A CRITICAL REVIEW OF THE ROLE OF SPATIAL VARIABILITY OF GROUND MOTION, SITE CONDITIONS, AND SOIL-STRUCTURE INTERACTION, IN BRIDGE ENGINEERING

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ABSTRACT: The objective of this paper is to critically evaluate the importance of common assumptions made during seismic design of bridges that are related to the asynchronous character of ground motion, local soil conditions and soil-structure-foundation interaction. To this effect, an extensive parametric analysis scheme is applied, and relevant results from these analyses, as well as from the literature are compared and discussed. It is concluded that although significant effort has been put in shedding some light on the above complicated and multiparametric phenomena, there is still a lot to be learnt towards a more rational, efficient and safe design of R/C bridges.

Keywords: Spatial variability, site effects, soil-structure interaction, R/C bridges

INTRODUCTION

As major bridge design projects aim at a safe performance under unfavourable geological, seismotectonic and geotechnical conditions, the need typically arises for advanced design capabilities and enhanced know-how that would allow for dealing with complex problems that are not covered by modern seismic codes. Moreover, the importance of such structures, in view of the high socioeconomic cost that a potential structural failure entails, calls for consideration and proper treatment of a number of uncertainties involved in the determination of the dynamic response under earthquake loading. To this end, it is of particular interest to focus on the importance of the simplifying assumptions typically made during seismic design, either when following code provisions or even during advanced dynamic analyses of bridge structures. Bearing in mind that to date significant research effort has already shed some light on the above phenomena and that important aspects of the dynamic bridge response have been thoroughly examined, it is often the case that the conclusions drawn are very much case dependent and, under certain circumstances they even appear contradictory, thus hampering the development of a definitive methodology for estimating the dynamic response of a bridge under earthquake loading. Such assumptions often refer to the 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. The extensive use of such simplifying assumptions in practical design, not only results in the oversimplification of the phenomenon studied, but also in the perpetuation of certain misconceptions and fallacies regarding the dynamic behaviour of bridges; some of them are discussed in the following.

COMMON BELIEFS REGARDING THE EFFECT OF SPATIAL VARIATION OF GROUND MOTION

"Excitation along the bridge length can be taken as uniform"

One of the most common hypotheses related to the dynamic analysis of bridge structures within the context of common design practice, is the assumption of a uniform acceleration time history for the synchronous excitation of all support points, an assumption which is primarily the result of the lack of accurate models rather than of concrete evidence. In fact, reality appears to be significantly more complex and difficult to predict; actual recordings obtained at extended arrays world-wide such as SMART1-Lotung LSST Lotung in Taiwan, Chiba in Tokyo, USGS-Parkfield and Imperial Valley in California, as well as at Euroseistest in Thessaloniki, Greece (http://euroseis.civil.auth.gr) clearly show that earthquake ground motion significantly varies in space and time in terms of amplitude, frequency content and arrival time, as a result of the fact that waves travel at a finite velocity thus arriving at each support point with delay, while at the same time they are subjected to multiple reflections, refractions and superposition that lead to loss of their coherency in terms of statistical dependence. Moreover, local site conditions at each support point affect the frequency content and amplitude of motion in a different way, which depends on the degree of soil properties variation along the bridge length. Additionally to the above, seismic motion is further modified by the bridge foundation, depending on its relative flexibility with respect to the soil, as a result of the fact that the foundation is not always able to vibrate according to the displacement field that is imposed to it by the incoming waves. This spatial and temporal variation of ground motion has been studied in depth and numerous, mostly experimentally derived, expressions and models have been developed for the description of the wave coherency loss (i.e. Luco and Wong, 1981, Hindy and Novak, 1981, Abrahamson 1991, Der Kiureghian, 1995). The asynchronous character of earthquake ground motion on the other hand, has also been recognised in some modern seismic codes either directly (Eurocode 8) or indirectly (AASHTO, ATC-32, ATC-35), and the above concerns regarding the nature of ground motion spatial variability have been reflected in the design of important bridge structures, such as the 2252 m length Rion-Antirion cable-stayed bridge in Southern Greece (Combault et al., 2000) the 500 m span Metsovitikos suspension bridge in Northern Greece, and in a number of research studies (e.g. the Warth bridge in Austria; Flesh et al., 2000).

"Applying the same time history waveform with an arrival delay is sufficient for describing spatial variability"

Spatial variation of earthquake ground motion is usually being dealt with by assuming a single wave travelling at a constant velocity through the soil media (Bogdanoff et al., 1965, Sandi, 1970 Dumanoglou et al., 1986), therefore arriving unchanged in terms of earthquake characteristics (frequency content, duration, intensity etc.) between support points and being only a function of shear wave velocity and angle of incidence.

Although this is a useful and simple approach, it does not take into consideration the fact that waves consist of particles that travel within the soil media at a different, frequency dependent, velocity, while they are subjected to various reflections, refractions and superpositions that result in the reduction of their coherency with both distance and frequency. The distinct acceleration time histories at each support point that reflect the effect of time delay and loss of coherency, can be expressed in the general form (Deodatis, 1996):

$$x_i(t) = 2\sum_{m=1}^{n}\sum_{l=1}^{N}\left|L_{jm}(\omega_{ml})\right|\sqrt{\Delta\omega}\cdot cos[\omega_{ml}t+\theta_{jm}(\omega_{ml})+\phi_{ml}] \qquad (1)$$

where L_{jm} is a a lower triangular matrix that results from the Choleski decomposition of the cross power spectral density matrix of the motions among support points, φ_{ml} are independent random phase angles, uniformly distributed in the range (0,2π), N represents the Nyquist frequency $\overline{\varpi}_N$, Δω is the frequency step and θ_{jm} is the phase, which is equal to:

$$\theta_{jm}(\overline{\varpi}_{ml}) = tan^{-1}\frac{Im[l_{jm}(i\overline{\varpi}_{ml})]}{Re[l_{jm}(i\overline{\varpi}_{ml})]} \qquad (2)$$

