed zero at all other support pairs.

3 THE EVRIPOS CABLE-STAYED BRIDGE

3.1 Description of the bridge

The Evripos bridge is a reinforced concrete roadway bridge that crosses Evripos channel, connecting the Euboean coast on the island of Evia to the Boeotean coast in continental central Greece (Figure 3). It has an overall length of 694.5m and it is formed by three parts; a central cable-stayed section 395 m long and two side parts made of pre-stressed beams that rest on elastomeric bearings. The central cable-stayed section is formed by a central span of 215 m and two side spans of 90 m length each, while both side parts of the bridge have four spans of 39 m (Euboean coast) and 35.875 m (Boeotean coast) length respectively. The deck in the central part of the bridge, about 13.00 m wide and only 0.45 m thick, is 40 m above sea level, suspended from 72 pairs of cables arranged in a semi-fan pattern, is monolithically connected to the two H shaped concrete towers (piers M5 and M6) of a total height of 90 m. A special mechanism at the deck's edges (piers M4 and M7) allows displacements along the longitudinal direction while those in the transverse direction are blocked [23–25]. At the present study, only the cable-stayed section is examined.

As already mentioned, the Evripos cable-stayed bridge has been constantly monitored since 1994 by EPPO-ITSAK. Since then, a series of small earthquakes at a distance range of 20-70 km have been recorded. Sensor positions are carefully selected, for the dynamic behavior of the bridge to be fully described. In particular, there are four triaxial sensors, two located at the pilegroup cap and two free-field. Furthermore, twenty-four sensors (six vertical and two transverse in the central span, four longitudinal, two of them at the level of the deck and the others at the pylons' top, two transverse at both pylons and two vertical at each side-span) are permanently monitoring the response of the superstructure. The solid-state accelerometers are interconnected to provide common triggering, common timing and common sampling, the latter at a rate of 200 sps.

In a hypothetical scenario, if the bridge were to be designed today, EC8 provisions would dictate consideration of spatial variability aspects of earthquake ground motion. As a result, this bridge seems to provide an excellent opportunity for the simplified methodologies mentioned above to be compared with real data recorded on-site.

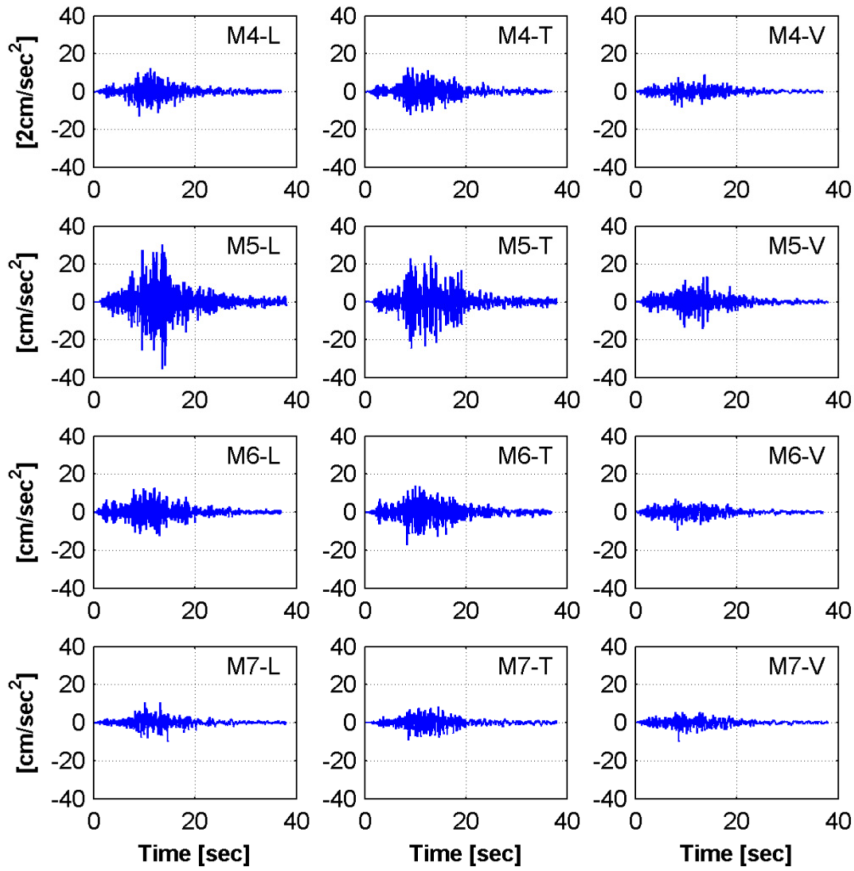

Figure 4: Time histories recorded at the base of piers M4-M7 during the Athens earthquake (7/9/1999, M_s=5.9)

