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Evaluation of the seismic ground amplification considering the variability of the bedrock depth and random shear wave velocity profiles

V. Licata
Anas S.p.A., Italy

G. Forte, H. Ebrahimian, A. d'Onofrio, F. Jalayer, A. Santo & F. Silvestri
Università di Napoli 'Federico II', Napoli, Italy

ABSTRACT: The paper shows the results of seismic response analyses, performed on five stratigraphic profiles in the Western area of Naples (Italy). They are aimed at evaluating the influence of the dispersion of the shear wave velocity, V_S, profiles and of the bedrock depth on the amplification of the ground motion. The V_S profiles as well as the morphology of the bedrock were defined on a wide collection of data. The V_S profiles were opportunely randomized by Monte Carlo simulations, while, the position of the bedrock was varied in a range of depths relevant for the site. Twenty different acceleration time histories were selected as seismic input motions, considering the focal mechanisms and the distance-magnitude pairs relevant to the tectonic and volcanic seismic sources affecting the city of Naples. The adopted signals are characterized by a high variability of both frequency content and peak ground acceleration, in order to comprehensively study the linear and non-linear seismic response of soil deposits. The results were finally synthesized in terms of amplification factors of PGA and Housner intensity distinguishing the response to weak and strong motions. The results highlighted that the distribution of the amplification factors is quite homogenous in the study area and the uncertainties of V_S hardly affects the soil response. On the contrary, the effect of bedrock depth is very significant, since ground amplification at high periods increases with its depth.

1 INTRODUCTION

Stochastic approaches, providing a robust estimation of the ground shaking, are quite often used as analyses tool to pursue different engineering goals. As discussed by Rathje et al. (2010), the main sources of uncertainties for the assessment of the seismic ground shaking, are the variability of the input motions, the intrinsic dispersion of the soil parameters (shear wave velocity model, non-linear properties and strength parameters) and the method of analysis adopted (non-linear or equivalent-linear methods). The contribution of each source of uncertainty, listed above, was investigated by different literature papers, revealing that the selection of the input motion may be a critical issue in the assessment of the soil response (Bazzurro and Cornell, 2004; Rathje et al. 2010). Uncertainties about soil model may lead to significant overestimation or underestimation of the ground shaking; they can be identified in the local site conditions, the level of seismicity, the dispersion of shear wave velocity and/or non-linear properties of the soils (Bazzurro and Cornell, 2004; Rathje et al. 2010, Li and Assimaki, 2010; Pagliaroli, et al. 2015).

This study was developed in the context of Metropolis research project (see also Ebrahimian et al. 2019; Licata et al. 2019), aimed at defining methodologies and sustainable, innovative technologies to assess and manage natural and man-caused hazards in urban environment. Within this frame, the paper shows some results of stochastic analyses aimed at studying the seismic site response of the Western area of Naples (Bagnoli-Fuorigrotta districts). One-dimensional seismic response analyses were carried out with the code Strata (Kottke et al.

2013) to evaluate two issues regarding the amplification of the ground motion: (i) the uncertainties of the shear wave velocity, V_S, profiles of Bagnoli-Fuorigrotta districts and (ii) the high variability of the depth of the bedrock.

The quantification of the uncertainties was evaluated by defining the amplification factors, AF, obtained by propagating a set of twenty accelerograms through different soil profiles, characterized by a different realization of Vs by Monte Carlo method. To isolate the effect of the dispersion on AF, the results inferred from the randomized Vs profiles were compared with those obtained adopting a deterministic Vs profiles (i.e. the profile based on the median value of the V_S).

For the evaluation of the influence of the position of the bedrock on the amplification, the accelerometric dataset was implemented in the seismic response analyses assuming the median V_S profile and varying the depth of the bedrock in a range between 10 and 335 m.

2 CASE STUDY

The study area is located at the Southeastern margin of the Phlaegrean fields, in a coastal depression occupied by the districts of Fuorigrotta and Bagnoli. Details about the geological and the geotechnical models of the study area can be found in Licata et al. (2016) and Licata et al (2019). Figure 1 shows the simplified geological map obtained synthetizing all the existing data. The collection of pre-existing in situ data (borehole logs, CPT profiles, CH, DH and MASW tests) was further integrated carrying out a deep down-hole test (100 m). Cyclic/dynamic torsional shear tests were also carried out on different undisturbed samples in order to characterize the non-linear and dissipative properties of the investigated soils.

