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MULTIPLE SUPPORT EXCITATION OF A BRIDGE BASED ON BEM ANALYSIS OF THE SUBSOIL-STRUCTURE-INTERACTION PHENOMENON

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Abstract. *This study presents a numerical investigation of the influence of spatial variability of earthquake ground motion, site effects and Soil-Structure Interaction (SSI) phenomena on the inelastic dynamic analysis of bridge structures, considering a 2D analysis of the soil profile via Boundary Element Method (BEM). First, seismic waves propagating through complex geological profiles are modeled, so as to recover ground motion records that account for local site conditions. To that purpose, the BEM is employed for computing time-history records for four different geological profiles considering (a) canyon topography, (b) soil layering and (c) material gradient effect. Then bridge support-dependent ground motions and equivalent dynamic impedance matrices at the soil-foundation interface are generated for each support point of a bridge along the canyon. More specifically, a reinforced concrete, straight bridge with monolithic pier-deck connections is adopted as a case study. Next, a series of time history analyses considering local nonlinearities is conducted for the bridge using the Finite Element Method (FEM) taking into account subsoil-structure-interaction phenomena. To emphasize the relative importance of the topographic effects and the asynchronous motion, bridge response is determined under both synchronous and asynchronous earthquake input. In sum, the numerical results of this study show that the effect of spatially variable earthquake ground motion on the seismic response of the bridge studied depends on the interplay between the dynamic characteristics of the structure, the variability in space of soil and the properties of the incoming wavefield itself. It is also demonstrated that the detrimental or beneficial effect of spatially variable earthquake input is primarily dependent on the interplay of all the above mentioned key parameters.*

1 INTRODUCTION

During an earthquake, seismic waves radiate from a fault and travel through the earth's crust. As seismic waves travel through bedrock and soil deposits, the various complex geological profiles produce local distortions in the incoming wave field which lead to large amplifications as well as strong spatial variations in frequency, amplitude and phase along the surface in the seismic motions. For elongated structures such as bridges, pipelines, communication and power transmission grids, dams etc., the effects of local site conditions become especially important because spatial variations of ground motion would lead to multiple support excitation of the structure. The structure would respond differently to a variety of input motions due to its dynamic characteristics that tend to be triggered differently under uniform and non-uniform earthquake excitation patterns. This relative difference between the motions of the soil and the structure is further pronounced by the fact that soil-structure-interaction phenomenon at each pier foundation-soil interface is strongly frequency-dependent, hence, inherently sensitive to the variations of seismic input along the bridge length.

So far, seismic codes for bridge design do not prescribe explicit procedures to simultaneously account for spatial variability, site effects and SSI phenomena maybe with the exception of some sporadic provisions to generate asynchronous ground motions (i.e., Eurocode 8 – Part 2) and some rough guidelines to account for soil compliance in the above code Annex.

Several previous studies have emphasized the significance of this complex problem for the seismic response of bridge structures. Among them, we mention Sextos et al (2003a;b), who developed a general methodology for deriving appropriate modified time histories that account for spatial variability, site effects and soil structure interaction phenomena. Parametric analyses were conducted and demonstrated that the presence of site effects, spatial variability and soil-foundation superstructure interaction strongly influences the input seismic motion and the ensuing dynamic response of the bridge. Jeremic et al. (2009) proposed a numerical simulation methodology and conducted numerical investigations of seismic SSI for a bridge structure on non-uniform soil. It was then stated that the dynamic characteristics of earthquakes, soil and structure all play a crucial role in determining the seismic behavior of an extended construction. Bi et al (2011) studied the simultaneous effect of SSI and ground motion spatial variation on bridge response and estimated the required separation distance that modular expansion joints must provide in order to avoid seismic pounding. Soyluk and Sicacik (2011) further investigated the effects of SSI and multiple support excitation on the seismic response of a cable-stayed bridge, though the latter type of bridges has been recently found to be a rather favorably affected by asynchronous excitations due to the relatively low contribution of the quasi-static component.

However, in all the above mentioned studies the influence of local site conditions is evaluated using models based on a uni-dimensional description of the local soil profile as a soil column and similarly for the seismic wave propagation path. Limited papers can be found which deal with the effects of local site conditions on bridge response considering 2D analysis of the soil profile. Esquivel and Sanchez-Sesma (1980) studied the influence of a semi-circular cylindrical canyon on the dynamic soil-bridge interaction for the case of incident harmonic plane SH waves. Analytical scattered and free-field solutions are used to determine the driving forces and impedance stiffness matrix for the bridge foundation, while the bridge is modelled as a shear beam and solved analytically. Zhou et al. (2010) investigated canyon topography effects on the linear response of continuous, rigid frame bridges under obliquely incident SV waves. The seismic response of the canyon was analyzed using the FEM, while the response of the bridge was computed by the "large mass" method. It was shown that the distribution of ground motions is affected by canyon topographic features and the incident angle of the waves. In case of vertical incident SV waves, the peak ground accelerations increase greatly at the upper edges of the canyon and decrease at its bottom lateral boundaries. Note here that these studies are restricted to either very simple geometry of the topographic effects (so that can be solved analytically) or to a simple frame-like bridge model which typically neglects salient features of a real bridge.

Along these lines, the main objective of the present work is to investigate the effects of (a) spatial variability of earthquake ground motion, (b) local site conditions and (c) SSI on the dynamic response of reinforced concrete bridges, considering 2D analysis of the soil profile via BEM. Briefly, the procedure consists of the following steps: (i) Time history records are considered as an input at the seismic bed of complex geological profiles with canyon topography, soil layering and material gradient effect; (ii) site dependent ground motions and soil spring coefficients are generated at the surface using the BEM; (iii) the generated ground motions are used as input to a three dimensional, model of a monolithic, straight in plan R/C, bridge; (iv) the bridge is assessed using the FEM under the support-dependent acceleration earthquake input and the dynamic impedance considerations at the pier-foundation-soil and the abutment-embankment interface (vi) the dynamic response of the bridge is then assessed parametrically to identify the relative impact of each one phenomenon studied.