3.2 Free-field measurements

Due to the significant overall length (395m) of the central section of the bridge, an effort is made to process specific groups of records available on-site in order to investigate the impact of SVEGM. For this purpose, a set of four ground motions was used, as recorded during the Athens earthquake, that occurred on 7/9/1999 at a source-to-site distance of approximately 43km with a surface Magnitude M_s=5.9. The recorded time histories are presented in Figure 4 where the longitudinal and transverse component is illustrated in different rows for each location (i.e., M4, M5, M6, M7 as defined in Figure 3).

Having ensured that the common time and common trigger condition was fulfilled, the records were first filtered in the frequency range of 0.65-25Hz in order to remove the influence of the vibration of the superstructure which was transmitting waves back to the soil due to inertial soil-structure interaction. Then, the coherency between all pairs of records was computed using a GUI-based, Matlab script written for this purpose. For each individual record, the power spectrum was computed after appropriate smoothing using an 11-point Hamming window [26] for 5% structural damping.

The diagrams of lagged coherency were computed separately for each component of all pairs of records and the spatially variable nature of ground motion was confirmed. As expected, at low frequencies and short separation distances the lagged coherency tends to unity, while it decreases with an increasing separation distance and frequency. Some of these diagrams are illustrated in Figure 5 and are compared with some of the most popular models for coherency loss prediction [27–32].

