SEISMIC RESPONSE OF LONG R/C BRIDGES: EFFECT OF COUPLED GROUND MOTION VARIABITY AND SOIL-FOUNDATION INTERACTION

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1 INTRODUCTION

Although bridge structures might seem at a first sight as rather linear and simple structural systems, their actual performance under earthquake loading is much more complicated than that of buildings, since bridges have typically an order of magnitude larger dimensions, cross non-uniform soil profiles whereas the contribution of higher modes of vibration is more important. In fact, design projects become more and more complex because the current socio-economic demands stretch the limits of the modern technology in order to prioritise time saving instead of cost, thus imposing the necessity of overcoming unfavourable topographic, geological, seismotectonic and geotechnical conditions. Bearing in mind that to date significant research effort has already shed some light to many bridge engineering problems, two of the most difficult aspects, which are also related to the highest relative uncertainty compared to the superstructure, is the definition of a ‘realistic’ input motion and the supporting conditions of the structure; both of them have been shown to be of paramount importance for the final dynamic response of the bridge in the time domain. To this end advanced analytical solutions and enhanced know-how is sought for dealing with the significant number of cases that are not covered by modern seismic codes, but the complexity is such that they are often strongly case-dependent and sometimes controversial. What is left therefore, is the performance of the design using significant simplifying assumptions in terms of spatial and temporal variation of ground excitation among the pier supports, the characterization of the underlying soil profile, as well as the interaction of the overall soil-foundation system with the structure. It is the scope of this paper to investigate the degree of detrimental influence, if any, of the aforementioned approximations by attempting to apply a comprehensive methodology that considers spatial variability of ground motion, site effects and soil-structure interaction to three 600m bridge structures.

2 CODE TREATMENT OF THE PROBLEM

During the last years, significant research has been carried out with respect to the identification of bridge sensitivity to multiple support excitation, the variation of soil profile along the bridge axis and the effect of soil-structure-foundation interaction. However, due to the inherent complexity of wave propagation issues and the multi-parametric nature of the foundation-soil influence to the overall structural response, it is often deemed more efficient and reliable to study the dynamic behaviour of the bridge by making ‘reasonable’ approximations with respect to particular features of the coupled seismic wave, 2D soil structure-foundation and structural system. Moreover, not all derived observations provide a widely accepted perspective of the role played by the aforementioned issues, hence highlighting the significant difficulty to propose general rules and even more, to quantify and parameterise the problem within the provisions of a seismic code. As a result, existing seismic codes provide rough guidelines often in an informative form and always treat the three phenomena separately.

As far as spatial variability is concerned, with the exception of Eurocode 8, Part 2, for bridges [1] that provides an expression for the relative displacement of adjacent piers and an informative annex for spatial variability analysis together with a threshold value of overall length for considering the effect of asynchronous motion, other modern codes deal with the problem on the basis of seating length provisions, such as the US Standard Specifications for Highways and Transportation Bridges [2] and

ATC-32 [3] or do not address the problem at all, like the Japanese Design Specifications for Highway Bridges [4]. It is worth-noting however, that this lack of detailed code provisions does not restrict the design of important structures to the synchronous excitation assumption but on the contrary, more refined approaches have been sought in major recent projects as the Metsovitikon [5] and the Rion-Antirion bridges [6] in Greece.

A discussion is also still open with respect to the feasibility of a more refined soil categorization and its implication for the corresponding amplification factors in the design spectra resulting only recently into the incorporation of a more refined site categorization in UBC2000 [7] and EC8. Soil-structure-interaction (SSI) on the other hand, is often treated as a beneficial phenomenon by ATC-3 [8] on the basis of the anticipated period elongation of the structure, as well as the energy dissipation at the foundation level caused by wave radiation and hysteretic damping. Recently, adequately detailed formulae and procedures are proposed by the Revised LFRD Design Guidelines for Highway Bridges [9], whereas similar expressions are also proposed by EC8. Along these lines, it was found particularly interesting to investigate whether it would be feasible to propose a comprehensive methodology for dealing with the aforementioned phenomena, and subsequently, to proceed to the performance of the adopted methodology for the evaluation of the current provisions reliability.

3 OVERVIEW OF THE METHODOLOGY

The aim is to introduce a comprehensive global approach to the seismic design and/or assessment of bridges that would allow for the application of a parametric analysis scheme, hence for the systematic study of all the parameters involved. This is achieved by incorporating and uncoupling all important issues (asynchronous motion, site effects, soil-structure-interaction) within the context of a general scheme for the inelastic analysis of bridges in the time domain. The methodology adopted and the analytical tool developed for its implementation are presented in detail elsewhere [10].

The idea however, is to first generate synthetic time histories, distinct at each support point (piers and abutments), through a refined spatial variability model which accounts for wave passage effect (arrival delay of non-vertical seismic waves), loss of coherency (coherency being a frequency dependent measure of the statistical dependence between seismic waves that decays with distance as waves are refracted, reflected and superimposed) and the effect of local soil conditions in terms of amplitude and frequency content of earthquake ground motion. Next, further modification of motion in the frequency domain allows for the consideration of kinematic interaction between soil and the foundation piles, that is, the filtering of seismic motion due to the inherent difficulty of the foundation to vibrate according to the imposed displacement field.

The derived motion can then be used as the asynchronous input to the bridge structure which is assumed to be supported on different at each support point Beam-on-Dynamic-Winkler-Spring systems (BDWS). The corresponding dynamic impedance matrices for the foundation-soil system at each pier support location are derived for all horizontal, rocking and coupled modes of vibration. For the rotational stiffness in particular, a non-linear moment-rotation relationship is proposed [10] in order to combine the rotational compliance of the foundation with a lumped plasticity model for the RC section that accounts for the plastic rotations caused by yielding at the pier base [11].