In order to illustrate the above significant difference, the example of a well-studied bridge structure (Calvi and Pinto 1996) was utilised, consisting of four 50m spans supported on three hollow piers of unequal heights, varying from 7 to 21m, and designed according to Eurocode 8. The bridge, which has been chosen as the "reference bridge" for further comparative analyses, was excited in the transverse direction by the Kallithea record obtained during the 1999 Athens earthquake, scaled to a PGA of 0.24g. The input motion was applied (i) as a single accelerogram, assumed to travel at a constant velocity of 300 m/sec (ii) as the same waveform as in case (i) that is propagating according to equation (1) while being fully coherent and (iii) as distinct time histories that not only differ in terms of arrival time but are also loosing their coherency according to the Luco and Wong (1986) model. The results, which are presented in Figure 1, indicate that assuming a simple time delay for the applied time histories, may lead to 25% difference in terms of pier top absolute displacements when the structure is excited according to the refined wave passage model of equation (1) and up to 100% compared to the further refined asynchronous motion model. Obviously, the results refer to this particular example, but the above differences are expected to be even more substantial in cases of longer bridges where the loss of coherency effect is more pronounced.

'Spatial variability model can be selected independently of the coherency model'

It is well known that the wave's coherency loss is generally dependent on the earthquake characteristics (intensity, frequency content, rupture mechanism), the propagation path and the dynamic properties of the local soil, which inevitably make the experimentally derived coherency functions to be soil and earthquake specific. Even the processing method in terms of stochastic

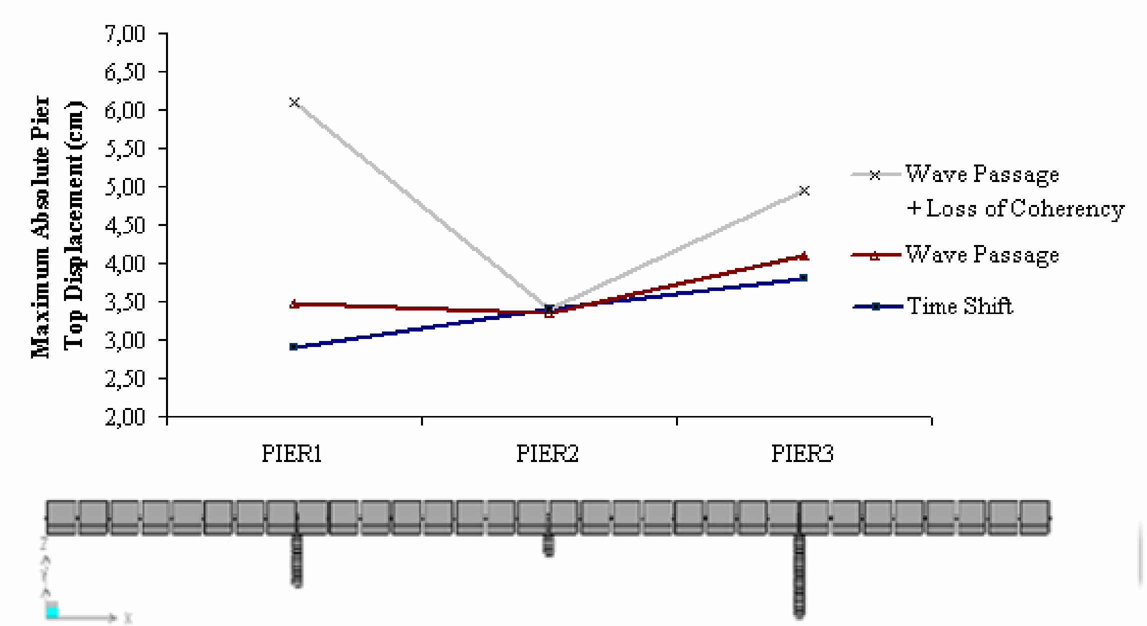

Fig 1 Maxima of pier top absolute displacements for different wave passage modelling assumptions.

properties and filtering of the recorded wavefield has a significant effect on the calculated coherency decay, thus inducing an additional uncertainty in the generation of synthetic ground motions and hence on the elastic/inelastic dynamic analyses of bridges. This uncertainty has also been reflected on the calculated dynamic behaviour of bridge structures that are subjected to motions derived from different loss of coherency models (Zerva, 1992; Soliman & Datta, 1994).

Along these lines, it is important to highlight the importance of obtaining a large number of earthquake records through well instrumented test sites and arrays, that would permit extensive data processing and the potential estamblishment of certain correlations between earthquake characteristics, soil and site properties, and coherency reduction patterns.

"Assuming synchronous support excitation is a conservative design approach"

One reason for disregarding the spatial and temporal variation of ground motion is the prevalent perception that the more the seismic motion differs between bridge support points, the more favourable the structure's dynamic response is. This view is widely accepted in the community of practicing engineers and has also been supported by certain research results (Kang & Wieland, 1988; Hao, 1989; Monti et al., 1994) that depict cases where asynchronous support excitation has a beneficial effect on the dynamic response of bridges. This observed reduction in action effects (displacements and/or forces) has often been related to the fact that the structure, when multiply excited, is subjected to lower inertial forces (Zerva, 1994), which in the extreme case of fully uncorrelated motions may even vanish (Monti et al., 1994).

