

Soil-structure interaction and motion incoherency effects on a concrete bridge with deep foundations

M Conțiu^{1*}, D M Ghiocel² and D Crețu³

¹ Faculty of Civil Engineering, Transilvania University of Brasov, Romania

² Ghiocel Predictive Technologies, Inc., Rochester, New York, USA

³ Dan Ghiocel Research Center, Technical University of Civil Engineering Bucharest, Romania

* E-mail: mircea.contiu@unitbv.ro

Abstract. The paper presents a seismic SSI study that has been conducted for a 242 m long concrete bridge in Braşov, that has deep foundations on drilled piles. The structure is typical for Romania and highly used throughout the country. The seismic soil-structure interaction were performed using the state-of-the-art ACS SASSI software. The soil-structure interaction analyses were performed for both coherent (synchronous) and incoherent (non-synchronous) seismic inputs. The main focus of the study is to evaluate the effects of soil – structure interaction and of the seismic motion incoherency on the bridge dynamic response. The paper includes comparisons of results obtained using the Eurocode 8 analysis procedures and the state-of-the-art seismic soil-structure interaction analysis using ACS SASSI. The final conclusions indicate the limitations of the current bridge design soil-structure interaction modelling and the simplified motion spatial variability modelling in Eurocode 8. Furthermore, the future directions of the research study are presented.

1. Introduction

Because most types of civil engineering structures are in direct contact with the surrounding soil, their behaviour is influenced by the soil properties. This fact is true for both static and dynamic loads (wind, earthquakes, etc.). The influence may be so strong for earthquakes that it could completely change the behaviour of the structure: in some cases, the overall response may be favourable, reducing the forces on the structures (and the execution costs), but may also be unfavourable, which can lead to disasters.

Observations and studies on recent earthquakes have highlighted the need to include SSI (soil-structure interaction) effects in the structural design, like the 1995 Kobe earthquake which severely damaged bridges along the Hanshin Expressway [1].

The study aims to draw a comparison between the typical seismic bridge design methodology according to Eurocode 8 and the state-of-the-art seismic SSI analysis methods, developed for nuclear structures, which include sophisticated SSI models and load modelling procedures, using measured data to estimate the incoherent behaviour of the seismic motion.

2. Description of the bridge structure and the local soil conditions

The structure being studied is a newly designed and built 242m long concrete bridge in Braşov, Romania. The bridge superstructure is composed of precast prestressed beams connected by a concrete



Content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](https://creativecommons.org/licenses/by/3.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

slab and with cast-in-place concrete diaphragms on the supports. The piers are composed of 2 circular columns with a diameter of 1.50 m, which are connected through a pier cap. The pier height varies between 6.50 – 9.00 m. All foundations consist of 6 drilled piles 17.00 m long connected by a pile cap [2].

The geotechnical study revealed a mixture of layers of gravel and sand up to a depth of about 20-25m [2].



Figure 1. The studied concrete bridge in Brasov, Romania.

3. Analysis models and SSI methodology

Two analyses will be carried out: a typical design analysis according to Eurocode 8 and a state-of-the-art sophisticated SSI analysis.

For the bridge structure itself, the same structural model composed of beam and shell elements will be used. The differences between the analyses lie in the SSI methodology and the way the seismic load is applied.

For the typical design analysis, the soil – pile interaction is considered through the widely accepted “beam on elastic foundation” (Winkler model) approach, where the stiffness of the springs varies linearly with depth (figure 2. a.). The seismic loading is introduced as uniform acceleration, acting on the whole structure, through three linear time-history analyses: one for each orthogonal direction. The dynamic earth pressure on the abutments is modelled according to the Mononobe-Okabe theory as linear varying pressures. The spatial variability of the seismic action is taken into account through static differential displacements at each foundation, according to the simplified model from EC 8.

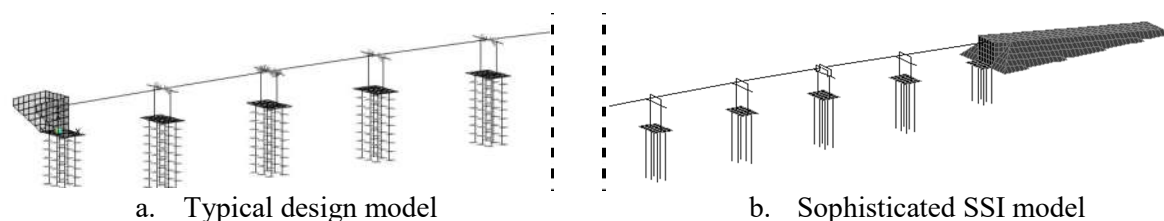


Figure 2. Bridge models used in the study.

The second sophisticated analysis uses the modern SSI (soil-structure interaction) methodology currently implemented in the ACS SASSI software for the design of nuclear structures in the US and all over the globe (figure 2. b.). The site is modelled as a series of horizontal layers overlying a

uniform half space at considerable depth; the soil materials properties are assumed to be visco-elastic. The analysis uses a complex frequency domain solution, so all systems have to be linearized [3, 4]. Seed and Idriss (1970) offer an equivalent linear procedure for the approximation of the non-linear hysteretic behaviour of the soil [5]. All points on the piles and pile cap are considered as interaction points between the structure and the soil column model used for the site analysis. The backfill is modeled with solid elements having the material properties of the type of soil used (gravel). Of course, the nodes at the base of the backfill are also interaction points.

The usual wave field combination is used: SV-waves for the bridge longitudinal direction (X), SH-waves for the bridge transverse direction (Y) and P-waves for the vertical direction (Z). The seismic waves propagate through the soil layers until they reach the structure; thus, the local soil conditions can have a strong effect on the seismic waves, before they reach the structure.