2 WAVE PROPAGATION IN COMPLEX GEOLOGICAL PROFILES: METHODOLOGY

There is a lack of high-performance computational tools able to simulate 2D and possibly 3D complex geological profiles. The BEM is nowadays recognized as a valuable numerical technique to solve wave propagation problems, due to its many advantages with respect to domain techniques such as the FEM. It is briefly mentioned herein that it is possible to deal with semi-infinite media in terms of high accuracy and minimal modeling effort.

In the present study, the BEM is used to model the seismic wave propagation through complex geological profiles so as to recover ground motion records that account for local site conditions. In particular, consider 2D wave propagation in viscoelastic, isotropic and inhomogeneous half-plane consisting of N parallel or non-parallel inhomogeneous layers Ω_n (n=0, 1, 2, …N) with a free surface and sub-surface relief of arbitrary shape. The dynamic disturbance is provided by either an incident SH wave or by waves radiating from an embedded seismic source, see Fig.1. For this problem, a non-conventional BEM is applied which is based on a special class of analytically derived fundamental solution for continuously inhomogeneous media with variable wave velocity profiles (Manolis and Shaw, 1996a, 1996b). The employed here BEM was recently developed and validated in Fontara et al. (2015).

More specifically, the material inhomogeneity is expressed by a spatially variable shear modulus and density of arbitrary variation in terms of depth coordinate. We define the inhomogeneity parameter as $c_n=C^{bottom\ (\Lambda n-1)/}\ C^{top\ (\Lambda n)}$ namely the ratio of the wave velocity at the bottom to that at the top of any given layer. This model is also able to account for wave dispersion phenomena due to viscoelastic material behaviour and to position-dependent material properties.

Next, for the formulation of the boundary integral equation we use the well-known boundary integral representation formula and insert as kernels the fundamental solutions for geological media with a velocity gradient (Manolis and Shaw, 1996a;b):

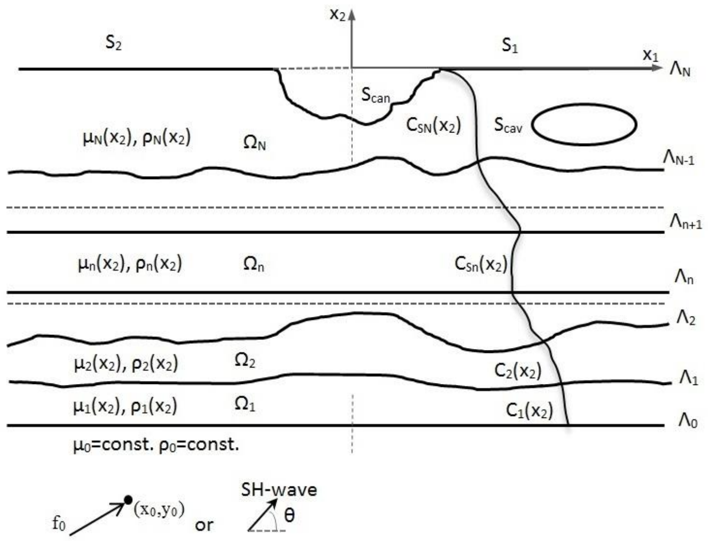

Figure 1: Geometry of the problem treated by BEM: A multi-layered, continuously inhomogeneous geological medium with surface topography and buried inclusions.

$$\boldsymbol{c}\boldsymbol{u}_3^{(i)}(\mathbf{x},\omega)=\int_\Gamma \boldsymbol{U}_3^{*(i)}(\mathbf{x},\mathbf{y},\omega)\boldsymbol{t}_3^{(i)}(\mathbf{y},\omega)\boldsymbol{d}\Gamma-\int_\Gamma \boldsymbol{P}_3^{*(i)}(\mathbf{x},\mathbf{y},\omega)\boldsymbol{u}_3^{(i)}(\mathbf{y},\omega)\boldsymbol{d}\Gamma \qquad (1)$$

$$\mathbf{x}\in\Gamma=\Omega_i\cup \boldsymbol{S}_{can}\cup \boldsymbol{S}_{cav}$$

In Eqn. 1, ***x, y*** are source and field points, respectively, *c* is the jump term, U^*_3 is the fundamental solution for geological media with variable velocity profile, and $P^*_3(\boldsymbol{x},\boldsymbol{y},\omega) =\mu(x_2)U^*_3(\boldsymbol{x},\boldsymbol{y},\omega)\, n_i(\boldsymbol{x})$ is the corresponding traction fundamental solution, where $i=1, 2\ldots N$ is the number of layers. The above equation is written in terms of total wave field and expresses the case of incident SH waves. We note that by using this closed form fundamental solution in the BEM technique, only the layer interfaces, as well as the free and sub-surface relief need be discretized.

After discretization of all boundaries with constant (i.e., single node) boundary elements, the matrix equation system is formed below and displacements along the free surface can be computed:

$$[\boldsymbol{G}]\{\boldsymbol{t}\}-[\boldsymbol{H}]\{\boldsymbol{u}\}=\{\boldsymbol{0}\} \qquad (2)$$

The above system matrices ***G*** and ***H*** result from numerical integration using Gaussian quadrature of all surface integrals containing the products of fundamental solutions times interpolation functions used for representing the field variables. They are fully populated matrices of size MxM, where M is the total number of nodes used in the discretization of all surfaces and interfaces, while vectors ***u*** and ***t*** now contain the nodal values of displacements and tractions at all boundaries.

Finally, the generation of transient signals from the hitherto derived time-harmonic displacements is achieved through inverse Fourier transformation. Note here that both negative and positive values in the frequency, as well as in the time domain, are considered and both real and imaginary values for the response parameter are employed. The aforementioned BEM numerical implementation and production of the final seismic signal is programmed using the Matlab (2008) software package.

