Recent developments in seismic site response evaluation and microzonation

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Recent developments in seismic site response evaluation and microzonation

Développements concernant l'évaluation de la réponse sismique du site et sa microzonation

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ABSTRACT: Seismic hazard and seismic actions for the design of buildings are strongly influenced by site response because of significant amplification expected for the specific stratigraphic and topographic conditions. Different approaches can be applied at the scale of the single building, but in complex morphological and geological contexts studies at the urban scale can provide relevant informations to be incorportated in the evaluation. The paper builds on the recent experience of seismic microzonation studies in central Italy in the aftermaths of the 2016 seismic sequence to provide an insight on the role of studies at different scales. Within this context, an example is also provided to illustrate recent methodologies that have been conceived to account for uncertainties in the characterization that affects both geophysical tests in situ and geotechnical tests in the laboratory for the assessment of the response of soils to cyclic loadings.

RÉSUMÉ: L'aléa sismique et le chargement sismique utilisé pour le dimensionnement sont fortement influencés par les effets de site, à cause des importantes amplifications qui sont attendues pour des stratigraphies spécifiques et des conditions topographiques. Des différentes approches peuvent être employées à l'échelle d'un seul bâtiment. Cependant, dans un contexte morphologique et géologique complexe, des études à l'échelle de la ville peuvent fournir des informations importantes à prendre en compte dans l'évaluation. Ce papier est basé sur l'expérience récente de microzonage sismique dans l'Italie centrale, développé à la suite de la séquence sismique de 2016, pour montrer l'apport d'études à différente échelle. Dans ce contexte, un exemple est discuté pour présenter des méthodologies récentes qui ont été conçues pour prendre en compte les incertitudes dans la caractérisation qui concerne les essais géophysiques in-situ et les essais géotechniques en laboratoire, réalisés pour l'estimation de la réponse des sols sous chargement cyclique.

Keywords: Earthquake, seismic site response, numerical analyses, microzonation, uncertainties

1 INTRODUCTION

The evaluation of seismic risk for existing buildings and seismic action for the design requires the determination of the expected ground motion, typically termed as *seismic hazard*. The probabilistic framework (Cornell 1968) is widely adopted to account for the related uncertainties with a rational approach.

The prediction of the desired set of intensity measures of the ground motion requires a broad variety of information. The factors that control the predicted ground motions are generally grouped into the *source*, *path*, and *site effects* (Figure 1). Specifically, the site response is primarily a function of the mechanical response of the subsoil and as such it is a primary task of geotechnical earthquake engineering. Site effects are typically quantified by the difference between the ground motion for the specific site condition and what would have occurred at for a reference condition (Figure 1). Many examples in the literature showed that the site contribution is one of the most influential elements in seismic hazard evaluation (e.g., Bazzurro and Cornell 2004). However, only the source and path effects are usually probabilistically treated adopting the Probabilistic Seismic Hazard Analysis (PSHA) method proposed by Cornell in 1968.

Site effects at a *small-scale* (i.e., for the single building) can be evaluated through the analysis of recorded ground motions and/or 1D numerical simulations. In addition, many International Regulations give the chance for a simplified assessment of the site effects at a small scale by means of a set of amplification factors based on different soil classification schemes. On the other hand, Seismic Microzonation (SM) studies propose an evaluation of the site effects from a *large-scale* different perspective. These studies usually adopt 1D and 2D (rarely, 3D) numerical simulations to assess the response of a broader investigated area (e.g., for a municipality), compared to small-scale applications.

Evidence of damages in past earthquakes showed the fundamental role of site response with reference to the amplification of the ground motion and to instabilities due to ground shaking. In situ *reconnaissance* surveys are essential to increase the knowledge of the seismic phenomena also in terms of their induced effects. Earthquake-reconnaissance reports date back to several centuries ago. A pioneering example is the report by Sarconi (1784) regarding the earthquake that occurred in Calabria (Italy) with several illustrations documenting the observed damages and the diffuse liquefaction phenomena. Recently a post-event reconnaissance was conducted after the seismic events of Central Italy in 2016 (Stewart et al. 2018). The double sequence of August-October caused significant damages and a huge loss of human lives with 299 casualties. Actually, the strongest earthquake stroke when many villages were abandoned after the initial seismic events. In the aftermaths of the

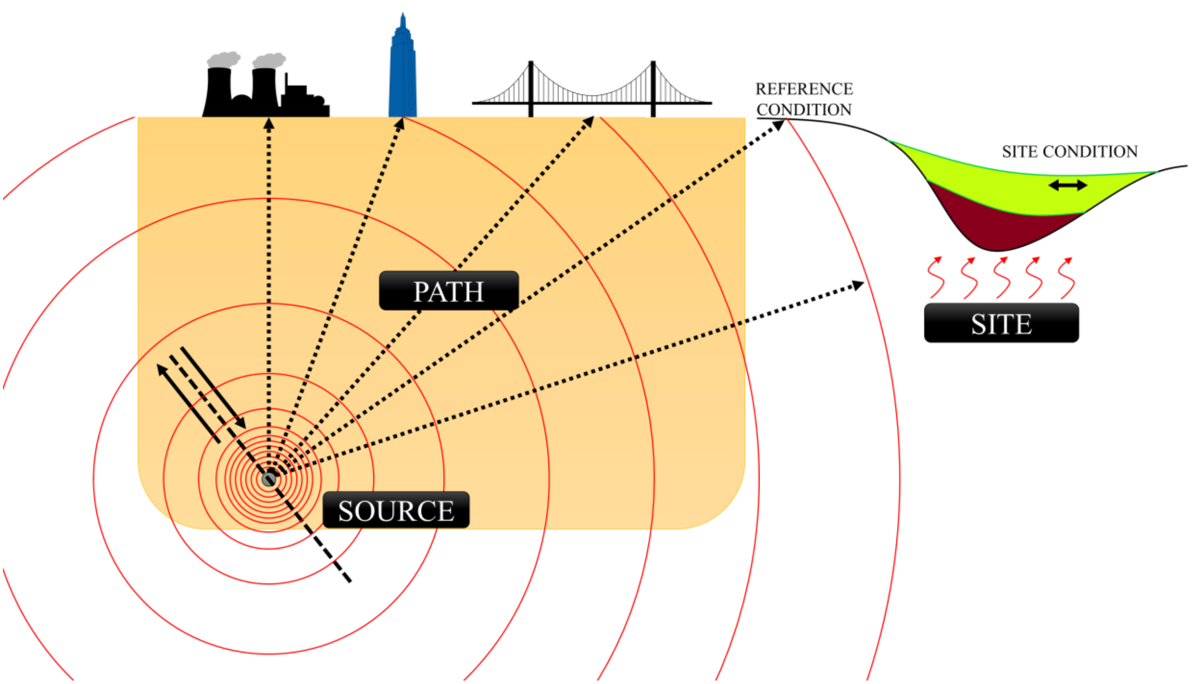


Figure 1 Source, path, and site contributions to the global seismic hazard (modified from Passeri 2019).

main events of the seismic sequences, many teams conducted on-field activities within the framework of the Geotechnical Extreme Events Reconnaissance (GEER) association (Stewart et al. 2017). Specifically, the localization of damages in the different villages showed the evidence of significant site effects (Sextos et al. 2018). Consequently, a large effort was founded by the Italian government for the seismic microzonation of the whole territory which was stroken by the seismic sequence. The whole process is documented in a special issue of the Bulletin of Earthquake Engineering (Hailemikael et al., 2019).