The aforementioned methodology has been implemented into the fully parameterised computer code ASING (Asynchronous Support Input Generator) [10] that results to different time histories and linear/non-linear spring-dashpot systems at all support points of a given bridge and allows the performance of inelastic dynamic analysis of the superstructure with the use of any commercial finite element code, but without the requirement of complex (and often prone to errors) FE modelling of wave propagation, site response and soil-structure interaction, as well as without the requirement for advanced concrete model features. Consequently, the study of the bridge sensitivity to the above phenomena may be performed though inelastic dynamic analysis and, if necessary, a Monte Carlo or directional simulation scheme.

4 PARAMETRIC ANALYSIS SCHEME

In order to meet the above requirements, a well-studied bridge structure [12] was selected as the reference case (Bridge “R”) of the parametric analysis. It is a straight, asymmetric, four-span bridge of 200m total length, supported on hollow section piers of height that varies from 7 to 21m. The concrete deck consists of a hollow box cross-section, which was taken as uniform along the length of the bridge. A monolithic pier-superstructure connection is assumed and the abutment bearings are pinned in the transverse while being free in the longitudinal direction. The concrete is class C30/35 and the modulus of elasticity is reduced by 50% to roughly account for R/C section cracking. The ultimate concrete strain ε_{cu} and the ultimate steel strain ε_{su} were taken equal to 0.008 and 0.1 respectively. The R/C sections' moment-curvature (M-φ) relationship and the corresponding ultimate and yield values (M_y=54465 kNm, M_u=65064 kNm, φ_y=0,000781 m^{-1}, φ_u=0,00443 m^{-1}) were calculated through the fiber-analysis code RCCOLA-90 [13].

The hypothetical subsoil structure of Fig. 1,2,3 was assumed in order to highlight the importance of local soil profile variation along the bridge axis. Its geometry, stiffness, density and damping (in terms of quality factor Q) properties are also presented in [10]. The structure is assumed to be supported on a a 3×4 pile group system of 1m diameter, 45m long piles, arranged at an axial spacing ratio S/D=3, and connected through a 8.0×11.0×2.0m pile cap that is designed according to Eurocode 7 and Eurocode 8 provisions. The assumption was also made that the bridge is located within a seismic zone characterised by a peak ground acceleration of 0.24g. The Kallithea (ATH-03) signal was used, recorded by the permanent instrumentation array of ITSAK (Earthquake Engineering Institute, Thessaloniki) during the 1999, M_w=5.9, Athens earthquake (0.3g maximum acceleration at 0.2 seconds period), scaled to the level of the desired peak ground acceleration and deconvoluted at the bedrock level. All ground motion simulations as well as the linear/nonlinear springs and dashpots that are required at the pier support points were calculated with the use of the code ASING. Using these key input data calculated from the program, the structure was discretized in finite elements (3D beams) and analysed in the time domain using the commercial FE package SAP2000 Non-Linear [14]. Results are reported here for excitation in the transverse direction only.

The parametric analysis involves 20 different bridges representing different structural types (in terms of fundamental period, symmetry, regularity, abutment support conditions, pier-to-deck connections), earthquake input (direction of excitation and frequency content of target input motion). It was also deemed interesting to investigate the effect of bridge dimensions in terms of span and overall length. This paper focuses on the particular response of the three 600m bridge structures selected. These structures are assumed to be located at the aforementioned geotechnical environment but have spans of 50 (Bridge 'A'), 100 (Bridge "B") and 150m length (Bridge "C") while being supported on 3, 5 and 11 piers respectively (Fig. 1, 2, 3).

It has to be noted, that it would be unrealistic to assume that the deck geometry would remain unaffected as the span length varies. As a result, for the models having span length different from that of the reference case for which the initial deck design was performed, an appropriate deck stiffness modification was applied. As a simple rule, it was decided to keep constant the ratio of the deck to pier normalized stiffness:

$$\left[\frac{EI_{deck}/\ell}{EI_{pier}/H}\right]_{Bridges'A','B','C'} \Bigg/ \left[\frac{EI_{deck}/\ell}{EI_{pier}/H}\right]_{Bridge'R'} \tag{1}$$

where H is the pier height and ℓ is the span length.

5 NUMERICAL OBSERVATIONS ON THE COUPLING OF SPATIAL VARIABILITY, SSI AND SITE EFFECTS.

5.1 A 'comprehensive' vs. the 'classical' approach

The structures described above were analysed in the time domain on the basis of cumulative analysis complexity starting from the 'classic' (most commonly used) approach of a fixed based structure excited by uniform earthquake motion that was generated with no particular consideration for soil amplification due to multi-layered soil profile (SC1). The effect of wave passage was considered in scenario 2 (SC2) while the loss of the coherency of the seismic waves was implemented additionally for the case of scenario 3 (SC3). The role played by the soil stratification on the magnitude and frequency content but also on the variation of ground motion is captured at scenario 4 (SC4) and the modification of seismic motion at each support location due to kinematic interaction is accounted for in scenario 6 (SC5). Flexibility and damping of the soil-foundation system are utilised in scenario 6 (SC6), as previously, additionally to the former assumptions. The latter case can be considered as the more advanced in terms of ground motion simulation and interaction at the foundation level, hence, for the shake of comparison it is considered as the 'comprehensive' approach.

