The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.

Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
 ISBN 978-0-367-14328-2

A comparative study on time domain 1D/2D seismic ground response analysis of Norcia basin during the M6.5 2016 October 30 earthquake

R. Rodríguez Plata & C. Smerzini
Politecnico di Milano, Italy

A.G. Özcebe
University of Pavia, and Politecnico di Milano, Italy

C.G. Lai & E. Zuccolo
University of Pavia, Italy

F. Bozzoni
EUCENTRE, Italy

ABSTRACT: Due to the combination of dominant near fault characteristics and amplification of ground motion by Norcia Basin, 2016 Central Italy earthquake sequence caused significant life and economic losses in the affected area. In this contribution, the response of the aforementioned basin during the M6.5 October 30 mainshock will be considered. The study focuses on the 1D and 2D responses of a single profile extracted from the idealized 3D depth-velocity model of the basin. Time domain finite element analyses (i.e. QUAD4M, Hudson, et al. 1994) and finite difference analyses (i.e. FLAC2D, Itasca 2016) are performed. In both approaches, soil layers are first assumed linear visco-elastic and, then, material nonlinearity is invoked. Analyses are conducted by scaling a signal that is recorded by a seismogram located on rock-like outcropping conditions. The results are presented in terms of maximum aggravation factors and Fourier amplification spectra for different verticals which are closer and far away from the lateral boundaries.

1 INTRODUCTION

Central Italy is widely known to be characterized by a high seismic hazard (Akinci et al., 2009; Frepoli et al., 2017). The region has been struck by several strong earthquakes in the past 20 years, such as the Mw 5.8 Molise (October 31, 2002), the Mw 6.1 L'Aquila (April 6, 2009), the Mw 6.0 Amatrice (August 24, 2016), and the Mw 6.5 Norcia (October 30, 2016). During the last event, substantial damaged occurred in the municipality of Norcia, which is located on a sedimentary basin of the same name. The seismicity of this geological structure is undoubtedly governed by the irregular bedrock-sediments interface and their dynamic properties. Observations from instrumented sites (e.g. Frankel et al.,2009; Furumura and Hayakawa, 2007) and numerical studies (e.g., Chen et al., 2015; Lee et al., 2008) have shown that the presence of lateral heterogeneities gives rise to different phenomena responsible for strong ground motion. Depending on the basin geometry, different wave propagation mechanisms develop at the boundary regions and at the center. For instance, the conversion of the incident waves into surface waves, and the focusing of the incoming waves and their subsequent constructive interference with the aforementioned surface waves are phenomena that occur in the edge or near edge region (Kawase, 1996). Nevertheless, the significance of all these effects is highly dependent on the frequency content of the incident motion and on the nonlinear response of the sediments (Chen et al., 2015; Gelagoti et al., 2012).

The assessment of the local seismic amplification performed via 1D ground response analyses in complex geological structures, such as sedimentary basins, does not consider the additional enhancement of ground motion given by their 2D configuration. A relatively recent proposal to include the additional effects accounted by 2D (or 3D) analyses is the use of aggravation factors (Chavez Garcia and Faccioli, 2000; Riga et al., 2016). These factors are commonly defined as the ratio between the multidimensional (2D or 3D) and 1D response spectra (Sa) computed for a certain point at the ground surface, and will be herein referred as Period Dependent Aggravation Factor (PDAF).

2 NORCIA BASIN MODEL

The Norcia basin is a quaternary tectonic depression located in Central Italy, formed during the Apennines chain uplift (Galadini et al., 2003). It is 10 km long and 3 km wide approximately and is mainly composed of two different Pleistocene to Holocene fluvial-lacustrine structures. The tectonic evolution of the basin has been dominated by the activity of a normal fault system located closed to the northeast border. This system is composed by Norcia, Campi and Preci faults and belongs to the parallel active normal faulting sets of the central Apennines (Galli et al., 2005).

