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SDMT V_S profiles in heterogeneous granular soil deposits

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ABSTRACT

Many urbanized areas of the Apennines, in Italy, have complex soil stratifications. A typical example is the historical center of L'Aquila and its outskirts, founded on layers of significantly heterogeneity and struck by a strong earthquake in 2009. Under these conditions, shear wave velocity profiles (V_S) obtained from in-situ measurements using SDMT techniques allow reliable analyses of local seismic response. In the soil of L'Aquila, the use of SDMT tests in sand-filled boreholes, following the procedure described by Totani et al. (2009), allowed V_S to be measured at considerable depths. This article presents the results of local seismic response analyses conducted to characterize the soil foundation of the hospital complex and adjacent university buildings in L'Aquila before their seismic retrofitting. The authors developed a soil model based on the Vs profiles retrieved from the SDMT tests. This approach provided a detailed understanding of the soil seismic behaviour, essential for the proper characterization of seismic action and consequently, the design of seismic interventions. The study emphasises the importance of accurate soil characterisation prior to seismic upgrades especially in deposits where there are multiple shear wave velocity inversions. The seismic demand coming from the Italian Building Code of 2018, based on the so-called soil categories from equivalent velocity of shear wave, was compared to the results of the local seismic response analysis conducted by using the real Vs profiles from SDMT, which are extended to a much greater depths than those generally required by the regulations.

Keywords: Shear wave velocity; Coarse-grain soil; SDMT; Inversion of Vs profile; Seismic response.

1. Introduction

Evaluation of ground response is the most common problems encountered by geotechnical earthquake engineers. Ground response analyses are crucial for accurate estimation of ground surface motions and depends on geotechnical characteristics of soil profile.

In situ geotechnical parameters affect the ground shaking intensity and in particular shear wave velocity at low strain is fundamentally related to the material behaviour and associated constitutive modelling especially in the case of multilayered and coarse materials (Durante et. al 2015).

The shear wave velocity (Vs) profile generally increases with depth but there are also geological settings where the velocity profile is characterized by inversions, when a stiffer layer (exhibiting higher Vs) overlies a softer one (with a lower Vs).

These conditions are widespread and require specific seismic site response analyses, both for structures and infrastructures design and for land planning (Fabozzi et al. 2021).

The area on the left side of the Aterno River, where the hospital-university complex are located, is characterized by presence of vast heterometric deposits of Quaternary, characterized by a significant heterogeneity.

Such deposits are composed of fine to coarse calcareous fragments of variable size (mostly of some centimeters) embedded in sandy or silty matrix characterized by high variable cementation. They are not penetrable by DMT or CPTu by conventional means. A drilled borehole, backfilled with sand is required to obtain Vs profiles

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This procedure was first devised by Totani et al. (2009) and has been improved afterwards. The emergency scenario after the 2009 earthquake imposed very strict time constraints for reconstruction the hospital so for an accurate subsoil characterization of the site were planned seismic dilatometer tests (SDMT) since these tests prove to be cost-effective and fast.

The aim of the present work is to study the effect of Vs spatial variability and velocity inversion on seismic site response of the studied area based on subsurface model reconstruction. One-dimensional (1D) ground response analyses were performed, in order to evaluate the influence of Vs inversion on ground shaking in terms of shear strain profiles and acceleration response spectra at the ground surface.

2. Site investigations

To obtain the geotechnical model, the area has been extensively investigated in by means of 13 boreholes to -100 m depth, 9 SDMT, 4 Down-Hole, SPT, and seismic noise measurements. Were also used the results of previous investigations from the seismic microzonation study.

As previously described, the subsoil across the hill where the hospital and university are built are very complex (fine to coarse calcareous fragments of variable size, mostly of some centimetres, embedded in sandy or silty matrix, characterized by highly variable cementation and mechanical properties) having thickness of about 100 m.

The planimetric location of the boreholes and the corresponding SDMT test locations are illustrated in Fig 1.

