

Chapter 11

Effects of Local Site Conditions on Inelastic Dynamic Response of R/C Bridges

Ioanna-Kleoniki Fontara, Magdalini Titirla, Frank Wuttke, Asimina Athanatopoulou, George D. Manolis and Petia S. Dineva

Abstract The purpose of this work is to study the effects of site conditions on the inelastic dynamic analysis of a reinforced concrete (R/C) bridge by simultaneously considering an analysis of the surrounding soil profile via the Boundary Element Method (BEM). The first step is to model seismic waves propagating through complex geological profiles and accounting for canyon topography, layering and material gradient effect by the BEM. Site-dependent acceleration time histories are then recovered along the valley in which the bridge is situated. Next, we focus on the dynamic behaviour of a R/C, seismically isolated non-curved bridge, which is modelled and subsequently analysed by the Finite Element Method (FEM). A series of non-linear dynamic time-history analyses are conducted for site dependent ground motions by considering non-uniform support motion of the bridge piers. All numerical simulations reveal the sensitivity of the ground motions and the ensuing response of the bridge to the presence of local soil conditions. It cannot establish a priori that these site effects have either a beneficial or a detrimental influence on the seismic response of the R/C bridge.

Keywords Bridges · Local site conditions · Hybrid methods · Inelastic effects

I.-K. Fontara · F. Wuttke (✉)

Institute of Applied Geo-Sciences, Christian-Albrecht's University, 24118 Kiel, Germany
e-mail: fw@gpi.uni-kiel.de

F. Wuttke

Chair of Marine and Land Geomechanics and Geotechnics, Kiel University, Ludwig-Meyn St. 10, 24118 Kiel, Germany

F. Wuttke

Faculty Civil Engineering, Formerly, Bauhaus-University Weimar, Coudraystrasse 11C, 99423 Weimar, Germany

A. Athanatopoulou · G.D. Manolis

Department of Civil Engineering, Aristotle University, 54124 Thessaloniki, Greece

M. Titirla · P.S. Dineva

Institute of Mechanics, Bulgarian Academy of Sciences, 1113 Sofia, Bulgaria

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11.1 Introduction

It is well known that geological irregularities of all types produce local distortions in the incoming wave field. Such distortions are generally known as “site effects”, and result in a pronounced spatial variation in seismically-induced ground motions. More specifically, spatial variation in seismic ground motions is manifested as measurable differences in amplitude and phase of seismic motions recorded over extended areas. It has an important effect on the response of lifelines such as bridges, pipelines, communication and power transmission grids, tunnels, etc., because these structures extend over long distances parallel to the ground and their supports undergo differential motions during an earthquake.

Simplifying assumptions regarding contemporary bridge design in Eurocode 8 (2003) state that: (i) seismic motion is transmitted to the structure through its supports and is identical at all piers and abutments and (ii) local site conditions are accounted for in terms of site categorization. However, seismic motions are influenced by the wave propagation path and the surface topography at the site of interest, making them a highly variable design parameter.

Several previous studies indicate that local site conditions can exert a crucial influence on the severity of structural damage. 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 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 soil-structure interaction 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 infrastructure-type projects. Zhou et al. (2010) investigated canyon topography effects on the linear response of continuous, rigid frame bridges under oblique 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 corners of the canyon and decrease at the bottom corners of the canyon.

In the above mentioned as well as other related studies, however, with exception of Zhou et al. (2010), 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. It is evident that there is a lack of high-performance computational tools able to simulate two and possibly three dimensional complex geological profiles. The BEM is nowadays recognized as a valuable numerical technique to solve the problem discussed here, due to many advantages in comparison with domain techniques such as the FEM. We briefly

mention here the possibility to deal with semi-infinite media in terms of high accuracy and minimal modeling effort.

The main objective of the present work is to investigate the effects of local soil conditions on the dynamic response of R/C bridges. 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) next, site dependent ground motions are generated at the surface using the BEM technique; (iii) these are used as input to a three dimensional, seismically isolated model of an R/C, non-curved bridge; (iv) the bridge is then modeled and analyzed using the FEM; (v) different time records are considered as input at each support point of the bridge; (vi) the dynamic response of the bridge due to site dependent ground motions is determined and the results are interpreted to establish changes in terms of what would be observed for a homogenous soil deposit.