Nevertheless, it is indeed extremely rare to observe such a reduction globally and unconditionally, i.e. for all piers and for all response parameters. On the contrary, asynchronous excitation of a bridge structure often has an adverse effect on displacements (absolute and relative), internal forces, reaction forces and ductility demand (Price & Eberhard, 1998; Der Kiureghian et al., 1997; Monti et al., 1997; Rassem et al., 1996). As a result, various levels of increase in response parameters have been observed under different circumstanses, e.g. wave passage and loss of coherency effects may lead to an increase in ductility demand by 50 %, and in internal stresses by 20% (Saxena et al., 2000). Furthermore, an extensive parametric analysis (Sextos et al., 2002b) involving 20 different bridge structures subjected to three different earthquake scenarios generated using the ASING (Asynchronous Support Input Generator) code (Sextos et al., 2002a) has also shown that the above response parameters may be strongly affected by the asynchronous character of ground motion; absolute displacements and pier base bending moments can be increased by 20 to 40%, relative displacements can increase by 5 to 40% for short bridges ($L<400$ m) and up to 350 % for longer bridges ($L=600$m), while an average increase in ductility demand by a factor of 1.25 was observed, which reached 3 at an extreme case. Along these lines, it is worth noting that Eurocode 8 prescribes the length of 600m as the threshold for considering spatial variability, an assumption that may lead to unconcervative design under certain circumstances. These results are illustrated in Figures 2 and 3 where Model A refers to the reference bridge described above, while the remaining correspond to various cases of effective stiffness (B1-B4), symmetry and regularity conditions (C1-D2), abutment to deck connection types (E1-E3), direction of excitation and frequency content (F1-F2), overall and span length (G1-G5).

The aforementioned unfavourable results, albeit rather controversial at first sight, in view of the reduction in inertial forces typically observed in the case of multiple support excitation, they are related to the increase in pseudo-static forces that leads to distress and relative displacements between successive piers (Winson & Jennings, 1985; Hao, 1989; Betti et al., 1993; Zerva, 1994b; Der Kiureghian, 1995; Der Kiureghian & Keshishian, 1997; Price & Eberhard, 1998) especially when input motions are uncorrelated at low frequencies (Zerva, 1994). It is clear therefore, that the interplay between inertial and pseudo-static forces may either lead to favourable or unfavourable (Kahan et al., 1996; Calvi, 1997; Shinozuka et al., 2000) 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.

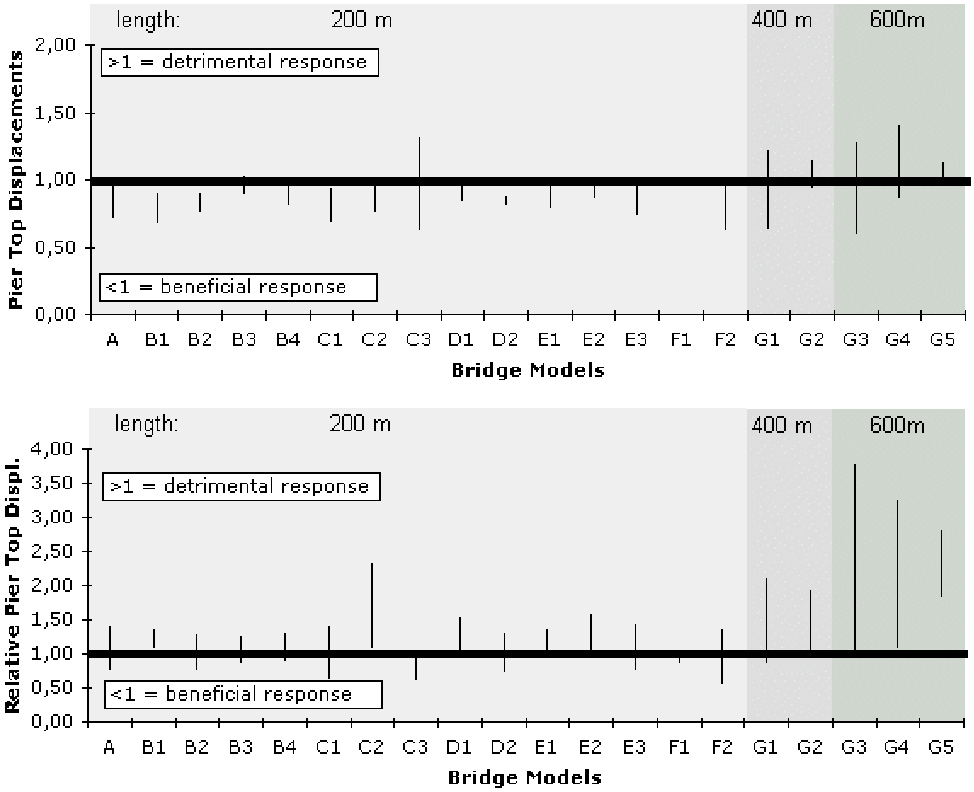

Fig 2 Absolute and relative pier top displacements of bridges subjected to wave passage effect compared to the synchronous case (Sextos et al. 2002b)