The dynamic response in terms of pier top displacements, of the three 600m bridges analysed with the 'classic' compared to the 'comprehensive' approach is presented in Figures 1,2 and 3, and it is indeed significant. Nevertheless, the difficulty to be attributed to a specific factor, poses the necessity for a detailed investigation of the parameters involved, through a stepwise evaluation all the analysis scenarios.

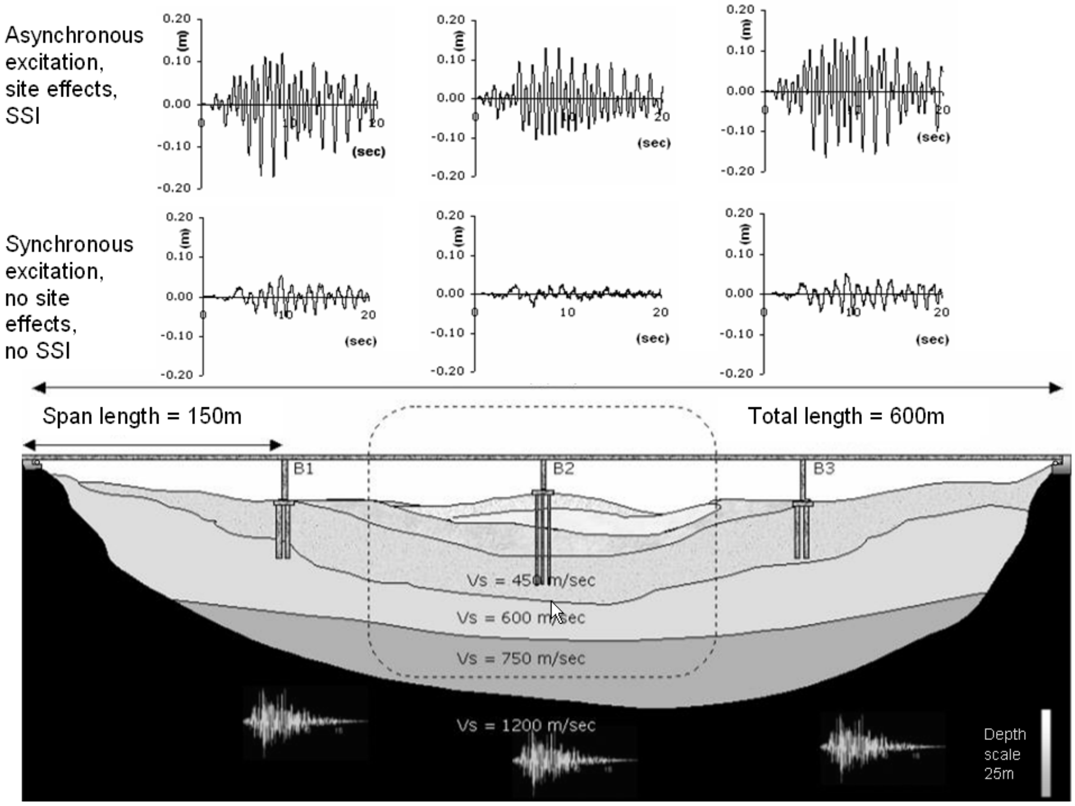

Fig. 1. Overview of Bridge “A”

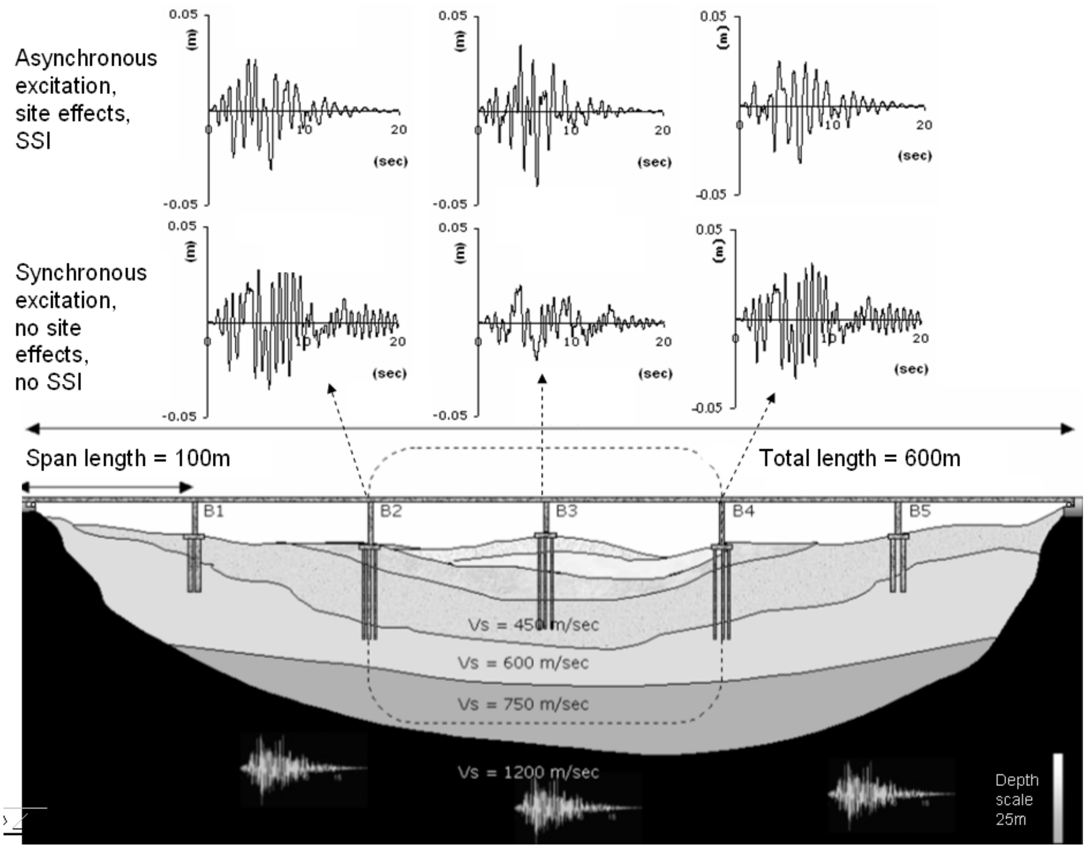

Fig. 2. Overview of Bridge “B”