11.2 Seismic Signal Recovery Methodology

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 two dimensional wave propagation in viscoelastic, isotropic and inhomogeneous half-plane consisting of N parallel or non-parallel inhomogeneous layers Ω_n ($n = 0, 1, 2, \dots N$) with a free surface and sub-surface

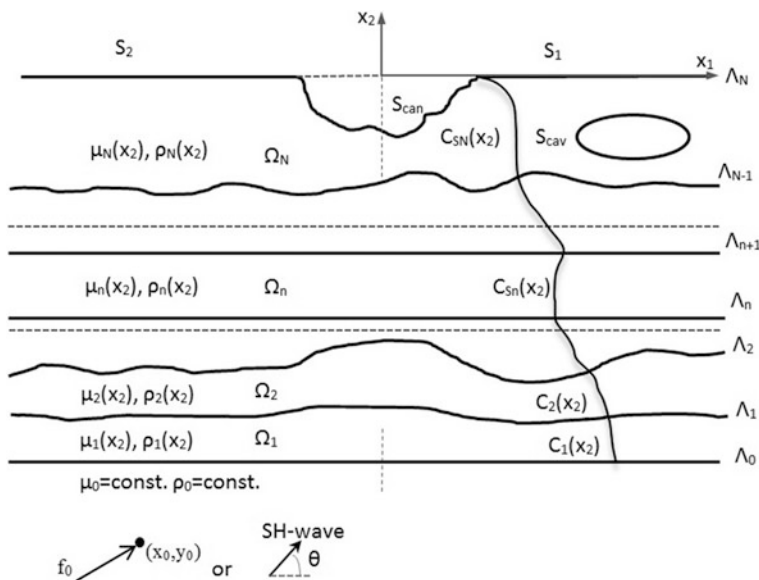


Fig. 11.1 Geometry of the problem treated by BEM: a multi-layered, continuously inhomogeneous geological medium with surface topography and buried inclusions

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. 11.1. 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, b). The employed here BEM was recently developed and validated in Fontara et al. (2015).

More specifically, the material inhomogeneity is expressed by a position-dependent shear modulus and density of arbitrary variation in terms of depth coordinate. We define the inhomogeneity parameter $c_n = C^{bottom(\Delta n-1)}/C^{top(\Delta n)}$ as 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).

$$cu_3^{(i)}(\mathbf{x}, \omega) = \int_{\Gamma} U_3^{*(i)}(\mathbf{x}, \mathbf{y}, \omega) t_3^{(i)}(\mathbf{y}, \omega) d\Gamma - \int_{\Gamma} P_3^{*(i)}(\mathbf{x}, \mathbf{y}, \omega) u_3^{(i)}(\mathbf{y}, \omega) d\Gamma \quad (11.1)$$

$$\mathbf{x} \in \Gamma = \Omega_i \cup S_{can} \cup S_{cav}$$

In the above, \mathbf{x} , \mathbf{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 $P_3^*(\mathbf{x}, \mathbf{y}, \omega) = \mu(x_2)U_3^*(\mathbf{x}, \mathbf{y}, \omega) n_i(\mathbf{x})$ is the corresponding traction fundamental solution, where $i = 1, 2 \dots N$ 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:

$$[G]\{t\} - [H]\{u\} = \{0\} \quad (11.2)$$

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 $M \times M$, 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.

11.3 Geological Profiles

The methodology described in the previous section is now applied to four different hypothetical geological profiles on which the R/C bridge in question is considered to be located, see Fig. 11.2, 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 configurations: (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 following the exact canyon geometry in which the bridge is located; (c) a double homogeneous 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 parameter $c = 1.2$ expressing an 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 elastic bedrock. The soil material properties of these subsoil geological configurations are shown in Table 11.1.