3 GEOLOGICAL PROFILES

The methodology described in the previous section is now applied to four different hypothetical geological profiles of increasing complexity, on which the R/C bridge in question is considered to be located, see Fig.2 below, in order to examine the influence of the following key parameters: (i) canyon topography; (ii) layering; (iii) material gradient. In particular, the site is represented by the following geological profiles: (A) a homogeneous layer with flat-free surface producing a uniform excitation at all support points of the bridge; (B) a homogeneous layer with a valley in which the bridge is located; (C) a two-layer deposit as a damped soil column with a valley at the surface; (D) a two-layer damped soil column with the bridge valley at the surface, in which the top layer is continuously inhomogeneous with inhomogeneity parameter c=1.2 expressing an otherwise arbitrary variation in the wave speed depth profile. The bottom layer is homogeneous and the interface between the first and the second layers is irregular. All geological profiles are overlying bedrock. The soil material properties of these subsoil geological configurations are shown in Table 1 and Fig.2.

Next, a suite of seven earthquake excitations given in Table 2 are recorded at outcropping rock on a class A site according to FEMA classification and are drawn from the PEER (2003) strong motion database. These records are considered as an input at the seismic bed level for all geological profiles. Note here that the selected ground motion sample is not necessarily unbiased.

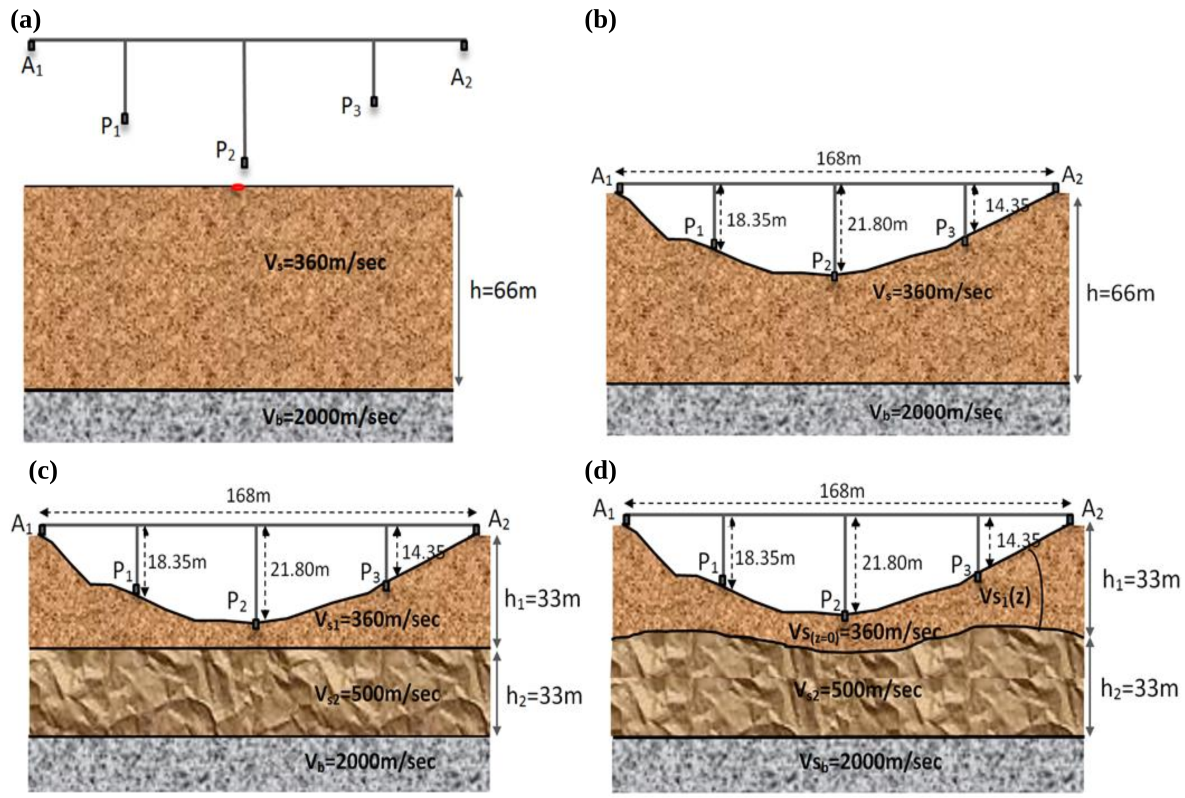

Figure 2: Four geological profiles, namely Types A-D, on which the R/C bridge is assumed to be located.

4 GROUND MOTIONS

We next investigate the influence of canyon topography, layering and material gradient on ground motions recorded along the free surface and start with the first geological profile com-

	Vs (m/sec)	**μ (Pa)**	**ρ (N/m^2)**
Layer 1	360	$233.28 \cdot 10^6$	1800
Layer 2	500	$450 \cdot 10^6$	1800
Bedrock	2000	$800 \cdot 10^7$	2000

Table 1: Material properties of the basic geological structure.

prising a single layer with a horizontal free surface that produces a uniform excitation pattern ridge as a reference case. Fig.3 plots the acceleration response spectra recorded at the surface of (a) Type B, (b) Type C and (c) Type D geological profile at the support points of the bridge at the canyon and for Northridge 2 ground motion (listed in Table 2). The shape of the recorded seismic signal is modified as the geological profile becomes more complex. This is also evident from the 3D time history generated along the surface of (a) Type B, (b) Type C and (c) Type D geological profile shown in Fig.5. From Fig.3 we observe that spectral values at the bridge support points are not the same and furthermore, they differ significantly at certain period values from those produced for the reference case of uniform excitation. An expected shifting to the right (higher periods) due to the layering effect is clearly depicted in Fig.3(b) and Fig.3(c). In case of Type D geological profile, the additional presence of material gradient increases the material stiffness gradually and the soil becomes stiffer. Moreover, the continuous variation of the wave speed with depth at the top layer reduces significantly the wave speed contrast between the first and the second layer (see Fig.4) thus, decreasing the amplification levels. As a result the spectral acceleration values are de-amplified across the entire range of periods examined herein.

