Title

Influence of topographic irregularities on the asyncronism of strong ground motions

Authors

Durante, Maria Giovanna
Brandenberg, Scott J
Ausilio, Ernesto
et al.

Publication Date

2018-06-25

Peer reviewed

Eleventh U.S. National Conference on Earthquake Engineering
Integrating Science, Engineering & Policy
June 25-29, 2018
Los Angeles, California

INFLUENCE OF TOPOGRAPHIC IRREGULARITIES ON THE AMPLITUDE AND PHASE OF STRONG GROUND MOTIONS

M. G. Durante[1], S. J. Brandenberg[2], E. Ausilio[3] and P. Zimmaro[4]

ABSTRACT

We investigate the role of topographic irregularities on the amplitude and phase of earthquake ground motion by means of numerical analysis performed with the open-source finite element software OpenSees. We first perform a verification of the numerical model for simple 2D topographic features and harmonic motions, against: (1) numerical solutions available in the literature and (2) boundary element method analyses utilizing a code specifically developed for this study. The analytical and boundary element solutions provide verification of the OpenSees simulations for simple geometries excited at a single frequency. OpenSees, by contrast, can handle irregular geometries and broadband ground motions. We then perform a comprehensive parametric investigation for a bridge crossing a 260m-deep canyon. Our analyses are performed considering homogeneous stiff rock site conditions to emphasize the role of topographic irregularities only, without the influence of soil/rock layers of varying stiffness. Results are presented in terms of phase angle and amplitude modifications for a few critical locations along the bridge axis, corresponding to the foundations of the central piers of the bridge. We also process results by using cross-correlation measures, showing that 2D topographic irregularities can strongly modify strong ground motions.

[1]Postdoctoral Scholar, Dept of Civil and Environmental Engineering, University of California, Los Angeles, CA 900095-1593 (email: mgdurante@ucla.edu)
[2]Professor, Dept of Civil and Environmental Engineering, University of California, Los Angeles, CA 900095-1593 (email: sjbrandenberg@ucla.edu)
[3]Professor, Dept of Civil Engineering, University of Calabria, Cosenza, IT (email: ernesto.ausilio@unical.it)
[4]Research Scientist and Lecturer, Dept of Civil and Environmental Engineering, University of California, Los Angeles, CA 900095-1593 (email: pzimmaro@ucla.edu)

Durante MG, Brandenberg SJ, Ausilio E, Zimmaro P. Influence of topographic irregularities on the amplitude and phase of strong ground motions. *Proceedings of the 11th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Los Angeles, CA. 2018.

Eleventh U.S. National Conference on Earthquake Engineering
Integrating Science, Engineering & Policy
June 25-29, 2018
Los Angeles, California

Influence of topographic irregularities on the amplitude and phase of strong ground motions

M. G. Durante[1], S. J. Brandenberg[2], E. Ausilio[3] and P. Zimmaro[4]

ABSTRACT

We investigate the role of topographic irregularities on the amplitude and phase of earthquake ground motion by means of numerical analysis performed with the open-source finite element software OpenSees. We first perform a verification of the numerical model for simple 2D topographic features and harmonic motions, against: (1) numerical solutions available in the literature and (2) boundary element method analyses utilizing a code specifically developed for this study. The analytical and boundary element solutions provide verification of the OpenSees simulations for simple geometries excited at a single frequency. OpenSees, by contrast, can handle irregular geometries and broadband ground motions. We then perform a comprehensive parametric investigation for a bridge crossing a 260m-deep canyon. Our analyses are performed considering homogeneous stiff rock site conditions to emphasize the role of topographic irregularities only, without the influence of soil/rock layers of varying stiffness. Results are presented in terms of phase angle and amplitude modifications for a few critical locations along the bridge axis, corresponding to the foundations of the central piers of the bridge. We also process results by using cross-correlation measures, showing that 2D topographic irregularities can strongly modify strong ground motions.

Introduction

Numerical site response analyses are often performed considering synchronous input motions at the base of the model. This assumption can be considered acceptable when the analysis is performed on sites that can be treated as 1D problems, or when the features being modelled are not spatially distributed. In the case of long structures and distributed infrastructure such as bridges, dams, tunnels, and pipelines, the resultant ground motion at each point at the base of the structure can be significantly different in terms of both amplitude and phase. For such spatially-