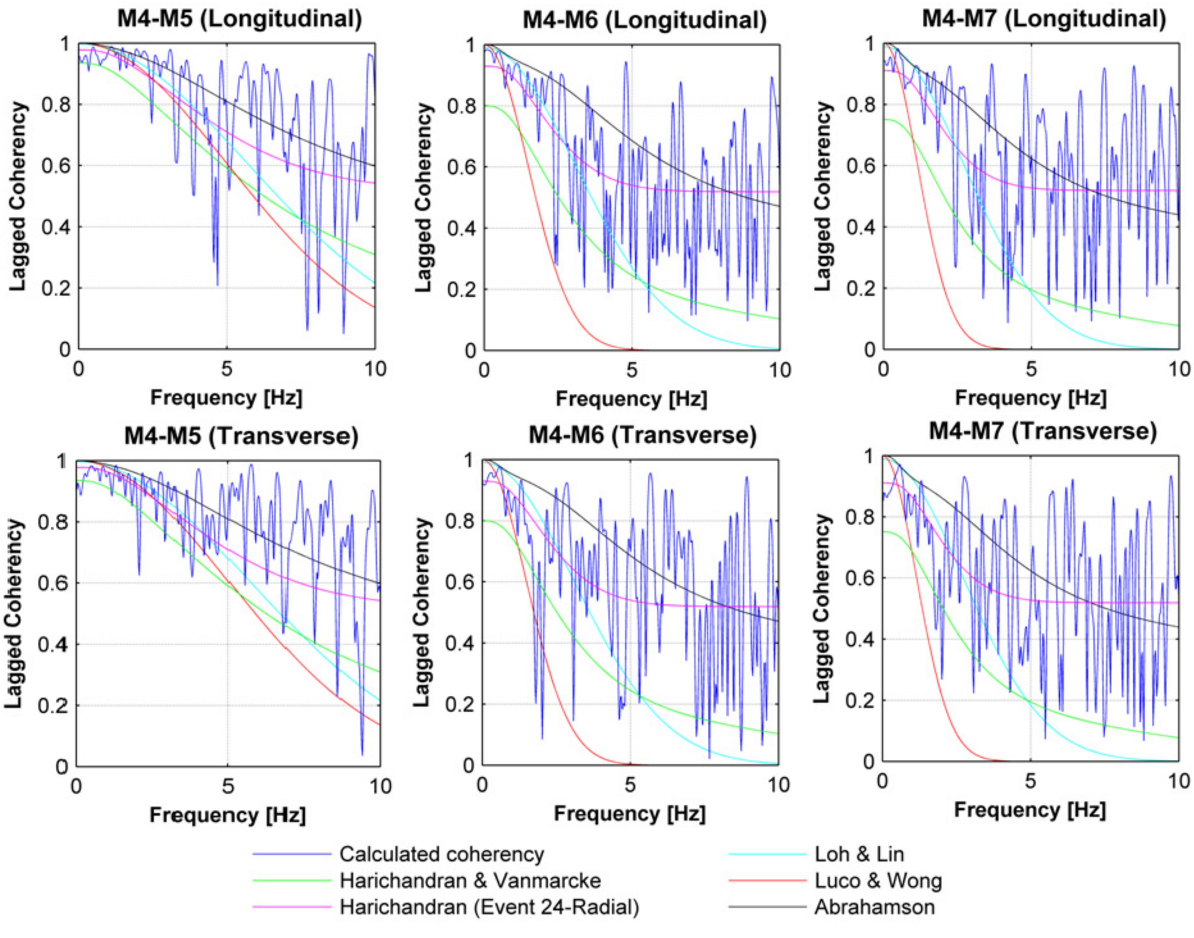

Figure 4: Computed lagged coherencies for the pairs of motions recorded during the Athens earthquake (7/9/1999,M_s=5.9)

4 FINITE ELEMENT MODEL UPDATING

The availability of bridge excitation data and the respective response records generally enables the development of reliable numerical models through the optimization of specific parameters whose response is in good agreement with the monitored ones. However, optimization methods cannot guarantee a univocal solution as the parameters' combinations for which the optimization process could actually result in a model with satisfactory response are numerous. Moreover, the parameters considered ought to be continuous functions for their values to be optimized. In the present study, parameters such as the supports' stiffness, especially at the two edges, cannot be considered as continuous functions as they heavily depend on other parameters like earthquake intensity, different soil layers' properties etc. Keeping in mind the scope of the present study, namely the investigation of the dynamic response of an existing bridge under asynchronous excitation and the comparison of the actual response to the ones stemming from simplified methodologies, it is obvious that the use of an optimization method does not serve its objectives. The provided data, therefore, proved to be a good opportunity to try to build up a more reliable model through an iterative process aiming to minimize, to an acceptable level, the differences between the recorded and the computed Fourier spectra of the accelerations at specific points on the structure.