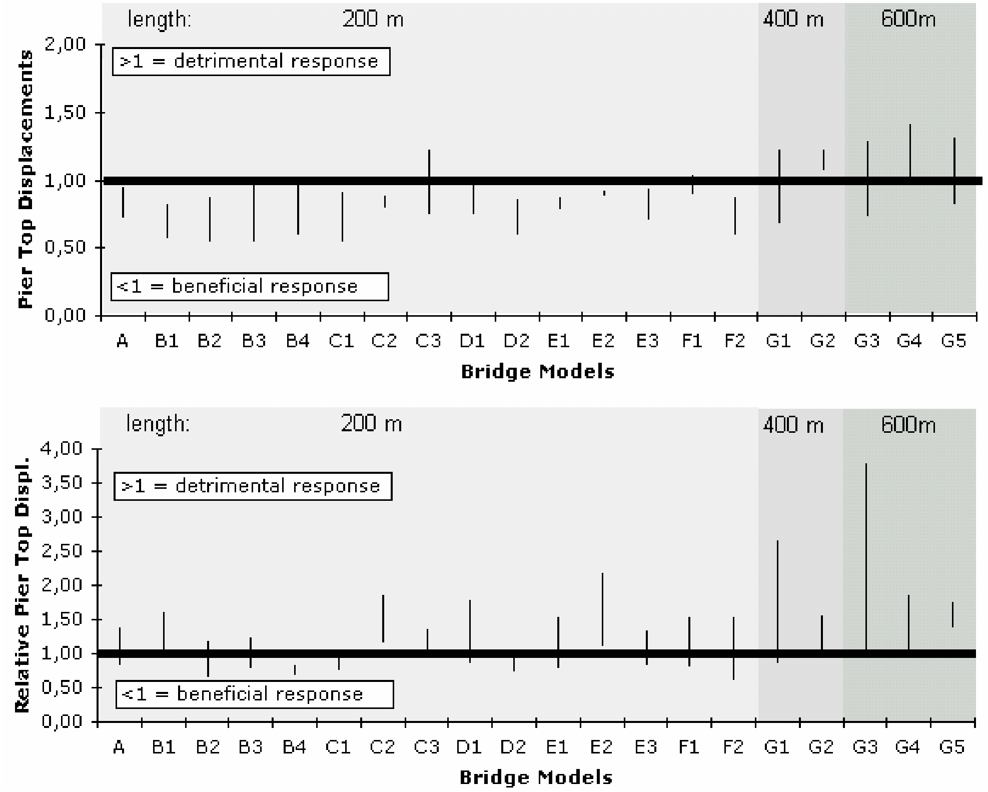

Fig 3 Absolute and relative pier top displacements of bridges subjected to wave passage and loss of coherency effect compared to the synchronous case (Sextos et al. 2002b).

In engineering practice, it is equally common to disregard the potential effect of the spatial variation of earthquake ground motion on the assumption that the structure is somehow “obstructed” to vibrate at its fundamental mode. This resonance inhibition has been observed in several cases (Tzanetos et al., 2000, Sextos et al., 2002b), and often results to reduction in action effects (Calvi et al., 1997). Nevertheless, it has also been observed that asynchronous input motion might trigger higher modes of vibration (Kahan et al., 1996; Price et al., 1998; Tzanetos et al. 2000). In the aforementioned study, involving 20 different bridge formulations (Sextos et al., 2002b) it was found that at least in eight cases the dynamic response of the structure was dominated by higher mode excitation.

“The total length of 600 m is the threshold for accounting for spatial variability”

In the aforementioned study by Sextos et al. (2002b) it was also observed that relative displacements significantly increased with the overall length, a fact that is of particular importance since relative deck movement can produce either distress or even unseating of the deck, depending on the pier to deck connection. An effort was made to relate the average (μ) and the standard deviation (σ) of the relative displacements ratio calculated for all spans during synchronous and fully spatially variable input motion, separately for the three total length categories (200m, 400m, 600m). It was found that both the average of the relative motion modification as well as its standard deviation show a systematic trend to logarithmically increase with length, hence they can be expressed in the empirical form presented in Eq (3). As a result, it could be considered that in the worst-case scenario, calculated on a $\mu+\sigma$ basis, the relative displacements δ_a expected for a bridge length $L \leq 600$m could be calculated as the product of the displacements δ_s derived using the ‘standard’ synchronous approach and an amplification factor R_D:

$$\delta_a = R_D\, \delta_s = (0.8\, ln(L) - 2.8)\, \delta_s \tag{3}$$

For instance, for a 450m bridge, the maximum relative displacements expected would be twice those calculated through a uniform excitation analysis, hence, depending on the pier to deck conditions, it might be necessary to adjust the seating length accordingly. Apparently, the above relationship cannot be claimed to apply in all cases, since it has not yet been checked against significantly different soil and input motion conditions. However, it may be provisionally used as a practical rule, pending a more definitive relationship.

“A more flexible and/or symmetric structure is less affected by spatially variable motions”

This is another ostensibly reasonable assumption, based on the perception that a more flexible structure is expected to assume more easily the shape imposed to it by asynchronous excitation, thus eliminating the additional pseudo-static forces that are generated due to spatially variable earthquake input. Nevertheless, dynamic analyses of bridge structures having fundamental periods varying from 0.4 to 1.0 sec and subjected to multiple support excitation (Sextos et al., 2002b) indicated that stiffer structures are not necessarily the ones with the most critical response, and their absolute pier top displacements as well as the pier base bending moments may in some cases be lower than those of more flexible structures. This apparently surprising trend may be explained by focusing on the pseudo-dynamic bending moments developed at the pier bases, which, as expected, are indeed significantly higher as stiffness increases. Therefore, what is of particular importance is to take into consideration the fact that the overall dynamic behaviour of bridges subjected to spatially variable support motion is an interplay between the dynamic and the pseudo-static component which is triggered in each case and cannot be easily assessed in advance on the basis of the structural performance under static loading.

COMMON BELIEFS REGARDING THE EFFECT OF LOCAL SITE AND SOIL CONDITIONS

“ Soil can be sufficiently described through the site categorization process”

Another simplifying assumption often made during seismic design of bridges is that local site conditions are accounted for through a code-defined design spectrum whose shape depends on the site classification, being therefore dependent on the reliability of this classification process. Although this is clearly a practical and indispensable design approach, inevitably it does not consider the fact that soil “columns” are actually multi-layered, damped 3D media laying over an elastic bedrock that transmits and reflects energy, hence they may potentially amplify both the spectral and the peak ground acceleration, especially in cases of abrupt stiffness change or of complex subsoil conditions (Pitilakis et al., 2001; Pitilakis et al., 2002 ; Raptakis et al., 2000). For illustrating the aforementioned effect, the reference bridge structure was also subjected to motions that accounted for local soil conditions through multiple transfer functions (properly implemented into the ASING code) that relate earthquake motion between the surface points of multi-layered damped soil profiles and the underlying elastic bedrock.