The paper first provides an overview of the procedures for the assessment of site effects on the basis of numerical simulations. Then, it summarizes standard procedures for seismic microzonation in Italy, incorporating examples from the recent experience in Central Italy. Finally, a case history is reported to illustrate a possible strategy to account for experimental uncertainties in site response evaluation.

2 EVALUATION OF SITE EFFECTS

The site response (i.e., site effect) is the process for which considerable modifications of the seismic waves are produced due to the variations of the material properties (i.e., stratigraphical amplification) and/or surface topography (i.e., geometrical amplification) near the Earth's surface (Aki 1993, Kramer 1996, Boore 2004) (Figure 1). Generic site response studies consider the differences in the expected motion in terms of amplitude, frequency content and duration between an established reference condition (typically, for flat and stiff outcropping formations) and the specific site condition. These studies should be performed within a probabilistic framework in order to *Identify, Quantify, and Manage* (i.e., IQM method) all the uncertainties and variabilities involved in the engineering process (Passeri 2019).

The effects of the site response are typically expressed in the frequency domain using Transfer Functions (TFs) defined as the module of the ratio of acceleration Fourier spectra calculated for two specific points of the model. Also, the site response can be described with Amplification Functions (AFs) defined as the ratio of the response spectrum at the surface of the site and the response spectrum of the input motion.

The methodologies and approaches for the evaluation of the site effects can be grouped into two classes depending on the scale of the problem. Small-scale site response studies are usually conducted for a specific single project. In this case, the site response study is dedicated to the design of a specific structure or facility that has a precise location and limited spatial extension. The second class includes large-scale microzonation studies (SM). These are implemented for a wide investigated area for urban planning and seismic risk evaluation.

Site specific studies are usually based on recorded ground motions (i.e., data-based) and/or 1D numerical simulations (i.e., simulation-based, usually termed Ground Response Analyses, GRAs). The data-based methods estimate the site response by collecting a large number of high-quality records, whereas for GRAs a great number of simulations should be performed in a probabilistic framework. Both approaches allow for a consistent prediction of the mean hazard at the site and the estimation of the uncertainties and variabilities in terms of the associated standard deviation (Stewart et al. 2014). Note that simulation-based methods represent the only possible choice when no records or insufficient records are available at the specific site (Olsen 2000, Rodriguez-Marek et al. 2014, Bommer et al. 2015, Faccioli et al. 2015). Therefore, data-based approaches are not covered in the present paper. An alternative approach is proposed in national regulations and building codes (e.g., CEN 2004). It is a simplified deterministic procedure based on a broad ground classification scheme. The categorization is based on synthetic parameters that represent the average stiffness of the deposit. Site effects are then estimated with a set of amplification factors, depending on the site category and the level of seismicity. This approach provides an estimate of the design ground motions, which can be used for preliminary assessments or for the design of ordinary buildings.

Microzonation studies are well-recognized as a crucial component for the implementation of urban planning management and seismic mitigation strategies in a given area (e.g., Iglesias, 1988; Fah, 1997; Finn et al., 2004; Pitilakis et al., 2006; Ansal et al., 2010; Crespellani, 2014; Pagliaroli et al., 2019). Seismic Microzonation (SM) studies provide maps of the spatial distribution of site response at urban scale with respect to the lithostratigraphic (i.e., mechanical) and morphological (i.e., geometrical) characteristics (e.g., Vinale et al., 2008; Ansal et al., 2009; Pagliaroli, 2018). The studies require expertise of multiple disciplines, namely geotechnical and structural engineering, seismology, geophysics and geology (Pagliaroli, 2018). A crucial element of a SM study is a reliable subsoil model with an overview of the main elements that control the site response. Site response studies for SM purposes are usually based on numerical simulations. 2D and 3D numerical analyses are hereafter termed Site Response Analyses, SRAs. Multidimensional effects can deeply affect the site response in the presence of irregular stratigraphic geometry and/or surface topography (Jibson, 1987). In these circumstances, 2D numerical analyses have been widely adopted in the past (e.g., Fah et al., 1997; Lanzo et al., 2011; Pagliaroli et al., 2019). More recently, some studies have been focused on 3D numerical simulations (e.g., Fah et al., 2006; Lee et al., 2009; Pitilakis et al., 2011; Smerzini et al., 2011; Falcone et al., 2018). Nevertheless, the complexity of the simulations and the high computational demand are still preventing the diffuse application of 3D approaches. The present paper will focus therefore only on 1D GRAs and 2D SRAs for SM studies.

2.1 Single site applications

Site response studies are usually conducted for specific engineering projects with a limited and precise spatial extension. The inclusion of uncertainties in these types of studies is fundamental for an accurate and consistent hazard study within a probabilistic framework for relevant projects.

2.1.1 Ground Response Analyses

The results of a GRA are affected by uncertainties and variabilities due to the assumption of horizontally stratified medium and to selected *model parameters*, particularly in case of strong nonlinear responses.

The applicability of the 1D assumption of GRAs has been addressed by Faccioli et al. (2002). The authors studied the complex site effects in predicting ground motions, including the topography. They found that, even for complex 2D-3D geological environments, the predominant resonance frequencies are controlled by the 1D simple formulations. However, 1D wave propagation models cannot account for the magnitude of the amplification, and the width of the relevant frequency band observed in weak motion records. For these purposes, an SRA could be required. Baise et al. (2011) and Thompson et al. (2012) stated that an initial assessment of the applicability of GRAs should always be performed by a taxonomic procedure. They classified the investigated sites as “simple” or “complex”, depending on the accuracy obtained by 1D GRAs. The analyst can select the most suitable type of analysis (GRA or 2D/3D SRA) depending on the site complexity (Thompson et al. 2012, Afshari and Stewart 2015), always accounting for the nonlinear response of the site (Zalachoris and Rathje 2015, Kim et al. 2016). In fact, preliminary results from GRAs found a general underprediction of the motion, for low periods (i.e., lower than the model period), possibly due to the difficulty in catching different phenomena (Kwok et al. 2008, Stewart and Kwok 2008, Li and Asimaki 2010). In some particular circumstances, 1D models also show a “base-isolation effect” due to high shear strains (i.e., small stiffness) in a specific layer. This phenomenon is prevented in case of 2D and 3D processes, thanks to the lateral heterogeneity that allows a more realistic spatial spreading of stresses (Makra and Chávez-García 2016).