The geo-lithological framework, reconstructed by the available field logs and literature works (such as Di Vito et al., 1999; Orsi et al., 2004), revealed that the area is mainly made of pyroclastic falls coming from the volcanic eruption of Phlegrean Fields, characterized by significant amounts (typically 40–60%) of sandy and silty fractions (see also Licata et al. 2015, 2017), or reworked in alluvial and marine environment.

In particular, the geology was characterized by two pyroclastic soils (RAPD, AMS); the tuff in both lithic and non-lithic facies (NYT); the alluvial (ARD) and marine (MS) sandy soils; the peat (P) and the aeolian (AS) sands covering the coastal line of the area and the made-ground layer (I).

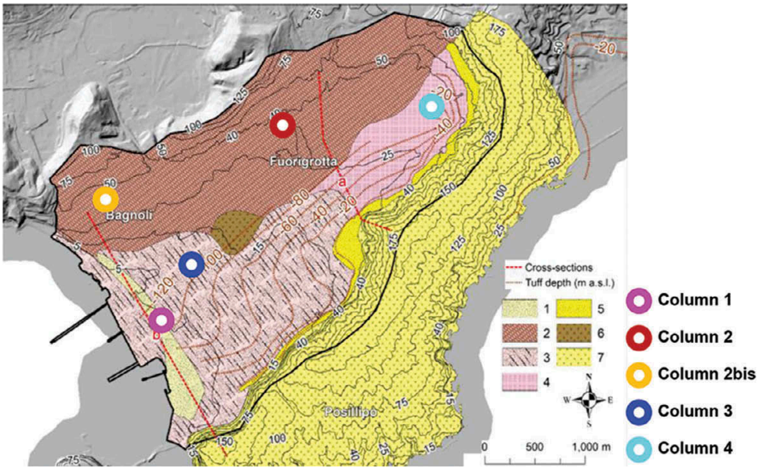

Figure 1. Geo-lithological map, representing the contours of the area with homogenous stratigraphic sequences: 1 - pyroclastic soils below dune sands; 2 - pyroclastic soils on unlithified NYT; 3 - pyroclastic and marine soils with peats on NYT (z> 20m); 4 - pyroclastic soils on NYT (z> 20m); 5 - pyroclastic soils on NYT (z< 20m); 6 - pyroclastic soils below Santa Teresa Tephra; 7 - NYT outcrop. Localization of seven soil columns assumed for the seismic response analyses (from Licata et al. 2019).

The interpretation of the stratigraphic logs allowed at identifying typical stratigraphic sequences grouped into geo-lithological complexes (Figure 1). The oldest complex is the Neapolitan Yellow Tuff (7), which is the only rock-like complex. For this reason, it was assumed as the seismic bedrock of the whole area. It crops out at the South-East side, along Posillipo hill, and it is buried within the plain up to more than 120 m below sea level. The tuff was not found in lithic facies in the central part of the plain, where, the tephra and tuff (6) remnants of the Santa Teresa Volcano (12.7 ky) crop out.

The other complexes are mainly constituted of sequences of layered pyroclastic soils. They were distinguished according to the lithic tuff depth (z), namely z<20 m (5) and z> 20 m (4), or the lack of it (2), while, in the complexes (1) and (3), the presence of aeolian sands and clayey silts with peat layers was highlighted.

The definition of the seven geo-lithological complexes permitted to define typical stratigraphic profiles for investigating the overall modifications of ground shaking due to the stratigraphic effects, in terms of variability of the soil layering and of the depth of the bedrock.

The soil columns, displayed in Figure 2, are representative of the geolitological complexes 1, 3, 4, and, for the complex 2, two different columns were defined (column 2 and column 2bis).