The results indicate that when accounting for the soil amplification effect, all response parameters increased by approximately 50% on the average, while pier top transverse displacements and bending moments were more than doubled in certain cases, a combined effect of spatial variability and local soil conditions, which has also been observed by Der Kiureghian & Keshishian (1997). This increase can be primarily attributed to the peak ground motion amplification depicted by the site response analysis and to a lower extent to the spectral amplification of motion, which is observed within the range of 0.6 to 0.8 sec. The above PGA amplification (approximately 40% increase) is of particular importance since it is directly related to the dynamic response of an (elastic) bridge structure. Moreover, both for the validation analyses performed for the selection of the hypothetical soil structure as well as from other research studies (Raptakis et al., 2000) it was found that the resulting surface peak ground acceleration is strongly related to a set of ground parameters describing the velocity contrast between the bedrock and the overlying layers, the dynamic properties of the soils and the thickness of the alluvial deposits. Issues regarding PGA and spectral amplification are discussed in detail elsewhere (Pitilakis et al. 2002). The main conclusion however, is that although NEHRP and EC8 (Draft No. 4) provisions are considerably improved with respect to design spectra as well as soil and site characterization, the estimation of site spectral coefficients is still a challenging issue.

COMMON BELIEFS REGARDING THE EFFECT OF SOIL-STRUCTURE INTERACTION

“Soil-structure-foundation interaction is beneficial with regard to action effects”

In engineering practice, bridges are most commonly considered as fixed base structures, or, at best, modelled as having foundations that are connected to the soil through “equivalent” linear, typically static, spring elements. Only structures of considerable length and/or of particular importance are designed on the basis of a full dynamic soil-stucture interaction analysis. Along these lines, significant reaserch effort has been put in identifying the interplay between earthquake characteristics, foundation geometry, dynamic soil properties, and dynamic characteristics of the structrure, with the aid of Finite Element or Boundary Element formulations, and hybrid (semi-analytical) methods. The reason for accounting only approximately for complex interaction phenomena when dealing with ordinary bridge structures is both the perception that the interaction of the bridge with its foundation and the surrounding soil leads to conservative design, and the lack of comprehensive, ready-to-use, and widely accepted methodologies that could be implemented within the frame of modern seismic codes and render feasible the determination of foundation compliance effects on the structural behaviour.

The previously mentioned comprehensive research, on the other hand, clearly indicates that even for bridges of moderate dimensions, the piers should not be assumed fixed at their base, as the bridge foundation is flexible, dissipates energy and interacts with the surrounding soil and the superstructure, in such a way that it filters seismic motion (kinematic interaction) while it is subjected to inertial forces generated by the vibration of the superstructure (inertial interaction). This phenomenon is complex and its beneficial or detrimental effect on the dynamic response of the bridge is dependent on a series of parameters such as (Pender, 1993; Wolf, 1994; Gazetas & Mylonakis, 1998) the intensity of ground motion, the dominant wavelengths, the angle of incidence of the seismic waves, the stromatography, the stiffness and damping of soil, as well as the size, geometry, stiffness, slenderness and dynamic characteristics of the structure.

Within the context of the comparative study of 20 different bridges (Sextos et al. 2002b) the effect of soil-structure interaction (SSI) was also investigated using the approach of uncoupling kinematic and inertial interaction (Makris et al., 1995; Mylonakis et al., 1997, Kawashima et al., 1998). It was shown, that when kinematic interaction is included in the 'standard' (non SSI) analysis, filtering of the higher frequencies takes place. For this reason, the absolute and relative pier top displacements, as well as the pier base bending moments, are uniformly decreased by up to 10%, with the exception of the long period bridges (L>400m) for which kinematic interaction leads to limited amplification of motion. This interaction would be expected to be significantly more detrimental if the non-uniform soil profile around the piles was accounted for.

Inertial interaction, on the other hand, had, as anticipated, an important effect on the bridge response in terms of displacements. A general increase by approximately 30% on the average was observed in the absolute displacements. This increase is the result of the introduced foundation flexibility and, as anticipated, the maximum observed modification refers to the middle pier of the bridges, which is founded on relatively softer surface soil formations. Such detrimental role of the SSI is in agreement with other recent research findings (Shinozuka et el., 2000).

Particular cases that exhibit reduced pier top displacements do exist though, involving structures of relatively long fundamental period. The reason is that these structures, while being flexibly supported, are subjected to decreased earthquake actions, due to the period elongation that shifts the structure towards the right of a standard-type spectrum (with ordinates decreasing in the long period range), the material and radiation damping introduced at the foundation-soil interface, and also, to a lesser degree, due to the kinematic filtering of the higher motion frequencies. In general, therefore, it can be claimed that the non-uniform fluctuation of the pier top absolute and relative displacements observed in the parametric analysis, is not surprising, but it is also a strong indication that the problem is complex and multiparametric and that the overall dynamic response is an interplay between the modified dynamic characteristics of the structure and the ground motion.

A general reduction, on the other hand, ranging from 10 to 50% was observed in terms of pier base bending moments, a fact primarily attributed to the flexible foundation, the foundation damping, and the reduced earthquake forces as previously. Nevertheless, an increase in moments of up to 20% has been observed in a number of piers of long bridge models. This increase would be significantly higher in case the spectral values of the input motion were not decaying towards periods longer than that of the fundamental period of the structures, as observed in a case studied by Mylonakis and Gazetas (2000).

"SSI phenomena can be modelled without accounting for site effects"

Within the context of the above comparative analysis, it was considered interesting to investigate whether the conclusions drawn with respect to soil-structure interaction would remain valid if the effects of spatial variability and local soil conditions were neglected. The 20 bridges in this case, only differ in terms of input motion since structural and foundation spring properties are identical on the basis that the difference in the properties of the frequency-dependent dampers was found to be not dominant. The significance is indeed impressive; the response parameters of the structures accounting for both SSI and local site effects, were all consistently higher, i.e. ignoring the effect of local soil conditions underestimated significantly the results of the soil-structure interaction analysis by approximately 50% for pier top absolute displacements, 30% for relative displacements, 50% for vertical deck displacements, and 40% for bending moments at the pier base. The reason for such differences is that, as soil interacts with the foundation and the structural period elongates, the structure becomes more sensitive to long period pulses which have been amplified due to the presence of the soil. Hence it is concluded that a realistic consideration of the multi-layer, damped soil structure is necessary prior to any effort to model the behaviour of the coupled soil-foundation-pier system.