No	**Date**	**Earthquake name**	**Magnitude (M)**	**Station name**	**Closest distance (Km)**	**Component (deg)**	**PGA (g)**
1	22.03.1922	San Francisco	5.3	Golden Gate Park	-	100	0.112
2	17.01.1994	Northridge 1	6.7	Mt Wilson CIT	26.8	000	0.234
3	17.01.1994	Northridge 2	6.7	Littlerock Brainard Can	46.9	090	0.072
4	17.01.1994	Northridge 3	6.7	Lake Hughes #9	28.9	090	0.217
5	18.10.1989	Loma Prieta	6.9	Monterey City hall	44.8	000	0.073
6	10.01.1987	Whittier Narrows	6	Mt Wilson CIT	21.2	000	0.158
7	12.09.1900	Lytle Creek	5.4	Cedar Springs, Allen Ranch	20.6 (Hypocentral)	095	0.071

Table 2: Ground motion records from the PEER (2003) strong motion database as recorded on a Class A site.

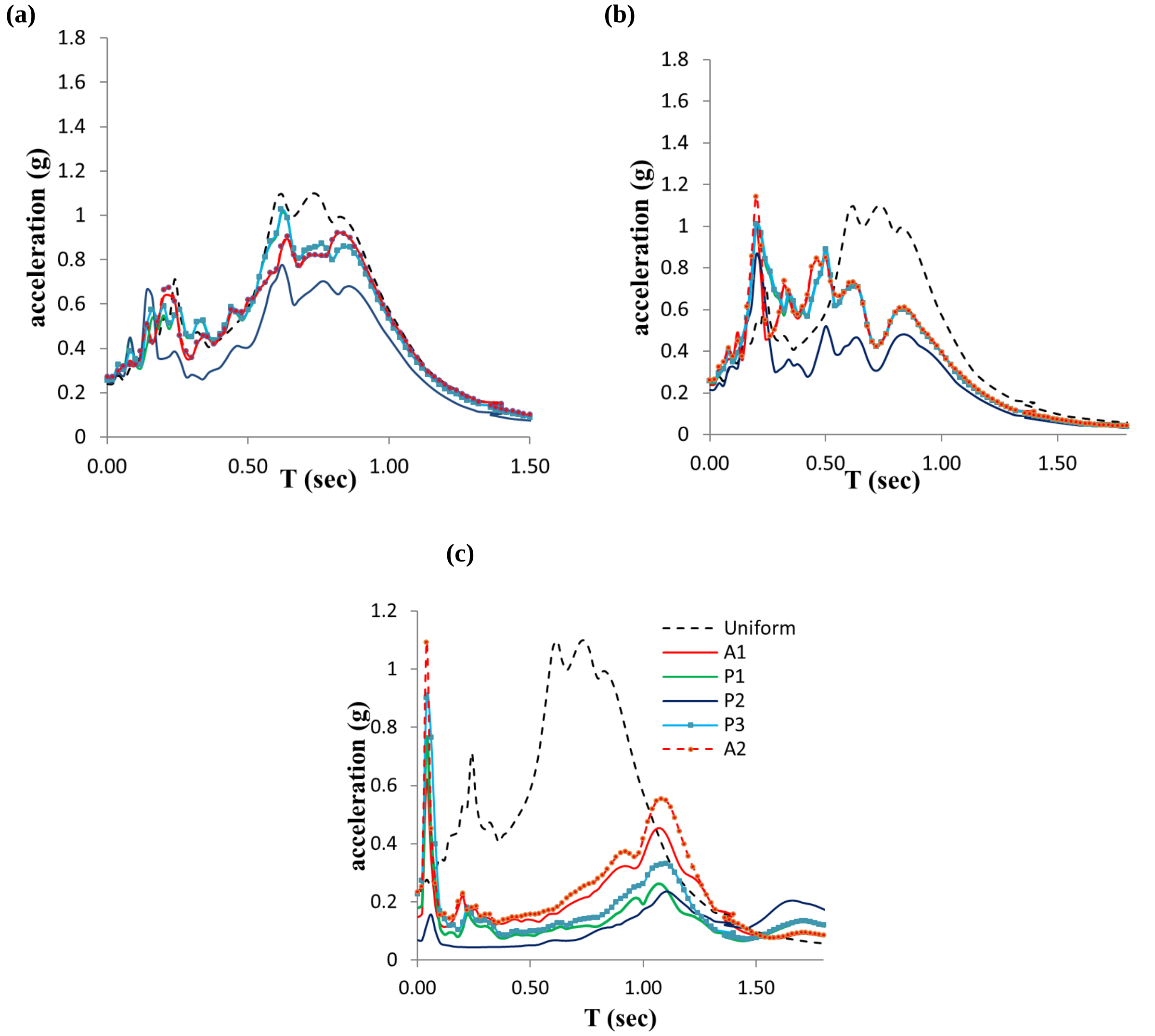

Figure 3: Acceleration response spectra of Northridge No2 ground motion recorded at the free surface of (a) Type B, (b) Type C and (c) Type D geological profile vs Uniform excitation (Type A).