Besides the model dimension, several studies have addressed the actual capabilities of GRAs in predicting the mean site response (Stewart and Baturay 2001, Baturay and Stewart 2003, Asimaki et al. 2008, Kwok et al. 2008, Stewart 2008, Li and Asimaki 2010, Asimaki and Li 2012, Kaklamanos et al. 2013a, Kaklamanos et al. 2013b, Afshari and Stewart 2015, Kaklamanos et al. 2015, Shi and Asimaki 2017). These results also proved that the user should possess specific expertise and particular knowledge of the global procedures and the physics of the phenomenon. This is particularly true in case of the strong nonlinear responses (Park and Hashash 2005, Hashash et al. 2010, Stewart et al. 2014, Kim et al. 2016, Régnier et al. 2016, Régnier et al. 2018).

Notwithstanding these limitations, GRAs are still the primary choice for the non-ergodic assessment of the site response (Stewart et al. 2014).

It is also recognized that GRAs are a useful tool to investigate the role of *uncertainties* and *variabilities* in site response studies (Field and Jacob 1993). Generally, uncertainties and variabilities are overestimated for low periods and underestimated for long periods (Rodriguez-Marek et al. 2014, Afshari and Stewart 2015, Pehlivan et al. 2016), compared to the results obtained with the data-based approach. However, other examples showed consistency with the variability obtained from recorded data (Papaspiliou et al. 2012a, Papaspiliou et al. 2012b, Kaklamanos et al. 2013b).

The probabilistic philosophy and the IQM method applied to GRAs should account for six main sources of uncertainties on the results, listed thereafter in order of relevance (Foti et al., 2019):

- Shear wave velocity (V_S) profile;
- Modulus reduction and damping (MRD) curves, describing the variations of the normalized shear modulus G/G_0 and the damping D with the cyclic shear strain γ_c;
- Input motions selection;
- Type of non-linear approach;
- Shear strength;
- Small strain damping (D_{min}).

The last two are important in specific conditions and are often not accounted as primary sources of uncertainties (e.g. Idriss 2004, Rathje and Kottke 2011). Specifically, the shear strength may be significant when large strains are expected (e.g. for thick and soft soil deposits).

2.1.2 *Simplified methods*

The simplified approaches for the assessment of the site effects synthetize the site response through a set of amplification factors that modify the ground motion characteristics evaluated for a reference condition. The amplification factors mainly depend on the local geology of the site accounted via the definition of a number of subsoil categories. Each category clusters different subsoil conditions sharing similar expected amplification. The classification scheme is a function of synthetic parameters representing the features of the soil deposit most affecting the site response (e.g., average stiffness, depth, fundamental frequency).

The main inspiration of the simplified approach is the pioneering study by Seed et al. (1976), which demonstrated the influence of soil conditions on the shape of the surface response spectra. Its results were incorporated into the ATC report (ATC 1978), which firstly introduced prescriptions for the estimate of the site effects. Precisely, it defined specific spectral shapes and amplification coefficients as function of the surface geology. Then, Borcherdt (1994) proposed a quantitative criterion for the classification of sites sharing common response, based on the $V_{S,30}$ parameter (i.e., the harmonic average of the shear wave velocity in the upper 30 m of the soil profile). This scheme considers a key quantity governing wave propagation and soil response (i.e., the V_S profile), whose characterization is possible without relevant effort, since the investigation is limited to a shallow portion of the soil deposit. Dobry et al. (2000) proposed a $V_{S,30}$-based site categorization system for the National Earthquake Hazard Reduction Program (NEHRP) provisions. A similar scheme was thereafter adopted in several building codes (e.g., CEN 2004, ICC 2015, ASCE 2010), which propose this approach for ordinary and for preliminary assessment studies, in absence of more advanced analyses.

The simplified approach introduced by most current building codes clusters different subsoil conditions into a limited number of site categories, identified by a range of $V_{S,30}$ values. For each site category, the approach prescribes a stratigraphic amplification factor, which is dependent on the characteristics of the specific ground motion (magnitude or peak ground acceleration), in order to account for the soil nonlinear behavior. The prescriptions also provide an estimate of the alterations of the ground motion due to topography by means of a topographic amplification factor.

Despite its ease-of-use, the simplified approach for the estimate of the design ground motions incorporates some drawbacks, due to the small number of parameters for the description of the subsurface geology and the synthesis of a complex phenomenon into a set of amplification factors. Due to these limitations, the field of application is restricted only to stable sites (i.e., not affected by problems of landslides, liquefaction or seismically-induced settlements) where the geology does not include lateral inhomogeneities and strong variations of the mechanical properties with depth (e.g. CEN 2004).

Moreover, several studies (e.g. Castellaro et al. 2008) questioned about the reliability of synthetizing the deposit characteristics into a single parameter, i.e. $V_{S,30}$. This scheme, indeed, cannot model the effect of other relevant elements for the seismic response, for instance the impedance contrast, the thickness of the soil deposit and mechanical parameters governing the nonlinear behavior as the plasticity index (Pitilakis 2004, Pitilakis et al. 2013, Pitilakis et al. 2018, Rodriguez-Marek et al. 2001, Ciancimino et al. 2018, Foti et al. 2018). Another topic of debate is the consistency of the $V_{S,30}$ itself as proxy for stratigraphic amplification, which might be misleading in some conditions (e.g., in presence of shallow velocity inversions, as pointed out by Di Giacomo et al. 2005). Therefore, new site classification schemes proposed to integrate or substitute the $V_{S,30}$ with parameters as the bedrock depth or the fundamental frequency of the soil deposit (e.g., Bouckovalas et al. 2006, Cadet et al. 2012, Pitilakis et al. 2013, Pitilakis et al. 2018).

Finally, the definition of a limited number of site categories can be misleading (Pitilakis 2004) and entails a large degree of variability of the predicted response (Ciancimino et al. 2018). Indeed, each category clusters various soil conditions exhibiting different levels of amplification. The large variability might impact the reliability of the simplified approach, since there may be a number of soil conditions for which the simplified approach does not provide an estimate on the safe side (Foti et al. 2018, Aimar et al. 2019).

For these reasons, the simplified approach is under constant study for its development and improvement, in order to implement a methodology for the assessment of the site response able to provide simultaneously simplicity of application and reliability and robustness of the estimate.

