16TH EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING
THESSALONIKI 18 - 21 JUNE 2018

ROLE OF THE SOIL THICKNESS IN THE SITE RESPONSE ANALYSIS: A PARAMETRIC STUDY

Marco TANGANELLI[1], Davide FORCELLINI[2], Stefania VITI[3]

ABSTRACT

Site Response Analyses (SRA) are generally performed in order to find the surface seismic excitations accounting for the specific soil properties of the site. In this regard, calibration of numerical models is the most critical issue. In particular, the results depend largely on many assumptions, such as soil thickness and mechanical properties. In this work, a refined 3D analytical approach has been performed by applying the credited platform OpenSees. Several parameters, such as mesh geometry and boundary conditions, have been calibrated and validated. In addition, SRA have been performed on various soil profiles. A large scatter in the main parameters (shear velocity and cohesion) has been introduced in order to represent the different soil classes, as proposed by the Eurocode 8 (EC8). Different values of thickness have been considered for each soil type and seismic intensity in order to check its effects on the obtained results. Ensembles of seven ground motions have been selected based on spectrum-compatible to the elastic spectra provided by EC8 for the soil-type A (bedrock). Three levels of seismic hazard have been considered.

Keywords: Site Response Analysis; surface seismic input; OpenSees; numerical simulation; model calibration

1. INTRODUCTION

The seismic input is one of the most unpredictable quantity in the seismic assessment with nonlinear dynamic analysis. In particular, the assumption of the seismic input involves two main issues: the choice of ground motions and the soil representation. Both of these aspects have been widely investigated by researchers in the last decades, such as Shome et al. 1998, Stewart et al. 2001, Bommer and Acevedo 2004 and Bazzurro and Cornell, 1999. In particular, this researchers assessed the role of the main parameters, such as the Magnitude, the distance from the rupture zone and the soil profile. In addition, different procedures for Ground Motions Selection and Modification (GMSM) have been developed by Katsanos et al. (2010), Tarbali and Bradley (2015), Iervolino et al. (2011), Al Atik and Abrahamson (2010), Seifried and Baker (2014) and Bradley BA (2010).

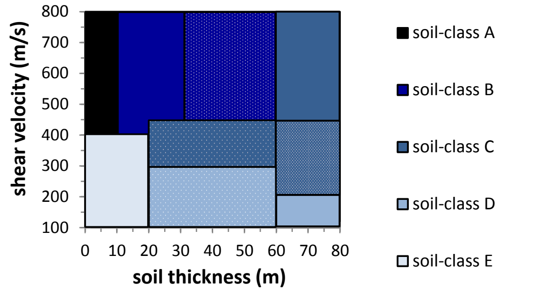
Most of the International Technical Codes (such as Eurocode 8, ASCE standards 7-05 and 4-98), provide seismic spectra defined after a proper soil classification, which is usually based on the uppermost 30 m shear-wave velocity ($v_{s,30}$) of the site. Assimaki et al. 2005, Ahikary and Singh 2012 and Anbazhagan et al. 2013 showed that under some conditions, this limit can be not completely adequate, since deep layers of soil can still affect the surface seismic input. D'Intinosante et al. 2016 showed that unexpected peaks of surface acceleration can be seen when superficial deposit lays over the bedrock, especially when the thickness of the deposit is lower. In such cases, averaging the soil properties over the uppermost 30 meters can induce to un-conservative results.

[1]Researcher, Department of Architecture (DiDA), University of Florence, marco.tanganelli@unifi.it
[2]Dr., University of San Marino, San Marino, davide.forcellini@unirsm.sm
[3]Researcher, Department of Architecture (DiDA), University of Florence, viti@unifi.it

If extensive investigations on soil mechanical properties are applied, more affordable evaluation of the surface seismic input can be developed. In this regard, Tanganelli et al. (2016), Tanganelli and Viti (2016), Viti et al. (2017) and Tanganelli et al. (2017) showed that there could be big differences between the surface seismic input on the basis of tests and the corresponding ones provided by the Code. In this work, the surface seismic input has been calculated by assuming a seismic input at the bedrock. The paper aims at conducting a parametric Response Site Analysis (RSA) by assuming different soil types, compatible to the current European classification. In the analysis, the role of the main parameters affecting the convolution analysis (such as soil modeling, mechanical properties and analytical procedures) has been assessed. In particular, the ultimate goal is a first assessment of the role of the considered soil thickness in the RSA, and the effects related to the most important parameters. In order to validate the software potentialities, a large number of case studies was performed.

2. SEISMIC INPUT AT THE BEDROCK

The seismic input at the bedrock is usually represented through an ensemble of ground motions spectrum-compatible to that provided by the Codes for rock condition. In this work, the seismic input at the bedrock has been selected following the provisions by European Code Eurocode 8 (EC8). In Figure 1, the soil classification provided by EC8 has been shown.



T_B = 0.15 sec, T_C = 0.40 sec, T_D = 2.00 sec, S = 1.00

Figure 1. Soil classification according to the European (EC8) classification.