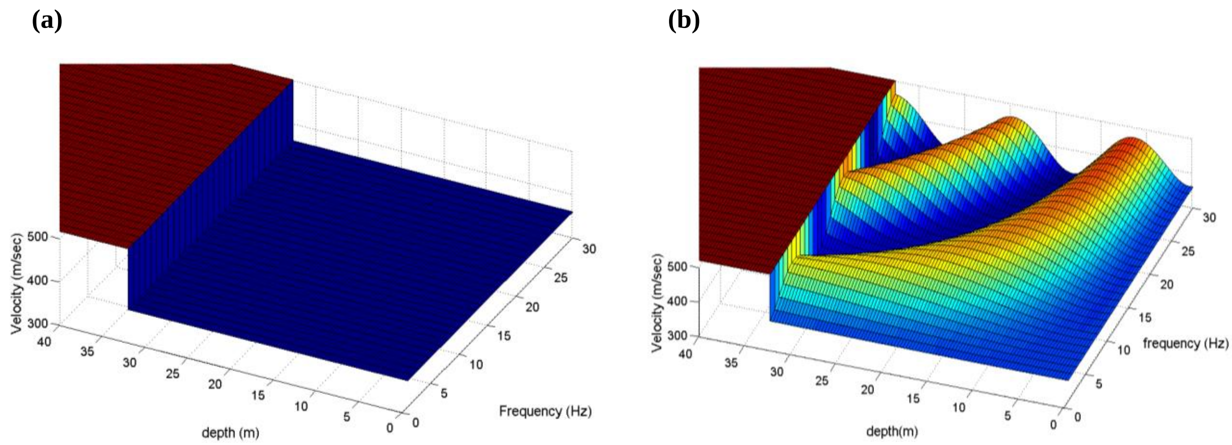

Figure 4: Velocity distribution of the subsoil structure: (a) Type C and (b) Type D geological profile.

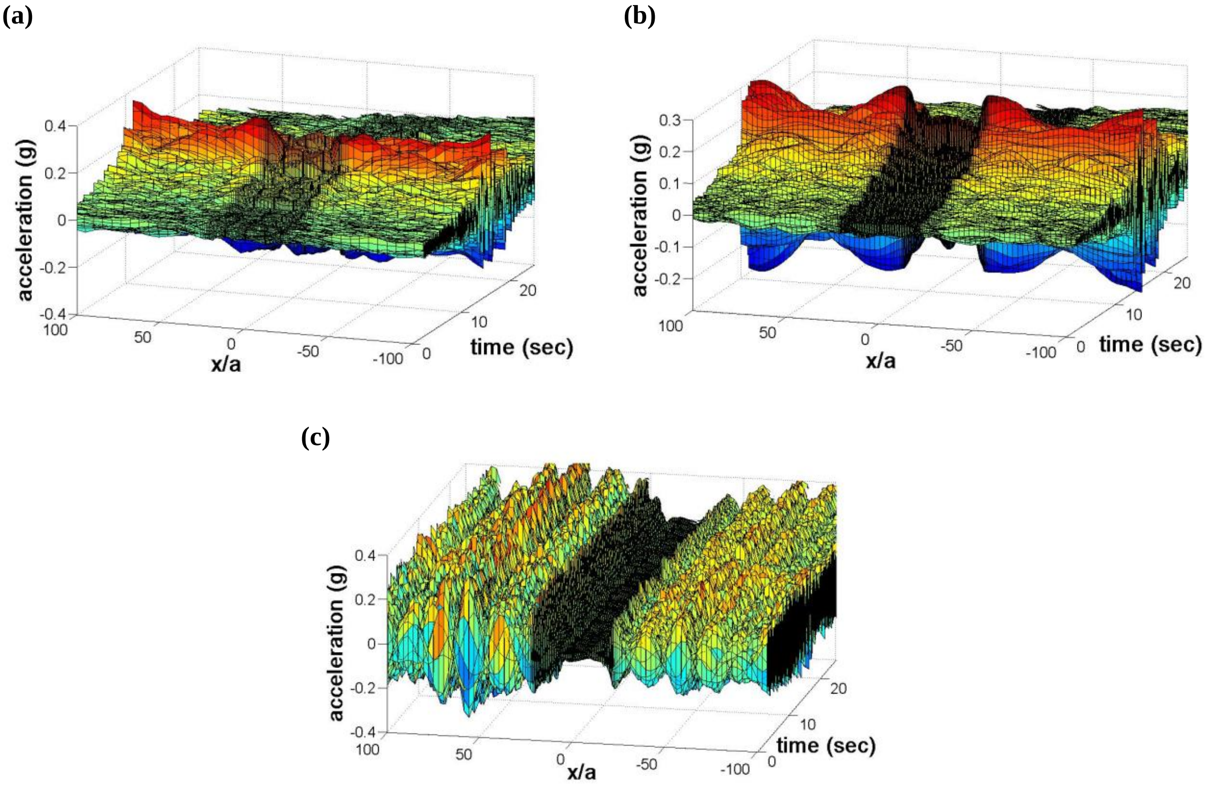

Figure 5: 3D acceleration time history of Northridge No2 ground motion recorded at the free surface of (a) Type B, (b) Type C and (c) Type D geological profile.

5 DESCRIRTION OF BRIDGE AND MODELING

We now focus on the nonlinear response of a theoretical monolithic, reinforced concrete, straight bridge with earthquake resistant abutments proposed by Mitoulis (et al., 2014). The total length of the bridge is equal to168m, supported on rectangular hollow piers of unequal height that varies from 14.35 to 21.8m, as shown in Fig.6.

In terms of some additional details, the two end spans are 39m long, while the two intermediate spans have span lengths of 45m each. The concrete deck is a hollow box girder with a constant cross section along the length. For the design of the expansion joints, 40% of the seismic movements of the deck are considered according to Eurocode 8, Part 2 (2003), as well as serviceability-induced constrained movements of creep, shrinkage, pressing and 50% of the thermal movements of the deck. The cracked flexural stiffness of the piers is estimated as equal to 65% of the original cross-section.

The bridge is modeled using the FEM commercial program SAP2000, ver14 (CSI, 2007). For modeling the bearings, a number of nonlinear-link elements, with bilinear equation, are used in order to reproduce the translational and rotational stiffness of the bearings. Piers and deck are modeled by frame elements. Gap elements are used to model the 25mm opening at the expansion joints, which separate the backwall from the deck. Note here that the nonlinear response of the bridge is localized and considered only by the geometrical non-linearities of the gap elements as both the deck and the piers are designed to remain elastic under the design earthquake.