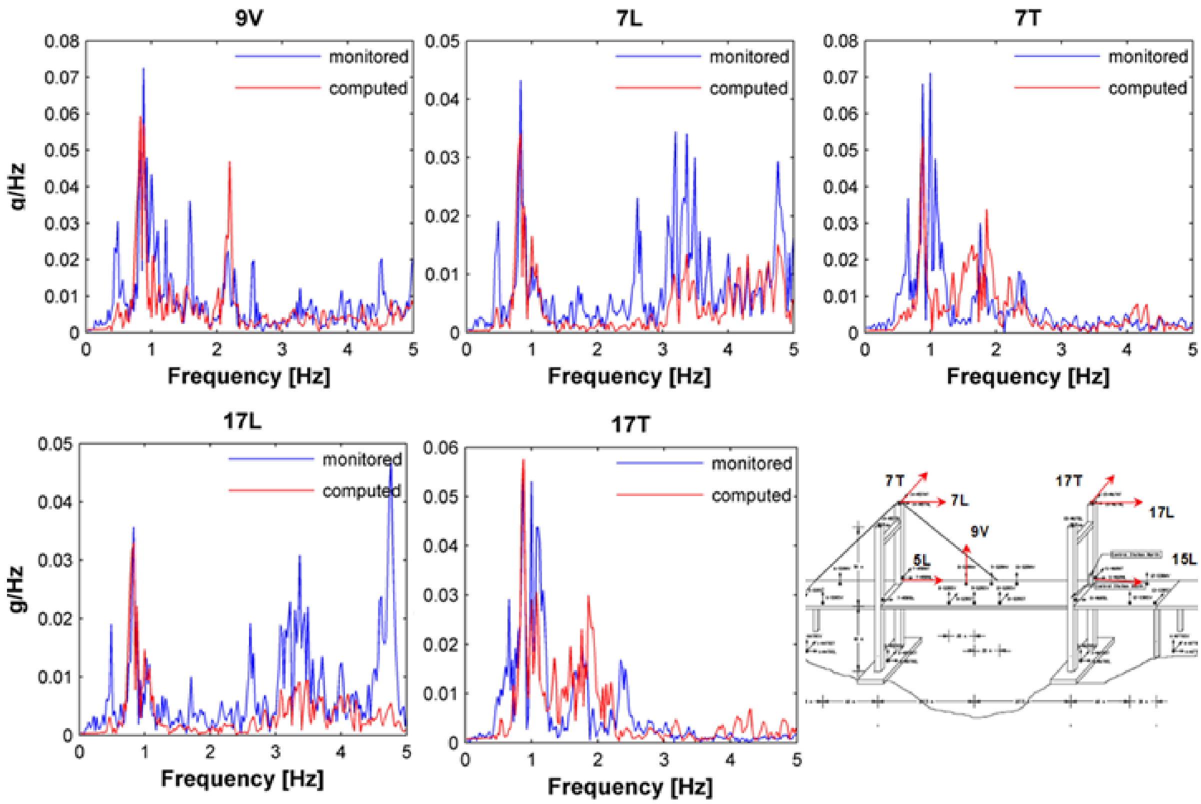

Figure 5: Comparison between the Fourier spectra of monitored and computed accelerograms at specific points of the superstructure.

The deck and the piers were modeled through shell and beam elements respectively, while the geometrical non-linearity induced by the bridge cables was taken into account assuming tension-only capabilities. Soil stiffness at the two edges and at the two pylons' foundation level, as well as the load combination factor ψ_{21} for traffic loads (according to EC8) were the parameters selected for optimization. The comparison was based on the sum of squared error between all the computed and monitored Fourier spectra at the location of the sensors within a frequency range of 0-5 Hz leading to a reasonably reliable finite element model that acceptably matches the observed response. Figure 6 illustrates the graphic comparison between the acceleration Fourier spectra of the recorded and the predicted transverse response at the top of pylons M5 and M6, as well as the vertical response of the deck (20m left from the middle of the central span). Matching was also optimized at 25 different superstructure locations.

5 COMPARATIVE ASSESSMENT OF PREDICTIVE MODELS AND RECORDED STRUCTURAL RESPONSE

The effect of SVEGM on structural response is investigated on the basis of the ratio ρ of the developed bending moment at the base of the main pylons M5 and M6 (Table 2) for the asynchronous case over the synchronous one, for all predictive models studied (i.e., EC8, EC8 modification and new Italian Code). Absolute values of seismic bending moments are also summarized in Table 3. A note that has to be made is that, for the case of the Athens earthquake records, the asynchronous over synchronous ratio ρ cannot be defined unless the "synchronous" idealization is decided first. To this end, the reference case of "synchronous" excitation is defined by uniformly applying each one of the four free-field recordings obtained at the base of pylons M4-M6 after appropriate scaling to match the same average spectral acceleration at the frequency of the first natural mode [33]. Naturally, this assumption led to four different asynchronous over synchronous ratios depicted as ρ synch M4-M7 in Table 2 below.

	Pier M5		Pier M6	
	M3	M2	M3	M2
ρ EC8	1.000	1.001	1.000	1.001
ρ EC8-Sextos& Kappos	1.008	1.024	1.008	1.024
ρ Nuti & Vanzi	1.003	1.039	1.000	1.015
ρ synch. M4	1.030	1.114	1.078	0.988
ρ synch. M5	0.755	0.685	0.767	0.608
ρ synch. M6	0.739	0.909	0.760	0.806
ρ synch. M7	0.700	0.820	0.703	0.729

Table 2: Ratios of seismic bending moments' ratios (asynchronous over synchronous response) resulting from the application of various predictive models.