Three different seismic intensities: low (L), medium (M) and high (H) have been considered, with values of Peak Ground Acceleration (PGA) respectively equal to 0.15g, 0.25g and 0.35g. For each seismic intensity, a different ensemble of seven ground motions has been selected by the database Itaca (2008). The software Rexel (Iervolino et al. 2009) was used for this selection. Unscaled ground motions have been adopted for all cases. Figure 2 shows each ensemble of ground motion spectra, together with the corresponding EC8 spectrum (A-soil, Type 1, Ms>5.5) for the three considered seismic intensities. As can be noted, the mean curve of each ensemble closely approaches the elastic-soil spectrum. The assumed ensembles are adequate to represent the bedrock seismic input, since their mean spectrum never exceeds the EC8 one more than + 10% and -30% in the range between 0.2 sec and 2.0 sec, as required by the Code. The main information of the assumed ground motions are listed in Table 1.

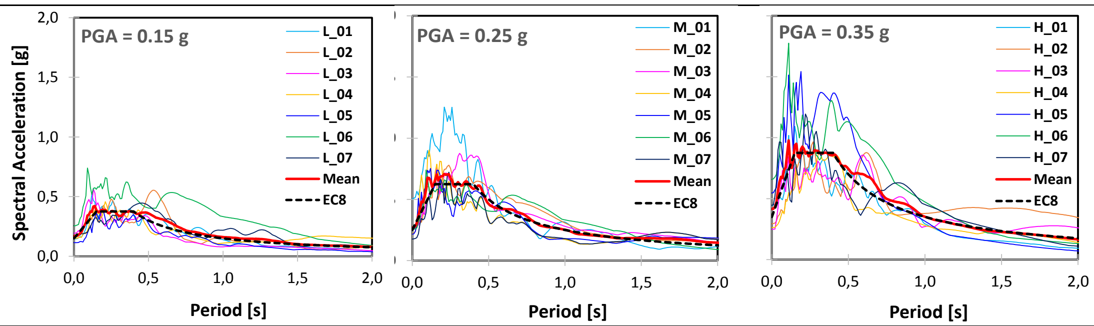


Figure 2. Comparison between the three ensembles and the elastic spectrum provided by EC8 (A-soil class)

Table 1. Adopted ground motions: low (L), medium (M) and High (H) intensities.

	Event	Date	Station	PGA (g)	Epicentral dist. (km)	Depth (m)	Magnitude (Mg)
L_1	Umbria-Marche	09/26/1997	CSA	0.172	22.3	5.7	5.8
L_2	Friuli	09/15/1976	GMN	0.255	4.0	11.3	6.0
L_3	Abruzzo	05/07/1984	CNS0	0.113	19.7	20.5	5.9
L_4	Emilia	05/29/2012	MIRH	0.150	4.5	8.1	6.0
L_5	Emilia	05/29/2012	T0811	0.193	14.3	8.1	6.0
L_6	Emilia	05/29/2012	T0818	0.161	8.7	4.3	5.5
L_7	Emilia	05/29/2012	T0824	0.145	14.2	8.1	6.0
M_1	Emilia	05/29/2012	BA	0.177	4.1	8.1	5.8
M_2	Friuli	09/15/1976	GMN	0.255	4.0	11.3	6.0
M_3	Emilia	05/29/2012	MIR	0.217	5.1	8.1	5.8
M_4	Emilia	05/20/2012	MRN01	0.262	16.1	9.5	5.9
M_5	Emilia	05/29/2012	MRN02	0.223	4.1	8.1	5.8
M_6	Emilia	05/29/2012	T0814	0.505	9.3	8.1	5.8
M_7	Emilia	05/29/2012	T0819	0.259	5.1	4.3	5.3
H_1	Abruzzo	06/04/2009	AQG	0.446	5.0	8.3	5.9
H_2	Abruzzo	06/04/2009	AQV01	0.657	4.9	8.3	5.9
H_3	Abruzzo	06/04/2009	AQV02	0.546	4.9	8.3	5.9
H_4	Emilia	05/20/2012	MRN01	0.262	16.1	9.5	5.9
H_5	Emilia	05/29/2012	MRN03	0.294	4.1	8.1	5.8
H_6	Emilia	05/29/2012	MIR08	0.248	8.6	8.1	5.8
H_7	Emilia	05/29/2012	T0814-01	0.445	9.3	8.1	5.8

3. RSA ANALYSES

RSA analyses have been performed by applying the assumed seismic input at the bedrock by performing soil column models with different properties. Six soil types with different values of shear velocity (v_s) and cohesion (C) have been considered, in order to evaluate the range of possible types of soil. In some cases, the combination of parameters are not strictly representative of realistic conditions, but they were performed in order to validate the software potentialities in correspondence of limit cases. Table 2 shows the considered soil types and the main information. In order to assess the role of soil thickness on the surface input, six different values of the thickness (ranging between 10m and 60m) have been considered in the analyses.

Table 2. Assumed soil types.