As discussed in the companion paper of this conference (i.e. Özcebe et al., 2018), the geometry and shear wave velocity distribution with depth of the sediment cover were estimated within the framework of the RELUIS Project RS2. The final model was constructed by combining the information provided by the available official geological information and additional geophysical and gravimetric data. As a result, the contour map representing the sediment-bedrock interface depth is presented on the left panel of Figure 1. The shear wave velocity distribution with depth $Vs_{(z)}$ is given by Eq. (1), which is compared with the measured Vs data available on the right panel of Figure 1, also showing that the sediment fill is rather stiff with Vs_{30} ~= 500m/s, corresponding to EC8 site class B.

$$Vs_{(z)} = Vs_{min} + \frac{2(Vs_{ref} - Vs_{min})}{1 + \left(\frac{z_{ref}}{z}\right)^n} \quad (1)$$

where Vs_{min} = 281.64 m/s; Vs_{ref} = 548.33 m/s; z_{ref} = 15 m; n= 1.29; z = depth.

On the contour map shown in Figure 1, the plan views of the two cross sections selected for the 2D (and 1D) wave propagation analyses are also displayed, as well as the position of three accelerometric stations. Stations NOR and NRC are located within the Norcia basin, while T1212 is placed on a rock-like site. Cross sections AA' and BB' are shown in detail in Figure 2, and will be also referred as profiles P1 and P2 respectively. Yet, the results and discussion herein presented are in relation to profile P2.

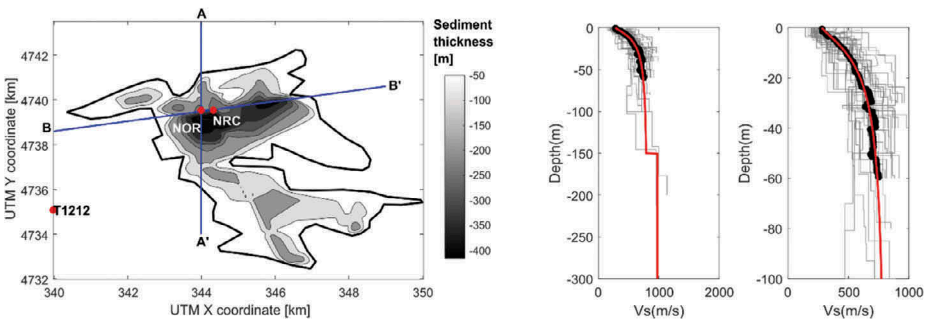
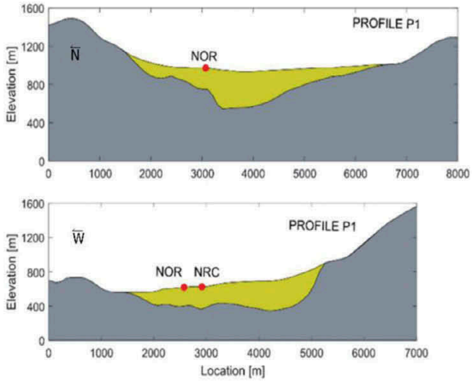


Figure 1. 3D depth-Velocity model adopted for the Norcia basin 2D numerical analyses. Right, spatial distribution of sediment thickness. Left, comparison of the basin velocity model with the available field data (measured VS-depth relation: gray lines, averages: black points, velocity model: red line).



Characteristics of the meshes used in Quad4m

Profile	Extension [Km]	N. of elements	Max. element length [m] For sediments	Max. element length [m] For bedrock	Max. Frequency [Hz]
P1	8.0	8757	23	55÷100	4
P2	6.7	7528	29	55÷80	5

Characteristics of the grids used in Flac 2D.

Profile	Extension [Km]	N. of zones	Max. zone length [m] For sediments	Max. zone length [m] For bedrock	Max. Frequency [Hz]
P1	8.0	118446	5	35	5
P2	6.7	83739	5	35	5

Figure 2. Left, Norcia basin cross sections used in the analyses. Left, details of the finite element mesh and finite difference grids implemented.