COMMON BELIEFS REGARDING INELASTIC DYNAMIC BEHAVIOR OF BRIDGES

"Inelastic analyses can be performed ignoring the foundation and soil issues"

It is quite common in studies focusing on inelastic response, to perform refined inelastic dynamic analyses of bridge structures without accounting for spatial variability, site effects and soil-structure interaction phenomena. For illustrating the effect of ignoring the coupling of propagation and interaction issues, additional inelastic analyses were performed involving the aforementioned 20 bridge structures, subjected to a) uniform, non soil-amplified, non foundation-modified motion and b) a complete spatially variable and affected by the local soil ground motion, applied through dynamic foundation-soil spring systems. The results, presented in detail elsewhere (Sextos et al., 2002c), indicated that, as anticipated, yielding of the R/C sections lead to an increase in both the energy dissipation and the natural period of the structures, but also that the calculated rotational ductility demand from the comprehensive analysis normalized to the ductility demand that would have resulted if the 'standard' approach was adopted, was increased by an average of 25%, which in the extreme case of long bridges exceeded a factor of about 3 (Fig. 4).

"Shortest piers are expected to undergo larger inelastic deformations"

Another particularly challenging issue is the seismic design of bridges supported on piers of unequal height, where in case that the cross-sections of the piers are identical, the shorter piers are expected to resist a higher level of inertia forces than the taller. This results from the fact that, unless the variation of the pier height is consistent with the fundamental mode shape of the bridge (in the transverse direction), the shorter piers are subjected to increased ductility demand and consequently damage tends to localize in these relatively stiffer piers. Nevertheless, recent studies (Kappos & Sextos, 2001) on a comparative case (Park, 1994) involving a system of 2×2 cylindrical R/C piles showed that the foundation type and the foundation compliance can significantly affect the lateral displacements and the stiffness of the overall soil-foundation-pier system.

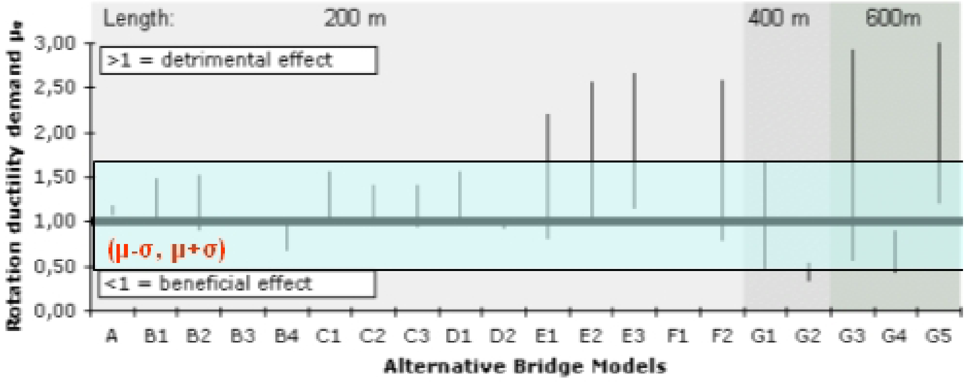

Fig 4 Rotational ductility demand in bridges subjected to wave passage, loss of coherency, site effects and soil-structure interaction compared to synchronously excited, fully fixed case (Sextos et al. 2002c)

It appears then feasible for the designer to obtain uniform yield displacements and ductility demands in the bridge piers by selecting different foundation types and/or adopting different approaches in the design of each foundation type (see also Kappos & Sextos 2001).

Another example supporting the argument that the distribution of ductility demand among bridge piers is far from easy to predict is the case of the aforementioned ‘reference bridge’ studied by Sextos et al. (2002b). Figure 5 (upper part) illustrates the inelastic behaviour of the piers in terms of moment-rotation (M–θ) curves, when the structure is uniformly excited, overlying a uniform, undamped, infinitely stiff soil (fully fixed piers). As anticipated, the shorter 7m (middle) pier is subjected to a higher level of inelastic deformations while the taller 21m pier (Pier 3) just enters the inelastic range. When the same structure is excited asynchronously through a complete spatial variability model that also accounts for soil flexibility and damping as well as for ground motion amplification due to the multi-layered character of the supporting soil profiles, the situation is reversed. In particular, the shorter pier is no longer damaged and the plastic deformations are surprisingly concentrated in the taller pier. By performing the above comprehensive analysis in successive stages, it is shown (Sextos et al., 2001) that as the soil profile at the location of the middle pier is significantly softer, the dynamic forces are redistributed according to the relative flexibility of the three complete pier-foundation-soil systems, thus relieving the middle pier. Moreover, two higher modes of vibration are triggered due to the asynchronous nature of the input motion, that primarily involve the transverse displacement of the taller Pier 3, thus leading to higher ductility demand at the base of this particular pier. It is clear, then, that the inelastic behaviour of bridge structures is governed by a complex interplay between different phenomena and a comprehensive analysis approach is often a necessary tool for identifying potential structural weaknesses or modelling uncertainties.