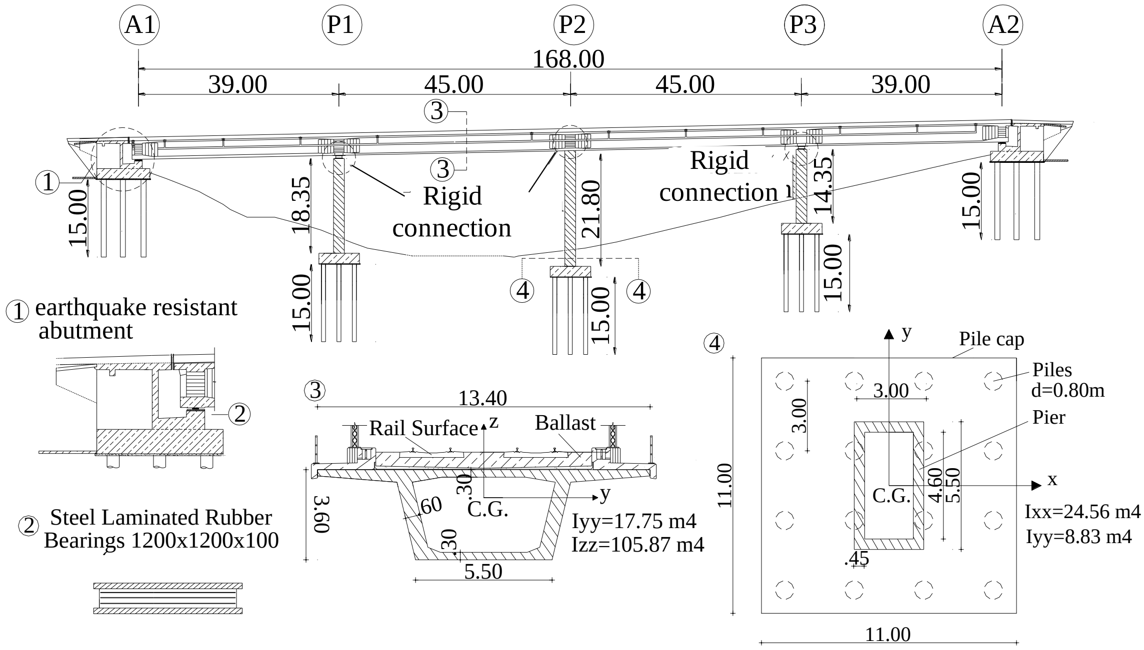

Fig. 6: Section details along the bridge span: (1) Bridge abutment; (2) steel laminated rubber bearings; (3) deck cross-section; (4) plan view of the pier and its foundation.

The interaction of the foundation with the subsoil-structure and the bridge is considered by assigning six spring elements at the contact points, namely three translational and three rotational. For all support points of the bridge and for four different geological profiles, site dependent spring coefficients are computed from closed form equations. For the present case of pile group foundation, equations referring to a single pile (Pender, 1993; Kavadas and Gazetas, 1993) are modified in order to account for the waves that are emitted from the piles and propagate towards the other members of the group. To that purpose, complex dynamic interaction factors α_{ij} are calculated from closed-form equations existing in the literature (Gazetas et al., 1990). Soil-Structure-Interaction is strongly frequency dependent. Nevertheless, it is assumed that the dynamic impedance matrix is calculated based on the predominant frequency of the input motion. This assumption is rather common in the literature but it may not be accurate under certain conditions (Makris and Gazetas, 1992). Hence a range of values between the predominant spectral period and the smoothed spectral predominant period of excitation is considered in the present study

Next, a series of Nonlinear Time History Analyses (NRHA) are conducted under the suite of seven ground motions for the following two cases: (i) the same seismic record is applied to all support points of the bridge(uniform case) and (ii) site dependent ground motions (i.e. the records are different for each support point of the bridge). These ground motions and the corresponding spring coefficients account for (a) canyon topography effect; (b) canyon plus soil layering effect and (c) canyon topography, layering with irregular interfaces and a material gradient effect.

In order to estimate the relative importance of the topographic effects and the subsequent multiple support excitation of the bridge two parametric sets of analyses are carried out.

Namely, the following cases are considered: (1) “uniform” spring values where spring coefficients have the same values for all support points of the bridge for each ground motion and (2) “multiple” spring values where spring coefficients have different values for each support point of the bridge and for each ground motion based on 2D analysis of the subsoil structure.

Fig.6 shows the mean value of piers’ dynamic lateral stiffness due to ground motions recorded at the surface of the Types A-D geological profiles that account for i) uniform excitation, ii) canyon effect, iii) canyon and layering effect and iv) canyon, layering and material gradient effect. As can be seen, in terms of the foundation dynamic impedance matrix the presence of local site conditions has a beneficial effect to the bridge foundation stiffness for all here examined ground motions.