Soil types	Vs_100	Vs_250	Vs_400	Vs_600	Vs_800	Vs_1000
Reference EC8 soil-type	D/E	C/E	B	B	B	A
Mass density (kN/ m^3)	1.5	1.5	2	2	2	2
Poisson	0.4	0.4	0.4	0.4	0.4	0.4
Shear Wave Velocity, v_s (m/s)	100	250	400	600	800	1000
Cohesion, C (kPa)	70	250	350	425	500	800
Peak Shear Strain	3	3	3	3	3	3
Number of Yield Surface	20	20	20	20	20	20

The finite element model (FEM) has been built with OpenSees (Mazzoni et al. 2009) that allows high level of advanced capabilities for modelling and analysing non-linear responses of systems using a wide range of material models, elements and solution algorithms. This platform consists of a framework for saturated soil response as a two-phase material following the u-p (where u is displacement of the soil skeleton and p is pore pressure) formulation. The original interface had been originally calibrated for pile analysis. Here, it has been modified by eliminating the pile elements in order to consider a free field case study. The model applies hysteretic elasto-plastic materials in order to take into account the degradation of soil stiffness and energy dissipation. In this regard, soil damping has been modelled by considering a nonlinear material (Parra, 1996 and Yang et al., 2003). Damping is not predefined by the user introducing a specific value, but it is calculated by the implemented soil models. In particular, permanent deformations and damping foundation (impedance) are deduced by the application of non-linear materials. These assumptions are fundamental in order to perform realistic soil behaviours. Plasticity is formulated based on the multi-surfaces and an appropriate non-associative flow rule (Prevost 1985, Dafalias 1986, Bousshine et al. 2001, Nemat-Nasser and Zhang 2002 and Radi et al. 2002). The nonlinear shear stress strain back-bone curve is represented by an hyperbolic relationship (Kondner 1963), defined by the two material constants: the low-strain shear modulus and the ultimate shear strength.

Based on previous studies (Forcellini and Gobbi 2015, Forcellini 2017a,b), the soil has been considered a one-layer homogenous cohesive material. It was modelled with 3D FE meshes (plan area: 150.0m x 37.5m) composed of brickUP linear isoparametric 8-nodes elements (Mazzoni et al. 2009). Discretization is built up with relatively small elements around the centre and gradually larger toward the outer mesh boundaries, by increasing the distance from the mesh outer edge. A preliminary calibration analysis has been performed by considering several meshes with number of nodes ranging between 396 and 3585. The assumed final mesh has 36 elements for each layer, and a different number of vertical layers (8, 10, 14, 18 and 18, respectively) depending on the considered thickness, with homogeneous heights. In addition, the real wave propagation has been modelled with periodic boundaries (Law and Lam, 2001) that have been located as far as possible from each other as to decrease their effects on the response and periodic boundaries. In this regard, base and lateral boundaries have been modelled to be impervious, as to represent a small section of a presumably infinite (or at least very large) soil domain and allowing the seismic energy to be removed from the site itself. Displacement degrees of freedom of the left and right boundary nodes have been tied together both longitudinally and vertically using the penalty method (more details in Forcellini 2017a,b). The base boundaries were set as rigid in order to concentrate all the effects of filtering inside the soil layers. In particular, this assumption was fundamental in order to compare the different configurations and to avoid that the results are affected by bedrock conditions.

4. RESULTS

4.1 Surface spectral acceleration

This paragraph shows the results in terms of mutual relationship between several parameters such as shear wave velocity, soil thickness and seismic hazard. The application of advanced constitutive law and models are fundamental in order to take into account non-linear effects of the soil. In particular, the role of soil damping affects the calculation of spectral accelerations, reported in the following figures. Figures 3, 4 and 5 show the obtained mean spectral acceleration found for the considered soil thickness, in correspondence with the three considered PGA values. In each Figure, the spectra provided by the SRA have been compared to the spectrum at the bedrock, represented through the black dotted line.

In correspondence to the thinnest layer (soil thickness equal to 10m), the surface acceleration experiences a large increase for soft soils (Vs_100, Vs_250, Vs_400). For the stiffer soil types, this increase is moderate. The 20m layer achieves its maximum increase for medium soils (v_s between 400 m/s and 800 m/s). The thicker layers (30m, 40m, 50m, 60m) experience larger surface acceleration for stiffer soils. In correspondence with the highest PGA value (PGA = 0.35g) and for different values of soil thickness (10m, 20m and 40m), the largest surface accelerations (slightly below 4.0g) are achieved.