[1]Postdoctoral Scholar, Dept of Civil and Environmental Engineering, University of California, Los Angeles, CA 900095-1593 (email: mgdurante@ucla.edu)
[2]Professor, Dept of Civil and Environmental Engineering, University of California, Los Angeles, CA 900095-1593 (email: sjbrandenberg@ucla.edu)
[3]Professor, Dept of Civil Engineering, University of Calabria, Cosenza, IT (email: ernesto.ausilio@unical.it)
[4]Research Scientist and Lecturer, Dept of Civil and Environmental Engineering, University of California, Los Angeles, CA 900095-1593 (email: pzimmaro@ucla.edu)

Durante MG, Brandenberg SJ, Ausilio E, Zimmaro P. Influence of topographic irregularities on the amplitude and phase of strong ground motions. *Proceedings of the 11th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Los Angeles, CA. 2018.

distributed systems, a common simplification is to consider that the asynchronous motion can be subdivided into three main effects: *(i)* wave passage (due to the finite travel speed of seismic waves, resulting in progressive excitation as a wave front passes); *(ii)* geometric incoherence of the input (it accounts for the wave scattering due to inhomogeneity in the soil, that change the signal contents); *(iii)* local site effects (it includes 1D,2D, and 3D effects). The latter term should also include topographic effects, which have been observed to significantly change the amplitude and phase of a motion during an earthquake [1-5].

In recent years, several case studies have provided examples of earthquake-induced damages to bridges and tunnels even if they were designed to resist seismic loads [6]. These unexpected poor seismic performances of spatially-distributed infrastructure systems are often due to the effects of asynchronous motions [7-9]. With reference to bridge applications, one of the first models proposed for the evaluation of asynchronous motion was developed by Vanmarcke [10]. This model introduced for the first time a probabilistic approach. Luco and Wong [11] proposed a simplified model for generating inputs based on the motion at the first point. Zerva [12] introduced the idea of using random signals as input. More complex methodologies have been developed in more recent studies [13, 14]. The majority of those studies account for wave passage effects and geometric incoherence terms, neglecting site effects. Sextos et al. [7] proposed a methodology for evaluating seismic response of bridges, including site effects by means of one-dimensional simulations (i.e. neglecting 2D-3D topographic effects) and soil-structure interaction effects.

The inclusion of site effects due to topographic irregularities is often neglected in the evaluation of the seismic response of bridges because of the challenges related to the implementation of such effects in relatively simple numerical models. Site response due to topographic effect strongly depends on the shape of the topographic feature (i.e. ridge, slope, or canyon). Trifunac [15] and Wong [16] studied for the first time wave propagation effects due to topographic irregularities for SH, P, and SV incident waves. In this study, they analyze the response of a half-space semi-circular canyon formed by elastic, homogeneous, and isotropic soil. Godinho et al. [17] used the method of fundamental solutions (MFS) to compute the surface displacement along a topographical profile of elastic half-space excited with elastic P, SV, and Rayleigh waves. More recently, Wu et al. [18] presented an improved methodology to include topographic effects in the definition of asynchronous motions for sites located in V-shaped canyons.

In this paper, we present the effects of topographic irregularities on the spatial variation of ground motions for a long bridge overcrossing a deep canyon in Southern Italy. A two-dimensional model of the site of interest was developed in the finite element software framework OpenSees [19]. The approach adopted for the analysis have been verified using available solutions from literature for regularly-shaped canyons (i.e. semi-circular and V-shaped). The elastic model of the site has been then excited using four ground motion recordings, selected to have a broad range of frequency content. Model results are reported in terms of amplification of horizontal and vertical displacements along the surface of the canyon relative to the input motion. More detailed analyses that include coherence and the phase angle of the signals at the base of the central piers of the bridge are also reported. Our results show that topographic effects cause variation of both amplitude and phase of the signals even for synchronous input motions.

Case Study

In this paper we analyze the seismic response of the *Viadotto Italia* bridge in Southern Italy along the *A2 Mediterraneo* highway (Fig. 1). The *Viadotto Italia* overpasses a 260m-deep canyon between the towns of Laino Castello and Laino Borgo in the Cosenza province. Remarkably, the *Viadotto Italia* is currently the second highest bridge in Europe, and it has been the highest in Europe in the period 1974-2004. The design of the bridge has been performed in the late 1960s and it represented a real challenge for that time [20]. The total bridge length was1160 m. Recently, the bridge has been renovated to align to more recent safety standards. The original design comprised 19 spans, 17 piers, and 2 abutments. The central part of the bridge was formed by three long steel spans (125m, 175m, and 125m respectively), while the other spans were curved and formed by pre-stressed concrete. The new layout comprises straight spans at the sides of the bridge, while the central part has not been changed. The piers are formed by hollow sections tapered along the height. As a result of that, the number and the position of same piers has changed. In this study, we modeled the 2D cross-section crossed by the new configuration of the viaduct (Fig. 2). Since the objective of the paper is to analyze the contribution of topographic effect to the seismic response of the canyon, the analyses are performed using an elastic and homogeneous soil deposit (shear wave velocity, V_s=500 m/s and Poisson ratio υ=0.33).The structure is not included in the present analysis.