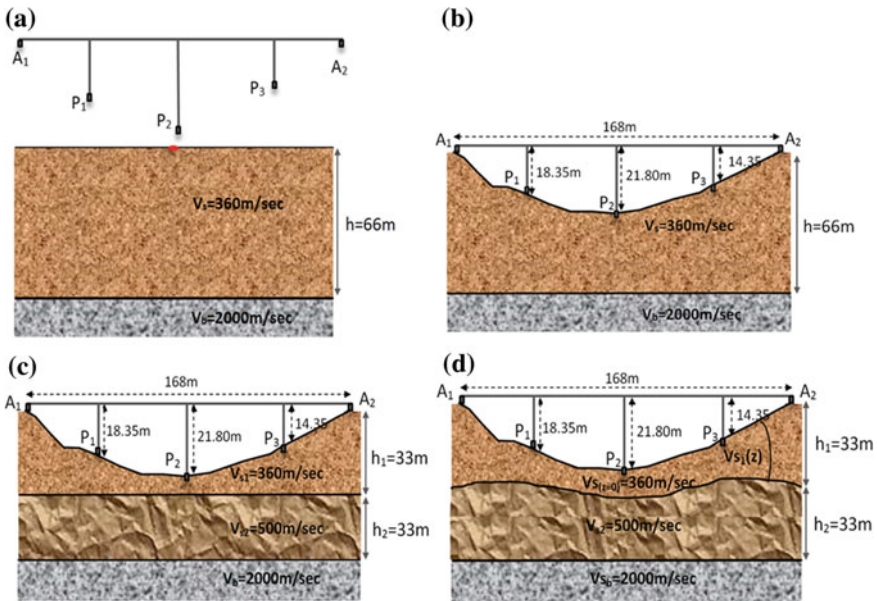


Fig. 11.2 Four geological profiles, Types a–d, on which the R/C bridge is assumed to be located

Table 11.1 Material properties of the basic geological structure

	V_s (m/s)	μ (Pa)	ρ (N/m ²)
Layer 1	360	233.28×10^6	1800
Layer 2	500	450×10^6	1800
Bedrock	2000	800×10^7	2000

Table 11.2 Ground motion records from the PEER (2003) strong motion database as recorded on a Class A site

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	Lyle Creek	5.4	Cedar Springs, Allen Ranch	20.6 (Hypocentral)	095	0.071

Next, a suite of seven earthquake excitations given in Table 11.2 are considered, recorded at the 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.

11.4 Ground Motions

We next investigate the influence of site effects on ground motions recorded along the free surface and start with the first geological profile comprising a single layer with a horizontal free surface that produces a uniform excitation pattern ridge as a reference case. Next, Fig. 11.3 plots the acceleration response spectra recorded at the surface of the Type B geological profile at the support points of the bridge at the canyon and for two different seismic motions. 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

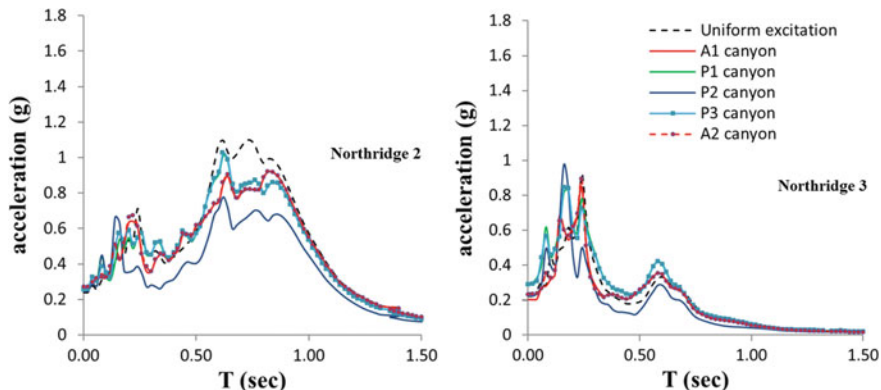


Fig. 11.3 Acceleration response spectra recorded at the free surface of Type B geological profile

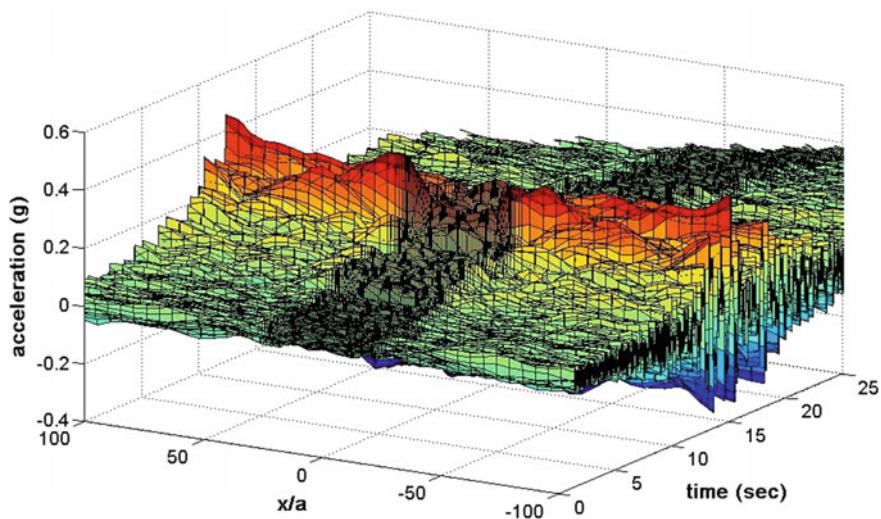


Fig. 11.4 3D acceleration time history recorded at the free surface of Type B geological profile