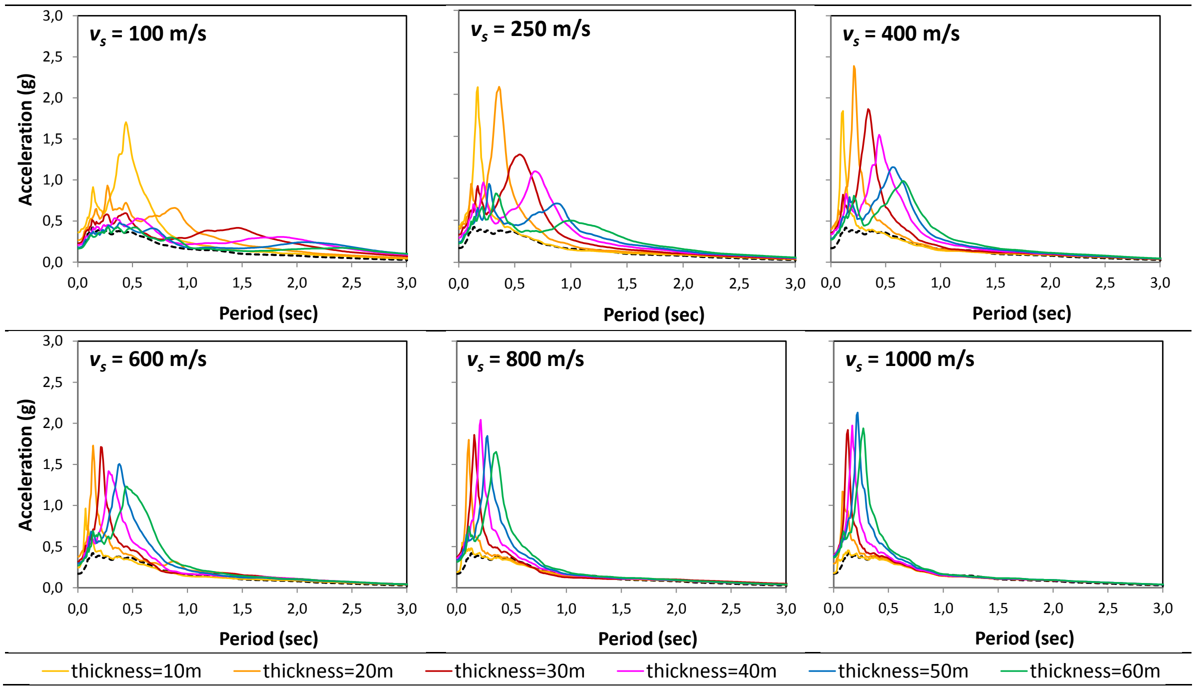


Figure 3. Surface spectral accelerations resulted from the SRA: PGA = 0.15g

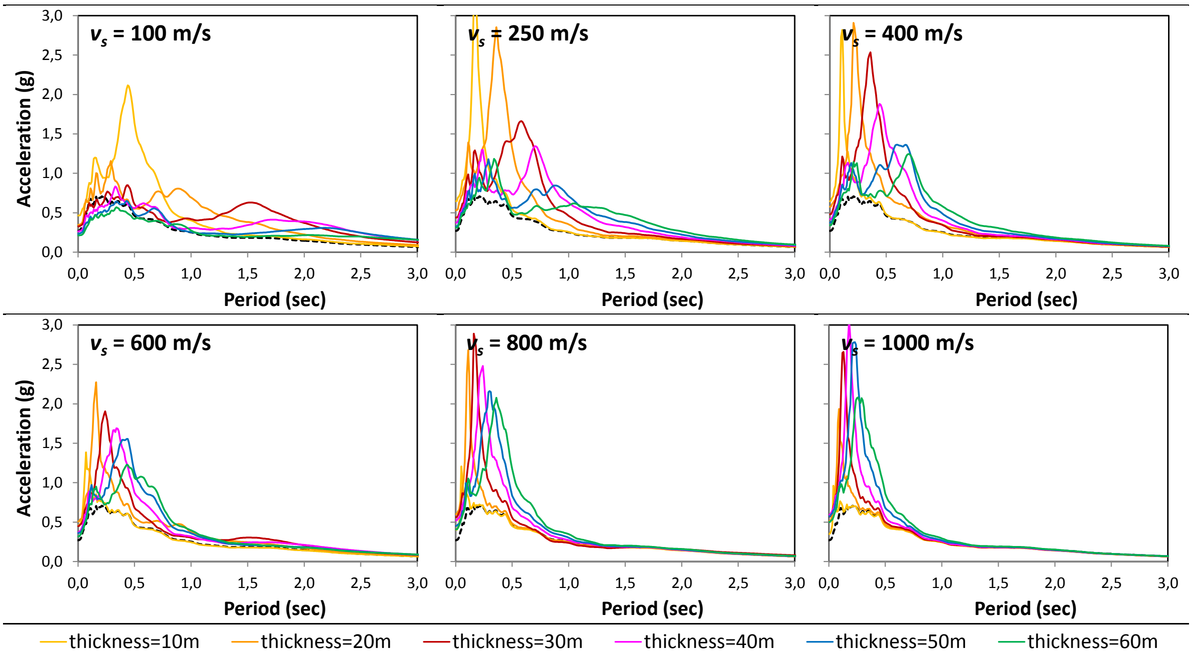


Figure 4. Surface spectral accelerations resulted from the SRA: PGA = 0.25g

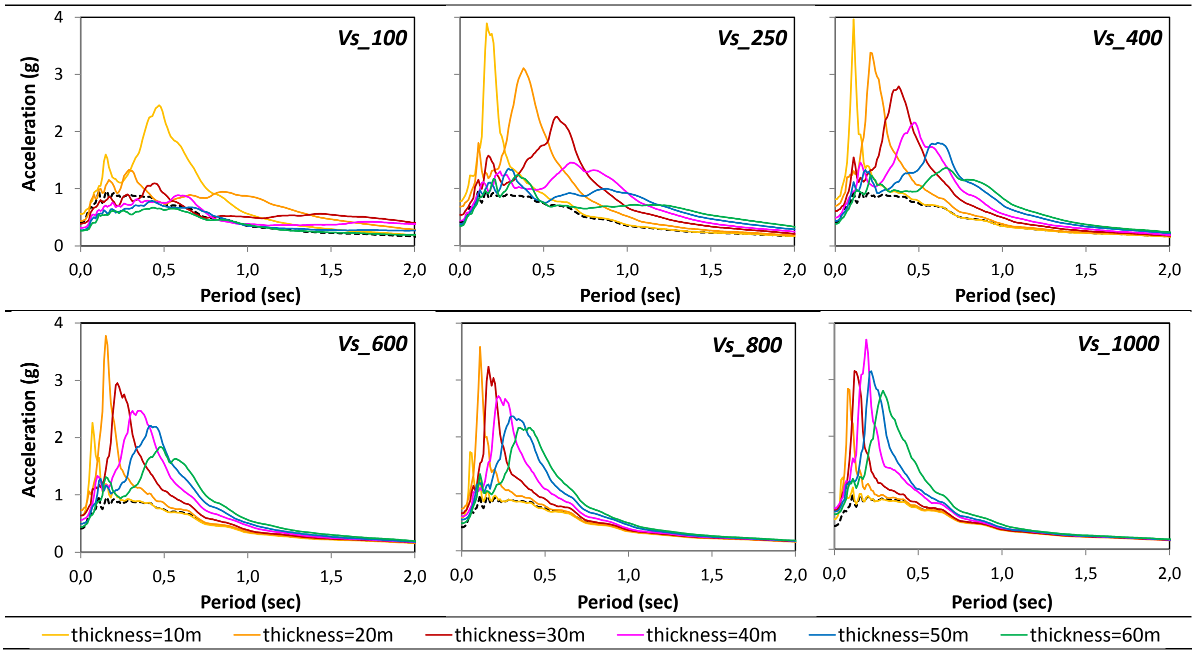


Figure 5. Surface spectral accelerations resulted from the SRA: PGA = 0.35g

4.2 Amplification functions

In order to assess the effects of the considered parameters, the results are shown in terms of Amplification Functions (AF). Such value is the ratio between the surface spectrum and the corresponding spectrum at the bedrock. Figures 6, 7 and 8 show the AF values calculated for the three PGA levels. The highest amplification factors occur for the lowest PGA, when the behaviour of the soil can be considered elastic. Soil models belonging to C, D and E classes (Vs_100, Vs_250) evidence the largest amplifications for periods bigger than 1.5 sec. In correspondence with soft soil and low thickness (10m, 20m), high values of amplification (exceeding value of 4) resulted.