Two different numerical codes were implemented, FLAC 2D and QUAD4M (Itasca, 2007; Hudson et al., 1994). FLAC 2D, is a numerical tool that employs an explicit finite difference scheme. QUAD4M, is finite element code suited for linear visco-elastic (LVE) wave propagation and equivalent linear (EQL) analyses. Both codes allow to apply absorbing boundary condition to the base of the model. The main difference in this sense resides on the conditions enforced at the lateral boundaries. In the case of FLAC 2D the imposition of free field boundaries is allowed, whereas in QUAD4M, the vertical nodal displacement (relative to the input motion) are enforced to be null, and the horizontal ones are free. The effect of this latter characteristic of QUAD4M was attempted to be reduced by placing the lateral boundaries at least 1.5 Km away from the basin edge (Figure 2).

Due to the memory limitations of QUAD4M the maximum frequency reached by the numerical analyses was around 5 Hz, as reported on the left panel of Fig 2. Hence, for comparison purposes the grids used in FLAC were also generated to reach such value. The simulations were carried out by considering vertical incidence of SV-polarized waves, and with Rayleigh damping calibrated to reach a minimum damping value of 1.2%. The horizontal motion recordings of the October 30, 2016 registered at station T1212 are reported in Figure 3, which were scaled to account for attenuation, and rotated in order to estimate the input motion that was later applied at the base of the models. The two additional permanent stations located in the municipality of Norcia, namely NOR and NRC, allowed the validation of the analyses.

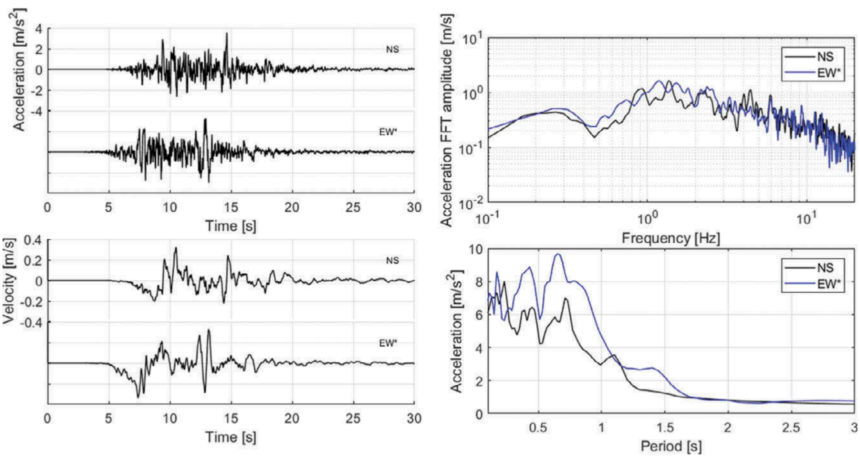


Figure 3. Input motion used in the analyses obtained from the recordings of station T1212, after being scaled and rotated. EW* stands for the azimuth of profile P2.