		Pier M5		Pier M6	
		M3 [kNm]	M2 [kNm]	M3 [kNm]	M2 [kNm]
EC8	Response Spectrum	71296.8	123375.9	71296.8	123375.9
	Set A	-1539.2	-1998.3	-1536.9	1992.5
	Set B	391.6	4508.3	391.6	-4508.3
	Combination	71314.5	123474.4	71314.4	123474.3
EC8 Sextos & Kappos	Set A	-8704.3	-11310.1	-8704.3	11310.1
	Set B	2216.3	25499.6	2216.3	-25499.6
	Combination	71860.4	126490.2	71860.3	126490.2
Nuti & Vanzi	1-2	3081.3	13979.6	-765.7	-4670.4
	2-3	-4213.3	-31649.3	305.7	20604.9
	3-4	-197.1	11578.1	2367.5	-17783.9
	Combination	71487.6	128135.5	71301.8	125171.8

Table 3: Absolute values of seismic bending moments at the base of pylons M5 and M6 resulting from the application of various predictive models.

From Table 2 it is seen that the effect of spatial variability for the case of Evripos bridge and the Athens earthquake records, is in general beneficial (ρ varying between 0.60-0.90). It is only when record M4 is used as the uniform excitation where the effect of SVEGM exceeds unity and leads to an increase of 11%. On the other hand, it is clear that all simplified predictive models share the same two distinct features: (a) they result to only minor increase of pylon base moments (i.e., avoiding excessive and unrealistic predictions), which in general is in agreement with the observed SVEGM effect and (b) lead to values of ρ that are, by definition, higher than unity as they are derived by the application of the SRSS rule. The latter essentially suppresses the fact that asynchronous excitation can be beneficial in case of specific structural configurations as the one studied herein.

This is a key issue for understanding the mechanism of multiple-support excitation and the subsequent relative contribution of the pseudo-static and dynamic component of motion. In fact, it is seen that the extremely thin deck of this cable-stayed bridge coupled with the significant length of the central span between the two pylons allows the structure to conform to the pseudo-static imposed displacements without any substantial distress (i.e., increase in the bending moments at the base of the pylons). This is indeed anticipated, as it has long been shown that the pseudo-static effects under asynchronous motion are more critical in the case of stiff structures [15], [17], [34]. To further illustrate this phenomenon, a simplified configuration, in terms of number of spans, of the Evripos bridge has been examined (Figure 7) under multiple-support excitation after appropriate variation of deck stiffness.

Figure 8 depicts the variation of pseudo-static component contribution (expressed as the ratio between the pseudo-static and the dynamic components of structural response) as a function of the deck stiffness for the case of the simplified bridge. It is clear that pseudo-static response (and subsequently, the potential impact of all the simplified EC8 and Italian Code predictive methodologies) is only minor (i.e., less than 10% for flexible deck structures) but it can greatly increase with increasing deck stiffness. Most importantly, the same trend is observed for the actual case of Evripos bridge when subject to non-uniform excitation for various levels of deck stiffness, illustrated in Figure 9. Again, should the deck had been stiffer, the contribution of the pseudo-static component of structural response would have been significantly higher.

Clearly, the above observation refers to the anticipated impact and outcome of the (essentially static) simplified methods proposed in seismic codes and does not imply that the actual overall response of the bridge would be always beneficial or detrimental for any bridge under every earthquake scenario. Indeed, most flexible structures are more tolerant to multiple-support earthquake input but the potential excitation of higher modes and the increase of specific critical engineering demand parameters should by no means be underestimated.

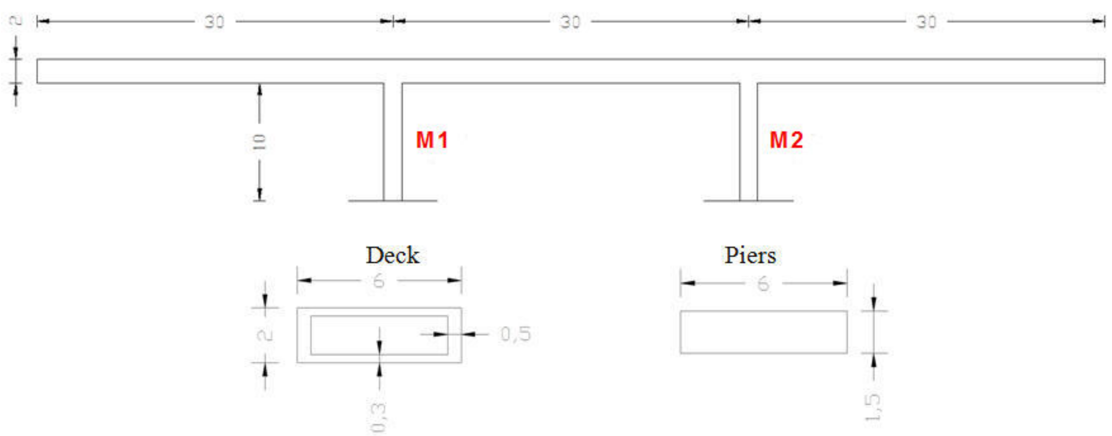

Figure 7:Simplified version of the Evripos bridge configuration for the investigation of the relative pseudo-static and dynamic component contribution to the overall response under asynchronous excitation.