excitation. Spectral accelerations are more pronounced for low values of period at the bottom of the canyon, while high period values lead to significant spectral acceleration at the edge of the canyon. Three dimensional time history recordings along the canyon are shown in Fig. 11.4, where it is obvious that the seismic signal depends strongly on the canyon topography.

We next examine the influence of canyon topography and of the soil layering on ground motions by comparing acceleration response spectra generated from the uniform excitation geological profile with those generated at the surface of the Type C geological profile that accounts for canyon topography and layering effect,

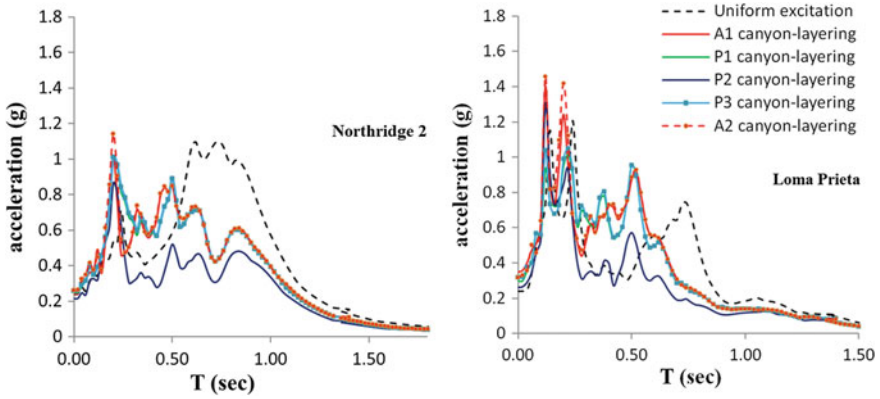


Fig. 11.5 Acceleration response spectra recorded at the free surface of Type C geological profile

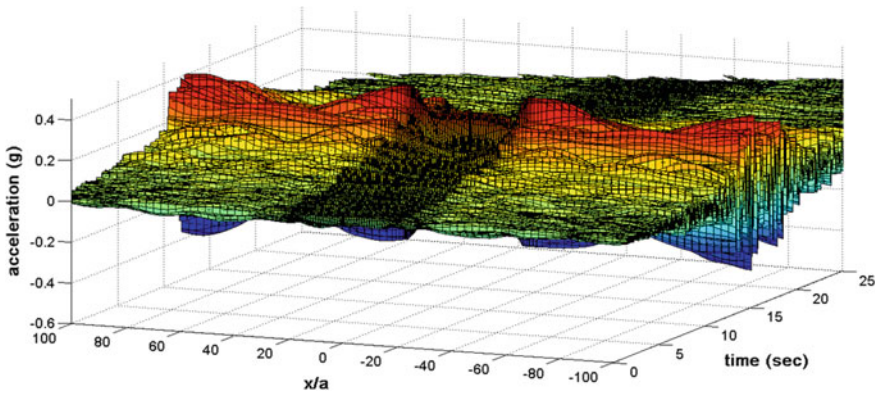


Fig. 11.6 3D acceleration time history recorded at the free surface of Type C geological profile

see Fig. 11.5. We can see that the ground motions are strongly affected by the combined soil layering and canyon topography structure. The shape of the response spectra is now modified, while an expected shifting to the right (higher periods) due to the layering effect is clearly depicted. This is also evident from the 3D time history recorded along the surface of the Type C geological profile shown in Fig. 11.6. There, the acceleration peaks become smoother due to the increased stiffness of the bottom layer.