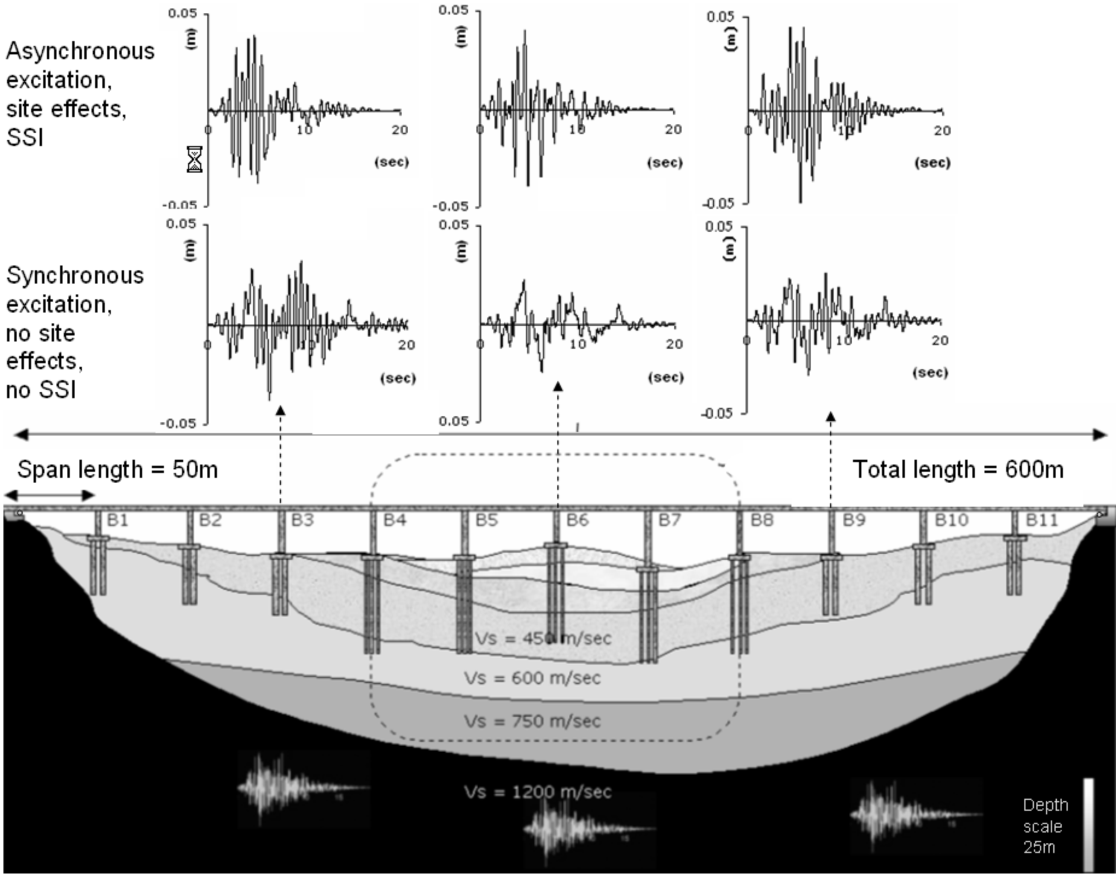

Fig. 3. Overview of Bridge “3”

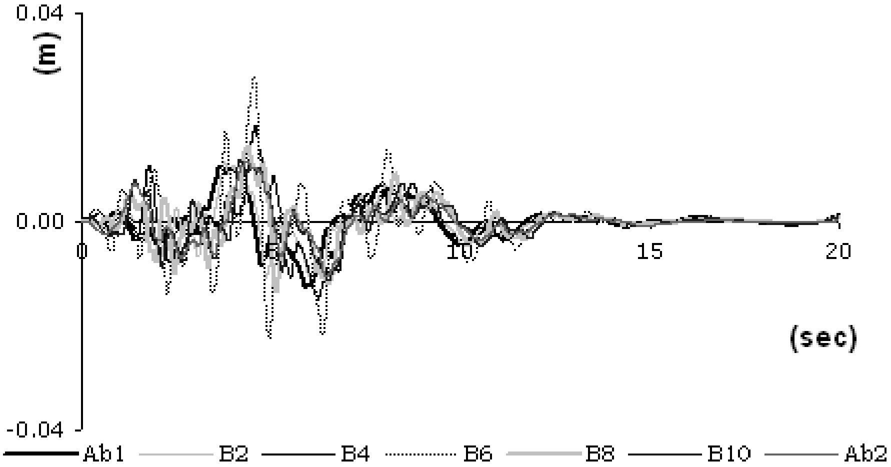

Fig. 4. Simulated earthquake ground motions at Bridge “C” pier supports

5.2. Spatial variability of ground motion

A first and fundamental observation resulting from the application of the above comprehensive procedure is that earthquake ground motion can differ significantly between the bridge supports especially for the case of the 600m bridges studied. This is in fact anticipated, since the longer the bridge is, the more soil profile diverges along the its axis whereas it is statistically expected that the abutments are founded on relatively stiffer formations than the supporting soil of the mid-piers (often soft allivia). Moreover, it has been shown [15, 16] among others, and also implemented in the ground motion generation code ASING, that the coherency of the waves decays with distance. As a result, seismic input at each support point is only partially statistically correlated and also corresponds to different frequency content. The above principles are reflected on the simulated input motions of Bridge “C” as presented in Fig. 4. It is also worth-noting the amplifying influence of the upper soft layers at the location of Pier B5 that is also apparent in the same Figure.