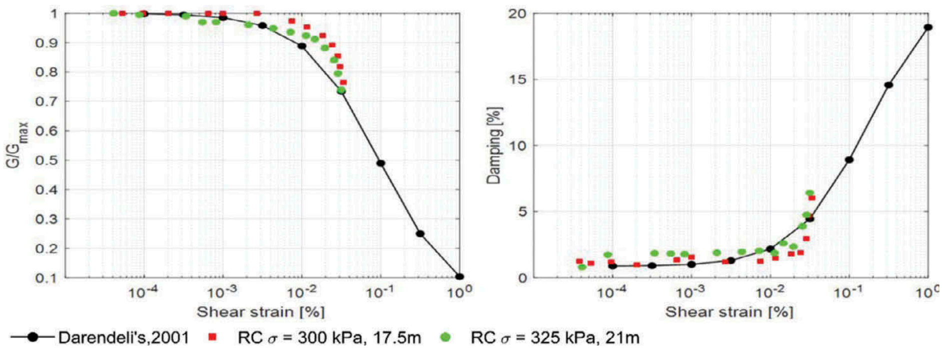


Figure 4. Calibration of modulus degradation and damping ratio curves model implemented on the equivalent-linear and hysteretic analyses. The scatter points correspond to the results of two resonant column (RC) tests, performed on samples retrieved at 17.5 and 21 m near the town of Norcia, under confining pressures (σ) of 300 and 325 kPa.

As for the non-linear analyses, the modulus degradation and damping curves were generated according to the model proposed by Darendeli (2001). Results of two resonant column tests were used to calibrate the final model, which is displayed in Figure 3. Due to the extension of the problem, a more comprehensive geotechnical characterization of the sediments cover was not feasible. As a further simplification, these properties were assigned to all the sediments elements. It is also worth mentioning that QUAD4M and FLAC follow two different approaches for the implementation of hysteretic damping. While QUAD4M implements a traditional equivalent linear scheme, FLAC employs a nonlinear model for which the shear modulus varies according to the degradation curve. The latter is referred as "hysteretic analysis" or HYST.

3 OVERVIEW OF 2D RESPONSE

The amplification functions (i.e. the ratio between the ground surface and outcropping rock Fourier spectra) found at the surface of profile P2 are reported in Figure 5, and correspond to the linear visco-elastic analysis carried out with the two numerical codes. The shape of the sediment cover definitely governs the 2D amplification pattern depicted. The 2D natural frequency (Fo_{2D}) coincides with Fo_{1D} for almost the entire basin, with the exception of the western edge region where $Fo_{1D}/F_{2D} \approx 2$ (Figure 5). Further disagreements between 2D and 1D analysis are related to the higher amplification levels given by the 2D analyses, that is the ratio $A_{(f)2D}/A_{(f)2D}$ is found to be between 1.2 and 1.6 for frequencies lower than 2 Hz. An additional remarkable aspect is the occurrence of several successive amplification peaks towards the eastern edge and towards higher frequencies absent in the 1D results. According to the observations made by Chavez-Garcia et al. (2000) and Semblat et al. (2005), this discontinuous amplification distribution arises from the constructive interaction between different types of waveforms.

The response of profile P2 corresponds to that of a shallow basin, controlled by 1D resonance plus the propagation of surface waves (Bard and Bouchon, 1985), meaning that the 2D site effects will be gravest at the near edge regions (Zhu et al., 2017). A more detailed analysis of a similar regular shaped basin (not reported in this document), indicates that the irregular sediment-bedrock interface is responsible for the additional discrepancies between 1D and 2D responses at the basin center. The panel located on the left of Figure 5 shows the comparison of the acceleration response spectra at two different locations near each edge, results from both LVE and non-linear analyses are displayed. The 2D analyses for the period range between 0.8s and 1.4s reports higher spectral ordinates, being the gravest roughly 22 m/s2 for the eastern location. When non-linearity is introduced in the analyses, in spite of the reduction