The analysis is carried out for both coherent and incoherent seismic input. The incoherency or the spatial variability of the ground motion is defined by the one-dimensional coherence function, assuming a homogenous and isotropic Gaussian stochastic field. Abrahamson (1993, 2005, 2006, 2007) has created various statistical databases of seismological information recorded in many dense arrays, and generated empirical plane-waves incoherency models for multiple soil conditions and foundation types, through the formulation on the coherence function [6, 7]. This study uses the 2005 Abrahamson plane-wave coherence model, along with introducing a wave passage effect for an apparent wave velocity of 1300 m/s along the bridge. The ACS SASSI software was used to compute 15 incoherent simulations on top of the coherent analysis at the beginning.

A uniform soil profile with average characteristics between gravel and dense sand is used in both models. Both models have been subjected to the same input accelerations, which generated from the site elastic response spectrum (figure 3).

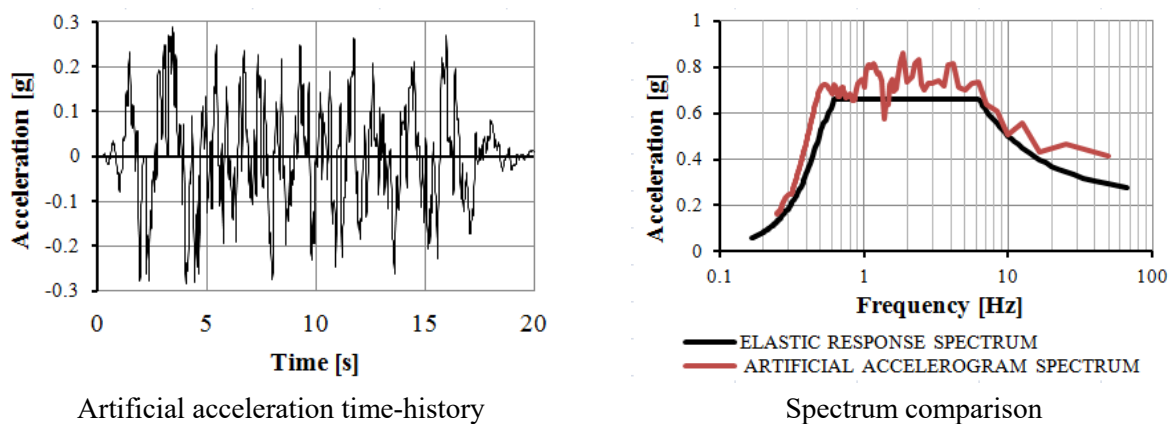


Figure 3. Seismic input [2].

4. Results and comparison

The results that will be compared are the structural stresses of the pier columns and a corresponding pile. Two piers are studied: a side pier (next to the abutment), which is the shortest and stiffest (about 5.90 m) and the mid pier (the one in the middle of the structure), which is the longest and most flexible one (about 8.0 m).

The following notations will be used throughout this section: both DESIGN and SPA-VAR refer to the typical design model; the first one shows the results from the time-history analysis and the second one from the static differential displacement loading according to the simplified procedure in the Eurocode 8. As for the sophisticated SSI model, the coherent analysis is abbreviated COH, the 15 incoherent simulations are named INCOH_RUNS; INCOH_MEAN is the average response computed from the incoherent runs. X, Y and Z refer to the direction of loading, meaning along the bridge, transverse to the bridge direction and vertical.

“M”, “V” and “N” are the bending moments, shear and axial forces; the local beam element directions are 1 – axial and vertical, 2 – along the bridge and 3 – transverse to the bridge axis. The results are presented in a graph with stresses along the horizontal axis and elevation on the vertical axis; the values above 0 elevation represent one of the pier columns and below 0 a corner pile from the corresponding foundation. All stresses have been computed in the analysis, but only the ones which offer an interesting insight about the goal of the paper will be presented.

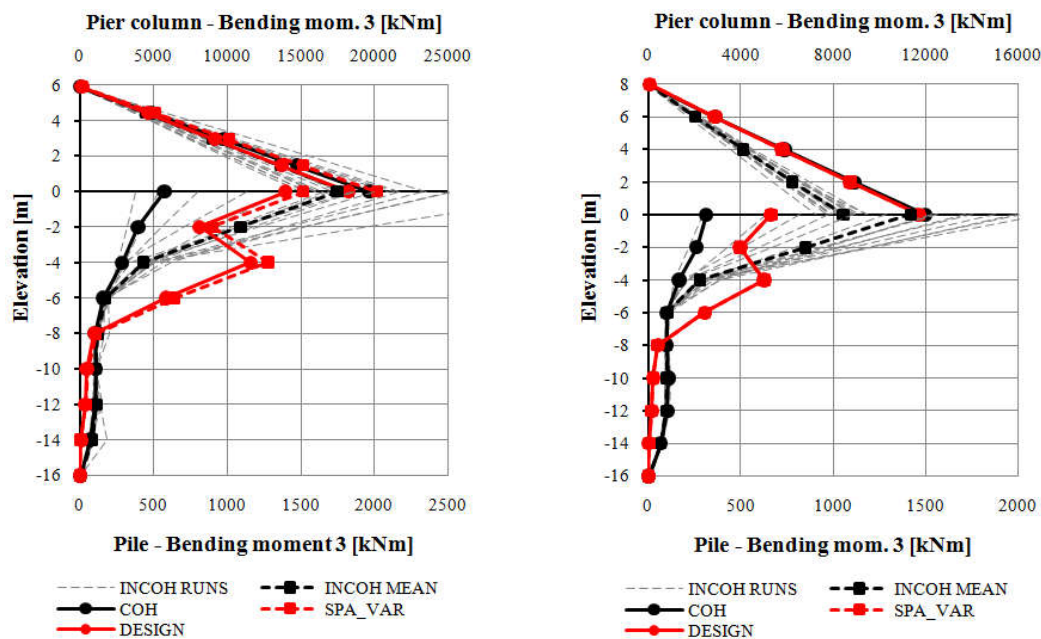


Figure 4. Bending moment 3 for earthquake loading in X direction (left=side pier, right=mid pier) [2].