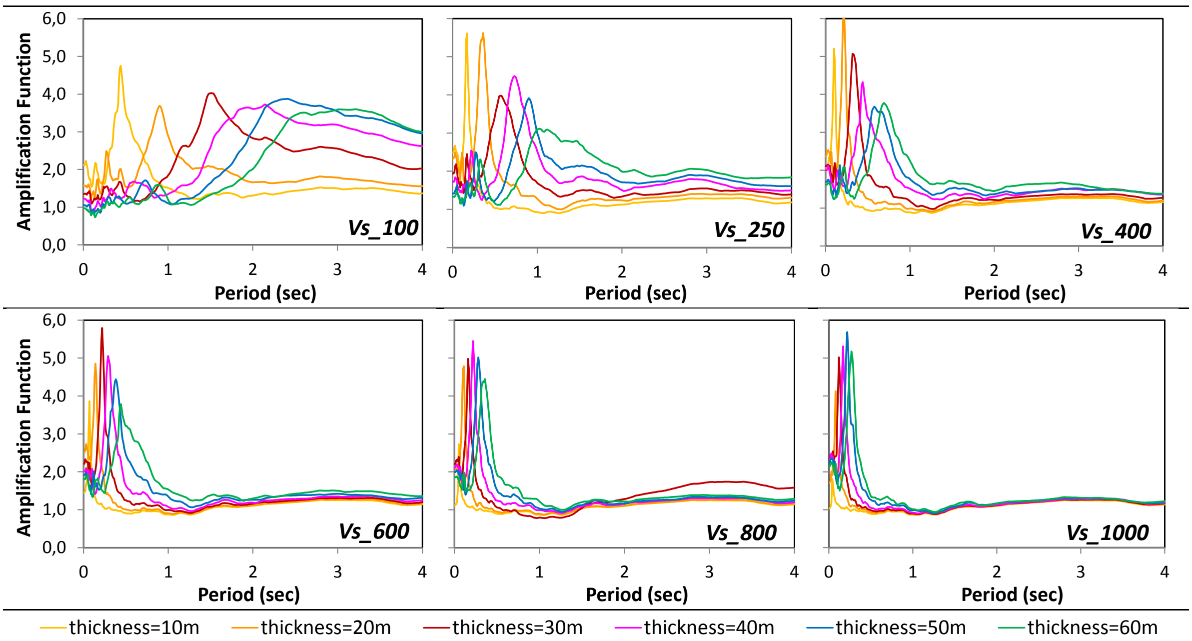


Figure 6. Amplification Functions: PGA = 0.15g

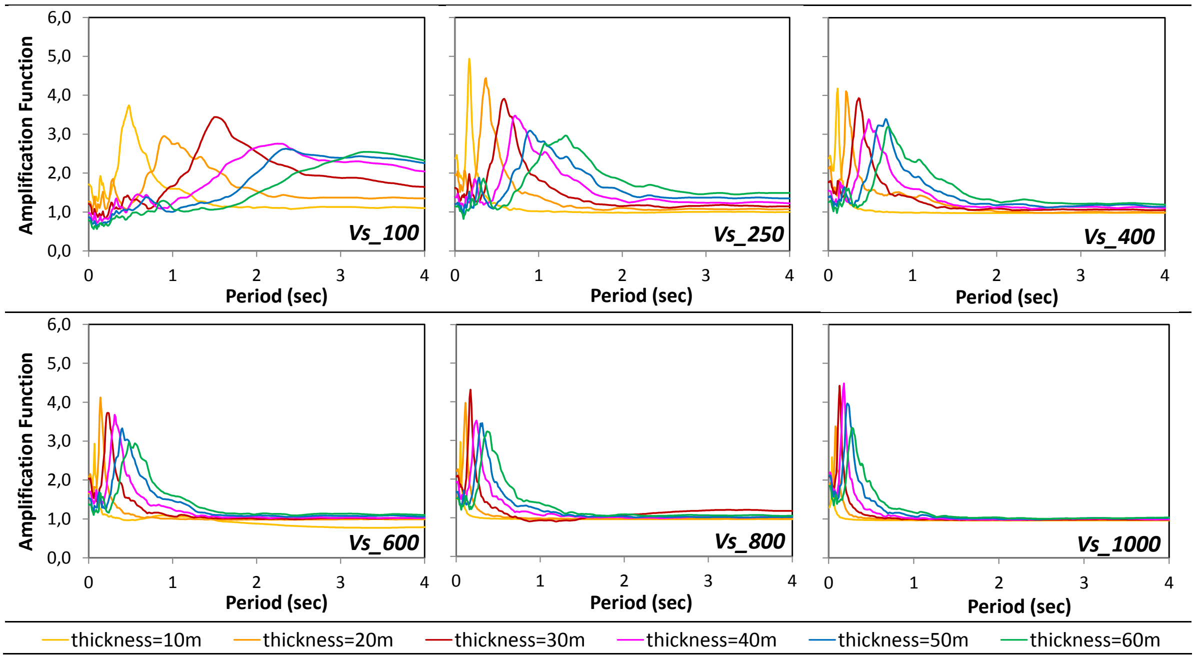


Figure 7. Amplification Function: PGA = 0.25g

The maximum amplification in correspondence with stiffer soils (Vs_400, Vs_600, Vs_800) have been reached for periods below 0.5 sec. Maximum values of amplification reach the value of 3, for the highest seismicity. AF ranges between 4 and 5 for lower PGAs, due to the elastic response of the soil. Finally, in correspondence with the stiffer soil (Vs_1000, classified as A-class according to EC8), the highest values of AF (between 4 and 6) are reached for low periods (below 0.3 s), depending on the considered PGA. In particular, the pictures shows that the peak values occur in correspondence of periods that differ from the elastic values (calculated with 4H/Vs and shown in table 3). The differences between the elastic values and those calculated, show the importance of considering non-linear constitutive law instead of simpler solutions (such as equivalent linear approximations).

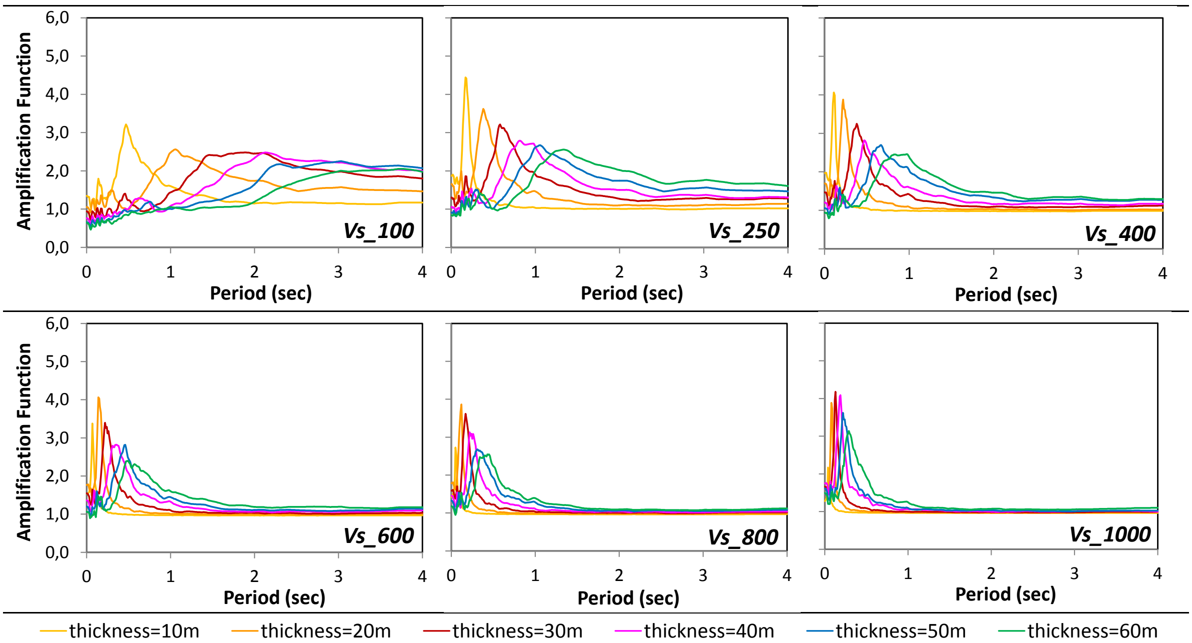


Figure 8. Amplification Functions: PGA = 0.35g

Table 3. Elastic Fundamental Periods (s).