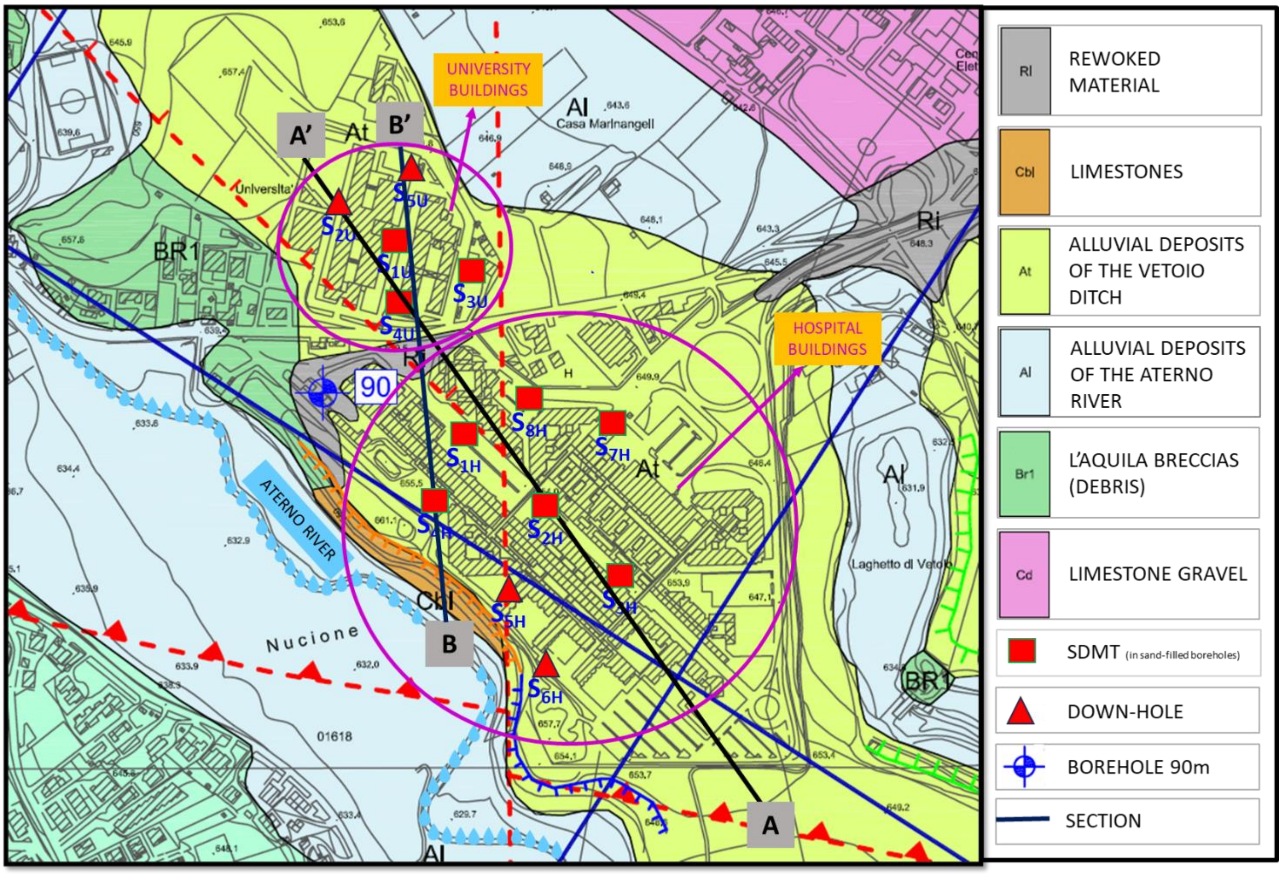

Figure 1. Map of the study area with tests locations and study sections.

All the surveys carried out in the area confirmed the generally coarse nature of the foundation soils and their marked ethereogenicity can be seen in Fig. 2. The observed dispersion of the measured Vs by SDMT reflect the variability in grain size distribution and cementation typical of this material Fig.3.