2.2 Urban scale applications

The reduction of the seismic vulnerability of urban areas cannot disregard the evaluation of the amplification phenomena that affect the expected seismic hazard. SM is therefore an essential tool to implement effective prevention strategies and to manage emergency situations in the aftermath of extraordinary events (Aversa and Crespellani 2016). The main purpose of large-scale applications is identifying zones characterized by homogeneous seismic behaviour in terms of site response and ground instabilities (ISSMGE 1999; Working Group ICMS 2008). The different scale of SM studies and single site studies causes considerable differences for both the intended outcomes and the applied methodologies (Foti et al. 2018). Within this framework, it is clear that SM studies and site-specific analyses are not interchangeable, but rather complementary activities.

In the following, the peculiarities of SM studies are analysed. The attention will be focused on the ground motion estimation, therefore ground instabilities are not treated in the present paper. The two proposed examples have been developed within the framework of the SM studies carried out for the reconstruction of the municipalities struck by the 2016 Central Italy seismic events (Hailemikael et al., 2019).

2.2.1 *Guidelines for Seismic Microzonation studies*

In the past years, the need to define a common methodology and to standardize SM studies has led to the development of several national and international practical guidelines (a detailed review can be found in Pagliaroli 2018). Among these, a milestone is constituted by the Manual for Zonation on Seismic Geotechnical Hazards developed by the Technical Committee on Earthquake Geotechnical Engineering of the International Society on Soil Mechanics and Geotechnical Engineering (ISSMGE 1999). The manual firstly introduced the concept of three different levels of SM, defined according to the available information and, as a consequence, to the purposes of the studies. The three levels, subsequently incorporated in the Italian Guidelines (Working Group ICMS 2008), are characterized by increasing complexity:

- Level 1: the investigated area is qualitatively subdivided into seismically homogeneous microzones on the basis of the existing data. Within this level, no analyses are carried out to quantitatively estimate site effects.
- Level 2: on the basis of the previous level, preliminary assessments of the site effects are obtained adopting simplified methods (i.e., tables and empirical laws). When necessary, insights for the uncertainties identified in Level 1 are addressed integrating the existing data.
- Level 3: a detailed SM map is developed from the results of specific numerical analyses carried out on areas characterized by high seismic hazard and/or economic and social relevance. The analyses are based on a detailed subsoil model defined by means of available data and additional surveys.

The SM map usually reports synthetic indicators of the site response associated with each seismically homogeneous microzones. For example, the computation can be based on the average amplification over a specific range of spectral periods in the acceleration response spectra (Working Group ICMS 2008), denoted as $\overline{AF}_{T_a-T_b}$ and computed according to the following formulation:

$$\overline{AF}_{T_a-T_b} = \frac{O_{T_a-T_b}}{I_{T_a-T_b}} \tag{1}$$

where T_a and T_b define the interval of spectral periods and $I_{T_a-T_b}$ and $O_{T_a-T_b}$ are, respectively, the mean values, within the spectral periods range, of the pseudo-spectral acceleration for the selected input motion SA_i and for a specific point at the surface of the site SA_o, namely:

$$I_{T_a-T_b} = \frac{1}{T_a-T_b} \cdot \int_{T_b}^{T_a} SA_i(T)dT \tag{2}$$

$$O_{T_a-T_b} = \frac{1}{T_a-T_b} \cdot \int_{T_b}^{T_a} SA_o(T)dT \tag{3}$$

The values of $\overline{AF}_{T_a-T_b}$, computed for a set of input motions, are subsequently logarithmically averaged to get stable estimates.

As for the Italian context, numerous efforts have been made in defining a widely accepted, practical methodology. The history of SM studies in Italy can be divided into three different generations, according to the available knowledge at that time and to the objectives of the studies (Crespellani 2014). The first generation is characterized by studies carried out mainly by researchers for scientific purposes, reference is made to the studies conducted in Tarcento (Brambati et al. 1980) and Ancona (VV. AA. 1981), consequently to the Friuli (1976) and Ancona (1972) earthquakes. Within this period, the first example of quick studies of practical value is given by the SM of 39 urban centres in the aftermath of the Irpinia (1980) earthquake. The project, carried out under the control of the National Geodinamica Project of the National Research Council (CNR 1983), has been intended to be a reference point for the reconstruction of the centres in the aftermath of the seismic event. The growing attention given by researchers and authorities to the SM studies has led, in 1986, to the development of the first example of Italian guidelines (Faccioli 1986).

After the Umbria-Marche seismic sequence (1997), the SM studies of about 80 villages have been undertaken with the prospect of proper planning for the reconstruction. It was clear, from that point forward, the need to introduce site effects into regional codes. As a consequence, a new generation of SM studies (i.e., the second generation) has been developed on a regional scale even with the support of the Italian regions (Crespellani 2014), e.g., the studies promoted by the Emilia Romagna region (Marcellini et al. 1998), the VEL (Evaluation of Local Effects) project promoted by the Toscana region (Ferrini, 1999), and the SM of Fabriano (Marcellini and Tiberi 2000) and Senigallia (Mucciarelli and Tiberi 2007). The importance of the construction of a reliable geological and geotechnical model for the numerical simulations of site response was recognized in this second generation, emphasizing the role of geotechnical laboratory tests and geophysical surveys to define the dynamic properties of the soil (Crespellani 2014). Within this framework, it is worth to mention the case study of L'Aquila (Working Group MS-AQ 2008) for his contribution in addressing both scientific and practical problems.

In 2008, the Italian Civil Protection coordinated a team of researchers and technical representatives of the Italian Regional Government Authorities in order to provide practical guidelines and to establish standard procedures for SM. The final products of the project are the National Guidelines of SM studies (Working Group ICMS 2008), approved by the National Department of Civil Protection and Conference of Regions and Autonomous Provinces.

The third, and last, generation of SM studies is characterized by different perspectives. The main goal of the studies is not of scientific nature: SM studies are not considered merely as post-earthquakes tools for the reconstruction, but they are also recognized to be effective ordinary strategies for the planning of seismic risk mitigation activities (Crespellani 2014). The studies should be carried out by practitioners as quickly as possible, accordingly with administrative needs and consistently to the Italian Guidelines (Working Group ICMS 2008). To provide scientific support to the authorities involved in the SM projects, the CentroMS has been founded in 2015, joining together research institutions and university departments.

2.2.2 GRAs for SM studies

GRAs are generally adopted also for microzonation studies where the one-dimensional hypothesis may be regarded as a reasonable assumption. Nonetheless, the significant spatial variability that characterizes each seismically homogeneus microzone implies the necessity to define an average site response, without considering the local specific features at the single-project scale. The following example, coming from the SM study of Tino, is presented to better explain the differences between GRAs for small- and large-scale applications (Foti et al. 2018).