The combined influence of canyon topography, layering and material gradient effect on the ground motions is now examined. As previously mentioned, in this case the top layer has a continuous variation of the wave speed with depth, avoiding this way the great wave speed contrast between the first and the second layers of the previously examined case, as shown in Fig. 11.7. In addition, we also introduce here a spatial irregularity in the interface between the two soil layers. More specifically, in Fig. 11.8 we compare the acceleration response spectra generated

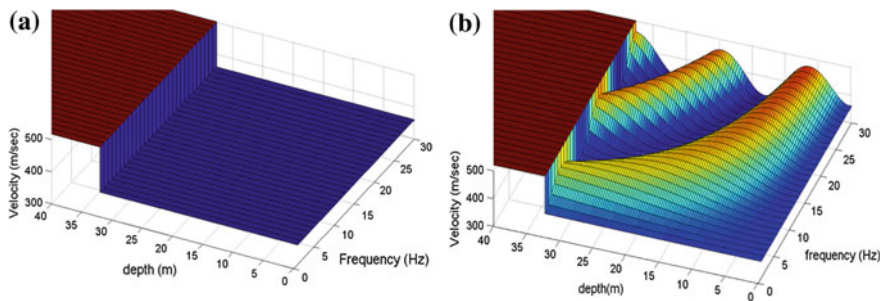


Fig. 11.7 Velocity distribution of the subsoil structure: **a** Type C and **b** Type D geological profile

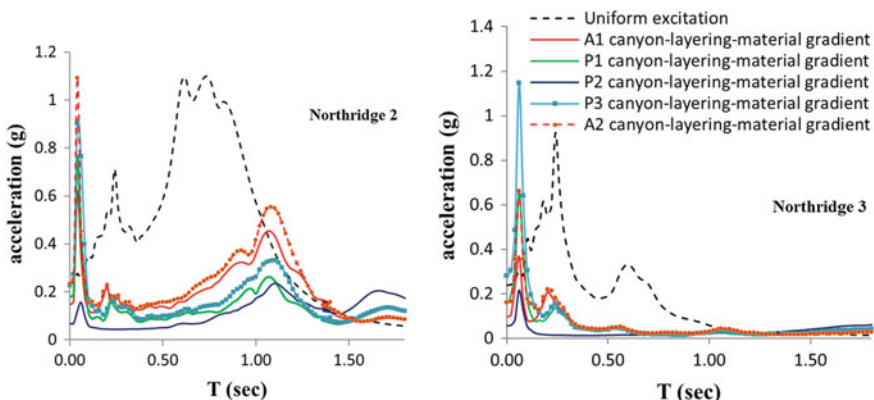


Fig. 11.8 Acceleration response spectra recorded at the free surface of Type D geological profile

for the reference case of uniform excitation with those spectra generated at the surface of the Type D geological profile. We clearly observe now how site effects significantly influence the seismic ground motions. The presence of material gradient increases the material stiffness gradually and the soil becomes stiffer. As a result, the spectral acceleration values are de-amplified across the entire range of periods examined herein.

11.5 R/C Bridge Modeling

We now focus on the nonlinear response of an existing R/C bridge. In particular, we consider the redesign scheme of the Greek Railway Organization (OSE) bridge located in Polycastro, Northern Greece (see Mitoulis et al. 2014). It is a seismically isolated, straight bridge with earthquake resistant abutments and a total length of 168 m supported on rectangular hollow piers of unequal height that varies from 14.35 to 21.8 m, as shown in Fig. 11.9.

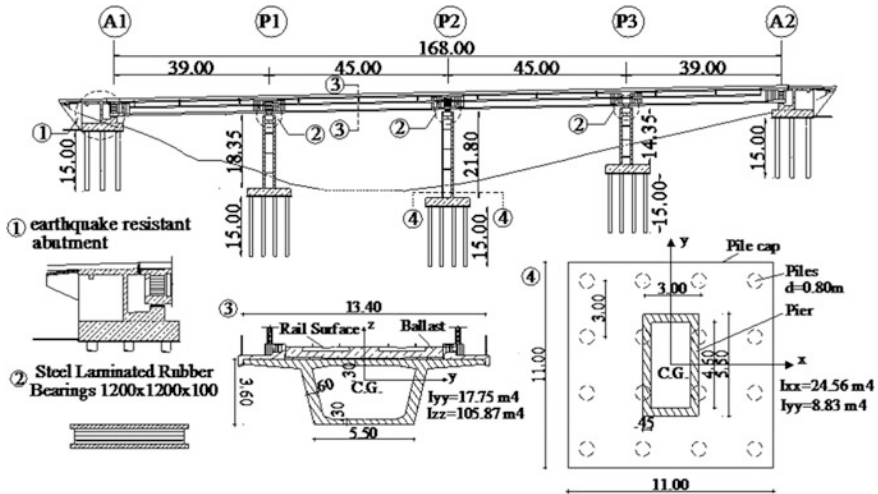


Fig. 11.9 Section details along the bridge span: 1 Longitudinal section of the abutment; 2 steel laminated rubber bearings; 3 deck cross-section; 4 plan view of the pier and its foundation

In terms of some additional details, the two end spans are 39 m long, while the two intermediate spans have span lengths of 45 m 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 fundamental period of the bridge along the X -axis is $T_x = 1.43$ s and along the Y -axis is $T_y = 0.71$ s.