Figure 1 – Overview of the *Viadotto Italia*

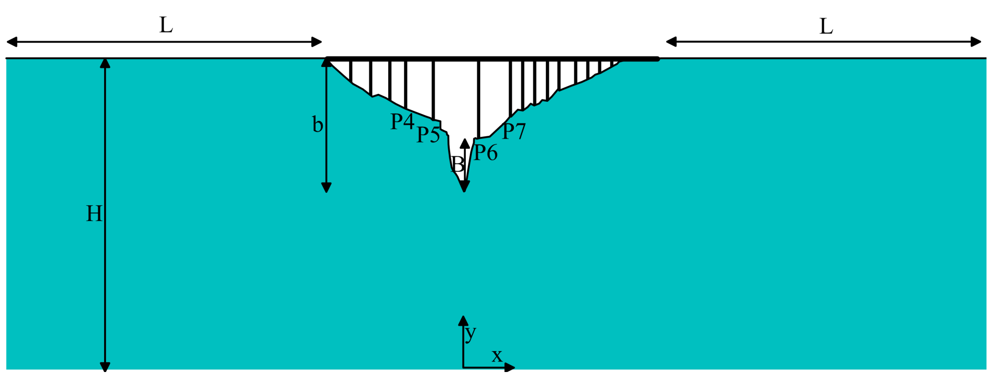

Figure 2. Schematic view of the analyzed cross-section.

Numerical Model

A schematic representation of the two-dimensional finite element method (FEM) model of the site is reported in Fig. 2. The analysis presented in this section are performed using the open-source software OpenSees. The soil domain is studied considering plain strain condition and it is discretized using four-node, bilinear, isoparametric finite elements with four point of integration each. The boundary conditions were modeled using Lysmer transmitting/absorbing boundaries using a set of viscous dampers normal and tangential to the soil boundaries [21]. More details about the formulation behind this approach, the implementation in the code and their accuracy are available in Zhang et al. [22]. The dynamic input is defined at each node of the base of the domain in terms of equivalent nodal forces proportional to the velocity of the seismic wave and the tributary surface area of each element. The input is applied in the horizontal direction to simulate vertically incident SV-waves. The dimensions of mesh elements in the model were chosen considering numerical accuracy of wave transmission processes [23]. As a result, the mesh adopted in this study, comprises elements smaller than one-tenth of the wavelength of the highest frequency component of the input.

Model Verification

The results obtained using the OpenSees FEM numerical model are compared with numerical solutions available in literature for canyons with regular shapes under the hypotheses of elastic uniform soil and vertically propagating harmonic SV waves. Two sets of analysis were performed for two alternative geometries: *(i)* semi-circular canyon shape (Fig. 3a), verified against the solution proposed by Wong [16], and a Boundary Element Method (BEM) solution [24-25]; *(ii)* symmetric triangular canyon shape (Fig. 3b), verified against BEM [24], and Godinho et al. [17] solutions; *(iii)* actual geometry of the canyon overcrossed by the *Viadotto Italia* (Fig. 2), verified against a BEM solution specifically derived for this study. The input considered is formed by sinusoidal vertically-incident SV waves. We performed analysis for a broad range of the dimensionless frequency (η), defined as:

$$\eta = \frac{\omega R_0}{\pi V_s} \tag{1}$$

where ω is the angular frequency of the input, R_0 is the representative geometric parameter of the canyon ($R_0=R=25m$ for semi-circular canyon, $R_0=a=25m$ for symmetric triangular canyon, and $R_0=B=100m$ for Lao river canyon) and V_s in the shear wave velocity of the soil (V_s = 500m/s in all the analyses).

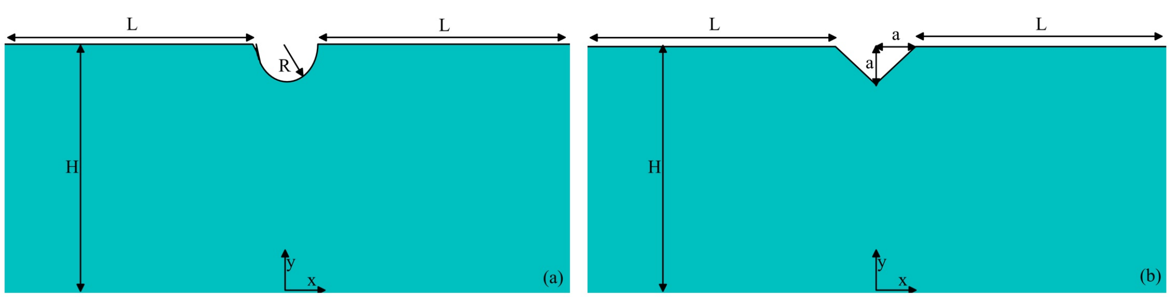

Figure 3. Definition of geometric parameter for: (a) semi-circular, and (b) symmetric V-shaped canyons.