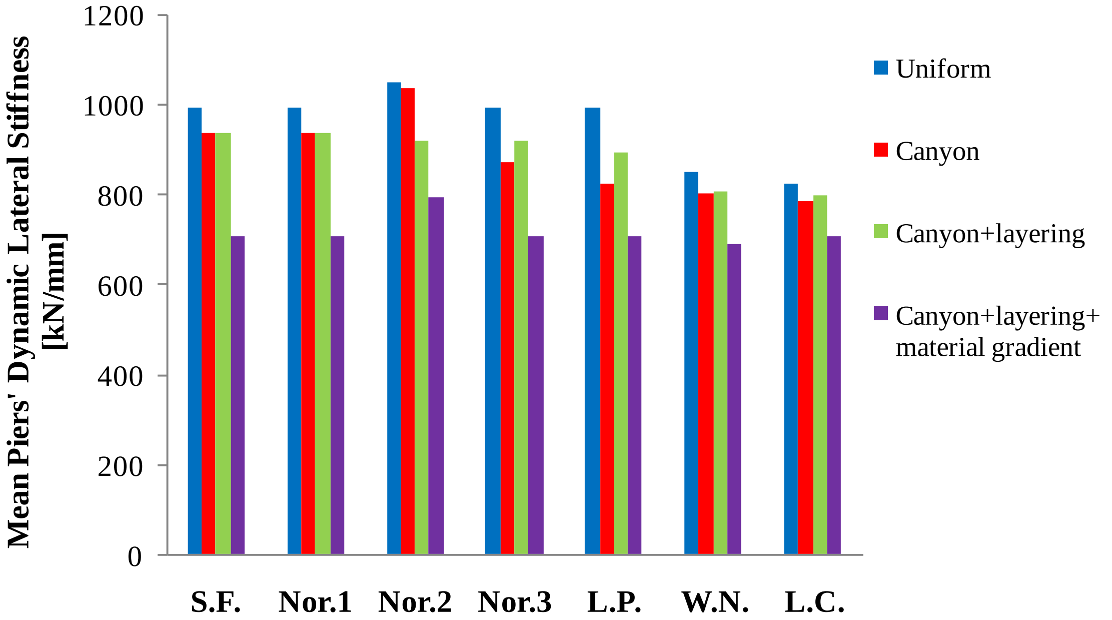

Fig. 7: Mean value of piers’ dynamic lateral stiffness due to ground motions recorded at the surface of the Types A-D geological profiles.

6 DYNAMIC RESPONSE OF THE R/C BRIDGE

The influence of (a) site effects, (b) spatial variability in terms of 2D analysis of wave propagation and (c) SSI on structural response of the R/C bridge is demonstrated in Figs.8-10. More specifically, maximum displacements of the bridge deck are shown in Fig.8 for the middle point of the first deck-span (joint A1-P1) and for the second deck-span (joint P1-P2) for the examined case of study. We observe that the presence of local site conditions can modify the kinematic response of the bridge either beneficially or detrimentally. For some ground motions, local site conditions have a significant effect on the response of the deck, while for other ground motions local site conditions produce a minor small difference in the displacement of the deck as compared with the reference type A soil deposit. The pronounce response of the bridge under excitation Northridge 2 and Whittier Narrows for the case of the uniform excitation compared to the other cases that account for site effects is reminiscent of dynamic resonance. In particular, the presence of a complex subsoil structure modifies the frequency of the propagating wave as well as the dynamic characteristics of the bridge through the change in the spring coefficients and the subsequent fundamental period of the structure.

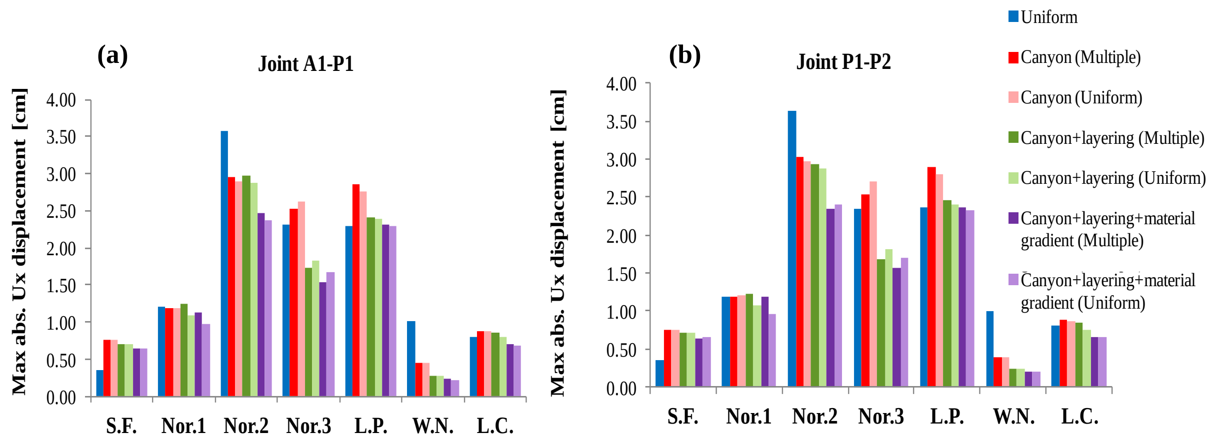

Fig. 8: Maximum absolute deck displacements at joints (a) A1-P1; (b) P1-P2, due to ground motions recorded at the surface of the types A-D geological profiles for (i) uniform spring values and (ii) multiple spring values.

Furthermore, we can see that the effect of multiple spring values for the support points of the bridge produces minor small difference in the deck displacements comparing with the uniform spring values for all support points for each ground motion. Next, maximum absolute displacements at piers P1 and P3 are shown in Fig.10, where we observe that both piers respond similarly to all examined here cases. Ignoring site effects may introduce difference up to 50% in the bridge response in terms of the displacements for the considered here case of study.

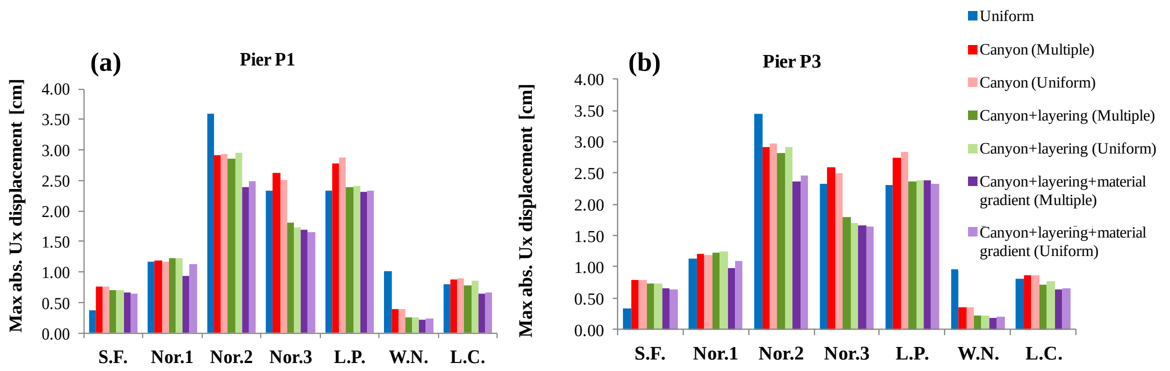

Fig. 9: Maximum absolute pier displacements at joints(a) P1; (b) P3, due to ground motions recorded at the surface of the types a-d geological profiles for (i) uniform spring values and (ii) multiple spring values.