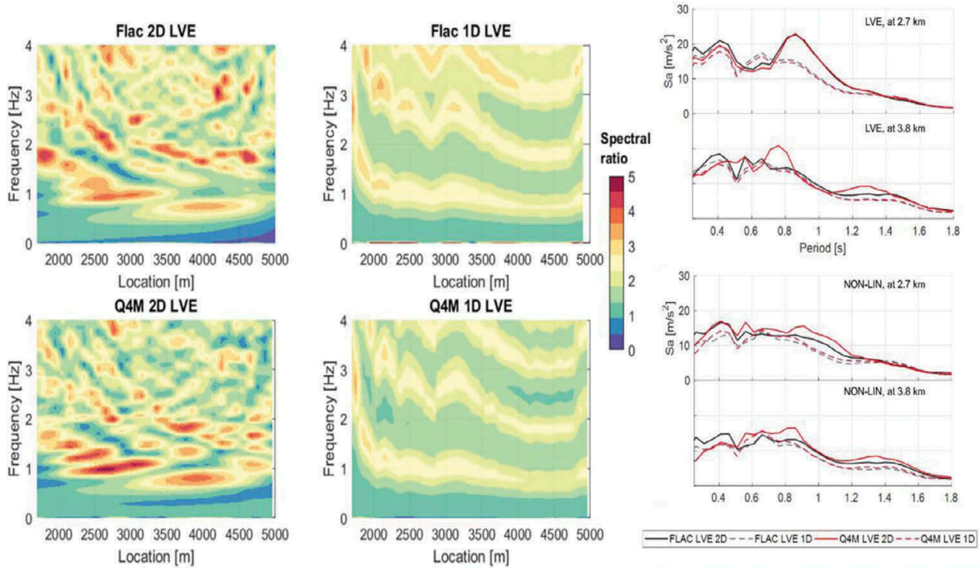


Figure 5. Left, comparison between the amplification functions (outcrop/surface acceleration Fourier spectra ratio) obtained in the LVE analysis of profile P2. Right, comparison in terms of acceleration response spectra of both linear and nonlinear analyses performed on profile P2.

of the magnitude of spectral ordinates, the 2D analyses still suggest a stronger response in the same period range as in the LVE analyses.

Overall, there is an acceptable agreement between the amplification patterns obtained by the two codes. Nonetheless, it is worth to highlight that the 2D amplification at the fundamental mode reported towards between 2.5 and 4.0 km by QUAD4M is at least 1.3 higher than the one obtained with FLAC. This is likely to be caused by the absence of proper free field boundaries in QUAD4M.

4 AGGRAVATION ANALYSIS

The PDAG distributions along the basin surface were computed according to Eq. (2), as a measure of the additional site effects found from the 2D analyses. The top panels to the left of Figure 6 depict the PDAG distribution obtained after the LVE analyses, while the results of the non-linear analyses are reported on the bottom panel. With respect to the formers, two different aggravated zones can be identified at 2.6 Km and at 4.0 Km. The first reaches an PDAG value of 1.6 and it is the manifestation of the so called *edge effect*, the constructive interaction between the edge-generated surface waves and the incoming obliquely propagating body waves, initially study by Kawase (1996). Likewise, Zhu et al. (2018) performed a similar analysis on the Mygdonian basin in Greece, and obtained values of PDAG ranging from 1.5 to 2.0 in the near edge region. Moreover, the deaggravation (i.e. PDAG < 1) preceding the peek around 1.8 Km in Fig 7, corroborates the occurrence of the edge effect, as it was noticed by Riga et al. (2016) and Gelagoti et al. (2010) for idealized shallow trapezoidal basins. Another similarity with the present case is the occurrence of aggravation for a period range slightly smaller than the 1D natural period of the central portion of the profile ($T\ o_{1D}$), which is around 1.2s. On the central portion of the profile, the aggravation peaks obey to the enhancement of high frequency motion owed to the refracted/diffracted waves generated by the highly irregular bedrock-sediments interface.