Figure 4 presents the bending moments generated by seismic loading in the X direction (along the bridge axis). There is a notable difference in the shape of the bending moment diagram for the piles: the classic design model yields a large value at a depth of about 2-3 times the pile diameter, while the SSI model shows an exponential growth to a maximum value at the pile cap level.

The SPA_VAR cases which represent the results on the design model, including the simplified spatial variability loading, underestimate the bending moment in the piles by comparison to the mean incoherent values INCOH_MEAN. An increase in the pile bending moment of 25% for the side pier and 100% for the mid pier is observed.

As for the pier columns, all analyses give approximately the same bending moment diagram for the side pier. The mid pier shows an interesting effect: while the coherent analysis and the design model show similar results, the incoherent analysis reduces the stresses with about 30% from the other analyses. This especially happens to flexible elements, like the mid pier, because, due to incoherency, the ground and the structure don't move together reaching big displacements like they do in a coherent analysis; now the ground movement is chaotic, with waves coming from all directions that cancel each other out.

Figure 5 presents the bending moments due to earthquake loading in the transverse direction to the bridge axis. The bridge response in the transverse direction is much stiffer, due to development of the foundations along this axis and the fact that the pier columns and pier cap act together as a frame.

The incoherent analysis generates an increase in the pile bending moments from the design values of about 55% for the very stiff side pier. The design values are spot on for the piles of the more flexible mid pier.

The incoherent analysis offers another interesting effect for the pier columns. The design model and the coherent analysis give similar results and exhibit a classic moment diagram for a laterally

loaded embedded frame, with maximum values at the base and the top and values close to 0 at the mid of the column. The side pier doesn't show this classic behaviour for the incoherent ground motion; the value at the middle of the pier is very large, while the values at the base and top of the pier are smaller than the ones from the design model / coherent analysis. This can generate real issues for the pier column, as the reinforcement in the middle of the element is often reduced in typical design and detailing practice. For the mid pier, both the coherent and incoherent analyses produce a reduction of column bending moments from the design model of about 30%.

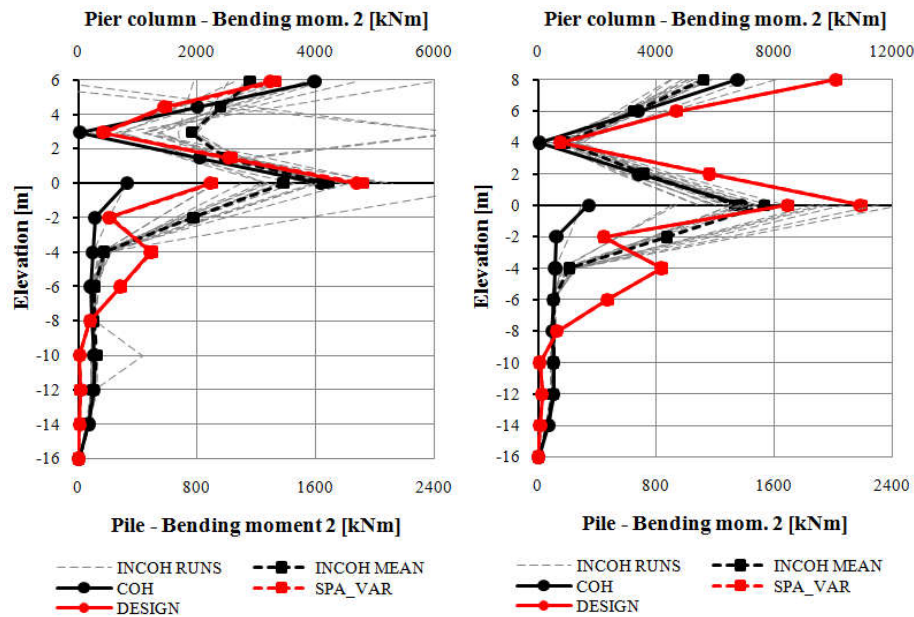


Figure 5. Bending moment 2 for earthquake loading in Y direction (left=side pier, right=mid pier) [2].

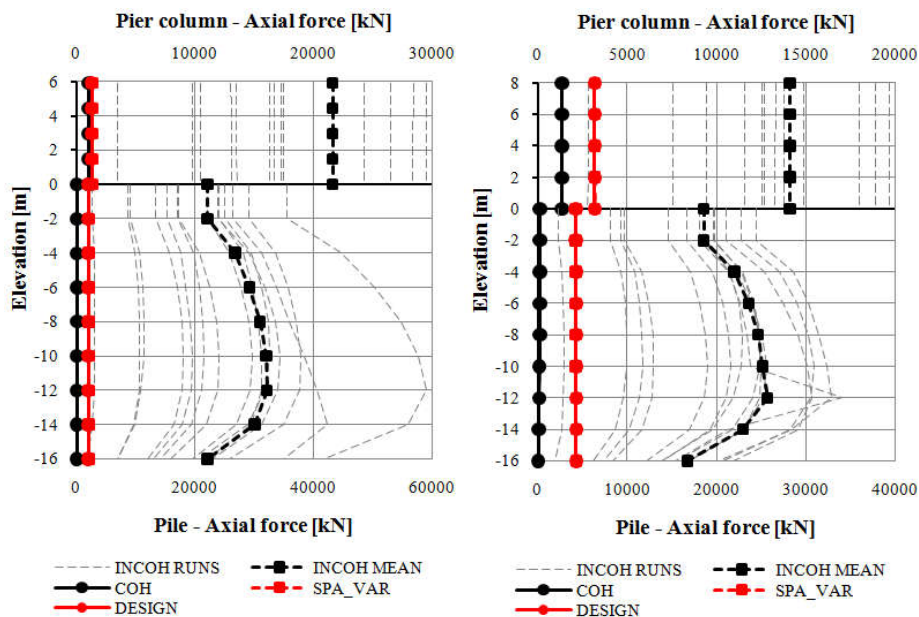


Figure 6. Axial force for earthquake loading in Y direction (left=side pier, right=mid pier) [2].