All comparisons between the available numerical solutions available in the literature and the results of the numerical FEM model presented in this study are performed in terms of horizontal (U_h) and vertical (U_v) components of the peak ground surface displacement. All quantities are normalized by the input amplitude for three values of dimensionless frequency η (*0.5*, *1.0* and *1.5*). Due to the boundary conditions adopted in this study, the verification also includes the total dimension of the model with variable ratios of the lateral extension of the model (*L*) and its height (*H*).

Figs. 4 and 5 show the comparison of the proposed FEM numerical model with the solutions available in literature for the semi-circular and V-shaped canyons. The horizontal and the vertical components at surface are plotted versus the distance from the center of the model, normalized by the ratio X/R_0. Figs. 4 and 5 show that the proposed FEM numerical model is in good agreement with the other solutions for all the cases analyzed. The horizontal amplification seems to be less affected than the vertical by the ratio *L/H*. In our FEM model, increasing L/H, increases the accuracy of the result. This effect is more evident for $\eta = 1$ for the semi-circular shaped canyon (Fig. 4) while the difference between $L/H = 5$ and $L/H = 6$ is not significant for the V-shaped canyon (Fig. 5).

Fig. 6 shows the comparison between the FEM model presented in this study and the BEM solution for the actual geometry of the canyon overcrossed by the *Viadotto Italia*. The discrepancy between the FEM and the BEM models are negligible in all cases. The FEM model produces practically equal results for $L/H=4$ and $L/H=5$.

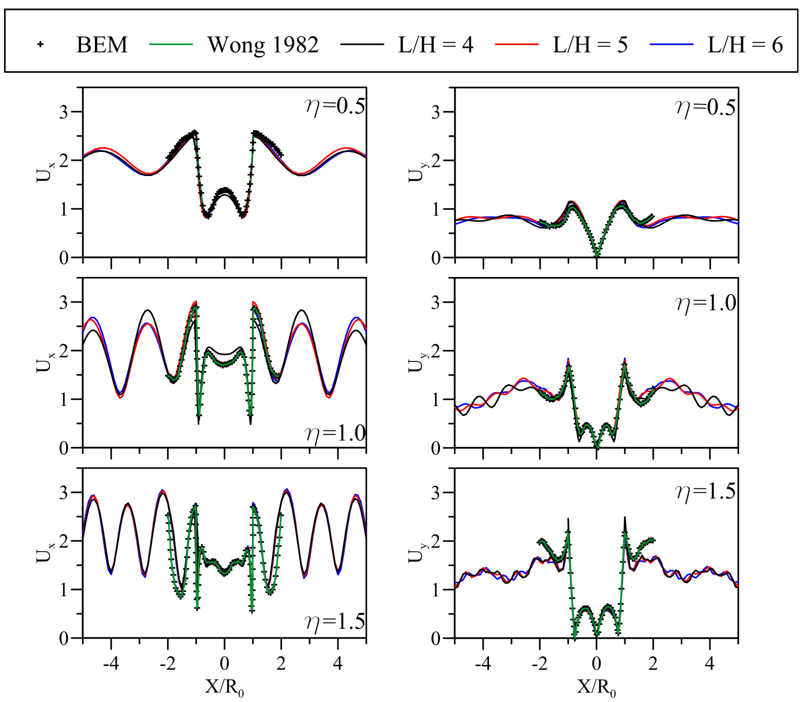

Figure 4. Semi-circular shaped canyon: comparison of the proposed FEM model with the available solutions for horizontal (U_x) and vertical (U_y) components at surface versus the normalized distance from the center of the model (X/R_0).