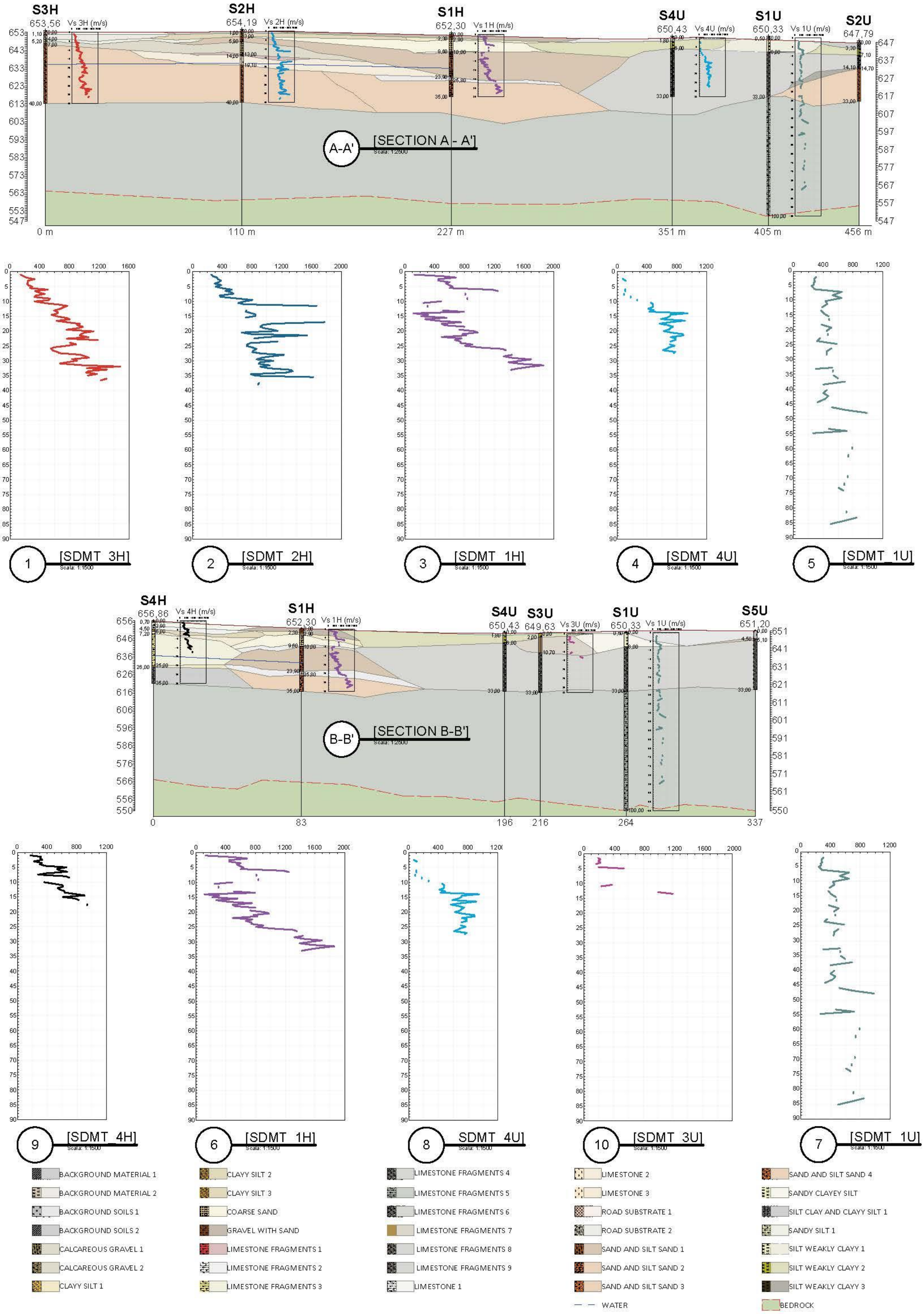

Figure 2. Section A-A’ and B-B’ whit soil material classification from boreholes and Vs profiles from SDMT.