The question that arises therefore, is not whether the earthquake loading varies between the supports of a long bridge but whether potentially significant difference as observed herein has a detrimental influence on the overall dynamic response of the structure as a whole in terms of forces (bending moments and ductility demand) and displacements (absolute and relative).

Until recently, and especially in engineering practice, the perception prevails that the more the seismic motion differs between bridge support points, the more favourable the structure's dynamic response is, either on the assumption that the structure is somehow “obstructed” to vibrate at its fundamental mode as observed in several cases [17,18] or on account of lower exciting inertial forces [19, 20, 21]. Nevertheless, the discussion is still open even for relatively short bridges, where it has been shown that asynchronous input motion might trigger higher, and often crucial, modes of vibration [17,18, 22].

Fig. 6 which illustrates the maximum pier top absolute displacement at all piers of the three 600m bridges studied under all scenarios of increasing analysis complexity, indicates that is indeed extremely rare to observe a displacement reduction globally and unconditionally, i.e. for all piers and for all response parameters; In fact, there is a complex fluctuation of the ratio between the transverse displacements that correspond to synchronous earthquake input (SC1) and those arising from a time-delayed support excitation (SC2) which reaches the level of ±50%. This phenomenon is even more apparent when ground motion is more ‘realistically’ reproduced by additionally accounting for the coherency loss of the seismic waves (SC3). In this case, transverse displacements are even almost doubled in the extreme case (Bridge “A”, Piers B1 and B3). A maximum increase factor of 3.5 has also been observed in terms of the relative transverse displacements of two successive piers [18]

Bending moments on the other hand which are illustrated in Fig. 7, show a tendency to increase as well (20% on average for Bridge “A”, 15% for Bridge “B” and 25% for Bridge “C”), although this observation does not apply to all piers of the three long structures. Pier base bending moments may also be increased up to a level of 50% in the most unfavourable case (Bridge “C”, Pier B5). It is worth-noting that, such detrimental effect of spatial variability of ground motion has also been depicted under certain conditions for shorter piers (even of overall length of 200m) [18] but clearly to a less extent.

The aforementioned unfavourable results, may be attributed to the increase in pseudo-static forces that leads to distress and relative displacements between successive piers [19, 20, 23]. It is clear therefore, that the interplay between inertial and pseudo-static forces may either lead to favourable or unfavourable [12, 22, 24] total dynamic response, depending on the geometry, structural system, span length and fundamental period of the bridge, the frequency content, shear velocity and angle of incidence of the propagating waves, and the response parameter sought. To this end, it is also interesting to note that Eurocode 8 prescribes the length of 600m as the threshold for considering spatial variability, an assumption that although may lead to unconcervative design under particular short bridge circumstances, it is at the same time an appropriate sign of warning for the design of long structures.

An effort to relate, as general trend, the bridge sensitivity to multiple support excitation with the overall length, has been made through a statistically derived amplification factor R_D for the case of relative displacements [18]:

$$\delta_a = R_D \, \delta_s = (0.8\, ln(L) - 2.8)\, \delta_s \qquad (2)$$

where δ_s is the expected relative displacements that would result from typical synchronous motion analysis and L is the overall length expressed in meters. Further research would be useful however for the generalisation and the more refined quantification of the problem.

5.3 Soil-structure-foundation interaction in the presence of the local site conditions effect

The presence of more realistic soil-foundation conditions (SC6) in terms of flexibility and damping is a second issue of particular interest. Figure 5 illustrates the modification of pier top displacements due to the combined effect of kinematic and inertial interaction. The isolated influence of the kinematic effect is presented elsewhere [18] but it is interesting to note that unlike what is oberved for shorter bridges, kinematic interaction has not uniformly beneficial effect for the 600m bridges. From the dynamic analysis results obtained, it is verified the common percetion that accounting for the soil-foundation system flexibility, the structure exchibits larger displacements (up to 50% for Brige “A” compared to the previous scenario SC4). Nevertheless, this does by no means apply to all piers of all structures, due to the SSI-induced modification of the dynamic characteristics of the structure. Moreover, and despite common beliefs that the assumption of a non-rigid foundation would somehow ‘releaf’ the structure from the anticipated distress, both due to the presence of flexibility and damping at the foundation-soil interface, the results indicate that although this is indee the general trend, specific cases also exist where pier base bending moments are increased up to 50% when SSI effects are considered (Bridge “C”, Pier B10). Such detrimental effect of SSI has also been discussed elsewhere [25]

This observation may attributed to the fact that the overall dynamic response of a bridge, is an interplay between the dynamic properties of the structure (which have been significantly modified due to soil flexibility and damping) and the frequency content of the input motion as well (which is also strongly influenced by the multi-layered, damped soil profiles overlaying an elastic bedrock). In fact, as soil interacts with the foundation and the structural period elongates, the structure becomes more sensitive to long period pulses which may have been amplified in certain cases and locations due to the presence of soft layers, abrupt change of soil stiffness and/or high bedrock-soil velocity contrast [26, 27].