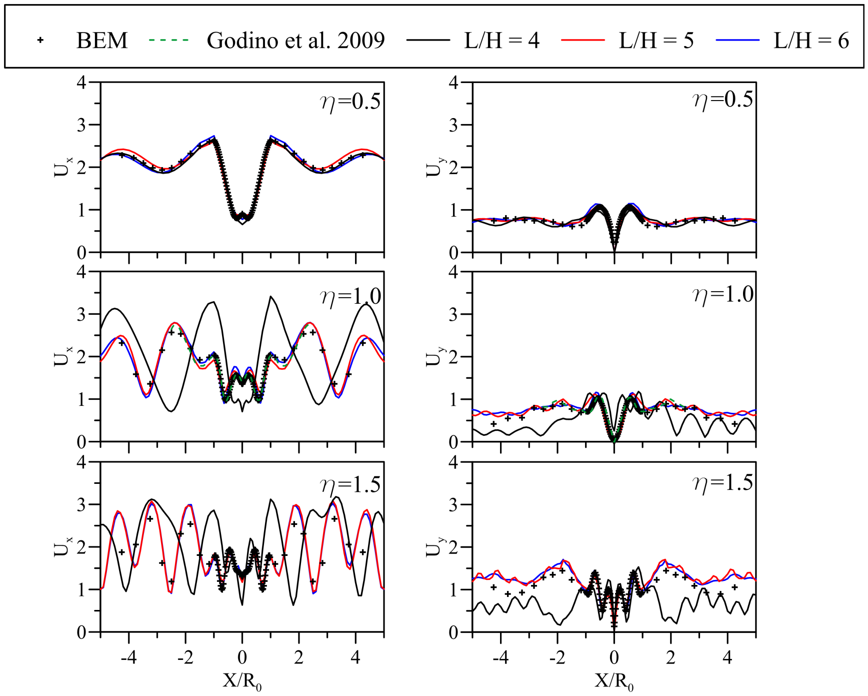

Figure 5. Symmetric V-shaped canyon: comparison of the proposed FEM model with the available solutions for horizontal (U_x) and vertical (U_y) components at surface versus the normalized distance from the center of the model (X/R_0).

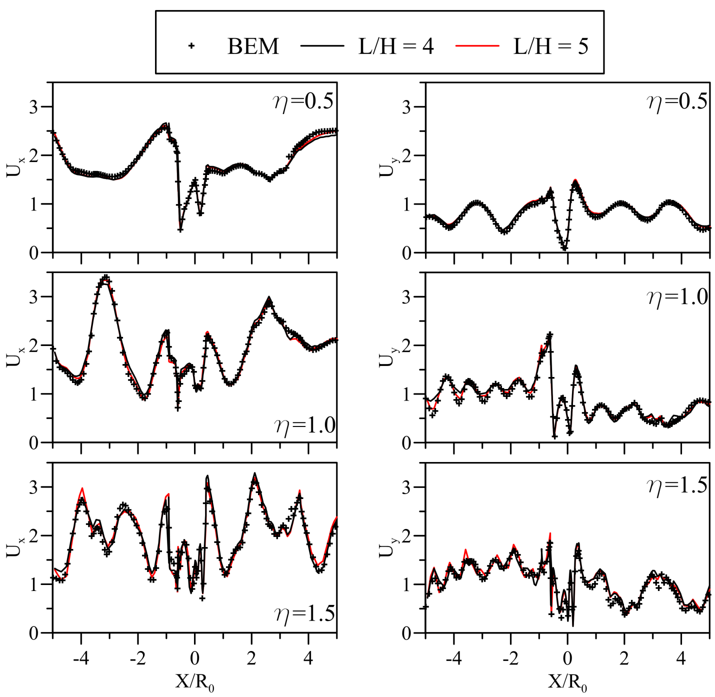

Figure 6. Lao river canyon: comparison of the proposed FEM model with the available solutions for horizontal (U_x) and vertical (U_y) components at surface versus the normalized distance from the center of the model (X/R_0).

Topographic effects at the *Viadotto Italia* site due to earthquake motions

The elastic model of the canyon has been excited with four earthquake ground motions, selected to have a broad range of frequency content. Fig. 7 shows the Response Spectra for the four motions selected, assuming a 5% structural damping. Since the model is elastic and its response is not dependent to the amplitude of the signal, the amplitude of the Response Spectra of each motion is plotted normalized by its maximum. Table 1 reports main details of the selected ground motions including peak ground acceleration (PGA) and significant duration ($D_{5\text{-}95}$).