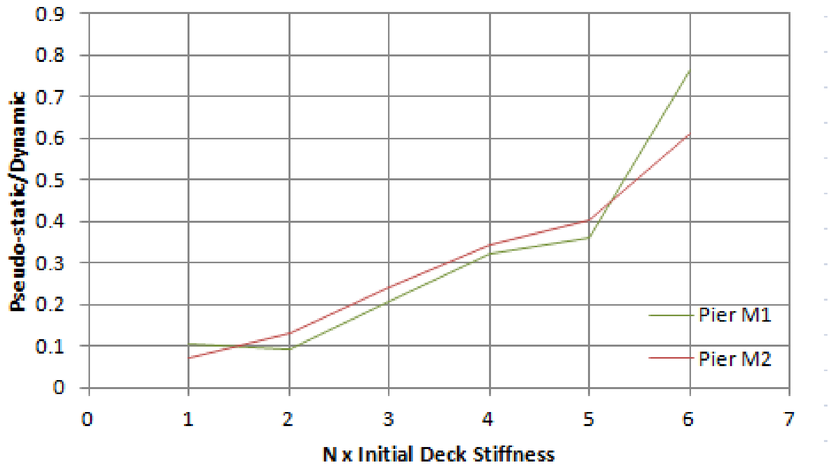

Figure 8: Variation of pseudo-static component contribution as a function of the deck stiffness (for the case of the simplified bridge).

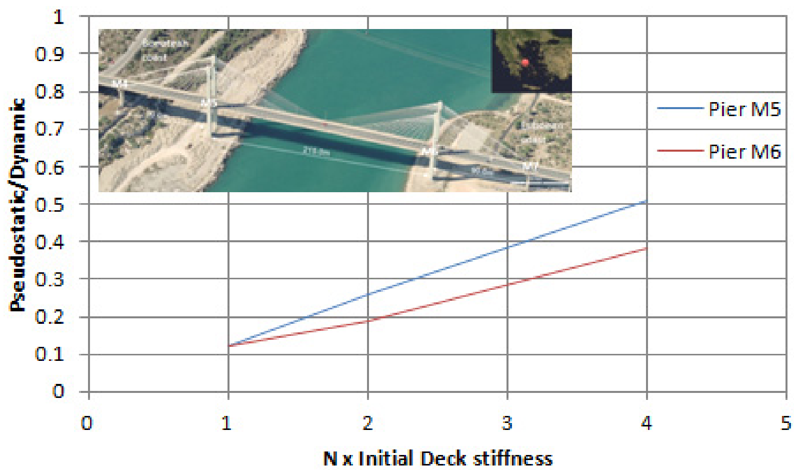

Figure 9: Variation of pseudo-static component contribution as a function of the deck stiffness (for the case of the Evripos cable-stayed bridge).

6 CONCLUSIONS

In this paper, the applicability of three simplified methods (EC8-Part 2 provisions and the improved by Sextos & Kappos and Nuti & Vanzi EC8-based methods) to capture the effects of spatial variability of earthquake ground motion is investigated through the case study of the Evripos cable-stayed bridge in Greece. The predicted, according to the simplified methodologies, structural response of the bridge is compared with the actually monitored behavior based on four free-field recording during the M_s=5.9, 7/9/1999 Athens earthquake. The coherency of these motions was computed for all the available pairs and incoherency patterns were duly identified. A detailed finite element model of the cable-stayed bridge was also updated based on the available measurements, until reasonable matching was achieved between the numerically predicted and the measured response. The results of the comparative assessment indicate that, the spatial variability of earthquake ground motion had a generally beneficial effect on the response of Evripos bridge with the exception of specific critical response components, a fact that is mainly due to the significant flexibility of the bridge deck. It was also shown however, that the impact of pseudo-static displacements depends heavily on the deck stiffness, hence the above observation can by no means be generalized. Specific concerns were also expressed with respect to the applicability of all the simplified code-based predictive models, as their inherent static nature essentially suppresses the dynamic impact of asynchronous excitation. When the application of such methods is inevitable, engineering judgment has to be exercised based on the whole range of results available in the literature.