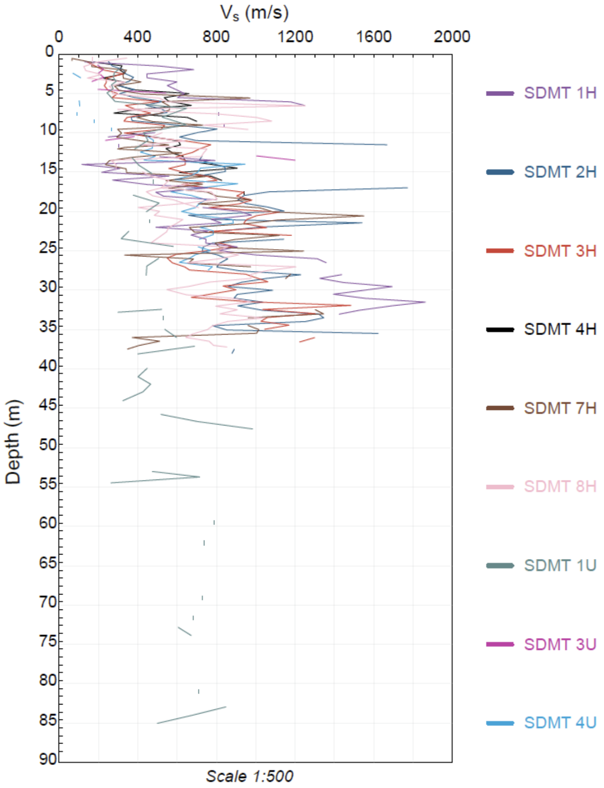

Figure 3. Superimposed profiles of VS measured by SDMT in backfilled boreholes

3. Ground response Analyses

The Earthquake resistant design of new structures and assessment of seismic damage in existing structures require estimation seismic ground motion based on design parameters that can be improved by site-specific ground response analyses or obtained from buildings codes. The design parameters developed by site-specific analyse are more accurate than those obtained from building codes and will probably result in a more economical design. Italian Building codes 2018 (IBC18) are constantly updated and improved in line with the knowledge and experience that increases over time.

In this study, each Vs profile collected by SDMT invistigation was used to determine the response of these complex deposits to seismic loading . The computer codes STRATA (Kottke 2009) makes an iteration of the 1D analysis in order to follow the variation in normalised shear modulus G/G0 and damping ratio D values with the shear strain. It assumes one-dimensional soil deposit conditions, such as the simplification of horizontal soil layers of infinite extent in the lateral sense.

Fig. 4 shows the input motions that consists of seven unscaled horizontal natural records selected from the ITACA archive (Luzi et al. 2008). The average of the selected spectra respects the compatibility with the Uniform Hazard Spectrum (characterised by a return period TR = 475 years) at rock conditions referred to as subsoil class A, in the 0.1–1.5 s period range for the area studied, as proposed by the IBC. Fig 4. shows the corresponding 5% damped response spectra with a comparison between the average input spectrum and the reference shape of IBC. The acceptance limits chosen for the average spectrum were +30% for the upprer one and -10% for the lower one, whit respect to the reference spectrum.

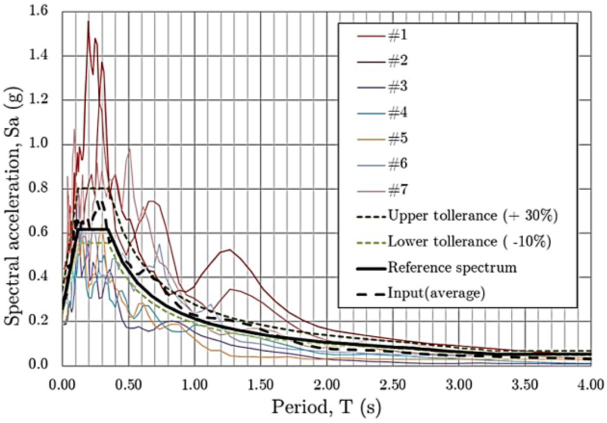

Figure 4. Comparison between response spectra of the 7 time histories (different colours) from ITACA selection as input motions, average shape spectrum (dashed black line) and reference spectrum from IBC2018 (continuous black line).

The subsurface model showed in Tab.1 presents a concise idealisation of mechanical behaviours of geotechnical units (GU$_S$). The curves of normalised shear modulus G/G$_0$ and damping ratio D versus shear strain was assumed from the literature. In addition, the bedrock was modelled with and elastic behaviour and an initial critical damping ratio D$_0$ equal to 0.5%.

Table 1. Mechanical and dynamical soil parameters of the geotechnical units

GUs	Type (/)	γ (KN/m^3)	G/G$_0$(γ) and D(γ) Curve
1	Fill material	18	Rollins (1998)
2	Lime and Sand	19	Darendeli and Stokoe (2001)
3	Gravel	20	Modoni and Gazzellone (2010)
4	Lacustrine	20	Seed (1970)
5	Bedrock	22	Elastic (D$_0$ = 0.5%)

The profiles of the V$_S$ were appropriately averaged in accordance with the stratigraphy of the survey and are shown in Fig. 5. It is important to emphasise that the profiles included in the Hospital area (H) have the following characteristics: 1) S3H shows a slight inversion of V$_S$ (over -20 m); 2) S2H shows a V$_S$ increasing with depth; 3) S1H shows a shallow inversion of V$_S$. Instead the profiles included in the University area (U) have the following characteristics: 1) S1U shows a V$_S$ increasing with depth; 2) S1U shows a consistent surface inversion for a thick layer.