Tino is a fraction of the village of Accumoli (Rieti) almost destroyed by the seismic events of Central Italy in 2016 (Stewart et al. 2018). The area has been characterized by means of geological and geotechnical surveys, aiming at defining a reliable subsoil model for site response analyses. Specifically, a Down Hole (DH) test carried out at the Tino site has provided the information regarding the V_S and V_P (i.e., the compression wave velocity) profile. Figure 2.a reports the results of the test, along with the subsoil stratigraphy. The site is characterized by a shallow 5 m thick layer of debris (V_S≈430m/s), a yellow sandstone middle layer from slightly weathered (V_S≈740m/s, about 9 m thick) to hard (V_S≈1135m/s, about 4 m) on an underlying 2-3 m thick layer of grey sandstones (V_S≈660m/s) and the seismic bedrock constituted by hard yellow sandstones (V_S≈930m/s).

The geological stratigraphy of the whole area is relatively homogenous. Moreover, neither an irregular stratigraphic geometry nor a particular surface topography are present. As a consequence, the area has been identified with a single seismically homogeneus microzone and the site response has been studied by means of GRAs. In order to reflect the large-scale application of the study, a simplified geological model has been developed for the seismically homogeneus microzone (Figure 2.b). The first layer (5-20 m thick) is constituted by debris, the underlying layer is constituted by the weathered sandstones (0-50 m thick) and the deepest part, constituted by hard havana sandstones, is the seismic bedrock of the model. Therefore, the hard sandstones between 14 and 18 m and the

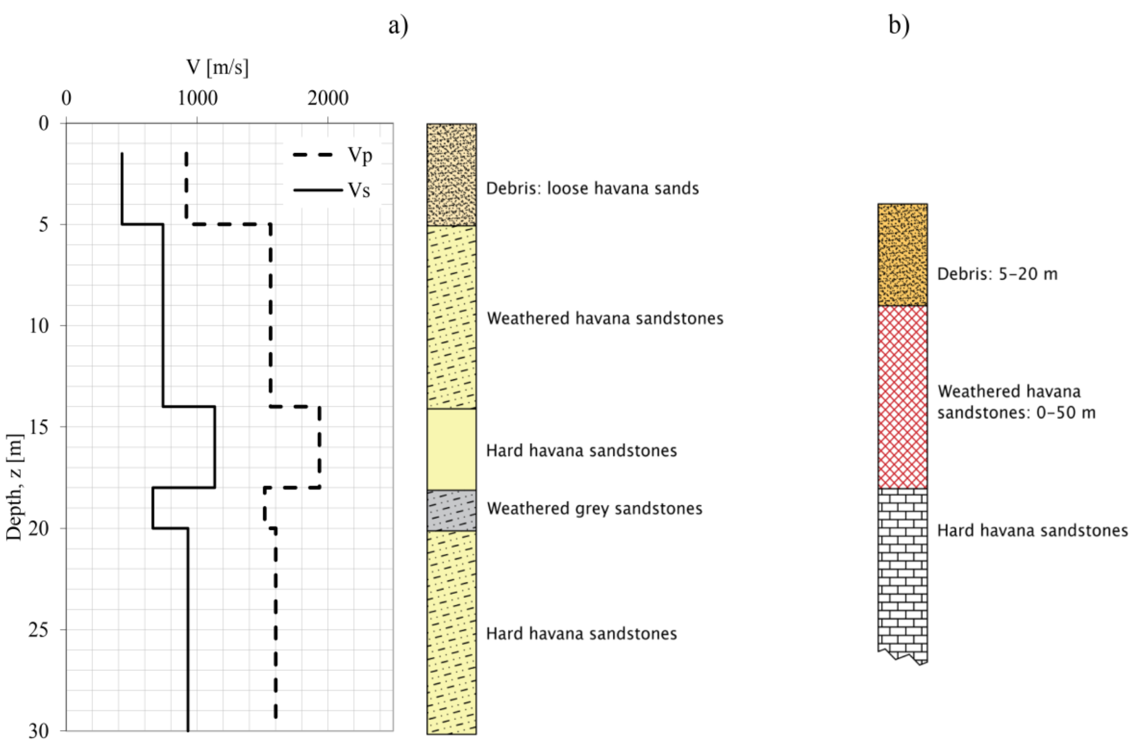


Figure 2 a) V_S and V_P profiles obtained from the DH test along with the subsoil stratigraphy; b) simplified sub-soil profile adopted for the GRAs of the SHM (modified from Foti et al. 2018).

underlying grey sandstones have been neglected in the simplified model. Table 1 presents the adopted dynamic properties for each lythotype, i.e. the interval velocity V_S, the unit weight γ and the MRD curves. The V_S profile has been defined on the basis of the DH test, while the MRD curves correspond to literature models derived on similar soils.

The spatial variability of the subsoil geometry within the wide area studied has been considered performing four GRAs, characterized by different thicknesses of the first layer which mainly affect the site response: 5, 10, 15, and 20 m, respectively. For the second layer, a constant thickness of 10 m has been adopted.

Table 1. Dynamic properties of the Tino simplified subsoil model.

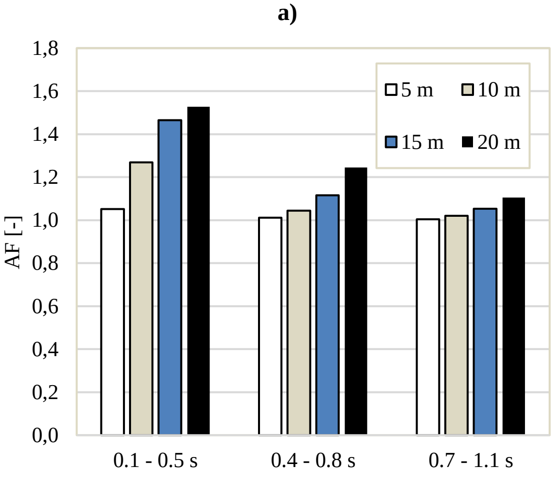
Lithotype	*Vs* (m/s)	γ (kN/m^3)	MRD curves
Debris	430	16	Seed and Idriss (1986)
Weathered sandstons	740	21	Rollins et al. (1998) (Upper Limit)
Bedrock	930	22	Linear Elastic *D*=0.5%

It must be pointed out that the methodology here adopted to take into account the spatial variability is not rigorous; it is just a convenient simplification to explain the differences between GRAs for small- and large-scale studies. The probabilistic assessment of site effects is beyond the scope of this example and will be specifically treated in Section 3.