The incoherent analysis shows a very large increase in the axial forces for both piles and pier columns (figure 6). The reason for this may be the fact that the incoherent vertical ground movement

is rigidly transmitted to the piles as axial displacements through the interaction nodes; of course, the piles themselves behave extremely stiff to these axial displacements and generate very high axial forces, as those exhibited in the analysis results. This is an issue that is being treated in the next phase of the study.

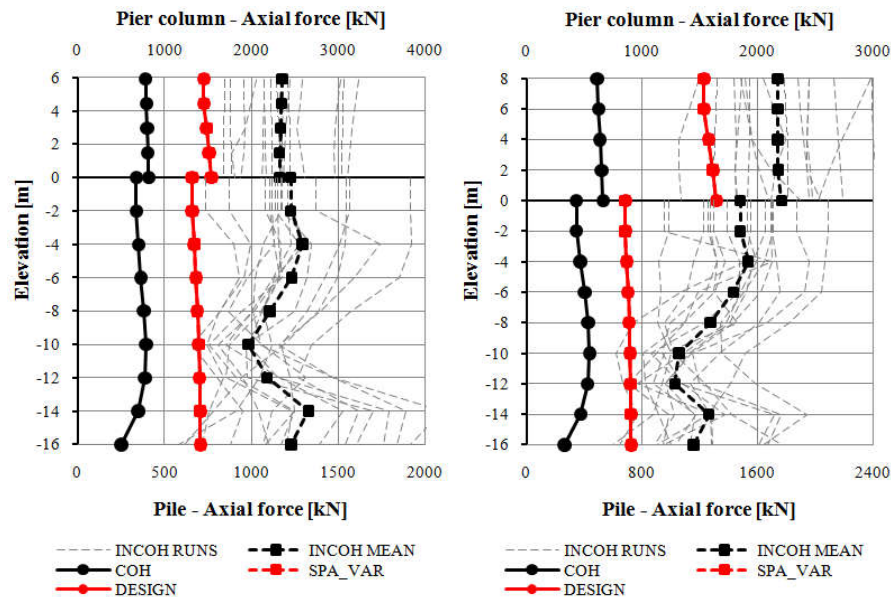


Figure 7. Axial force for earthquake loading in Z direction (left=side pier, right=mid pier) [2].

The axial forces due to earthquake loading in the vertical direction are plotted in figure 7. The incoherent analysis shows an increase in the axial forces of about 50-80%. Still, the increase isn't as big as the one from the transverse seismic action described before; this may mean that the extreme axial forces from before have something to do with the very strong rocking motion of the bridge in the transverse direction. This is supported by the fact that the increase of the axial forces from the incoherent ground motion in the longitudinal direction (X) are similar to the one exhibited here and do not show the extreme values from the Y direction.

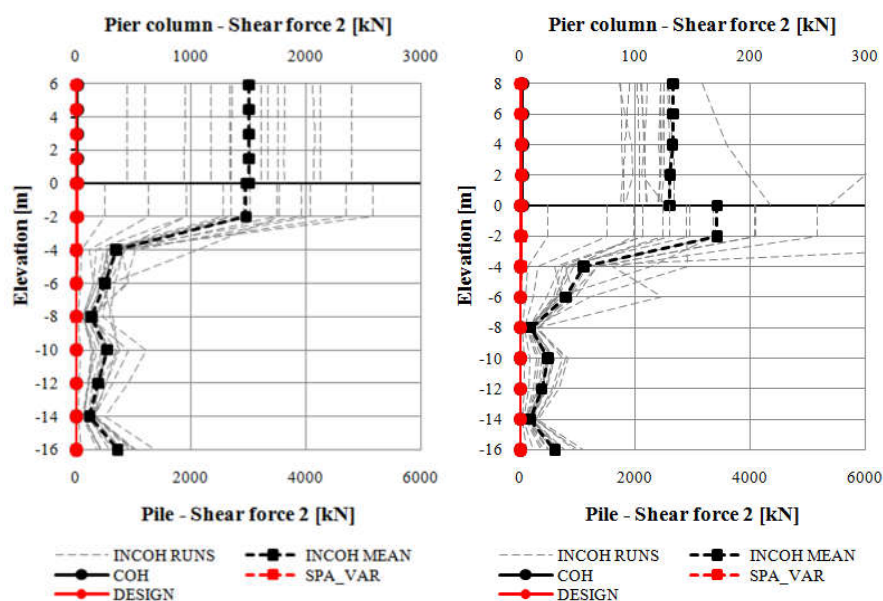


Figure 8. Shear Force 2 for earthquake loading in Z direction (left=side pier, right=mid pier) [2].

A behaviour that is completely ignored in the design model and the coherent analysis is that the vertical seismic action produces shear forces and bending moments in the structural elements. This is attributed to the fact that the vertically propagating seismic waves also generate horizontal waves through the reflection / refraction that occurs at the interface between soil layers. As figure 8 points out, the response is much stronger for stiffer elements (side pier), than that of the more flexible ones.

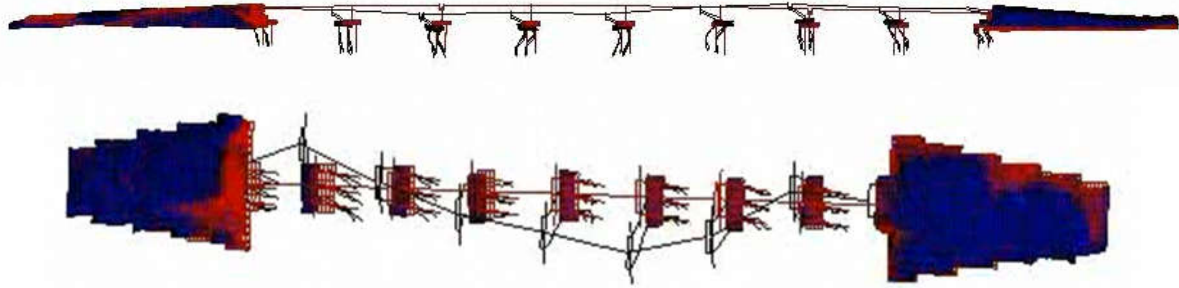


Figure 9. Instant incoherent accelerations of bridge structure in elevation and planview (deformed shape shown in blue, undeformed shape in red) [2].