The bridge is modeled and subsequently analyzed using the FEM commercial program SAP (2007). For modeling the bearings, a number of N -link elements are used in order to reproduce the translational and rotational stiffness of the bearings. Piers and deck are modeled by frame finite elements. The flexibility of the foundation of the piers and of the abutments was modeled by assigning six spring elements at the contact points, namely three translational and three rotational ones. These soil spring values were obtained by the geotechnical in situ tests conducted during the final design of the actual bridge. Gap elements are used to model the 25 mm 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 non-linearities of the gap elements and of the isolators.

Next, a series of Nonlinear Time History Analyses (NRHA) are conducted under the following conditions: (i) a suite of ground motions applied uniformly to all support points of the bridge and (ii) the same suite of site dependent ground motions, which are now different for each support point of the bridge. These motions also 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.

11.6 Dynamic Response of the R/C Bridge

The influence of site effects on structural response of the R/C bridge is demonstrated in Figs. 11.10, 11.11, 11.12 and 11.13 where the input is ground motions at rock outcrop that have been filtered by the complex soil deposits of Fig. 11.2 so as

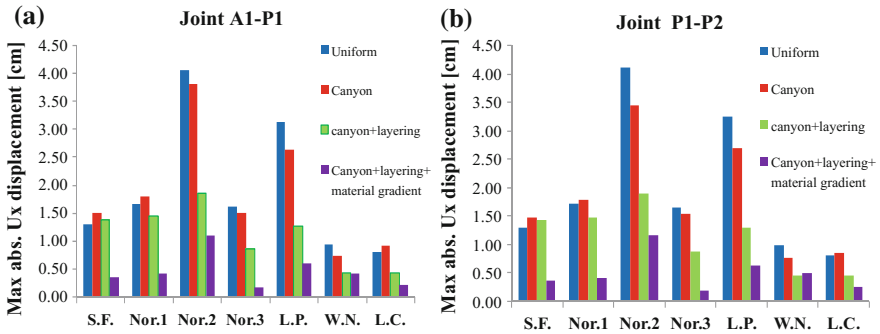


Fig. 11.10 Maximum absolute deck displacements at joints **a** A1–P1; **b** P1-P2, due to ground motions recorded at the surface of the Types A–D geological profiles

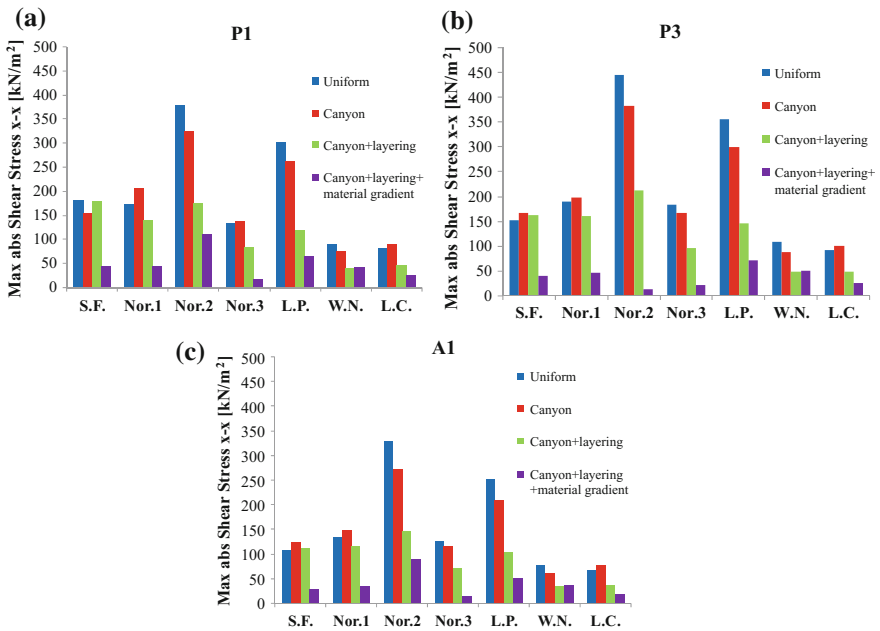


Fig. 11.11 Maximum absolute bearing shear stresses at bearing **a** P1; **b** P3; **c** A1, due to ground motions recorded at the Types A–D geological profiles