$$PDAG_i = SA_{2D,i}/SA_{1D,i} \tag{2}$$

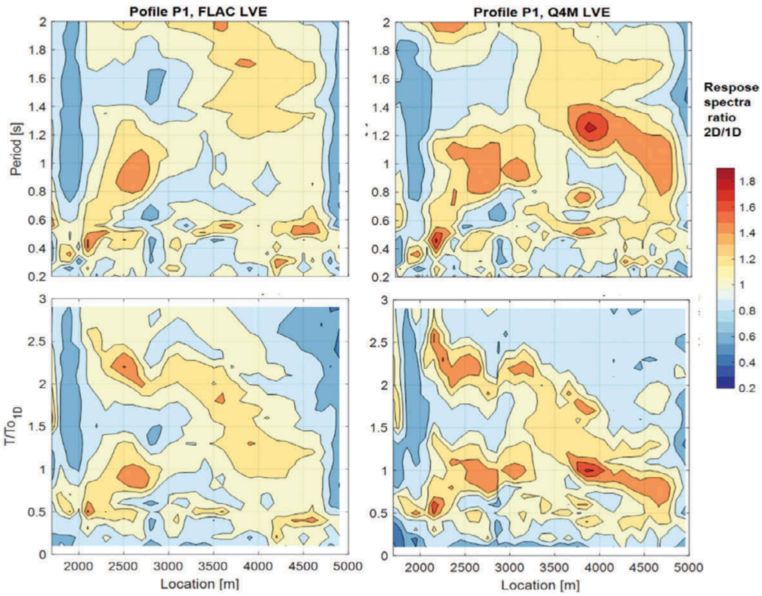


Figure 6. Period dependent aggravation factor distributions after the analyses performed on profile P2 with FLAC 2D and QUAD4M. Top row, LVE analysis PDAG distribution. Bottom row, PDAG distributions computed from the non-linear analyses (QUAD4M-EQL and FLAC-HYST).

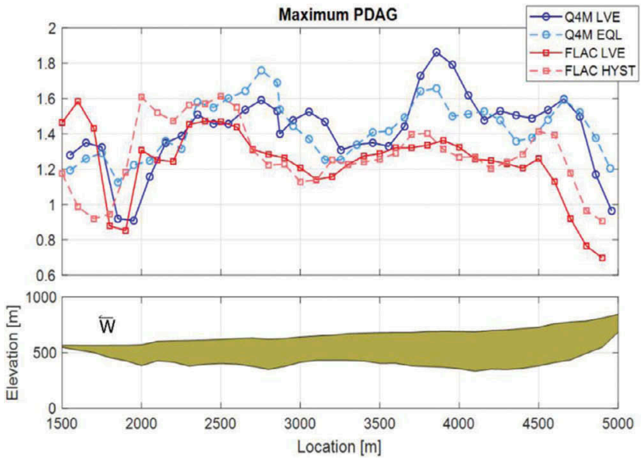


Figure 7. Comparison between the PDAG distribution found for 4 different period windows between the nonlinear and linear analyses.

where *i* stands for every receiver position at the basin surface; $SA_{2D,i}$ and $SA_{1D,i}$ for the acceleration response spectra obtained from the 2D and 1D analyses respectively at the receiver *i*.

The nonlinear analyses depict a similar picture in terms of PDAG distribution. However, the PDAG concertation around 1.6 Km reaches a value almost 20% higher than in the LVEcase, and for the FLAC 2D analysis it is slightly shifted towards the west. This peak was expected to be attenuated by the additional damping introduced by the nonlinear analyses (Zhang and Papageorgiou, 1989), yet, it did not take place due to the eased entrapment of the refracted waves given the high modulus degradation that occurred in the zone near the soil-bedrock interface. A similar mechanism was observed by Riga et al. (2018) and Gelagoti et al. (2012).

As a final result, the maximum PDAGs found for natural periods between 0.6 and 1.4s along the sediment cover surface are shown in Fig 7. In this period range, the most significant concentrations of aggravation (and de-aggravation) were found. It is worth to recall that the 2D over-amplification near the western edge found by QUAD4M is presumably due the lack of proper free-field boundary conditions.

5 CONCLUSIONS

This contribution presented the comparison between 1D and 2D ground response analysis carried out on a cross section of the Norcia basin considering both linear visco-elastic and nonlinear analysis. According to the definition given in the EC8, the sedimentary fill corresponds to a site class B. In spite of this rather stiff materials, important differences between the dimensional analysis were found. In the frequency domain, the 2D analysis gave rise to an enhancement of the low frequency components, especially around the fundamental frequency. At the eastern edge the succession of several amplification peaks around the fundamental frequency served as an indication of the presence of edge-generated surface waves.