Figure 9 shows two acceleration plots of the SSI model from the incoherent analyses. The bridge is not subjected to a constant acceleration in the same direction, but to accelerations that seem random both in amplitude and direction. The shape of the plots seems “broken”, especially for the piles and the bridge deck; these elements are subjected to variable accelerations along their length.

In the above described study, differences in behaviour have been observed between the typical design model and the sophisticated SSI model that need to be taken into account in the design stage of the bridge. The issue of the extremely high axial forces still needs to be resolved. Therefore, the study focuses now on improving the foundation model. The results obtained so far are presented next.

5. Improving the foundation model

As the complete bridge model is too big for a complex analysis on the foundations, the study will focus, at first, on a single pier with the corresponding deck weight attached. After a satisfactory solution has been obtained, the complete bridge analysis will be recomputed.

A phenomenon that all studies on the matter acknowledge is the degrading of the soil in the immediate vicinity of the foundation, both due to the execution of the foundations and the hysteretic ground motion during an earthquake. This effect cannot be included in the present beam model. Furthermore, the wave propagation effect in the area near the beams will be distorted. Thus, the decision has been made to model the foundation and the near-field soil with solid elements.

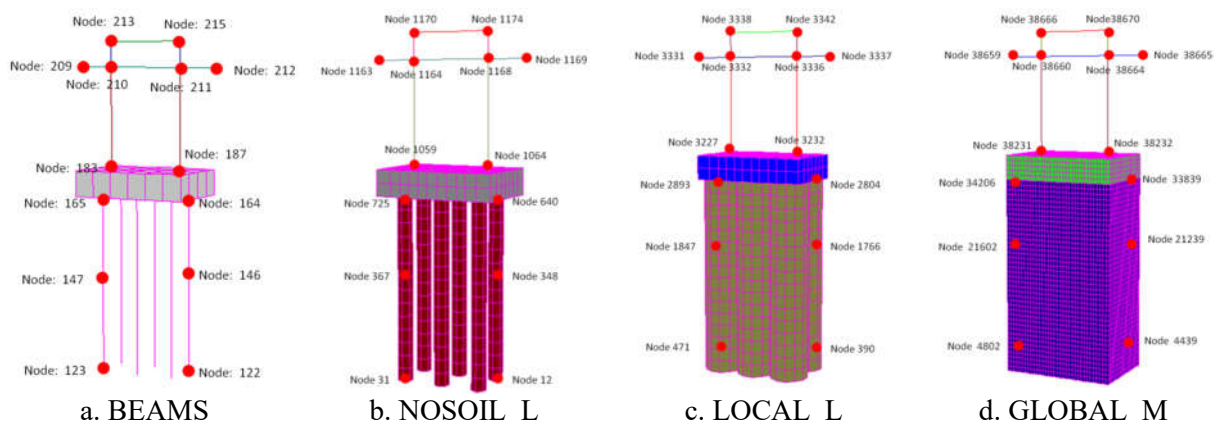


Figure 10. Foundation models.

For this stage, the pier and its corresponding foundation will be modeled in 4 methods:

- BEAMS – the piles are modeled as beam elements, similar to the global bridge model
- NOSOIL – both the piles and the pile cap are modeled with solid elements
- LOCAL – in addition to the NOSOIL model, a soil column is modeled with solid elements around each pile; this is the same procedure as described by Novak (2003)
- GLOBAL – a soil box is modeled with solid elements around the foundation, and all piles are embedded into it

Each of the models with solid elements (NOSOIL, LOCAL, GLOBAL) has a couple of variants, depending on mesh size (large L and medium M) and the substructuring methodology (flexible volume FV and flexible interface FIT). Figure 10 contains a picture of each model.