Table 1. Ground motions used in the analysis

Event ID	Event (station)	PGA (g)	$D_{5\text{-}95}$ (sec)
ID1	**M**7.6 Izmit, 1999 - (IST180)	0.30	37.6
ID2	**M**6.2 Morgan Hill, 1984 - (Gilroy Array #1)	0.38	9.5
ID3	**M**6.9 Loma Prieta, 1989 - (LGP000)	1.24	12.8
ID4	**M**6.7 Northridge, 1994 - (NSC52)	1.26	26.7

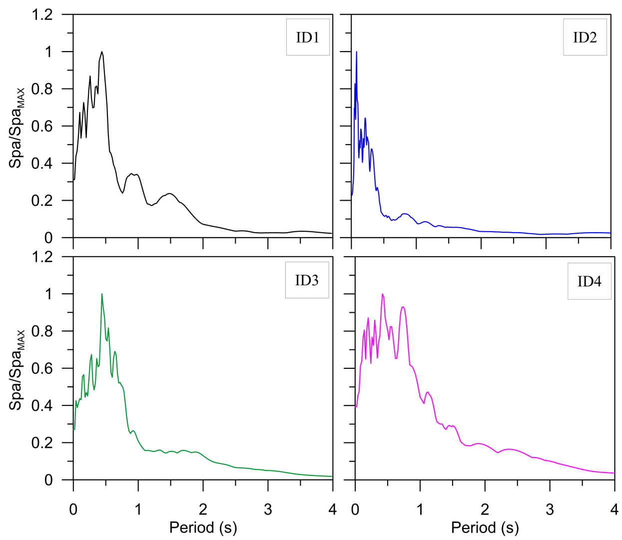

Figure 7. Response spectra (5% structural damping) of the selected ground motions.

Fig. 8 shows the results along the surface of the canyon, reported in terms of horizontal (A_h) and vertical (A_v) aggravation factors [26] defined as the ratio between the peak ground acceleration for the topographic irregularity (horizontal and vertical component, respectively) and the horizontal peak ground acceleration in the free-field condition. The frequency content of the input changes the response along the canyon for both the horizontal and vertical components. In particular, the aggravation factors are higher for the input ID3 and ID4 that are characterized by the lower frequency content.

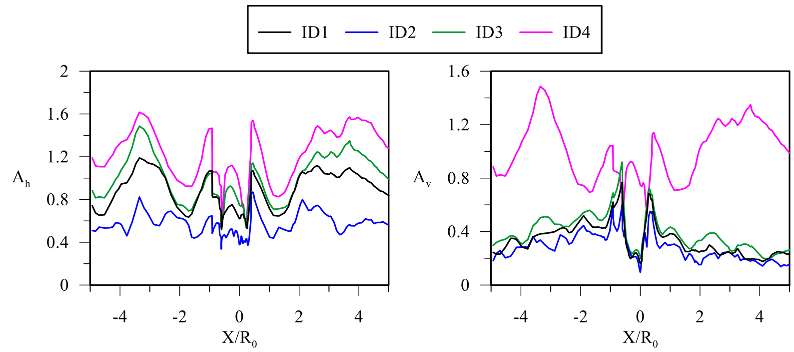

Figure 8. Horizontal and vertical amplification for selected ground motions.

Figs. 9 and 10 show phase angle and lagged coherence [27, 28] of all inputs at the base of the taller piers of the *Viadotto Italia* (P4, P5, P6, and P7 in Fig. 2), with reference to the free field signal. The variation of the response at the base of each pier, shown in Fig. 9, is caused by the combination of the wave passage effect from the base to the surface, and also by the reflection and refraction of the waves due to the combination of the topographic irregularity with the frequency content of the input. Fig. 10 shows that for all pier locations the ground motion ID2 produces the lowest values of coherence. This may be due to the fact that this earthquake input has high amplitude for a wide range of frequency.

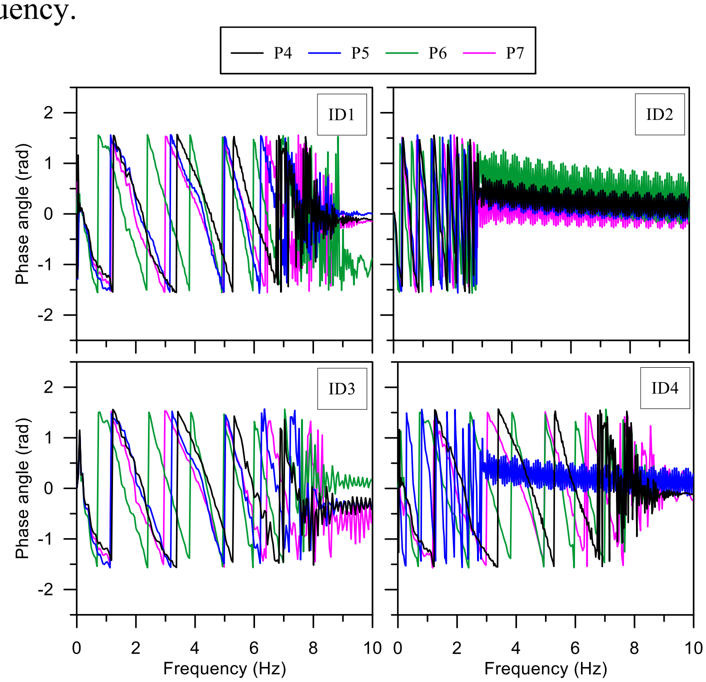

Figure 9. Phase angle versus frequency for P4, P5, P6, and P7.