The input motions consists of seven unscaled horizontal natural records, selected by the ITACA archive (itaca.mi.ingv.it/, Luzi et al. 2017) to be on average compatible, as suggested by the Italian Building Code (MIT 2018), with the Uniform Hazard Spectrum (return period of 475 years) at reference conditions. More details about the selection process are reported in Luzi et al. (2019).

The results of the GRAs are reported in Figure 3.a in terms of average $\overline{AF}s$ for the three spectral periods fields suggested by the Italian Guidelines (Working Group ICMS 2008), i.e., 0.1-0.5 s, 0.4-0.8 s and 0.7-1.1 s. Figure 3.b reports the average input and output SAs.

It is clear that the first layer dominates the site response: the higher is the thickness of the layer, the lower is the resonance frequency and, as a consequence, the higher are the $\overline{AF}s$ in the considered ranges of periods. In absence of specific information about the distribution of the soil stratigraphy in the considered area, the model characterized by the higher $\overline{AF}s$ (i.e., thickness



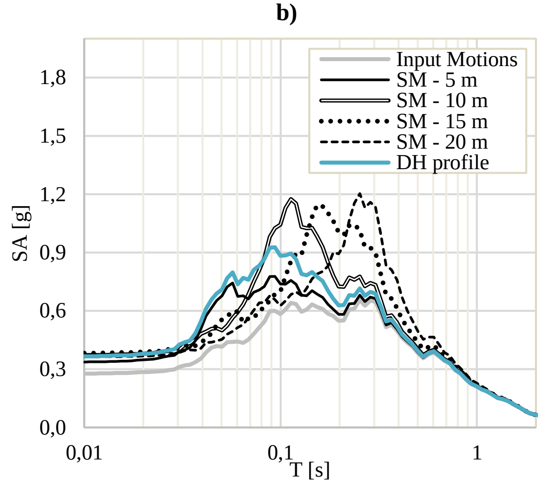


Figure 3. Results of GRAs for the Tino site in terms of a) $\overline{AF}_{T_a-T_b}$ and b) SA (modified from Foti et al. 2018).

equal to 20 m) has been considered as representative of the whole seismically homogeneus microzone.

Figure 3.b also reports the average SA obtained from GRAs performed on the specific V_S profile coming from the DH test (Figure 2.a). The latter would be used to define the site response for a hypothetical project to be realized in the specific investigation site. The site responses are quite different, especially for periods ranging from 0.1 to 0.5 s (typical vibration periods of ordinary buildings in that area). In the case of a site-specific project characterized by a specific natural vibration period of 0.1 s, the SA coming from the SM study would be not on the safe side. Conversely, for large-scale applications involving projects characterized by different vibration periods, the adoption of a simplified model (but able to capture the average site response) prevents that differences related to the specificity of a single-site influence the $\overline{AF}s$ of the whole seismically homogeneus microzone.

2.2.3 SRAs

The main strengths of SM studies are the opportunity of relying on experts of multiple disciplines and the possibility to build a reliable subsoil model wide enough to capture the multidimensional phenomena. Consequently, SRAs can be carried out for large-scale applications. Conversely, GRAs are sometimes carried out for site-specific analyses also in presence of 2D/3D effects, given the lack of appropriate information to define the subsoil model. Multidimensional effects are subsequently taken into account by means of simplified approaches incorporated in most seismic code provisions (e.g., CEN 2004, MIT 2018). However, these approaches are not always able to capture the site response for complex

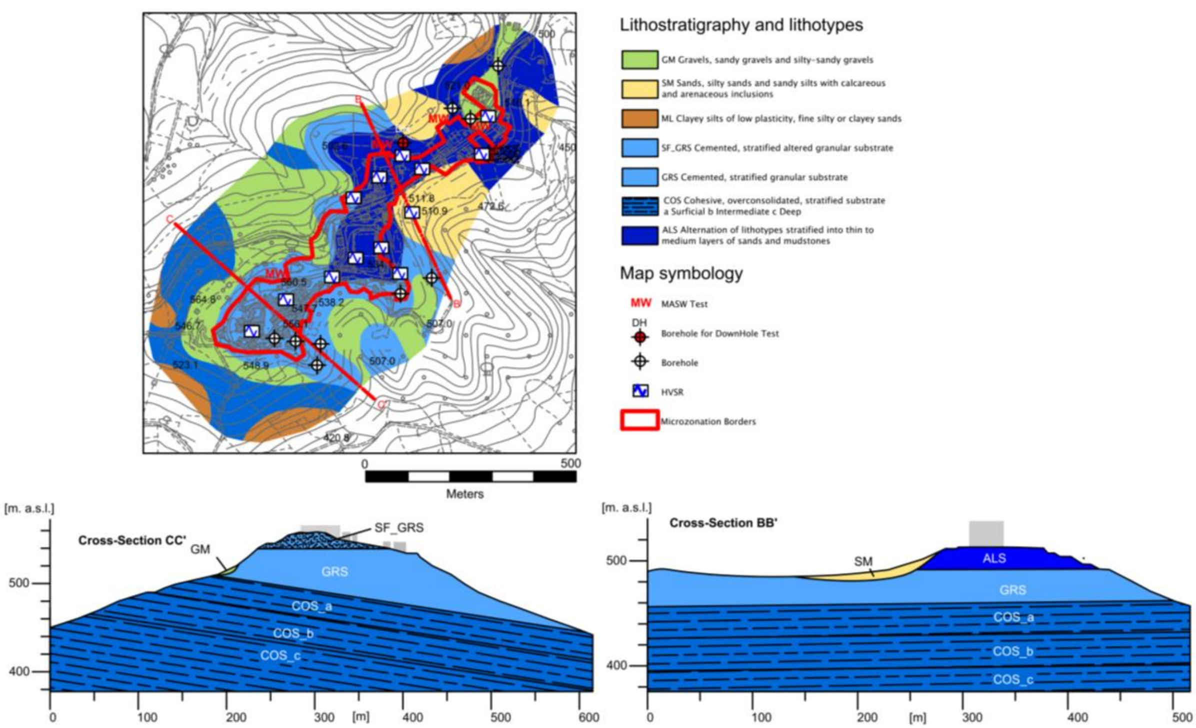


Figure 4. Lithotechnical map and cross-sections of the Montedinove historical centre (from Pagliaroli et al. 2019).

surface topography and morphological conditions.

A case in point is represented by the SM study carried out at the Montedinove site, in the province of Ascoli Piceno, Marche region (further details about the case study can be found in Angelici 2018, Foti et al. 2018 and Pagliaroli et al. 2019). The area is divided into three different zones: the localities of Lapedosa and Croce Rossa and the historical center. The historical center presents a quite interesting stratigraphic condition: it lies mainly on a cemented granular from weathered (SF_GRS) to unweathered (GRS) bedrock, and on an alternation of stratified lithotypes (ALS). The topography of the site is characterized by a NE-SW hilly ridge. The deepest portion is constituted by the Blue Clays Formation with a pelitic lithofacies (hereafter identified as cohesive, overconsolidated stratified bedrock, COS). On the sides of the ridge, there are 3-15 m thick coverings, classifiable as gravels and sandy gravels (GM) and sands and silty sands (SM). Figure 4 reports the lithotechnical map of the Montedinove historical centre and the cross-sections adopted for the SRAs.