Soil types	Vs_100	Vs_250	Vs_400	Vs_600	Vs_800	Vs_1000
Thickness: 10 m	0.40	0.16	0.10	0.066	0.05	0.04
Thickness: 20 m	0.80	0.32	0.20	0.133	0.10	0.08
Thickness: 30 m	1.20	0.48	0.30	0.198	0.15	0.12
Thickness: 40 m	1.60	0.64	0.40	0.266	0.20	0.16
Thickness: 50 m	2.00	0.80	0.50	0.333	0.25	0.20
Thickness: 60 m	2.40	0.96	0.60	0.396	0.30	0.24

5. CONCLUSIONS

This work consists of a preliminary parametric study aimed at assessing the role of soil thickness on the evaluation of the surface seismic input. Several SRA on different soil models have been performed with a 3D FEM non-linear platform (OpenSees). In order to assess Opensees potentialities, several combinations have been studied. Not all of them can be considered strictly representative of realistic soil conditions, but they were necessary in order to validate the software. In particular, six different soils ($v_{s,30}$ between 100 m/s and 1000 m/s and C between 70 kPa and 800 kPa), six different thickness values (between 10m and 60m) and three different seismic intensities (PGA equal to 0.15g, 0.25g and 0.35g) have been considered. For each assumed intensity, an ensemble of 7 unscaled ground motions has been selected. The mean surface accelerations have been compared to those in correspondence with the bedrock. Implementation of Opensees was shown to be fundamental in order to study the effect of non-linearity in assessing the influence of soil thickness. Input amplification has been shown to be significant especially in case of medium-consistent soils (belonging to the B-class). The period corresponding to the amplification peak is shown to be affected especially in correspondence with softer soils (belonging to C, D and E classes). These results will allow further studies aimed at investigating multiple-layered soil models.

6. REFERENCES

Adhikary S, Singh Y (2012). Effect of Soil Depth on Inelastic Displacement Spectra Proc. *15 WCEE*, Lisbon.

Al Atik L, Abrahamson N (2010). An improved method for nonstationary spectral matching. *Earthq Spectra* 26 (3), pp. 601–617, doi.org/10.1193/1.3459159.

Anbazhagan P, Sheikh MN, Parihar A (2013). Influence of rock depth on seismic site classification for shallow bedrock regions. *Natural Hazards Review,* 14 (2), pp. 108-121, doi.org/10.1061/(ASCE)NH.1527-6996.0000088.

ASCE (2000). Seismic analysis of safety-related nuclear structures and commentary. *ASCE standard no. 004-98, American Society of Civil Engineering.*

ASCE (2006). Minimum design load for buildings and other structures. *ASCE standard no. 007-05, American Society of Civil Engineering.*

Assimaki D, Kausel E, Gazetas G (2005). *Soil-Dependent Topographic Effects*: A Case Study from the 1999 Athens Earthquake. Earthquake Spectra, 21 (4), pp. 929–966, doi.org/10.1193/1.2068135.

Bazzurro P, Cornell CA (1999). Disaggregation of seismic hazard. *Bull Seismol Soc Am* 89 (2), pp. 501–520, Print ISSN 0037-1106

Bommer JJ, Acevedo A (2004). The use of real earthquake accelerograms as input to dynamic analysis. *Journal of Earthquake Engineering* 8 (sup001), pp. 43–91, doi.org/10.1080/13632460409350521

Bousshine L, Chaaba A, De Saxce G (2001). Softening in stress-strain curve for Drucker-Prager nonassociated plasticity. *International Journal of Plasticity* 17 (1), pp. 21–46, doi.org/10.1016/S0749-6419(00)00017-6.

Bradley BA (2010). A generalized conditional intensity measure approach and holistic ground-motion selection. *Earth Eng Struct Dyn* 39 (12), pp. 1321–1342, DOI: 10.1002/eqe.995.

D'Intinosante V, Baglione M, Gallori F (2016). La microzonazione sismica di terzo livello: l'esempio di Fivizzano (http://www.ingenio-web.it).

Dafalias YF (1986). Bounding surface plasticity I: mathematical formulation and hypoplasticity. *Journal of Engineering Mechanics*, ASCE 112 (9), pp. 966–987, doi.org/10.1061/(ASCE)0733-9399(1986)112:9(966).

EC 8-3 (2005) Design of structures for earthquake resistance, part 3: strengthening and repair of buildings. *European standard EN 1998-3.* European Committee for Standardization (CEN), Brussels

Forcellini D, Gobbi S (2015). Soil structure interaction assessment with advanced numerical simulations, *Proceeding of Computational Method in Structural Dynamics and Earthquake Engineering conference (COMPDYN),* Crete Island, 25 – 27 May 2015.