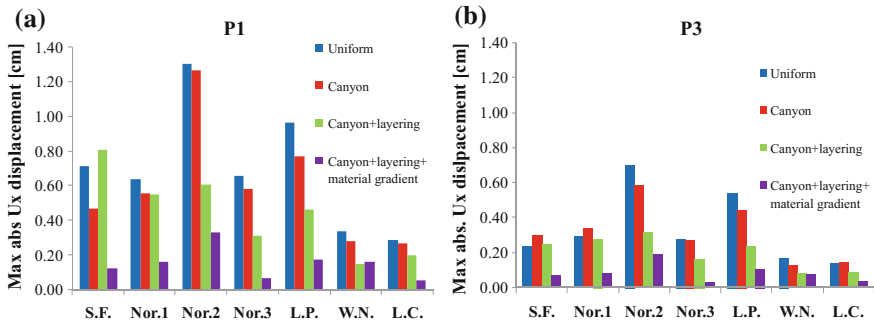


Fig. 11.12 Maximum absolute pier displacements at joint a P1; b P3, due to ground motions recorded at the surface of the Types A–D geological profiles

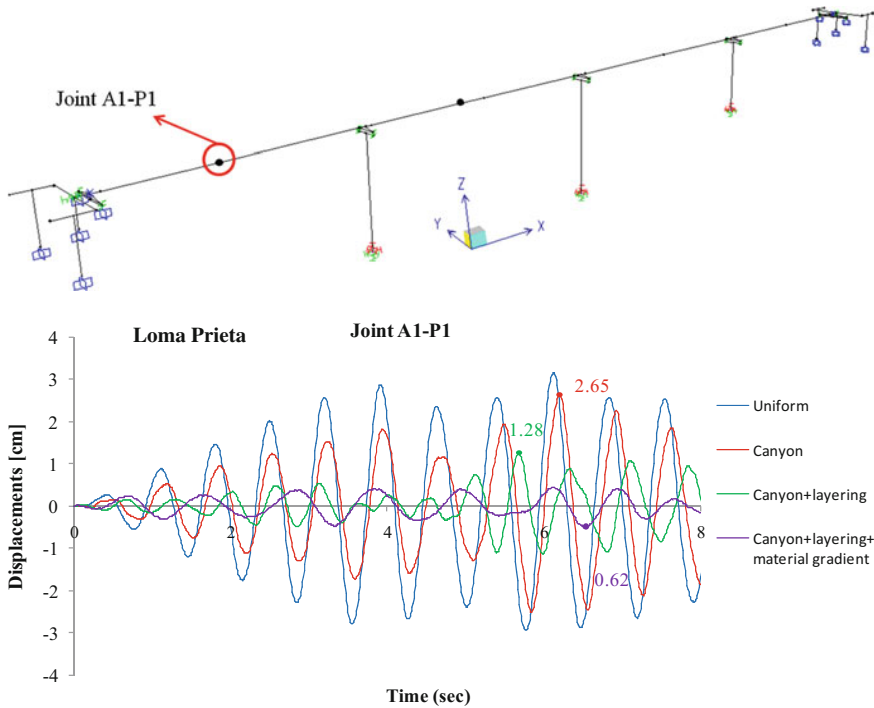


Fig. 11.13 Displacement time history recorded at point A1–P1 on the deck due to ground motions recorded at the surface of the Types A–D geological profiles

to account for (i) uniform excitation, (ii) canyon effect, (iii) canyon and layering effect and (iv) canyon, layering and material gradient effect.