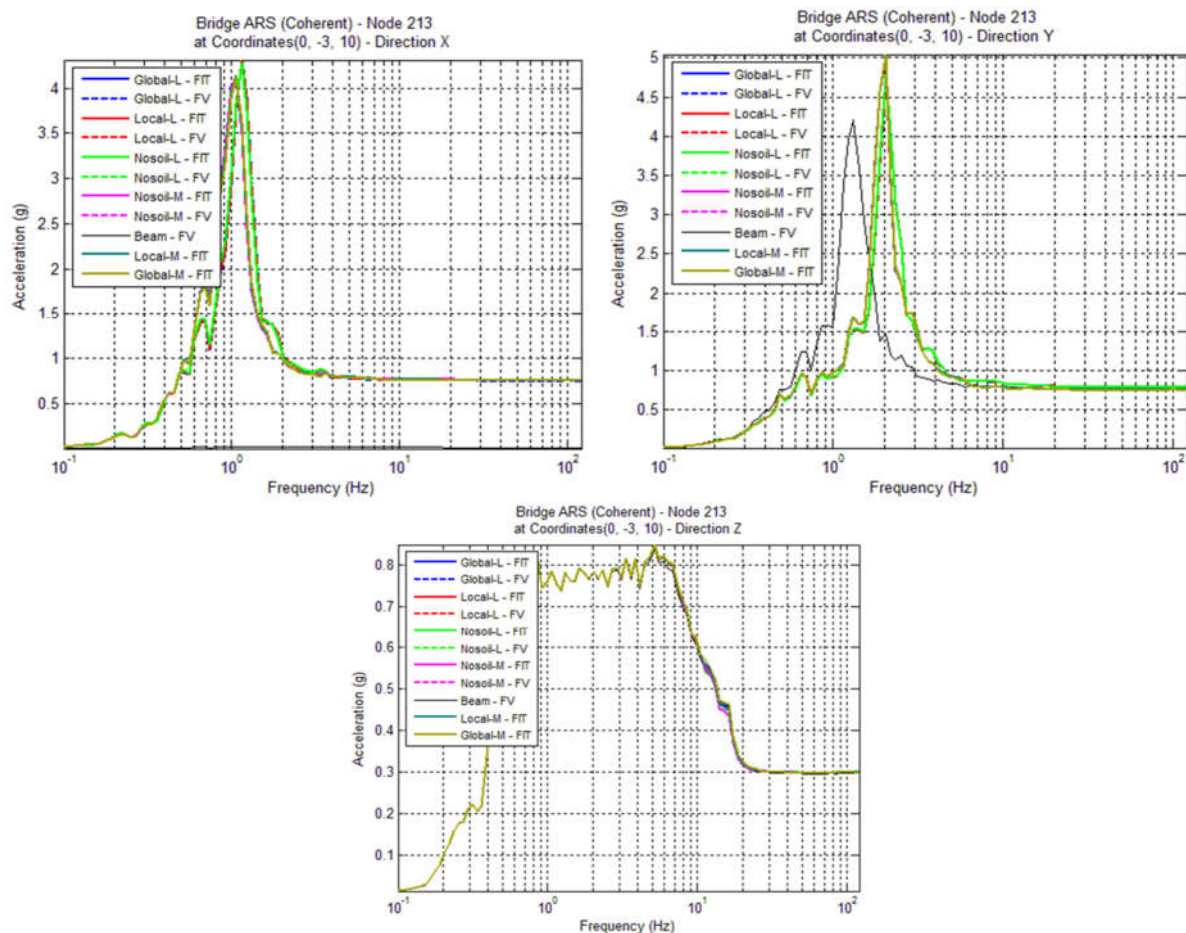


Figure 11. Foundation models acceleration response spectrum.

Figure 11 contains the acceleration response spectra at deck level (the top of the pier). The use of the solid near-field soil elements does not have almost any effect; that was to be expected, as their influence will be truly felt when nonlinearity is added to their behaviour.

The BEAMS model underestimates the stiffness of the model, as can be seen in the acceleration response spectrum in Y direction. The differences in behaviour of the models with solid elements are very small and may be neglected. The larger mesh size (L) will be preferred for the next stages of analysis to the more refined mesh (S) due to reduction in model size and analysis duration it provides. The good correlation between the flexible volume FV and flexible interface FIT substructuring methods, validates to use of the FIT method for the rest of the study, which, again, reduces the model size and analysis times considerably.

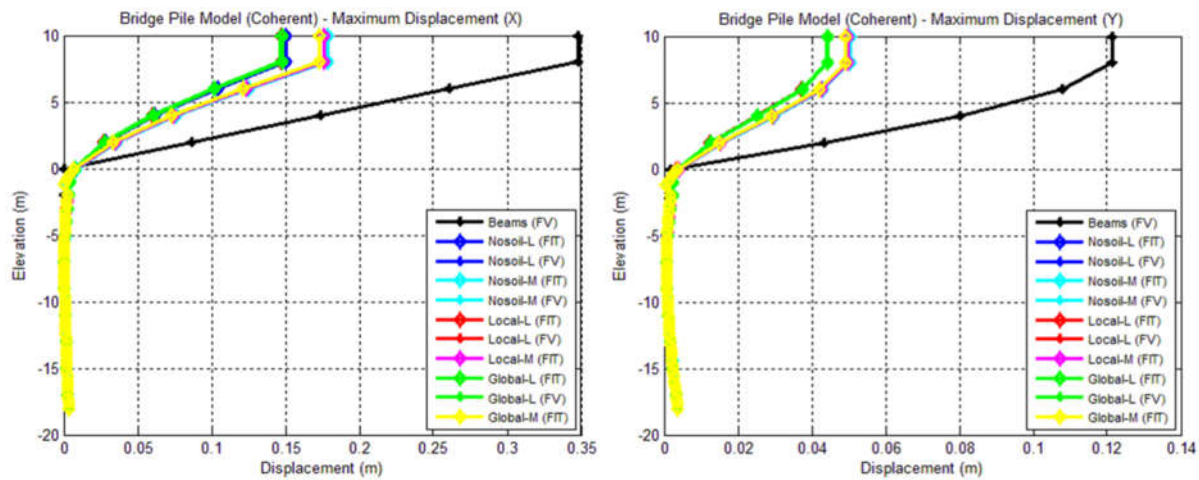


Figure 12. Foundation models maximum horizontal displacements.

The BEAMS model generates very large displacements and will be disregarded in the following analyses (figure 12). The other models yield similar displacements with a total variation of less than 10%.

Having decided that the models with solid elements will be used further, the next step is to add the nonlinear behaviour of the near field soil to the analysis. For this, the same Seed and Idriss (1970) linearized model will be used.

For the nonlinear analysis, the foundation model needed to be changed, because the pile cap was in direct contact with the soil layers from the site analysis. This would ensure a rigid connection between the structure and the site model and the near-field soil elements would not be loaded at their true capacity. Thus, a solid element “belt” with soil mechanical properties and nonlinear behaviour has been added around the pile cap. Figure 13 shows the complete analysis model to the left and the two main components to the right: the structural concrete model and the near-field soil elements.