In order to gain insights about the additional basin-induced amplification found in relation with the Mw 6.5 Norcia (October 30, 2016) event, the period dependent aggravation factor (PDAG) distribution was computed. As a whole, a moderate aggravation level was found for almost the entire profile with a mean value of PDAG=1.2. The most significant aggravation peaks were found for periods within 0.85s < T < 1.25s, hence below the 1D fundamental period of the basin midpoint, which is around 1.2s. This observation is consistent with the recommendation given by Chavez-Garcia et al. (2000) and Riga et al. (2016) about considering the basin effects for periods shorter than T0,1D of the central portion of the basin. The maximum PDAF found at the near-edge regions are around 1.6 and 1.4 for profile P1 and P2 respectively, and considering the rather stiff sediments comprising the basin, such values are slightly larger than the mean values obtained by the statistical study performed by Riga et al. (2016), which for the long period range were around 1.3. The gravest aggravation occurred at the eastern near edge region reaching a maximum value of PDAG=1.4 and 1.6 for the LVE and non-linear analyses respectively. Such increment was due to the further entrapment of refracted waves eased by the shear modulus reduction at the sediment-bedrock interface

ACKNOWLEDGEMENTS

This work is financed by RELUIS under the framework of Research Project RS2. Authors would like to acknowledge the fruitful discussions made with Prof. Massimiliano Porreca from University of Perugia and Dr. Maurizio Vassallo, Dr. Francesca Pacor, and Dr. Lucia Luzi from INGV during the definition of the model for Norcia Basin. Furthermore, authors would like to express their gratitude to local geologists for their kind cooperation in sharing their data. Finally, Dr. Böhm's kind sharing of the reflection test data in digital format is warmly acknowledged.

REFERENCES

Akinci, A., Galadini, F., Pantosti, D., Petersen, M., Malagnini, L., and Perkins, D. (2009). Effect of Time Dependence on Probabilistic Seismic-Hazard Maps and Deaggregation for the Central Apennines, Italy. *Bulletin of the Seismological Society of America*, *99(2A)*:585–610.

Bard, P. and Bouchon, M. (1985). The Two-Dimensional Resonance of Sediment-Filled Valleys. *Bulletin of the Seismological Society of America*, *75(2)*: 519–541.

Chavez-Garcia,F., Raptakis, D., Makra, K., and Pitilakis, K. (2000). Site effects at Euroseistest—II. Results from 2d numerical modeling and comparison with observations. *Soil Dynamics and Earthquake Engineering*, *19(1)*:23–39.

Chavez Garcia, F. J. and Faccioli, E. (2000). Complex site effects and building codes: Making the leap. *Journal of Seismology*, *4(1)*:23–40.

Chen, G., Jin, D., Zhu, J., Shi, J., and Li, X. (2015). Nonlinear Analysis on Seismic Site Response of Fuzhou Basin, China. *Bulletin of the Seismological Society of America*, *105(2A):*928–949.

Darendeli, M. B. (2001). Development of a New Family of Normalized Modulus Reduction and Material Damping Curves. *(Doctoral dissertation)*, *page* 395.

Frankel, A., Stephenson, W., and Carver, D. (2009). Sedimentary Basin Effects in Seattle, Washington: Ground-Motion Observations and 3d Simulations. *Bulletin of the Seismological Society of America*, *99 (3):*1579–1611.

Frepoli, A., Cimini, G., De Gori, P., De Luca, G., Marchetti, A., Monna, S., Montuori, C., and Pagliuca, N. (2017). Seismic sequences and swarms in the Latium-Abruzzo-Molise Apennines (central Italy): New observations and analysis from a dense monitoring of the recent activity. *Tectonophysics*, *712–713*:312–329.