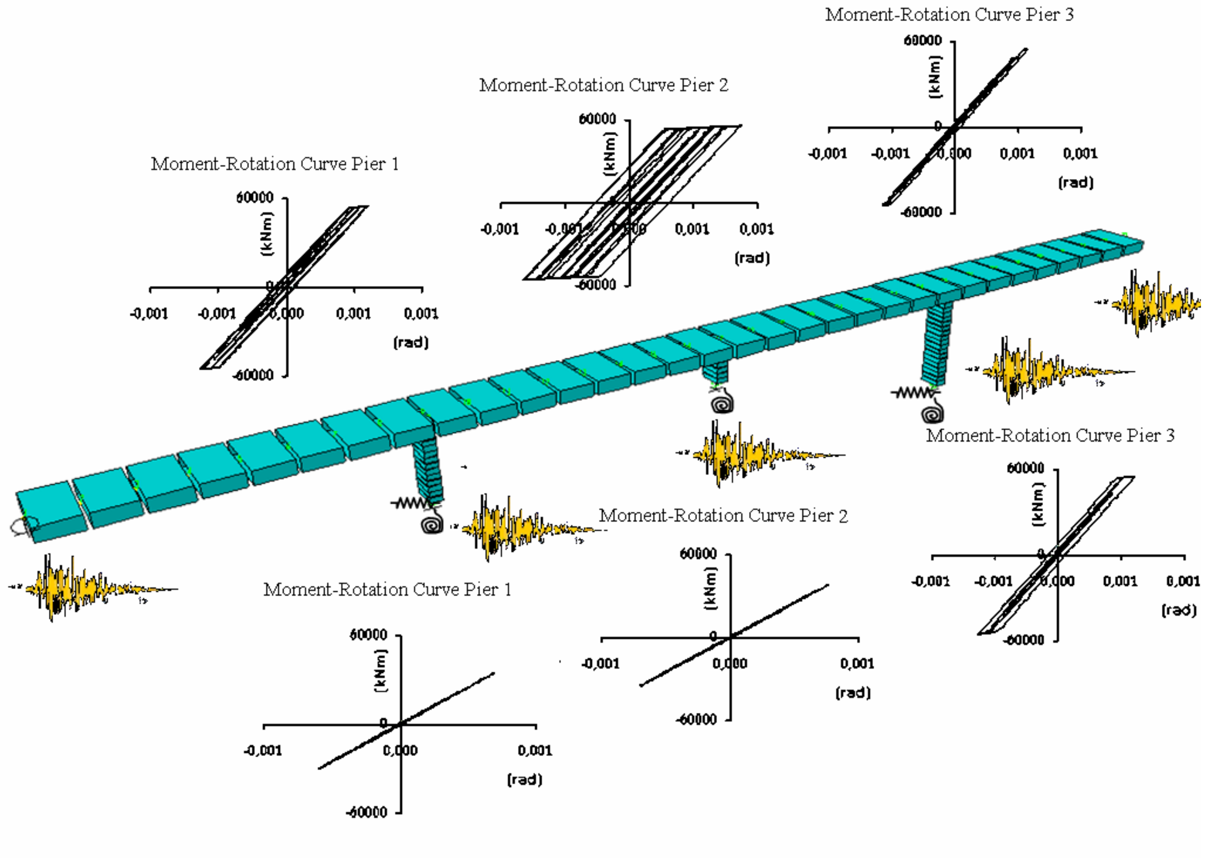

Fig 5 Calculated moment-rotation curves for bridges subjected to wave passage, loss of coherency, site effects and soil-structure interaction (bottom) compared to synchronously excited, fully fixed structures (top) (Sextos et al. 2002).

CONCLUDING REMARKS

A critical review was attempted herein of important issues in modelling and design of R/C bridge structures. The effect of spatial variability, local soil conditions and soil-structure interaction was discussed in the light of inelastic dynamic analysis, while significant uncertainties imposed by the complexity and coupling of the above phenomena were highlighted by performing additional comparative inelastic analyses of 20 different bridge structures. It is concluded that although significant aspects of the dynamic bridge response have been already clarified, there is still a clear need for further research, which would contribute towards a more realistic, refined and reliable seismic design of R/C bridges.

REFERENCES

Abrahamson, N.A. , Schneider, J.F. & J.C. Stepp (1991) "Empirical Spatial Coherency Functions for Soil-Structure Interaction Analyses", *Earthquake Spectra,* Vol. 7, No. 1, 1-27.

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

Betti, R., Abdel-Ghaffar, A.M. & A.S. Niazy (1993) "Kinematic Soil Structure Interaction for Long Span Cable Supported Bridges", *Earthquake Engineering and Structural Dynamics,* Vol. 22, No.5, 415-430.

Bogdanoff, J.L., Goldberg, J.E. & A.J. Schiff (1965) "The effect of ground transmission time on the response of long structures", *Bulletin of Seismological Society of America,* Vol. 55, 627-640.

Calvi, M. & Pinto, P. (1996) "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.

Combault, J. , Morand, P. & A. Pecker (2000) "Structural response of the Rion-Antirion bridge", *Proc. of the 12th World Conference on Earthquake Engineering, New Zealand Society for Earthquake Engineering*, Paper No. 1609.

Deodatis, G. (1996) "Simulation of ergodic multi-variate stochastic processes"*, Journal of Engineering Mechanics,* Vol. 122, No. 8, 778-787.

Der Kiureghian, A., (1996) "A coherency model for spatially varying ground motions", *Earthquake Engineering and Structural Dynamics,* Vol. 25, 99-111.

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

Dumanoglou, A.A., Severn, R.T. & J.M.W. Brownjohn (1986) "Asynchronous Seismic Analysis of Bosphorus and Humber Suspension Bridges", *Proc. of 8th European Conference on Earthquake Engineering, Lisbon,* 6.9/1-6.9-8.

Flesch, R., Darin, M, Delgado, R., Pinto, A., Romanelli, F., Barbat, A. & M. Kahan (2000) "Seismic Risk Assessment of Motorway Bridge Warth / Austria", *Proc. of the 12th World Conference on Earthquake Engineering,* CDROM Volume, Paper No. 0445.

Gazetas, G. & Mylonakis, G (1998) "Seismic soil-structure interaction: new evidence and emerging issues", *Geotechnical Special Publication 75, Geotechnical Earthquake Engineering and Soil*

Dynamics III, ASCE, Vol. 2, 1119-1174.