REFERENCES

[1] A. Zerva, “Spatial Variation of Seismic Ground Motions: Modelling and Engineering Applications,” *Nonlinear Dynamics*. CRC Press, Taylor & Francis Group, LLC, p. 460, 2009.

[2] S. Biondi, G. Leoni, C. Nuti, G. Tropeano, and I. Vanzi, “Non synchronous earthquake motion in bridges design,” in *15th World Conference on Earthquake Engineering*, 2012, no. 2004.

[3] T. Albanesi, C. Nuti, and I. Vanzi, “Site specific spectrum-compatible non-synchronous motion,” in *1st US-Italy Seismic Bridge Workshop*, 2007.

[4] P. E. Pinto and P. Franchin, “Open Issues in the Seismic Design and Assessment of Bridges,” vol. 17, M. Garevski and A. Ansal, Eds. Dordrecht: Springer Netherlands, 2010.

[5] S. Liao and A. Zerva, “Physically compliant, conditionally simulated spatially variable seismic ground motions for performance-based design,” *Earthquake Engineering & Structural Dynamics*, vol. 35, no. 7, pp. 891–919, Jun. 2006.

[6] A. Der Kiureghian and A. Neuenhofer, “Response spectrum method for multi-support seismic excitations,” *Earthquake Engineering and Structural Dynamics*, vol. 21, no. September 1991, pp. 713–740, 1992.

[7] A. G. Sextos, K. D. Pitilakis, and A. J. Kappos, “Inelastic dynamic analysis of RC bridges accounting for spatial variability of ground motion, site effects and soil-structure interaction phenomena. Part 2: Parametric study,” *Earthquake Engineering & Structural Dynamics*, vol. 32, no. 4, pp. 629–652, 2003.

[8] A. J. Kappos, *Seismic Design and Assessment of Bridges*, vol. 21. Dordrecht: Springer Netherlands, 2012.

[9] fib [fédération international du béton], “Structural solutions for bridge seismic design and retrofit—a state of the art,” 2007.

[10] A. Lupoi, P. Franchin, P. E. Pinto, and G. Monti, “Seismic design of bridges accounting for spatial variability of ground motion,” *Earthquake Engineering and Structural Dynamics*, vol. 34, no. 4–5, pp. 327–348, 2005.

[11] A. G. Sextos, K. D. Pitilakis, and A. J. Kappos, “Inelastic dynamic analysis of RC bridges accounting for spatial variability of ground motion, site effects and soil-structure interaction phenomena. Part 1: Methodology and analytical tools,” *Earthquake Engineering & Structural Dynamics*, vol. 32, no. 4, pp. 607–627, 2003.

[12] A. G. Sextos and A. J. Kappos, “Evaluation of seismic response of bridges under asynchronous excitation and comparisons with Eurocode 8-2 provisions,” *Bulletin of Earthquake Engineering*, vol. 7, no. 2, pp. 519–545, 2009.

[13] L. Carnevale, S. Imperatore, D. Lavorato, C. Nuti, G. Leoni, and G. Tropeano, “Assessment of Seismic Behavior of R.C. Bridges under Asynchronous Motion and Comparison with Simplified Approaches,” in *15th World Conference on Earthquake Engineering*, 2012.

[14] A. Zerva and V. Zervas, "Spatial variation of seismic ground motions: An overview," *Applied Mechanics Reviews*, vol. 55, no. 3, p. 271, 2002.

[15] A. Zerva and M. Shinozuka, "Stochastic differential ground motion," *Structural Safety*, vol. 10, pp. 129–143, 1991.

[16] M. Shinozuka, V. Saxena, and G. Deodatis, "Effect of spatial variability of ground motion on bridge fragility curves," in *8th ASCE Specialty Conference on Probabilistic Mechanics and Structural Reliability*, 2000.