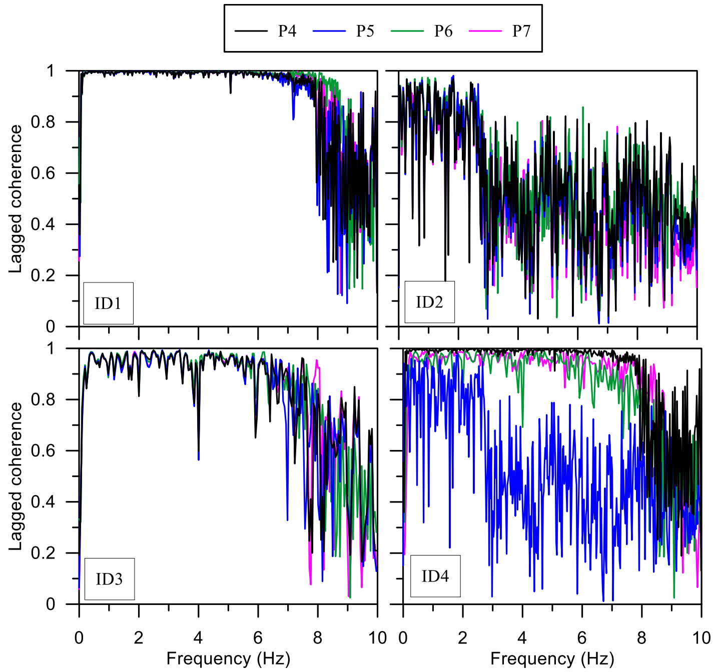

Figure 10. Lagged coherence versus frequency for P4, P5, P6, and P7.

Conclusions

The paper presents the effect of topographic irregularities on the amplitude and phase of dynamic excitation using the finite element software OpenSees. We verified the numerical approach using analytical and numerical solutions available in literature for canyons with simple geometries. After the verification phase, we performed numerical investigations of the 260m-deep canyon overcrossed by the *Viadotto Italia* in Southern Italy, using earthquake ground motions. To analyze topographic effects in isolation. Our analyses are performed with synchronous input motions and homogeneous elastic soil deposit. In our numerical models we do not include the bridge. Results are reported in terms of horizontal and vertical aggravation factors along the surface of the canyon and in terms of phase angle and amplitude modifications for the locations corresponding to the foundations of the central piers of the bridge. Our numerical simulations show that the two-dimensional topographic irregularities can strongly modify ground motion in both amplitude and phase. We anticipate that results from this study will be used to assess the complex behavior of bridges overcrossing deep canyons. Future studies will be devoted to the evaluation of topographic effects in combination with asynchronous input motions.

References

1. Davis, L L., West, L. R. Observed effects of topography on ground motion, *Bull. Seismol. Soc. Am.*, 1973 **63**: 283-298.
2. Siro, L. Southern Italy November 23 1980 Earthquake, *Proceedings of the 7th European Conference on Earthquake Engineering*, Athens, Greece, September 20-25, 1982.
3. Celebi, M, Hanks T. Unique site response conditions of two major earthquakes of 1985: Chile and Mexico, *Proceedings of the International Symposium of Engineering Geology Problems in Seismic Areas*, vol. IV, Bari, Italy, April 1986
4. Assimaki D, Gazetas G. Soil and topography amplification on canyon banks and the 1999 Athens earthquake. *Journal of Earthquake Engineering* 2004; 8:1, 1-43.

5. Assimaki D, Jeong S. Ground-Motion Observations at Hotel Montana during the M 7.0 2010 Haiti Earthquake: Topography or Soil Amplification? *Bulletin of the Seismological Society of America* 2013; **103**: 2577-2590.

6. Elanashai A.S., Borzi B., and Vlachos S. Deformation-based vulnerability functions for RC bridges. *Struct. Eng. Mech.* 1999; **17**(2): 215–244.

7. Sextos A.G., Pitilakis D., Kappos A.J. Inelastic dynamic analysis or RC bridges accounting for spatial variability of ground motion, site effects and soil structure interaction phenomena. Part 1: Methodology and analytical tools. Part 2: Parametric study. *Earthquake engineering & Structural Dynamics* 2003; **32**(4): 607-652.