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

Hindy, A. & Novak, M. (1980) "Pipeline Response to random ground motion", *Journal of Engineering Mechanics,* ASCE, Vol. 106, 339-360.

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

Kang, K.D. & Wieland M. (1988) "Application of Response Spectrum Method to a Bridge subjected to Multiple Support Excitation", *Proc. of 9th World Conference on Earthquake Engineering,* Tokyo, Japan, Vol. 6, 551-536.

Kappos, A.J. & Sextos, A. (2001) "Effect of foundation compliance on the lateral load response of R/C bridges", *Journal of Bridge Engineering,* ASCE, Vol. 6, No. 2, 120-130.

Kawashima, K., Sakai, J. & H. Takemura, H. (1998) "Evaluation of seismic performance of Japanese bridge piers designed with the previous codes", *Proc. of the 2nd International Workshop on Implication of Recent Earthquakes on Seismic Risk*, Tokyo, Japan, 303-316.

Luco, J.E. & Wong H.L. (1986) "Response of a rigid foundation to a spatially random ground motion", *Earthquake Engineering and Structural Dynamics,* Vol. 14, 891-908

Makris, N., Gazetas, G. & E. Delis (1995) "Dynamic soil-pile-foundation-structure interaction: records and predictions", *Geotechnique*, Vol. 46, No. 1, 33-50.

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

Mylonakis, G., Nikolaou, A. & G. Gazetas (1997) "Soil-Pile-Bridge Seismic Interaction: Kinematic and Inertial Effects. Part I: soft soil", *Earthquake Engineering and Structural Dynamics,* Vol. 26, 337-359.

Mylonakis, G. & Gazetas, G. (2000) "Seismic soil-structure interaction: Beneficial or detrimental?", *Journal of Earthquake Engineering*, Vol. 4, No. 3, 277-301.

Park, R. (1994) "Comparative Bridge Examples", *2nd International Workshop on Seismic Design of Bridges,* Queenstown, New Zealand 1994, Vol. 2, 135-145.

Pender, M.J. (1993) "Aseismic pile foundation design analysis", *Bulletin of the New Zealand National Society on Earthquake Engineering,* Vol. 26, No. 1, 49-161.

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

Pitilakis, K., Makra, K., Raptakis, D. (2002) "Site effects in engineering practice: recent considerations", *Proc. of the 4th Symposium of implications of recent earthquakes on Seismic Risk*, Tokyo, Japan.

Price, T.E. & Eberhard, M.O. (1998) "Effects of Spatially Varying Ground Motions on Short Bridges", *Journal of Structural Engineering*, Vol. 124, No.8, 948-955.

Raptakis, D., Chavez-Garcia, F.J., Makra, K. & K. Pitilakis (2000) "Site effects at EURO-SEISTEST. 2D model, observations and coMParison with 1D analysis", *Soil Dynamics and Earthquake*

Engineering, Vol. 19, No. 1, 1-22.

Saidi, H. (1970) “Conventional seismic forces corresponding to non-synchronous ground motion”, *Proc. of the 3rd European Symposium in Earthquake Engineering,* Sofia, Bulgaria.

Sextos, A (2001) “Effect of spatial variability of ground motion, local soil conditions and soil-structure interaction phenomena on the inelastic dynamic analysis of R/C bridges”, *PhD Thesis, Aristotle University Thessaloniki (in Greek).*

Sextos, A. , Pitilakis, K & A. Kappos (2002a) “A global approach for dealing with spatial variability, site effects and soil-structure-interaction for non-linear bridges: a. verification study”, *submiitted for publication.to Earthquake Engineering and Structural Dynamics.*

Sextos, A. , Pitilakis, K & A. Kappos (2002b) “A global approach for dealing with spatial variability, site effects and soil-structure-interaction for non-linear bridges: b. Parametric analysis”, *submiitted for publication.to Earthquake Engineering and Structural Dynamics.*

Sextos, A. ; A. Kappos and Pitilakis, K (2002c) “Effect of Analysis Complexity on the ductility demand of R/C bridge piers”, *accepted for publication in the Proc. of the 12th European Conference on Earthquake Engineering*, London, 9-13 September, 2002.

Shinozuka, M., Saxena, V & G. Deodatis (2000) “Effect of Spatial Variation of Ground Motion on Highway Structures”, *Technical Report*, *MCEER, Rep. 00-0013.*

Soliman, H., O. Datta, T K. (1994) “Response of Continuous Beam Bridges to Multiple Support Ground Motion”, *European Earthquake Engineering*, Vol. 3, No. 2, 31-34.

Rassem, M., Ghobarah, A. & A.C. Heidebrecht (1996) “Site effects on the seismic response of a suspension bridge”, *Engineering Structures*, Vol. 18, No. 5, 363-370.

Tzanetos, N., Elnashai, A.S., Hamdan, F. and Antoniou, S. (2000) “Inelastic dynamic response of RC bridges subjected to spatial non-motion”, *Advances in Structural Engineering*, Vol. 3, No. 3, pp. 191-214.

Winson, J.C. and Jennings, P.C. (1985) “Spatial variation of ground motion determined from accelerograms recorded on a highway bridge”, *Bulletin of the Seismological Society of America,* Vol. 75, 1515-1533.

Wolf, J.P. (1994) *Foundation vibration analysis using simple physical models*, Pentice Hall, USA.

Zerva, A. (1992a) “Seismic Ground Motion Simulations from a class of spatial Variability models”, *Earthquake Engineering and Structural Dynamics*, Vol. 21, 351-361.

Zerva, A. (1994a) On the spatial variation of Seismic Ground Motion and its effects on lifelines, *Journal of Engineering Structures*, Vol.16, 534-546.

Zerva, A. (1994b) Spatial Variability Effects on the Seismic Response of Bridges, *Proc. of the 10th U.S.-Japan Workshop on the Seismic Design of Bridges,* Lake Tahoe, Nevada, 1994.