The mechanical properties of the soils were addressed on the basis of the wide collection of V_S data: for each profile the median value of the Vs (colored lines in Figure 2) were defined. Moreover, the results of the cyclic torsional shear tests allowed defining the shear modulus decay and the damping curves reported in Figure 3. No data were available about the non-linear and dissipative properties of the silty sands, reworked in alluvial and marshy environment (ARD) and the pyroclastic soils of Monte Sant'Angelo eruption (MST). Their mechanical properties were, hence, assimilated to RAPD, as mainly constituted of ashes, with a low content in pumices, or to MS, as some portions of these volcanic products were deposited in marine environment.

In order to just isolate the effect of the dispersion of Vs profile, all the columns subjected to the propagation (columns 1, 2, 2bis, 3 and 4) were opportunely selected at the same depth of the bedrock, equal to 100m (see columns in Figure 2). Moreover, in order to investigate the

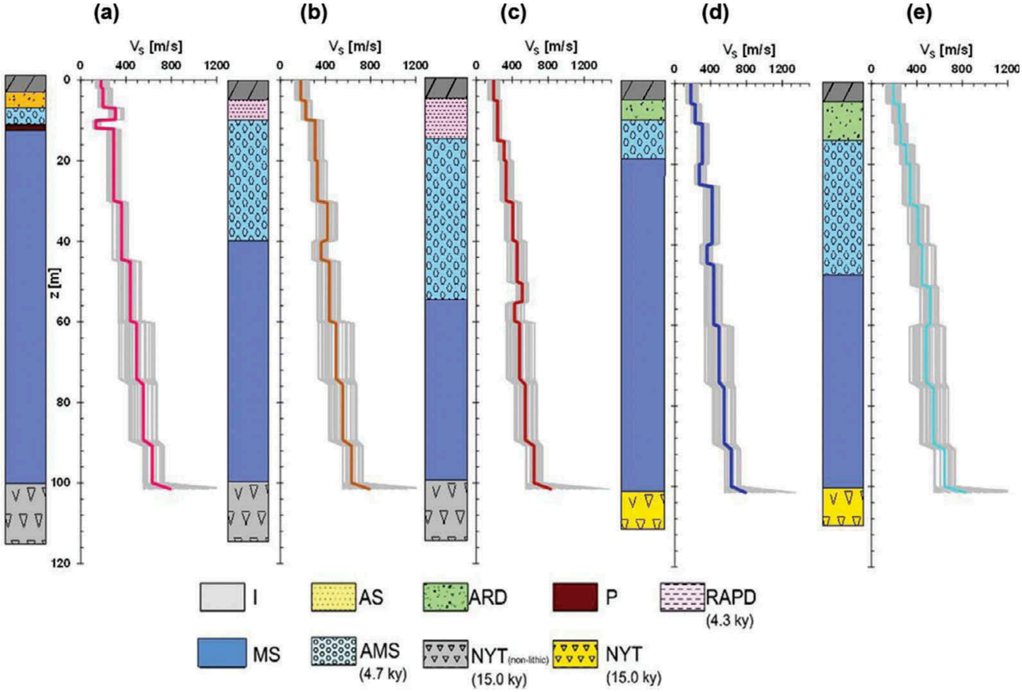

Figure 2. Soil profiles, randomized and median shear wave velocity profiles for (a) column 1, (b) column 2, (c) column 2bis, (d) column 3 and (e) column 4.

influence of the position of the bedrock, the median Vs profile was assumed for all the column and the depth of the bedrock was varied from 10m to 335m deep.

Finally, Figure 3 shows the normalized shear modulus and the damping curve assumed for the lithotypes.

2.1 *Randomized Vs profiles and variation of the position of the bedrock*

To properly evaluate the seismic ground shaking, the seismic response analyses were performed assuming aleatory Vs profiles and depths of the tuff bedrock.

The shear-wave velocity profiles were generated by Monte Carlo simulations. The randomization was based on the statistical model by Toro (1995), implemented in the code Strata (Kottke et al. 2013), which assumes a lognormal distribution of the shear wave velocity at each layer. In the model, it is possible to associate the median shear-wave velocity at each layer, V_{median}, and to account for the dispersion of the data by defining two quantities: the standard deviation, σ, and the standard normal variable, Z_{i-1}, in the i-th layer. In this work, it was assumed that each standard normal variable, Z_i, is correlated to the layer above it, Z_{i-1}, by using the dependence on soil class.