Furumura, T. and Hayakawa, T. (2007). Anomalous Propagation of Long-Period Ground Motions Recorded in Tokyo during the 23 October 2004 Mw 6.6 Niigata-ken Chuetsu, Japan, Earthquake. *Bulletin of the Seismological Society of America*, *97(3):*863–880.

Galadini, F., Messina, P., Giaccio, B., and Sposato, A. (2003). Early uplift history of the Abruzzi Apennines (central Italy): available geomorphological constraints. *Quaternary International*, *101–102*:125–135.

Galli, P., Galadini, F., and Calzoni, F. (2005). Surface faulting in Norcia (central Italy): a "paleoseismological perspective". *Tectonophysics*, *403(1–4):*117–130.

Gelagoti, F., Kourkoulis, R., Anastasopoulos, I., and Gazetas, G. (2012). Nonlinear Dimensional Analysis of Trapezoidal Valleys Subjected to Vertically Propagating SV Waves. *Bulletin of the Seismological Society of America*, *102(3):*999–1017.

Gelagoti, F., Kourkoulis, R., Anastasopoulos, I., Tazoh, T., and Gazetas, G. (2010). Seismic Wave Propagation in a Very Soft Alluvial Valley: Sensitivity to Ground-Motion Details and Soil Nonlinearity, and Generation of a Parasitic Vertical Component. *Bulletin of the Seismological Society of America*, *100(6):*3035–3054.

Hudson, M., Idriss, I. M., and Beiake, M. (1994). QUAD4m: A computer program to evaluate the seismic response of soil structures using finite element procedures and incorporating a compliant base. Report Prepared for Department of Civil and Environmental Engineering, University of California Davis, Davis, California.

Itasca (2016). FLAC, Fast Lagrangian Analysis of Continua Version 8.0. *Itasca Consulting Group*, *Minneapolis*.

Kawase, H. (1996). The Cause of the Damage Belt in Kobe:"The Basin-Edge Effect," Constructive Interference of the Direct S-Wave with the Basin-Induced Diffracted/Rayleigh Waves. *Seismological Research Letters*, *67(5):*25–34.

Lee, S.-J., Chen, H.-W., Liu, Q., Komatitsch, D., Huang, B.-S., and Tromp, J. (2008). Three- Dimensional Simulations of Seismic-Wave Propagation in the Taipei Basin with Realistic Topography Based upon the Spectral-Element Method. *Bulletin of the Seismological Society of America*, *98(1):*253–264.

Riga, E., Makra, K., and Pitilakis, K. (2016). Aggravation factors for seismic response of sedimentary basins: A code-oriented parametric study. *Soil Dynamics and Earthquake Engineering*, *91:*116–132.

Riga, E., Makra, K., and Pitilakis, K. (2018). Investigation of the effects of sediments inhomogeneity and nonlinearity on aggravation factors for sedimentary basins. *Soil Dynamics and Earthquake Engineering*, *110:*284–299.

Semblat, J., Kham, M., Parara, E., Bard, P., Pitilakis, K., Makra, K., and Raptakis, D. (2005). Seismic wave amplification: Basin geometry vs soil layering. *Soil Dynamics and Earthquake Engineering*, *25(7–10):*529–538.

Zhang, B. and Papageorgiou, A. S. (1989). Simulation of the Response of the Marina District Basin, San Francisco, California, to the 1989 Loma Prieta Earthquake. *Bulletin of the Seismological Society of America*, *98(5):*1382–1400.

Zhu, C., Thambiratnam, D., and Gallage, C. (2017). Inherent Characteristics of 2d Alluvial Formations Subjected to In-Plane Motion. *Journal of Earthquake Engineering, pages* 1–19.

Zhu, C., Thambiratnam, D., and Gallage, C. (2018). Statistical analysis of the additional amplification in deep basins relative to the 1d approach. *Soil Dynamics and Earthquake Engineering*, *104:*296–306.