8. Lupoi A., Franchin P., Pinto P.E., and Monti G. Seismic design of bridges accounting for spatial variability of ground motion. *Earthquake Eng. Struct. Dyn.* 2005; **34**: 327–348.

9. Park D., Sagong M., Kwak D.Y., Jeong CG., Simulation of tunnel response under spatially varying ground motion, *Soil Dynamics and Earthquake Engineering* 2009; **29**: 1417–1424

10. Vanmarcke E.H. *Random Fields: Analysis and Synthesis*. MIT press, Cambridge, MA. 1983, p. 247-264.

11. Luco J.E., Wong H.L. Response of a rigid foundation to a spatially random round motion. *Earthquake Engineering and Structural Dynamics* 1986, 891-908.

12. Zerva, A. Response of multispan beams to spatially incoherent seismic ground motions. *Earthquake Eng. Struct. Dyn.* 1990; **19**: 819–832.

13. Sextos A.G., Pitilakis D., Kappos. Evaluation of the new Eurocode 8-Part 2 provisions regarding asynchronous excitation of irregular bridges. *4th European Workshop on the Seismic Behaviour of Irregular and Complex Structures*, Thessaloniki, Aug. 2005, Paper no. 04.

14. Nuti C., Vanzi I. Influence of earthquake spatial variability on differential soil displacements and SDF system response. *Earthquake Engineering and Structural Dynamics* 2005; **34**: 133-1374.

15. Trifunac M.D. Scattering of plane SH waves by a semi-cilindrical canyon. *Earthquake Engineering and Structural Dynamics* 1973; **1**: 267-281.

16. Wong H.L. Effect of surface topography on the diffraction of P, SV and Rayleigh waves. *Bulletin of the Seismological Society of America* 1982; **72**: 1167-1183.

17. Godinho L., Amado Mendes P., Tadeu A., Cadena-Isaza A., Smerzini C., Sànchez-Sesma F. J., Madec R., Komatitsch D. Numerical Simulation of Ground Rotations along 2D Topographical Profiles under the Incidence of Elastic Plane Waves, *Bulletin of the Seismological Society of America*, 2009; **99**(2B): 1147–1161.

18. Wu Y., Gao Y., Zhang N., Li D. Simulation of Spatially Varying Ground Motions in V-shaped Symmetric Canyons. *Journal of Earthquake Engineering* 2016, **20**(6): 992-1010.

19. McKenna F., Fenves G. L. *The OpenSees command language manual, version 2.5*, http://opensees.berkeley.edu, Pacific Earthquake Engineering Research Center, University of California, Berkeley, 2005.

20. Cestelli Guidi C., De Miranda F., Pellegrino Gallo C. Il progetto del viadotto sul fiume Lao dell'Autostrada Salerno-Reggio Calabria. *Acciaio e Costruzioni Metalliche* 1965; 6: 454-458. *(in italian).*

21. Lysmer J., Kuhlemeyer R.L. Finite Dynamic Model for Infinite Media. *Journal of the Engineering Mechanics Division* 1969, ASCE, **95**(EM4):859-877.

22. Zhang Y., Yang Z., Bielak J., Conte E.J.P., Elgamal A. Treatment of seismic input and boundary conditions in nonlinear seismic analysis of a bridge ground system. *16th ASCE Engineering Mechanics Conference*, July 16-18, 2003, University of Washington, Seattle.

23. Kuhlemeyer, R.L. and Lysmer. J. Finite Element Method Accuracy for Wave Propagation Problems. *Journal of the Soil Dynamics Division* ASCE 1973, **99**, 421-427.

24. Ausilio E, Conte E, Dente G. "Seismic Response of Alluvial Valleys to SH Waves" *Seismic Engineering Conference*, AIP Conference Proceedings, 2008, Vol. 1020, pp. 199-206; doi.org/10.1063/1.2963835

25. Ausilio E., Zimmaro P. Topographic effects evaluation for performance-based design. *Proceedings of Second international conference on performance-based design in earthquake geotechnical engineering*. Taormina (Italy),

May 28-30, 2012.

26. Assimaki D, Gazetas G, Kausel E. Effects of Local Soil Conditions on the Topographic Aggravation of Seismic Motion: Parametric Investigation and Recorded Field Evidence from the 1999 Athens Earthquake. *Bulletin of the Seismological Society of America* 2005; **95**: 1059-1089.

27. Abrahamson N.A., Schneider J.F., Stepp J.C. Empirical spatial coherency functions for applications to soil structure interaction analyses. *Earthquake Spectra* 1991; **7**: 1-27.

28. Harichandran R.S., Vanmarcke E.H. Stochastic variation of earthquake ground motion in space and time. *Journal of Engineering Mechanics* 1986; 11.