The depth of the bedrock was inferred from a well drilled in the area and therefore set at approximately -90-100 m and was assigned the V$_S$ of 1250 m/s.

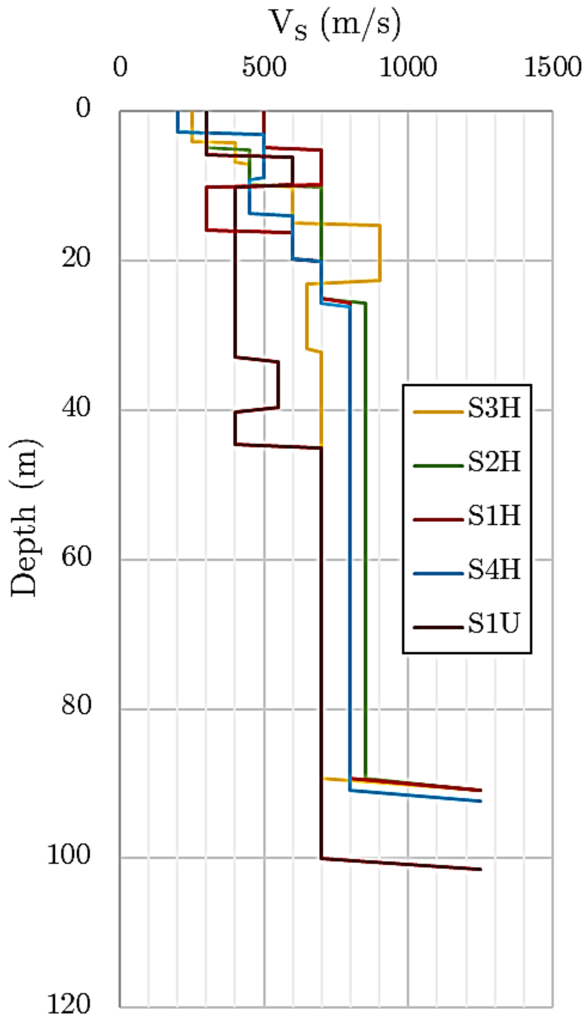

Figure 5. SDMT V_S profiles appropriately averaged for the ground response analyses

In this part of the basin, the majority of significant HVSR, properly referable to fundamental resonance frequencies (f_0) of the quaternary deposits fall in the range of frequency 0.8-1 Hz while higher frequencies values (5 -10 Hz) are associated with superficial fill material and/or Sandy lime soil.

4. Results

The results are offered in terms of transfer function (TF) and elastic response spectra (SA) showed in Figures 6,7 and 8.

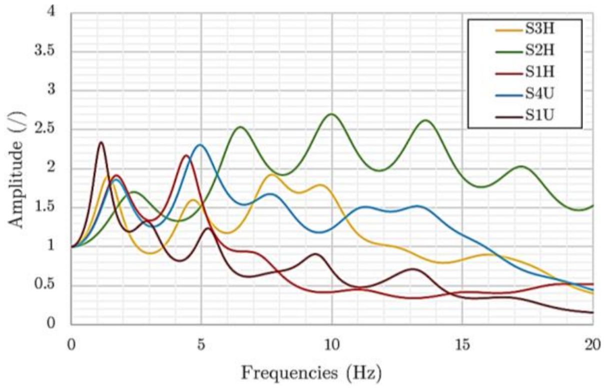

Figure 6. Average TF_S for the ground response analyses at five investigations point (different colours).

Fig. 7 shows a further comparison, for each study's profile, between the resonance amplitudes relative to the f_0 estimated from the 1D analyses and the theoretical ones obtained under the assumptions of an ideal visco-elastic homogeneous layer over a deformable substrate. For the theoretical subsoil, an average Vs was assigned from the "inhomogeneous" profiles from measured Vs and an average damping D_0 of 0.6% from the literature curves assigned in Tab 1. A regression law was defined to fit the numerical results for f_0. For completeness, the resonance amplitudes for the upper mode whit frequence f_1 were added to show a dispersion of the data.