In particular, the correlation coefficients, defined by Toro (1995) for a soil class C (180 m/s<V_{s30}<360 m/s), were assumed for all the columns.

Figure 2 shows the results of fifty realizations of V_S generated by Monte Carlo simulations on each column. The median value of each layer (colored line) was defined on the data available from the field tests. Grey lines in Figure 2 show all the simulated Vs profiles assumed in the 1D seismic response analyses.

The variability of the depth of the bedrock was modeled by assuming a log-normally distributed random variable too. The possible range of variability for each column of Figure 1 was assumed considering the minimum and the maximum depth of the bedrock reached in the different geo-lithological areas, i. e. in the range of depths relevant for the study area (from 10m to 335m depth).

In the model, the median V_S was assumed for the soil profile and the position of the bedrock was modified by varying the thickness of the deepest soil layers. For the deepest layer (Vs=645 m/s, cfr. Figure 2), the decay and damping curve of MS - p'=400kPa was adopted, thus, neglecting the increase of the elastic threshold with the increasing depths (i.e. the applied mean effective stress, p'). However, the seismic response analyses showed that the maximum strains mobilized in the deepest layer are on average below the value 0.01%, thus, the behaviour of the layer remains in the linear range, resulting poorly influenced by the G/G_0 – D curve adopted.

2.2 *Selection of input motions*

The reference input motions were a set of seismic records selected from the from the Next Generation of Attenuation NGAWest2 database (Ancheta et al. 2014). As suggested by Bazzurro & Cornell (2004), the selection was executed considering the focal mechanisms (normal/

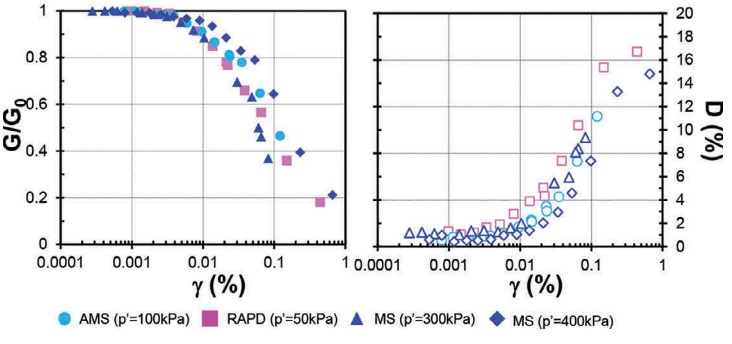

Figure 3. Decay shear modulus and damping curves assumed for the soils (from Licata et al. 2019).

strike-slip), as well as, the distance and the magnitude range characteristic of the seismic sources (Appennine chain and Phlegrean Fields/Somma-Vesuvius districts) affecting the city of Naples (magnitude, Mw=5–7.5; epicentral distance, Repi=10–100km).

Figure 4 displays the 5%-damped response spectra of a suite of 20 selected ground-motion records. The waveforms do not respect any compatibility with a target spectrum, because it is of interest to investigate the behavior of the deposits for a wide range of frequency values. Moreover, the signals were selected having values of the peak ground acceleration, PGA, ranging from about 0.001g to 1g, to study the linear as well as the non-linear behavior of the deposits.

Finally, in the context of Metropolis project, the high variability in the frequency content and PGA of the signals was also needed to implement the results of seismic response analyses in the definition of site-specific attenuation law (see also Ebrahimian et al. 2019).

3 RESULTS OF SEISMIC RESPONSE ANALYSES

In order to cover the entire range of fundamental vibration periods relevant for the heterogeneous urban pattern, the results of the seismic response analyses were elaborated in terms of amplification factors of PGA and Housner intensity evaluated in the periods, 0–0.1s; 0.1–0.5s; 0.5–1s; 1–2s.