[17] A. G. Sextos, A. J. Kappos, and K. D. Pitilakis, "Inelastic dynamic analysis of RC bridges accounting for spatial variability of ground motion, site effects and soil-structure interaction phenomena. Part 2: Parametric study," *Earthquake Engineering & Structural Dynamics*, vol. 32, no. 4, pp. 629–652, 2003.

[18] L. Lou and A. Zerva, "Sensitivity of the Nonlinear Seismic Response of a Short RC Bridge to Numerical Modeling," in *15th World Conference on Earthquake Engineering*, 2012.

[19] L. Lou and A. Zerva, "Effects of spatially variable ground motions on the seismic response of a skewed, multi-span, RC highway bridge," *Soil Dynamics and Earthquake Engineering*, vol. 25, no. 7–10, pp. 729–740, 2005.

[20] C. Nuti and I. Vanzi, "Influence of earthquake spatial variability on differential soil displacements and SDF system response," *Earthquake Engineering & Structural Dynamics*, vol. 34, no. 11, pp. 1353–1374, 2005.

[21] C. Nuti and I. Vanzi, "Design Of Bridges For Non Synchronous Seismic Motion," in *Seismic Engineering Conference Commemorating the 1908 Messina and Reggio Calabria Earthquake*, 2008.

[22] Ministero Infrastrutture, "Norme Tecniche per le Costruzioni. Gazzetta Ufficiale. 29:(S.O. 30) (in Italian)." 2008.

[23] V. Lekidis, M. Tsakiri, K. Makra, C. Karakostas, N. Klimis, and I. Sous, "Evaluation of dynamic response and local soil effects of the Evripos cable-stayed bridge using multi-sensor monitoring systems," *Engineering Geology*, vol. 79, no. 1–2, pp. 43–59, 2005.

[24] V. Lekidis, C. Karakostas, and D. Talaslidis, "Instrumentation, measurements and numerical analysis of bridges: an example of the cable-stayed bridge on Evripos channel, Greece," *Strong Motion instrumentation for Civil Engineering*, pp. 481–493, 2001.

[25] C. Karakostas, A. Sextos, V. Lekidis, and S. Papadopoulos, "Investigation of the Cable-Stayed Bridge in Greece , under Asynchronous Ground Motion Records," in *COMPDYN 2011, 3rd ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, 2011.

[26] N. A. Abrahamson, J. F. Schneider, and J. C. Stepp, "Empirical spatial coherency functions for applications to soil-structure interaction analyses," *Earthquake Spectra*, vol. 7, no. 1, pp. 1–27, 1991.

[27] R. S. Harichandran, "Estimating the spatial variation of earthquake ground motion from dense array recordings," *Structural Safety*, vol. 10, pp. 219–233, 1991.

[28] R. S. Harichandran, A. Hawwari, and B. N. Sweidan, "Response of Long-Span Bridges to Spatially Varying Ground Motion," *Journal of Structural Engineering*, vol. 122, no. 5, pp. 476–484, 1996.

[29] R. S. Harichandran and E. H. Vanmarcke, "Stochastic variation of earthquake ground motion in space and time," *Journal of Engineering Mechanics*, vol. 112, no. 2, pp. 154–174, 1986.

[30] J. E. Luco and H. L. Wong, “Response of a rigid foundation to a spatially random ground motion,” *Earthquake Engineering and Structural Dynamics*, vol. 14, pp. 891–908, 1986.

[31] C. H. Loh and S. G. Lin, “Directionality and simulation in spatial variation of seismic waves,” *Engineering Structures*, vol. 12, pp. 134–143, 1990.

[32] N. A. Abrahamson, “Spatial variation of multiple support inputs,” in *Proceedings of the 1st U.S. Seminar on Seismic Evaluation and Retrofit of Steel Bridges. A Caltrans and University of California at Berkeley Seminar*, 1993.

[33] C. Karakostas, A. G. Sextos, V. Lekidis, and S. Papadopoulos, “Investigation of the dynamic response of the Evripos cable-stayed bridge in Greece, under asynchronous ground motion records,” in *3rd ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, 2011.

[34] J. P. Nicoletti, M. J. N. Priestley, F. Seible, and G. M. Calvi, *Seismic design and retrofit of bridges*, vol. 12, no. 3. New York: Wiley, 1996.