It is interesting to notice that when the flexibility and damping of the pier foundation-soil system is considered alone, and the asynchronous character of the seismic motion as well as the soil variation along the bridge axis are neglected in the analysis of the three 600m bridges “A:, “B” and “C” (SC7), the SSI effects were beneficial in the view of structural distress and bending moments developed (Fig. 6); clearly because the first transverse periods of vibration of the three structures (T_A = 1.13 sec, T_B = 0.77sec, T_c =0.69 sec) where already longer than the dominant period of the initial (uniform and unaltered) Kallithea target input motion (0.2 sec) and further elongation inevitably resulted to reduced inertial forces. It also indicates though, that ignoring the effect of local soil conditions underestimated significantly the results of the soil-structure interaction analysis by approximately a maximum factor of 3.0 at the extreme case, for both pier top absolute displacements (i.e. Bridge “A”, Pier B2) and bending moments at the pier base (i.e. Bridge “B”, Pier B5). It is concluded therefore, that a more ‘realistic’ representation of the input motion is of paramount importance when assessing the effect of soil-structure interaction and that both the multi-layer, damped nature of the soil structure and the wave propagation issues should be considered as thoroughly as it is feasible.

5.4 Ductility demand as a function of analysis complexity

The aforementioned detrimental cases are reflected to the ductility demand of the structures examined through inelastic dynamic analyses. It is shown [28] that the final rotational ductility demand of the piers is strongly affected by the assumptions made with respect of pier base fixity conditions, site effects and multiple support excitation and can be underestimated by a factor of 3.0 when the ‘classic’ approach is followed. As a result, it is strongly recommended that for bridges of high importance, a set of well selected parametric analyses should be performed in order to estimate not an absolute maximum but a reasonable envelope of the potential inelastic bridge response under different seismic input.

6 CONCLUSIONS

The effect of spatial variability, local soil conditions and soil-structure interaction was examined herein for three fictitious but adequately realistic bridge structures that match the length that Eurocode 8 prescribes as the minimum for assessing the effect of spatial variability of ground motion. Through a step-by-step cumulative analysis complexity approach, it is concluded that although significant progress has been made with respect to the above issues, the coupling of ground motion variation and soil-foundation-structure interaction is strong that under certain circumstances, code provisions do not necessarily lead to conservative design.