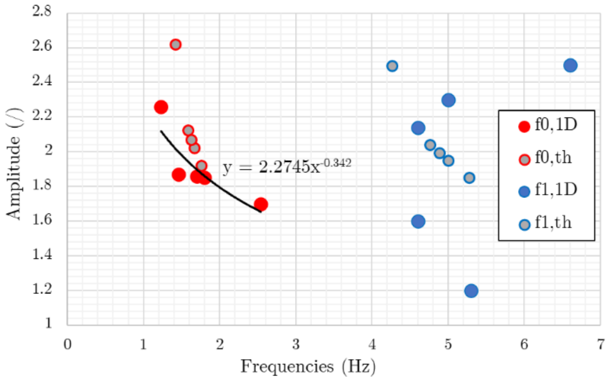

Figure 7. Comparison between f_0 and f_1 from 1D analyses (red and blue full points) and theoretical ones under the assumptions of an ideal visco-elastic homogeneous layer over a deformable substrate (red and blue empty points). Also are show a fitting regression law only for numerical f_0.

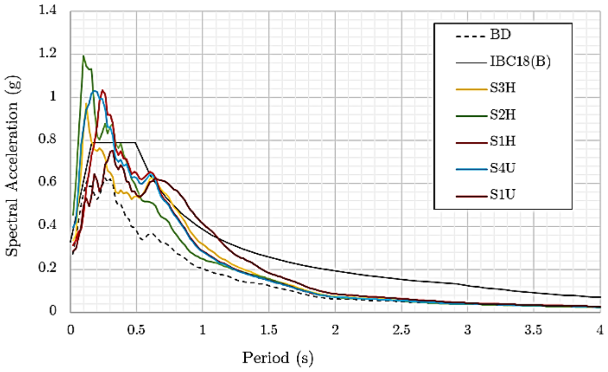

Figure 8. Average SAs for the ground response analyses at five investigations point (different colours), average SA for the bedrock (dotted black line) and the IBC spectra for the subsoil category B (continuous black line) i.e. IBC18(B).

5. Comments

The following comments can be made for the TF results: 1) the TF_S represent the general dynamic behaviour in terms of frequencies of amplification and in particular a low-frequency resonance of basin was identified (i.e. 1 Hz); 2) At higher frequencies there is dispersion due to the seismic stratigraphic complexity of the more superficial layers 3) regarding low frequencies, in agreement with Fabozzi et al. (2021), appear a greater amplification for profiles that show a V_S inversion (i.e. S3H, S1H and S1U).

According to Rovithis et al. 2011 Fig. 7 show that for an inhomogeneous soil the "equivalent" homogeneous approximations (in this study the average of V_S profiles and D_0 for the material behaviours) remain a promising solution for the amplitude of f_0 given that deep soil deposits are encountered. On the contrary, resonant amplitudes may be significantly overestimated or underestimated when an equivalent homogeneous soil approach is adopted, especially at higher resonances.

The following comments can be made for the SA results: 1) SA_S curves represent the complexity of seismo-stratigraphic conditions; 2) First amplification peaks can be noted for the low periods associated with softer surface layers (0.1 – 0.3 s); 3) a second system of peaks for higher periods can be associated with both the deep impedance between deposit and bedrock and the inversion of velocity within the entire layer (i.e. 0.6-1 s); 4) the latter two effects are superimposed.

6. Conclusions

The SDMT Vs profiles obtained in this area of L'Aquila have made possible to reconstruct a reference subsurface model for the 1D seismic response analyses. The site response analysis presented in this study is performed in order to represent the complexity of geotechnical condition: 1) heterogeneous stratifications; 2) granular deposits; 3) inversion of V_S profiles.

Some authors (Fabozzi et al. 2021) show that the effect of the hard upper layer is to exert a confining action on the soft layer below and so two different results are possible: a de-amplification for the lower period and a more evident amplification effect in the higher period.

Other authors (Rovithis et al. 2011) emphasise that a homogeneous (i.e. simplified) equivalent profile (i.e. simplified) leads to over-underestimations of the true amplification for vibrational modes higher than the fundamental one.

The soft layer, depending on its V_S and thickness, is therefore the main controlling element of the 1D column under these complex geological conditions. Therefore, it must be emphasize that SDMT Vs profiles can capture these variations and are also able and efficient to study aspects still under discussion.

Finally, given the purpose of the work, the analyses were conducted in the 1D dimension, including only the lithostratigraphic effect, so the results and conclusions discussed are only valid under this condition. In this complex morphological/geometric context, the 2D effects together with the influence of the Vs profile inversion are also relevant, and therefore further studies will be approached in the future.

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7. References

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