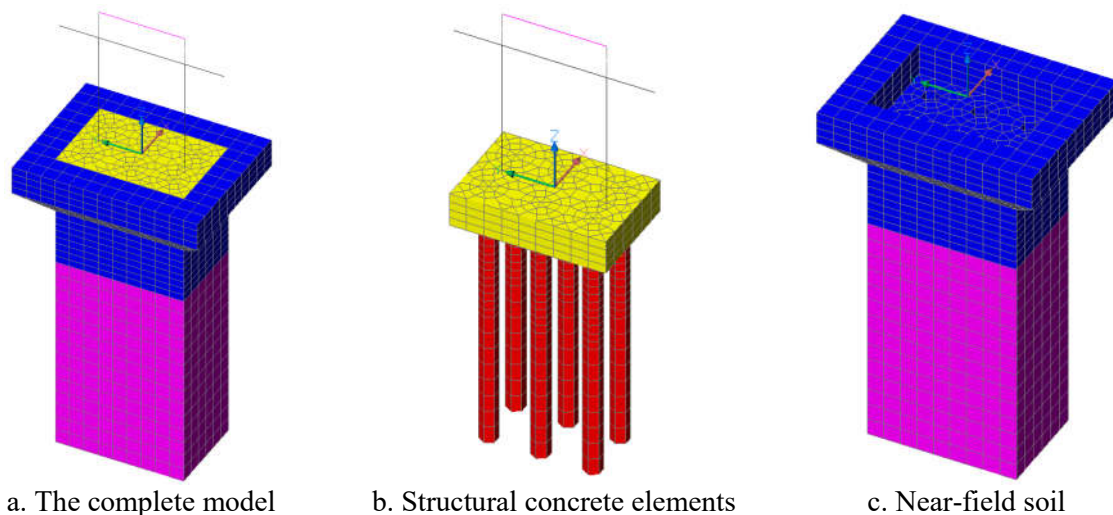


Figure 13. Foundation model for nonlinear analysis.

Figure 14 presents the acceleration response spectrum at deck level (top of the pier) for the three orthogonal directions. Both coherent / incoherent and linear / nonlinear analyses are presented. The incoherent graph represents the mean values of the 15 incoherent simulations that were studied.

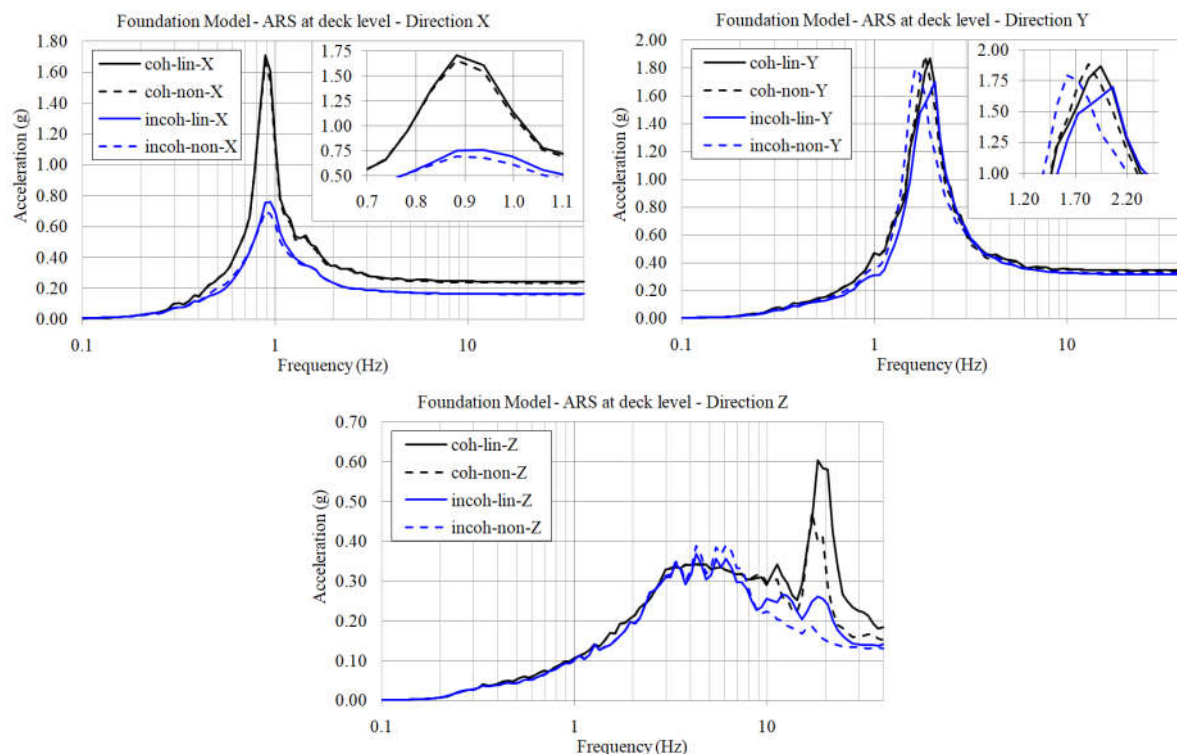


Figure 14. Foundation model acceleration response spectrum for coherent / incoherent and linear / nonlinear analysis.

For the X direction (along the bridge axis), the incoherency reduces the seismic response of the bridge to less than 50%, having an important positive effect on the structure. There is no frequency shift between the peaks, which means that the seismic waves scatter in all directions and partially cancel each other out. The nonlinear behaviour provides an additional reduction of around 5% which can be attributed to damping in the soil, because almost no frequency shift can be observed.

In the transverse direction (Y), the incoherency in the linear analysis generates a reduction of about 5%. The nonlinear analysis exhibits a frequency shift of 0.1 Hz for the coherent analysis and 0.5 Hz for the incoherent analysis. Also an amplification of the spectral acceleration of about 6% can be observed in the incoherent analysis between the nonlinear and linear results; this phenomena leads to an increase in the forces acting on the structure.

The vertical direction (Z) shows a strong decrease of spectral acceleration at the 11 Hz peak due to incoherency effects.

Figure 15 presents pile and pier column element forces corresponding to the seismic loads acting in longitudinal (X) and transverse direction (Y). The following conclusions can be drawn for the foundation model:

- for the piles, the incoherency effect generates a considerable increase in structural response in comparison to the coherent SSI analyses; for the pier columns the effect is the opposite, as incoherency reduces the element forces.
- the nonlinearity of the near-field soil doesn't have an important effect on the structural forces in the pier columns; for the piles, an interesting effect can be observed: the axial forces are reduced, while the transverse forces (shear forces that further generate bending) increase by more than 25%;
- the typical design procedure will generate higher structural forces, with the exception of the pile bending moment due to earthquake loading in the longitudinal direction (X), where the design clearly underestimates the structural response; for this structure, a more economical

design could be achieved for the pier columns and the length of the piles by considering the sophisticated SSI model.