The synthesis of the results is presented in Figures 5 and 6 distinguishing the analyses performed with the weak motions (WM), the strong motions (SW) and the global results (Tot). The difference between the weak motion and the strong motion was set with reference to a peak ground acceleration of the input signal (PGA_{input}) equal to 0.1g (see Licata et al. 2019). In correspondence of such PGA_{input} threshold of the input signals, in fact, the soils exhibit markedly non-linear behavior (for $PGA_{input} \geq 0.1g$) or, on the contrary, remain in the linear fields (for $PGA_{input} < 0.1g$).

Figure 5 represents the average amplification factors, above mentioned, inferred from the analyses with the randomized V_S profiles against those inferred from the deterministic V_S profile, obtained for the five columns.

Figure 6 shows the average amplification factors inferred from the median Vs profiles of each column, varying with the position of the bedrock.

By inspecting Figure 5, AF_{PGA} and AF_H in the periods (0-0.1s, 0.1–0.5s and 0.5–1s) show a homogenous response of the soils for which the ground motion is amplified by a factor of approximately 2 or slightly higher in the case of the propagation of weak motions. The results of Figure 5a lay on the black line showing little differences in the amplification factors predicted by the randomized and deterministic profiles. At higher period, $AF_{H1\text{-}2s}$, the amplification significantly decreases to a mean value of 1.7 and the effect of randomization is hardly significant even in this case.

For the strong motion analyses (SM) in Figure 5b, the distribution of the amplification in the different period is opposite to what observed for the weak motion. In general, the amplification

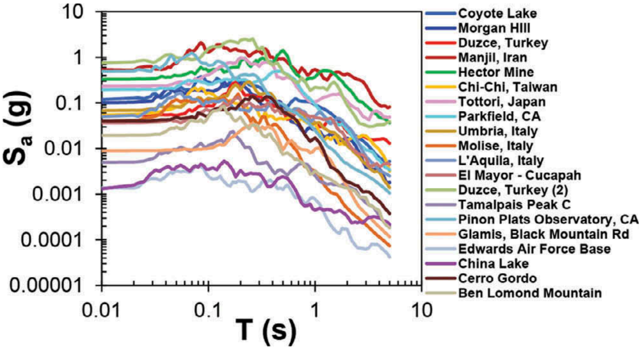

Figure 4. Response spectra of the signals selected for the seismic response analyses (from Licata et al. 2019).