Forcellini D (2017a). Cost Assessment of isolation technique applied to a benchmark bridge with soil structure interaction. *Bulletin of earthquake Engineering*, DOI: 10.1007/s10518-016-9953-0.

Forcellini D (2017b). Seismic assessment of a base isolated benchmark building with soil structure interaction. *Bulletin of earthquake Engineering*, DOI: 10.1007/s10518-017-0268-6.

Iervolino I, Galasso C, Cosenza E (2009). REXEL: computer aided record selection for code-based seismic structural analysis. *Bulletin of Earthquake Engineering*, 8 (2), pp. 339-362, doi.org/10.1007/s10518-009-9146-1.

Iervolino I, Chioccarelli E, Convertito V (2011). Engineering design earthquakes from multimodal hazard disaggregation. *Soil Dyn Earthq Eng* 31 (9), pp. 1212–1231, doi.org/10.1016/j.soildyn.2011.05.001.

Itaca (2008). Database of the Italian strong motions data. http://itaca.mi.ingv.it.

Katsanos EI, Sextos AG, Manolis GD (2010). Selection of earthquake ground motion records: a state-of-theart review from a structural engineering perspective. *Soil Dynamic & Earthquake Engineering* 30 (4), pp. 157–169, doi.org/10.1016/j.soildyn.2009.10.005.

Kondner RL (1963). Hyperbolic stress-strain response: Cohesive soils. *Journal of the Soil Mechanics and Foundations Division*, 89(SM1), pp. 115-143.

Law HK, Lam IP (2001). Application of periodic boundary for large pile group, J*ournal of Geotechnical Geoenvironmental. Engineering*, 127 (10), pp. 889–892, doi.org/10.1061/(ASCE)1090-0241(2001)127:10(889).

Mazzoni S, McKenna F, Scott MH, Fenves GL (2009). Open System for Earthquake Engineering Simulation, User Command-Language Manual. Pacific Earthquake Engineering Research Center, University of California, Berkeley, OpenSees version 2.0.

Nemat-Nasser S, Zhang J (2002). Constitutive relations for cohesionless frictional granular materials. *International Journal Plasticity* 18 (4), pp. 531–547, doi.org/10.1016/S0749-6419(01)00008-0.

Parra E (1996). Numerical modeling of liquefaction and lateral ground deformation including cyclic mobility and dilation response in soil systems." Ph.D. thesis, Rensselaer Polytechnic Institute, Troy, N.Y.

Prevost JH (1985). A simple plasticity theory or frictional cohesionless soils. *Soil Dynamics Earthquake Engineering*, 4 (1), pp. 9-17.

Radi E, Bigoni D, Loret B (2002). Steady crack growth in elastic-plastic fluid-saturated porous media. *International Journal of Plasticity* 18 (3), pp. 345–358, doi.org/10.1016/S0749-6419(00)00101-7.

Seifried AE, Baker JW (2014). Spectral variability and its relationship to structural response estimated from scaled and spectrum-matched ground motions. In: *Proc. 10NCEE*, Anchorage, Alaska, July 21–25, 2014.

Shome N, Cornell CA, Bazzurro P, Carballo JE (1998). Earthquakes, records and nonlinear responses. *Earthq Spectra* 14(3):469–500

Stewart JP, Chiou SJ, Bray JD, Graves RW, Somerville PG, Abrahamson NA (2001). Ground motion evaluation procedures for performance-based design. *Technical Report, PEER Center*: University of California, Berkeley.

Tanganelli M, Viti S (2016). Effect of soil modeling on the seismic response of buildings. *Proc. SEMC*

2016: Cape Town, South Africa, 5 - 7 September 2016, Alphose Zingoni, vol. Insights and Innovations in Structural Engineering, Mechanics and Computation, pp. 284-290, ISBN:978-1-138-02927-9.

Tanganelli M, Viti S, Forcellini D, D'Intisonante V, Baglione M (2016). Effect of soil modeling on Site Response Analysis (SRA). *Proc. SEMC 2016*, Cape Town, South Africa, 5 - 7 September 2016, Alphose Zingoni, vol. Insights and Innovations in Structural Engineering, Mechanics and Computation, pp. 364-369, ISBN:978-1-138-02927-9.

Tanganelli M, Viti S, Mariani V, Pianigiani M (2017). Seismic assessment of existing RC buildings under alternative ground motion ensembles compatible to EC8 and NTC 2008, *Bull Earthquake Eng* 15 (4), pp.1375–1396, doi.org/10.1007/s10518-016-0028-z.

Tarbali K, Bradley BA (2015). Ground motion selection for scenario ruptures using the generalized conditional intensity measure (GCIM) method. *Earthq Eng Struct Dyn* 44 (10), pp. 1601–1621, DOI: 10.1002/eqe.2546.

Viti S, Tanganelli M, D'Intinosante V, Baglione M (2017). Effects of soil characterization on the seismic input. *Journal of Earthquake Engineering* 21(6), http://dx.doi.org/10.1080/13632469.2017.1326422.

Yang Z, Elgamal A, Parra E (2003). A computational model for cyclic mobility and associated shear deformation. *Journal of Geotechnical and Geoenvironmental engineering (ASCE)*, 129 (12): pp. 1119-1127, doi.org/10.1061/(ASCE)1090-0241(2003)129:12(1119).