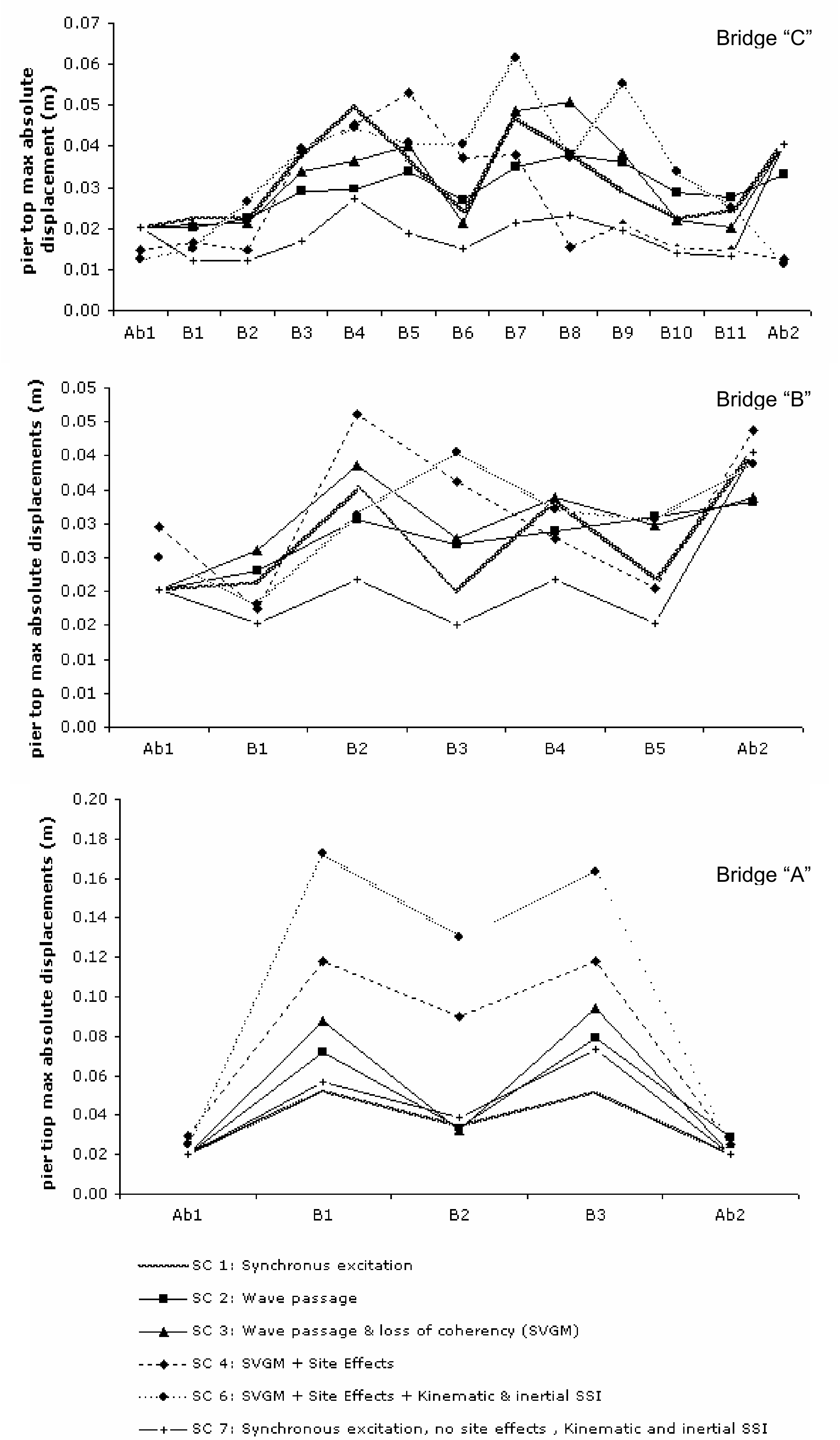

Fig. 5. Pier top maximum absolute displacements of Bridges "A", "B" and "C" for the seven scenarios

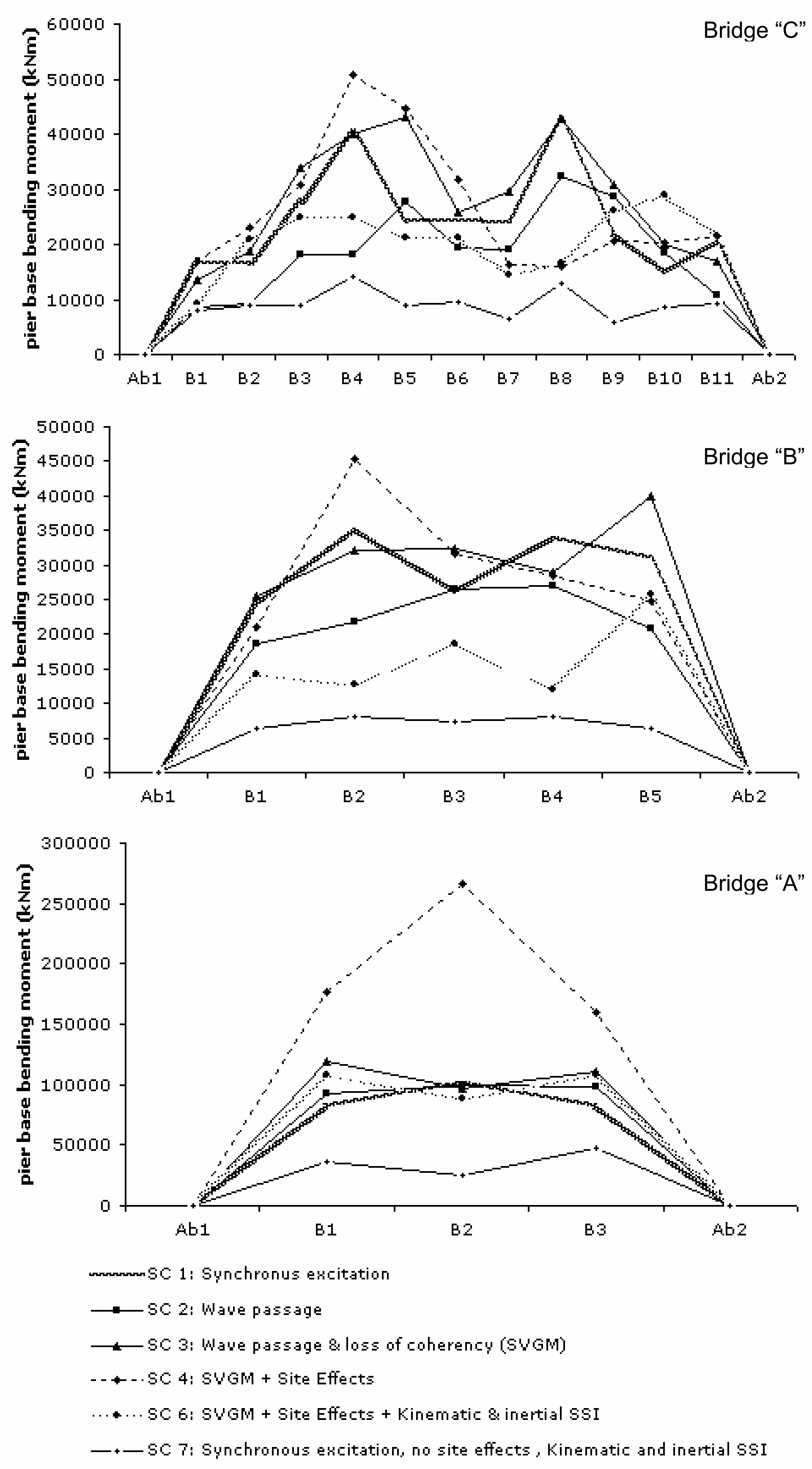

Fig. 6. Pier base bending moments of Bridges “A”, “B” and “C” for the seven scenarios

REFERENCES

[1] CEN. Eurocode 8 – Design provisions for earthquake resistance of structures. Part 2: Bridges , ENV 1998-2, *CEN*, Brussels, 1994.

[2] American Association of State Highway and Transportation Officials, *AASHTO*, Standard Specification for Highway Bridges, 16th edition, 1996.

[3] Applied Technology Council, Improved Seismic Design Criteria for California Bridges: Provisional Recommendations", ATC-32, National Bureau of Standards, Washington DC, U.S.A. 1996.

[4] Public Works Research Institute (PWRI), Design Specifications of Highway Bridges, Part V, Seismic design Technical Memorandum of EED, No. 9801, Japan, 1998.