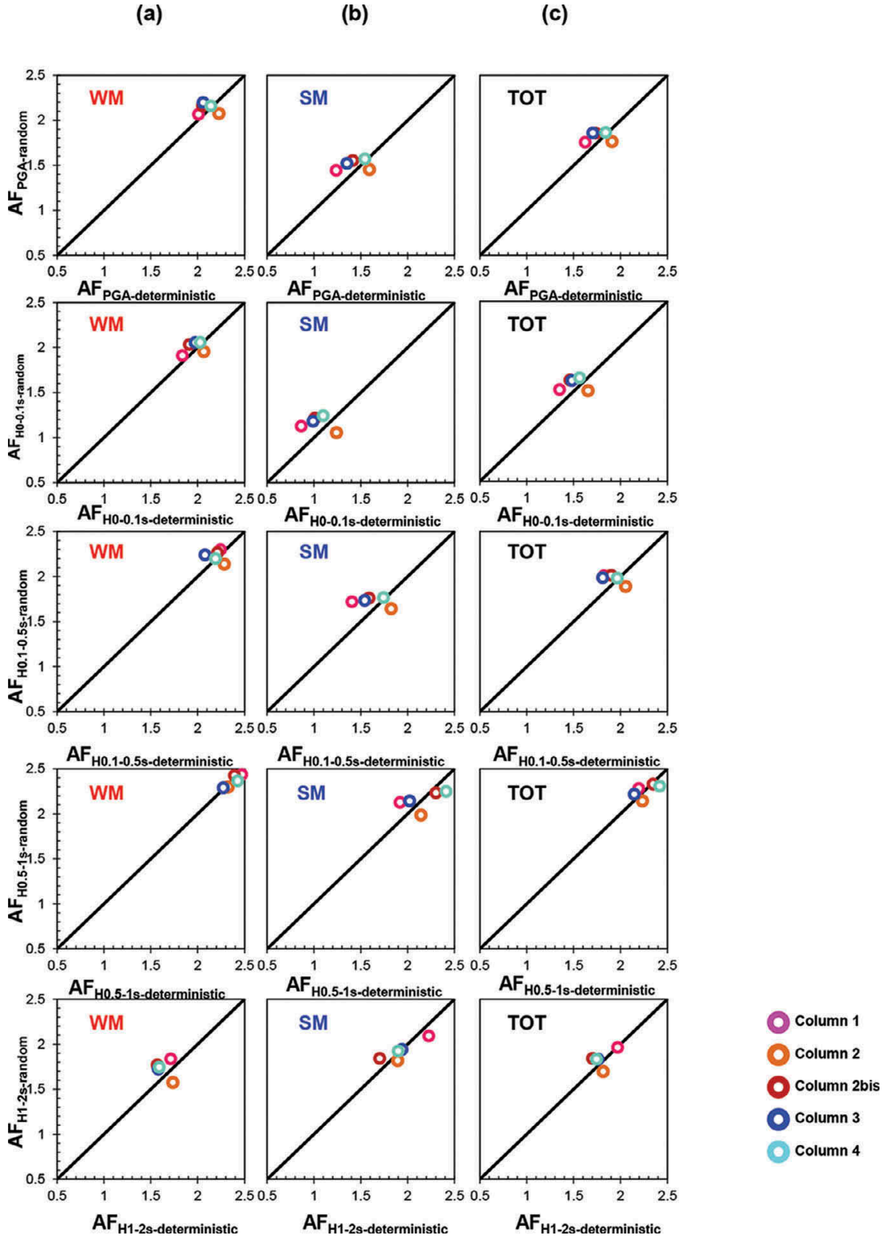

Figure 5. Average amplification factors of PGA and Housner intensity (in the periods 0–0.1s, 0.1–0.5s, 0.5–1s and 1–2s) obtained from the randomized V_S profiles against those inferred from the deterministic V_S profiles.

is around 1.5 for the very low and low periods (AF_{PGA}, $AF_{H0\text{-}0.1s}$, $AF_{0.1\text{-}0.5s}$). At high periods, $AF_{H0.5\text{-}1s}$, the amplification reaches its highest values for the strong motions and slightly decreases in correspondence of 1–2s. Respect to the results of the weak motions, the data of the randomized analyses appear slightlymore dispersed, showing a little overestimation of the amplification at very low and low periods (0–0.1s and 0.1–0.5s and 0.5–1s) against the deterministic amplification factors.

Summarizing, Figure 5 shows that the difference of AF of both PGA and Housner intensity for the randomized and deterministic V_S profiles are quite negligible.