More specifically, maximum displacements of the bridge deck are shown in Fig. 11.10 for the middle point of the first joint (A1–P1) and for the second joint

(P1–P2) along the bridge span for the four types of geological profiles. In most cases, the modified ground motions due to local site effects play an important role in modifying the kinematic response of the bridge in a way that is considered as beneficial. Moving on to the stress field that develops in the R/C bridge, Fig. 11.11 gives the maximum absolute shear stresses at the bearings located at abutment A1 and at piers P1 and P2. We observe that for some seismic motions, local site conditions have a significant effect on the response of the bearings, while for other ground seismic motions local site conditions produce a minor small differences in the bearing response as compared with the reference Type A soil deposit. For at least three ground motions histories, canyon topography results in motions that subsequently overstress the aforementioned supports. However, the input of identical motions as excitations at the bridge’s supports will not always yield what is construed as a conservative response, indeed for the examined here case canyon topography effect can lead to 15% increase on the bearings response. Next, maximum absolute displacements at piers P1 and P3 are shown in Fig. 11.12, where we observe that pier P1 is the one most affected by the influence of local soil conditions. For all the cases examined here, ignoring site effects may introduce amplification effects reaching up to 70% in terms of the displacements.

Displacement time histories of the bridge deck, and in particular of the middle point of the first span, are presented in Fig. 11.13 for Loma Prieta ground motion (listed in Table 11.2) due to uniform excitation case and to the ground motions that account for canyon, soil layering and material inhomogeneity. It is observed that canyon topography effect may either amplify or de-amplify the displacement time history of the deck (the latter 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 a shifting of the peaks. The combination of canyon, layering and material gradient effect significantly modifies the

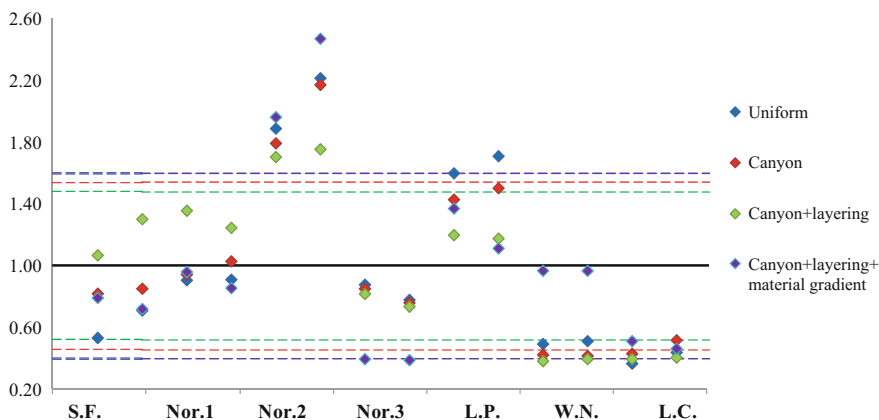


Fig. 11.14 Maximum and minimum normalized deck displacement versus standard deviation for the input ground motions and the four types of geological profiles

displacement time history computed at the deck in terms of resonance frequencies and amplification levels.

In order to generalize the structural behaviour trends, Fig. 11.14 plots the maximum and the minimum normalized displacements of the deck for each ground motion case and for four geological profiles. Comparison is in terms of a mean value plus the standard deviation. As previously mentioned, we again observe that for some ground motions the structural response is significantly affected by the presence of local site conditions, while for other ground motions structural response is only slightly affected.

11.7 Conclusions

In the present study, the influence of local site conditions on the inelastic dynamic response of an existing reinforced concrete bridge located in Northern Greece is investigated using a 2D analysis of the subsoil configuration. A nonconventional BEM technique is applied in order to recover time history records at the surface of complex geological profiles that account for the following combinations: (i) uniform excitation; (ii) canyon effect; (iii) canyon and layering effect; (iv) canyon layering and material gradient effect. Following that, a series of dynamic analyses of the bridge, accounting for lumped nonlinearity, are conducted under site dependent ground motions provided by the previous development, which consider multiple support excitation. From the numerical simulation results, the following conclusions can be drawn:

- Local site conditions cannot be ignored since they significantly influence the inelastic dynamic response of bridges.
- 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 ground motions and the subsequent response of the R/C bridge are strongly affected by the canyon topography, layering and material gradient effect and this effect is frequency-dependent.
- It is not true from the cases examined herein that ignoring site effects and spatial variability of input motions leads to beneficial results for the R/C bridge. Also, it cannot establish a priori that site effects have beneficial influence on the seismic response of bridges.
- Ignoring site effects may introduce an error around 70% in terms of the kinematic field for the particular case examined herein.
- The presence of canyon topography may introduce an increase of 15% in the kinematic response of the R/C bridge.

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