The subsoil model has been defined by means of the existing data collected in the level 1 of the SM study and of the additional investigations carried out within the level 3 of the project, i.e. one 35 m deep DH test, five MASW (Multichannel Analysis of Surface Waves) tests, and 24 HVSR (Horizontal to Vertical Spectral Ratio) tests. Figure 5.b reports the results of the DH test in terms of V_S and V_P profiles. The V_S of the lithotypes not inferred by the DH test have been defined by means of non-invasive tests. In particular, the V_S of the COS lithotype has been defined on the basis of the MASW tests carried out in the near Lapedosa locality, where the COS is outcropping. The lithothype has been then subdivided into three different units, with an increasing V_S, i.e. the upper (COS_a, V_S=560 m/s), the intermediate (COS_b, V_S=650 m/s) and the lower (COS_c, V_S=800 m/s). The profile is characterized by a marked V_S inversion between the GRS and the underlying COS_a.

The MRD curves of the COS have been defined on the basis of the Resonant Column test carried out on a sample retrieved for the same soil from the municipality of Monte Rinaldo (Ciancimino et al. 2019). For the other materials,

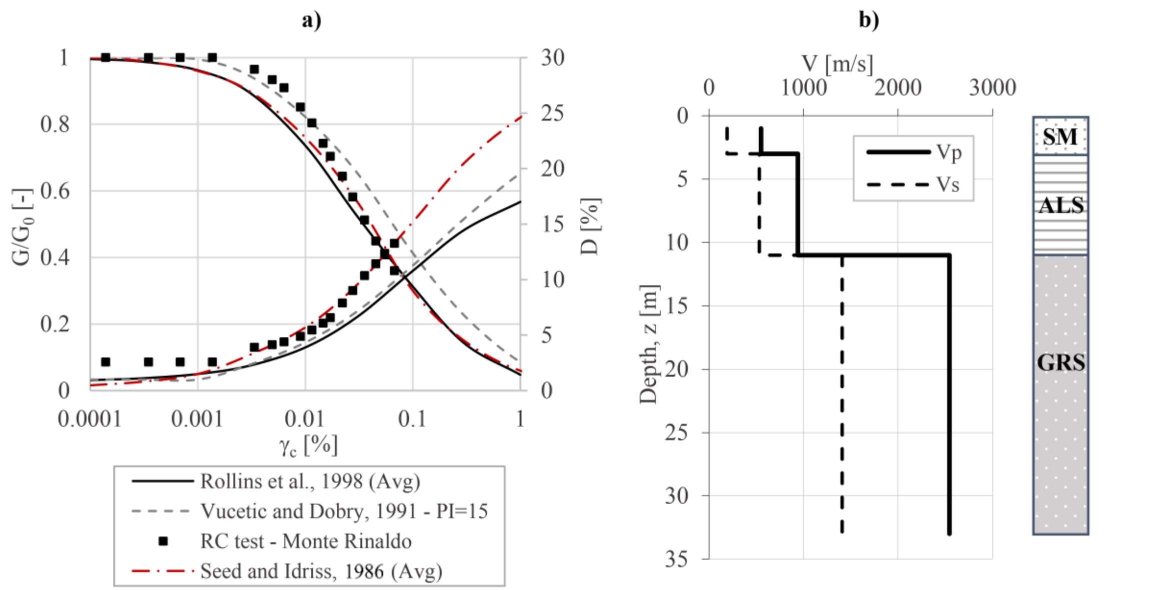


Figure 5. Montedinove subsoil model: a) MRD curves; b) V_P and V_S profiles from the DH test (modified from Pagliaroli et al., 2019).

literature data obtained on similar soils have been adopted. The MRD curves are reported in Figure 5.a and the dynamic properties adopted for the subsoil model are summarized in Table 2.

Table 2. Dynamic properties of the Montedinove subsoil model.

Lithotype	*Vs* (m/s)	γ (kN/m^3)	MRD curves
SF_GRS	550	19.0	Rollins et al. (1998)
GRS	1400	22.0	Linear Elastic D=0.5%
GM	340	18.6	Rollins et al. (1998)
SM	190	17.6	Seed et al. (1986)
ALS	530	19.6	Vucetic and Dobry (1991) - PI=15
COS_a	560	19.6	Resonant Column test
COS_b	650	19.6	
COS_c	800	19.6	Linear Elastic D=0,5%

SRAs have been performed for the two cross-sections (i.e., BB' and CC') represented in Figure 4. The $\overline{AF}s$ for the three ranges of period here considered are represented in Figure 6.a. Maximum amplifications are observed at the ridge crest, where topographic site effects are expected. A peak is also present on the left edge of the ridge for section BB', where a large impedance contrast between the SM and the underlying GRS is present.

Figure 6.b reports the average output SA obtained from SRAs and from GRAs carried out on 1D models developed on the basis of the stratigraphy at the ridge crest (red dots in the cross-sections). For a direct comparison between GRAs and SRAs, a constant factor has been applied to the SA obtained from GRAs, in order to take into account the topographic effects with the simplified method proposed by Italian Regulations (NTC18). Specifically, both the cross-sections have been classified within the topographic class T4 (i.e., ridge characterized by a slope angle higher than 30°) and, then, a factor of 1.4 has been applied.

The comparison highlights the role of the topographic effects, since the SAs obtained by SRAs are, for this case study, significantly higher than the ones computed through GRAs. In particular, for the cross-section CC', a maximum aggravation factor (defined as the ratio between 2D and 1D analyses) of 3 is observed, in contrast with the lower value predicted by the simplified method. In this situation, the site response is mainly dominated by complex 2D effects that can be captured just performing advanced SRAs. Within the context of large-scale applications, this is possible thanks to the wide subsoil model defined for the whole area of interest.

3 CASE STUDY

The goal of the present case study is to provide some insights about the effects of the uncertainties on the site response and their role in the probabilistic prediction of the design ground motions. The need for a consistent stochastic approach derives from the impossibility of selecting a-priori conservative values of model parameters in dynamic analyses taking into account the role of soil-nonlinearity. For example, an underestimation of soil stiffness would cause large strains and therefore an overestimation of material damping, which could overdamp the actual response of the soil deposit. On the other side, an overestimation of soil stiffness would provide small impedance constrasts and therefore a possible underestimation of stratigraphic amplification.