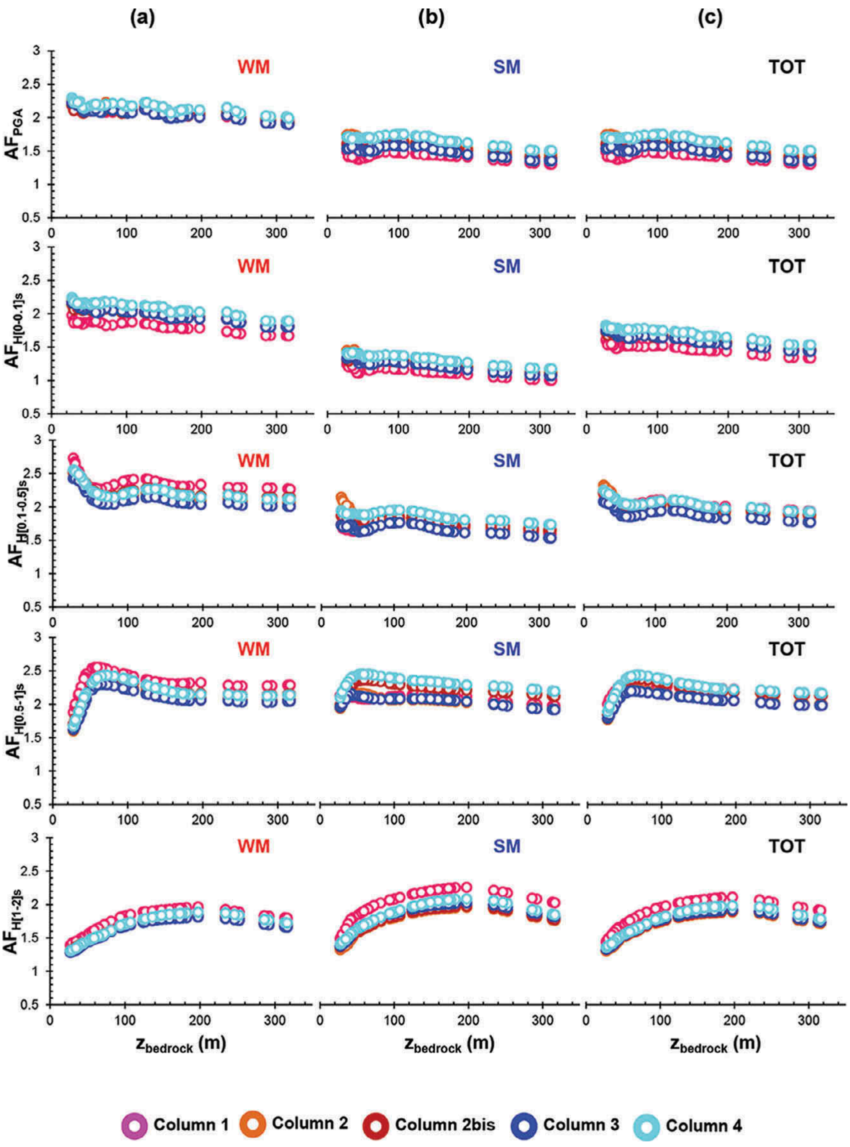

Figure 6. Average amplification factors evaluated for weak motion (a), strong motion (b) and all the signals against the variability of the depth of the bedrock.

Figure 6 shows the results of the analyses performed by assuming the deterministic V_S profile and variable depth of the bedrock. The results illustrate that the influence of the variability of the bedrock is significant for the ground amplification. In particular, the results of the weak and strong motions (Figure 6a and 6b) highlight that the amplification is quite independent from the depth of the bedrock in the range of very high frequencies (AF_{PGA}) while, the amplification factors $AF_{H0\text{-}0.1s}$ slightly decreases at increasing the depth of the bedrock.

At shallower depths of the bedrock (< 60m), Figures 6a and 6b show that in the WM analyses $AF_{H0.1\text{-}0.5s}$ decreases while $AF_{H0.5\text{-}1s}$ strongly increase. This evidence is less marked for the SM analyses. At very low frequencies ($AF_{H0.5\text{-}1s}$), the response is amplified more significantly in the SM analyses where the non-linearity of the soils dominates the overall response. The amplification factors increase up to 200m of the bedrock depth and then, beyond 200m, decrease. This observation is expected as, for very deep soil deposits, the fundamental vibration frequencies are very far from the frequency content of the signals.

4 CONCLUSION

This study was developed within the research project ‘Metropolis’ with the main focus on the evaluation of the seismic vulnerability of the Western area of Naples. It shows some results of 1D seismic response analyses performed to study the role of the uncertainties of V_S profiles and the influence of the depth of the bedrock on the soil response. The analyses were performed on five columns representative of the stratigraphic heterogeneity of the area for which, to evaluate the effect of shear wave velocity dispersion, 50 determinations of Vs profiles were generated by Monte Carlo method. To evaluate the influence of the depth of the bedrock, the deterministic Vs profile was assumed varying the position of the bedrock from 10m up to 335m.

The results, elaborated in terms of amplification factors of PGA and Housner intensity in the periods, 0–0.1s, 0.1-0.5s, 0.5–1s, 1–2s, highlighted that the dispersion of the V_S profile is negligibly significant. The amplification due to the variability of the bedrock strongly increases in the range of low frequencies up to 200m depth; beyond this depth the amplification decreases because the fundamental frequencies of the columns becomes less relevant compared to the frequencies content of the signals.

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