[5] Oldham, M., Lubkowski, Z., Duan X. & Sturt R., Seismic Design of the Metsovitikos Suspension Bridge, Pindos Mountains, Greece, Proc. of the 3rd National Seismic Conference on Bridges & Highways, Advances in Engineering and Technology for Seismic Safety of Bridges in New Millennium, Portland, Oregon, April 28-May 1, 2002.

[6] Combault, J., Morand, P., Pecker, A., Structural response of the Rion-Antirion Bridge, Proc. of the 12th World Conference on Earthquake Engineering, Auckland, New Zealand, Paper No. 1609, 2000.

[7] Uniform Building Code, Structural Engineering Design Provisions, International Conference of building officials, 2, Whittier, California, 2000.

[8] Applied Technology Council (ATC), Tentative provisions for the development of seismic regulations of buildings: a cooperative effort with the design profession, building code interests and the research community, ATC-3, National Bureau of Standards, Washington DC, 1978.

[9] American Association of State Highway and Transportation Officials, *AASHTO*, Comprehensive Specifications for the Seismic Design of Bridges, Revised LFRD Design Specifications, NCHRP 12-49, 2001.

[10] Sextos, A. , Pitilakis, K & A. Kappos, A global approach for dealing with spatial variability, site effects and soil-structure-interaction for non-linear bridges: a. verification study, Earthquake Engineering and Structural Dynamics, Vol. 4, 607-629, 2003.

[11] Kappos, A.J., Sextos, A. Effect of foundation compliance on the lateral load response of R/C bridges, Journal of Bridge Engineering, ASCE, Vol. 6, No. 2, 120-130, 2001.

[12] Calvi, M., Pinto, P., Experimental and numerical investigations on the seismic response of bridges and recommendations for code provisions, European Consortium of Earthquake Shaking Tables, Prenormative Research in Support of Eurocode 8, Report 4, 1996.

[13] Kappos A, RCCOLA-90 : A Microcomputer Program for the Analysis of the inelastic Response of Reinforced Concrete Sections, Dept. of Civil Engineering, Aristotle University of Thessaloniki, Greece, 1993.

[14] Computers and Structures Inc., SAP 2000 Nonlinear, Berkeley, U.S., 1999.

[15] Hindy A, Novak M. Pipeline Response to random ground motion, Journal of Engineering Mechanics, ASCE, Vol. 106, 339-360, 1981.

[16] Loh, C., Yeh Y., Spatial Variation and Stochastic Modeling of Seismic Differential Ground Movement, Earthquake Engineering and Structural Dynamics, Vol. 16, 583-596, 1988.

[17] Tzanetos N, Elnashai AS, Hamdan F, Antoniou S. Inelastic Dynamic Response of RC Bridges Subjected to Spatial Non-Synchronous Earthquake Motion, Journal of Advances in Structural Engineering, Vol. 3, No. 3, 21-38, 2000.

[18] Sextos, A. , Pitilakis, K & A. Kappos, A global approach for dealing with spatial variability, site effects and soil-structure-interaction for non-linear bridges: b. Parametric analysis", Earthquake Engineering and Structural Dynamics, Vol. 4, 630-647, 2003.

[19] Zerva, A., On the spatial variation of Seismic Ground Motion and its effects on lifelines, Journal of Engineering Structures, Vol. 16, 534-546, 1994.

[20] Hao, H. Effects of spatial variation of ground motions on Large multiply-supported structures, UBC/EERC-89/06, Berkeley:Earthquake Engineering Research Center, University of California, 1989.

[21] Monti, G. , Nuti, C. , Pinto, P. & I. Vanzi Effects of non-synchronous seismic input on the inelastic response of bridges, Proceedings of the 2nd International Workshop on Seismic Design of Bridges, Queenstown, New Zealand, Vol. 1, 90-107, 1994.

[22] Kahan, M., Gibert, R. & P.-Y. Bard, Influence of spatial wave variability on bridges: A sensitivity analysis, Earthquake Engineering & Structural Dynamics, Vol. 25, No. 8, 795-814, 1996.

[23] Der Kiureghian, A. & Keshishian, P., Effects of incoherence, Wave Passage and Spatially Varying Site Conditions on Bridge Response, Proceedings of the FHWA/NCEER Workshop on the National Representation of Seismic Ground Motion for New and Existing Highway Facilities, Technical Report, NCEER, 393-407, 1997.

[24] Shinozuka, M., Saxena, V & G. Deodatis, Effect of Spatial Variation of Ground Motion on Highway Structures, Technical Report, MCEER, Rep. 00-0013, 2000.

[25] Mylonakis G., G. Gazetas. Seismic soil-structure interaction: Beneficial or detrimental? Journal of Earthquake Engineering, Vol. 4, No. 3, 277-301, 2000.

[26] Pitilakis K., Makra K., D. Raptakis, 2D Versus 1D Site Effects with Potential Applications to Seismic Norms: The Cases of EUROSEISTEST and Thessaloniki. Proceedings of the 15th International Conference on Soil Mechanics & Geotechnical Engineering, Earthquake Geotechnical Engineering Satellite Conference, Turkey, 2001.

[27] Raptakis D, Chávez-García FJ, Makra K, Pitilakis K., Site effects at EUROSEISTEST - I. Determination of the valley structure and confrontation of observations with 1D analysis. Soil Dynamics and Earthquake Engineering 2000, Vol. 19, No. 1, 1-22, 2000

[28] Sextos, A., Kappos, A. & Pitilakis, K Effect of Analysis Complexity on the ductility demand of R/C bridge piers, Proceedings of the 12th European Conference on Earthquake Engineering, London, 9-13 September, 2002.