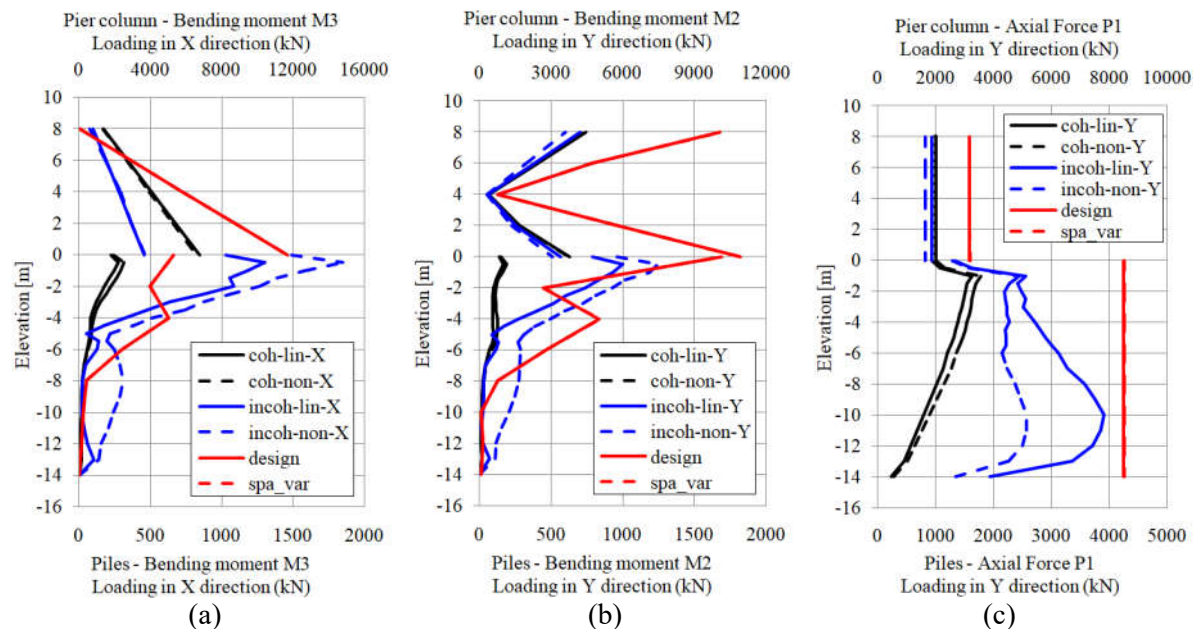


Figure 15. Bending moment M3 for earthquake loading in X direction / Bending moment M2 and axial force P1 for earthquake loading in Y direction (coherent / incoherent and linear / nonlinear analysis, design and simplified spatial variation model).

6. Conclusions and future directions

The scope of this paper was to compare the results of a state-of-the-art seismic SSI analysis of a bridge structure to the current design procedure according to Eurocode 8. Along the course of the study, a methodology has been developed for modelling the bridge structure and foundations in order to obtain adequate results from the SSI analysis.

The overall conclusion is that the Eurocode 8 design can be considered acceptable for small structures where SSI effects and motion incoherency do not play such a large role. However, when dealing with large structures, the simplified spatial variation model given in Eurocode 8 will influence the structure very little. Furthermore, this simplification completely ignores the large shear forces that the piles are subjected to, due to incoherent differential displacements in the soil.

Several interesting effects of motion incoherency on bridge structures have been highlighted throughout the paper. Based on the investigated case study results, no clear answers can be given to whether the design model overestimates or underestimates the structural response. The only thing that can be clearly stated is that the current design practice does not capture all the effects displayed by the state-of-the-art SSI analysis. Incoherent SSI analyses should be mandatory for the seismic design of large bridges and are still recommended for smaller structures.

As a future direction of the study, the complete bridge SSI model will be analysed, taking into account the nonlinear behaviour of soil in direct contact or in the immediate vicinity of the foundations. Also, an improved model for the superstructure will be implemented, that offers a better representation of the spatial distribution of stiffness and mass.

References

- [1] Mylonakis G, Gazetas G, Nikolaou S and Michaelides O 2000 The role of soil on the collapse of 18 piers of the Hanshin expressway in the Kobe earthquake *12th World Conference on Earthquake Engineering*, Auckland, New Zealand, 1074

- [2] Contiu M, Ghiocel D M and Cretu D 2014 Incoherent soil-structure interaction (SSI) effects for a 242 m long concrete bridge founded on deep piles *Proceedings of 2ECCES : EAEE Session*, Istanbul, Turkey
- [3] Ghiocel D M 2007 *Stochastic and Deterministic Approaches for Incoherent Seismic SSI Analysis as Implemented in ACS SASSI*, Appendix C, Electric Power Research Institute, Palo Alto, CA and US Department of Energy, Germantown, D, EPRI Report TR-1015111, USA
- [4] Ghiocel D M 2009 *ACS SASSI NQA Version 2.3.0 - An Advanced Computational Software for 3D Dynamic Analysis Including Soil Structure Interaction*, User Manuals, Technical Reports, GP Technologies, Inc., Rochester, New York, USAA
- [5] Seed H B, Idriss I M 1970 *Soil Moduli and Damping Factors for Dynamic Response Analysis*, Earthquake Engineering Research Center, Berkeley California, Report EERC 70-10, USA
- [6] Abrahamson N 2006 *Spatial Coherency for Soil-Structure Interaction*, Electric Power Research Institute, Palo Alto, CA and US Department of Energy, Germantown, MD, EPRI TR-1014101, USA
- [7] Abrahamson N 2007 *Effects of Seismic Motion Incoherency Effects*, Electric Power Research Institute, Palo Alto, CA and US Department of Energy, Germantown, MD, EPRI TR-1015110, USA