Displacement time history of the bridge deck, and in particular of the middle point of the first span, is presented in Fig.10 for Northridge Nr3 ground motion (listed in Table 2) due to uniform excitation case and to the ground motions that account for canyon, soil layering and material inhomogeneity for uniform or multiple values of spring coefficients. It is observed that canyon topography effect may amplify or de-amplify slightly the displacement time history of the deck (the former holds for the present case). When the canyon effect is combined with soil layering, the effect produces strong de-amplification, due to the increase in stiffness of the soil system, plus an obvious shifting of the peaks. The presence of material gradient additionally to canyon and layering effect does not change the shape of overall time history picture. However in case of multiple spring coefficient values the additional effect of the material gradient produce a small decrease in the amplification levels.

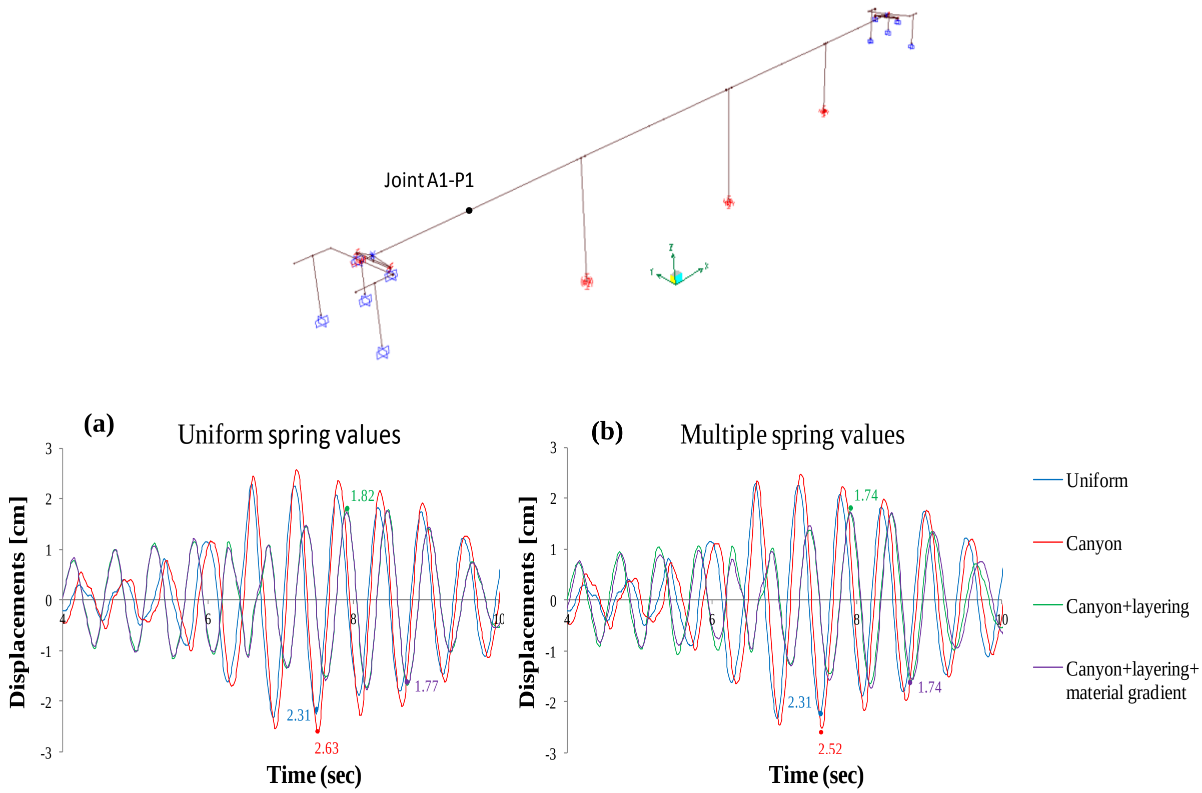

Fig. 10: Displacement time history recorded at point A1-P1 on the deck due to ground motions recorded at the surface of the types A-D geological profiles for (a) uniform spring values and (b) multiple spring values.

7 CONCLUSIONS

In the present study, the influence of local site conditions, spatial variability and Soil-Structure-Interaction on the inelastic dynamic response of a monolithic reinforced concrete bridge are all investigated using a 2D analysis of the subsoil configuration via BEM. Site-dependent time history records and equivalent soil spring coefficients are recovered at the surface of complex geological profiles that account for the following combinations: (i) uniform excitation; (ii) canyon effect; (c) canyon and layering effect; (iv) canyon layering and material gradient effect. Then, a series of dynamic analyses of the bridge, accounting for local nonlinearities, are conducted under site dependent ground motions provided by the previous development, which considers multiple support excitation. From the numerical simulation results, the following conclusions can be drawn:

- Site dependent ground motions are generated by a new-developed BEM that can represent wave propagation in complex geological media with variable velocity profile, nonparallel layers, surface relief and buried cavities and tunnels.

- The site dependent ground motions and the subsequent soil spring coefficients are strongly affected by the canyon topography, layering and material gradient effect and this effect is frequency-dependent.

- The combination of local site conditions, spatial variability and SSI effects influence significantly the nonlinear dynamic response of bridges. These effects cannot be neglected and should be modeled and implemented in as much as possible.

- SSI effect is beneficial in terms of foundation dynamic impedance matrices regardless of the presence of site effects. However, in terms of structural response the combination of SSI, spatial variability and site effects can be detrimental, at least for the bridge examined here.

- Ignoring site effects via 2D analysis of the soil profile may introduce an error around 50% in terms of the kinematic field for the case examined herein.

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