The example focuses only on the two components of the soil model that mainly affect the uncertainties in the results: the V_S profile and the MRD curves. Field and Jacob (1993) demonstrated that these parameters dramatically influence the ground response. The uncertainties in the input motions are implicitly accounted for by using multiple records for the analyses. The uncertainties due to other parameters (e.g., the nonlinear approach) will not be considered in this example.

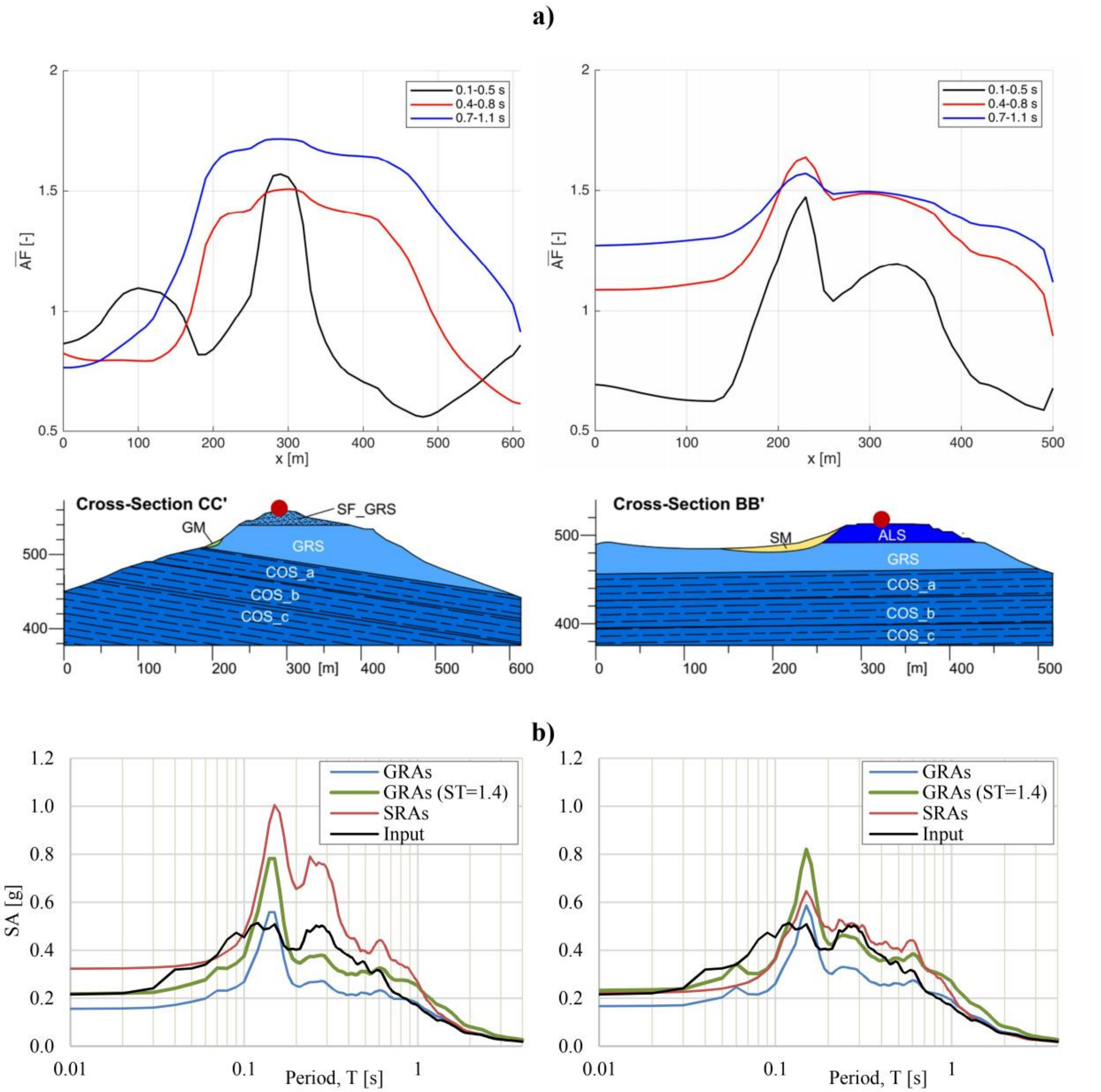


Figure 6 Results for the Montedinove site in terms of a) $\overline{AF}$s and b) SAs from GRAs, SRAs and GRAs with an aggravation topographic factor (as defined by NTC18) of 1.4 (modified from Pagliaroli et al., 2019).

A Monte-Carlo simulation has been conducted to develop a statistical sample of ground models, whose parameters are generated from the results of the geophysical and geotechnical investigations. The nonlinear modeling of the seismic response refers to EQuivalent Linear (EQL) GRAs (Idriss and Seed 1968), which assume linear viscoelastic materials, with time-invariant shear stiffness and damping ratio. The procedure accounts for the nonlinear behavior of the soil by computing strain-compatible quantities derived from the MRD curves at an effective strain level usually equal to 65% the maximum value. The computation has been performed with the DEEPSOIL v7.0 software (Hashash and Park 2001, Hashash et al. 2017).

3.1 Site description

The village of Marsia falls in the municipality of Roccafluvione (AP), in the Marche region, which has been struck by the seismic sequence started on the 24th August 2016. The site, together with other 140 municipalities, was object of intense geological and geotechnical investigations, resulting into a detailed ground model.

A DH and a MASW tests were conducted at the locations shown in Figure 7 for the definition of the interval velocity (V_S) and the harmonic average ($V_{S,z}$) profile shown in Figure 8.a-b.

The two geophysical surveys provided similar results, but some differences can be observed in terms of depth of the halfspace and thickness of the shallower layer. A reason of such discrepancies may lie in the different investigated volumes by the two surveys: the DH test focuses on a single vertical, whereas the MASW test detects the wave propagation along the array and its result averages potential lateral heterogeneities of the soil deposit (Passeri 2019). Also, the location of the two surveys is not the same and differences can be due to the 2D local geology of the slight slope. For these reasons, the

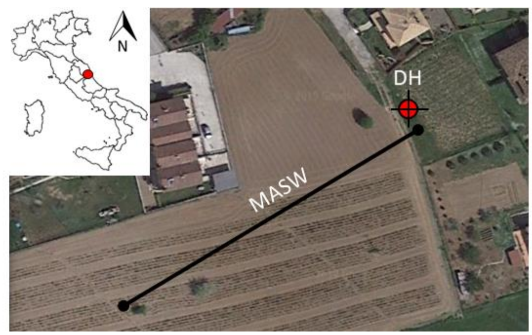


Figure 8. Location of the geophysical surveys.

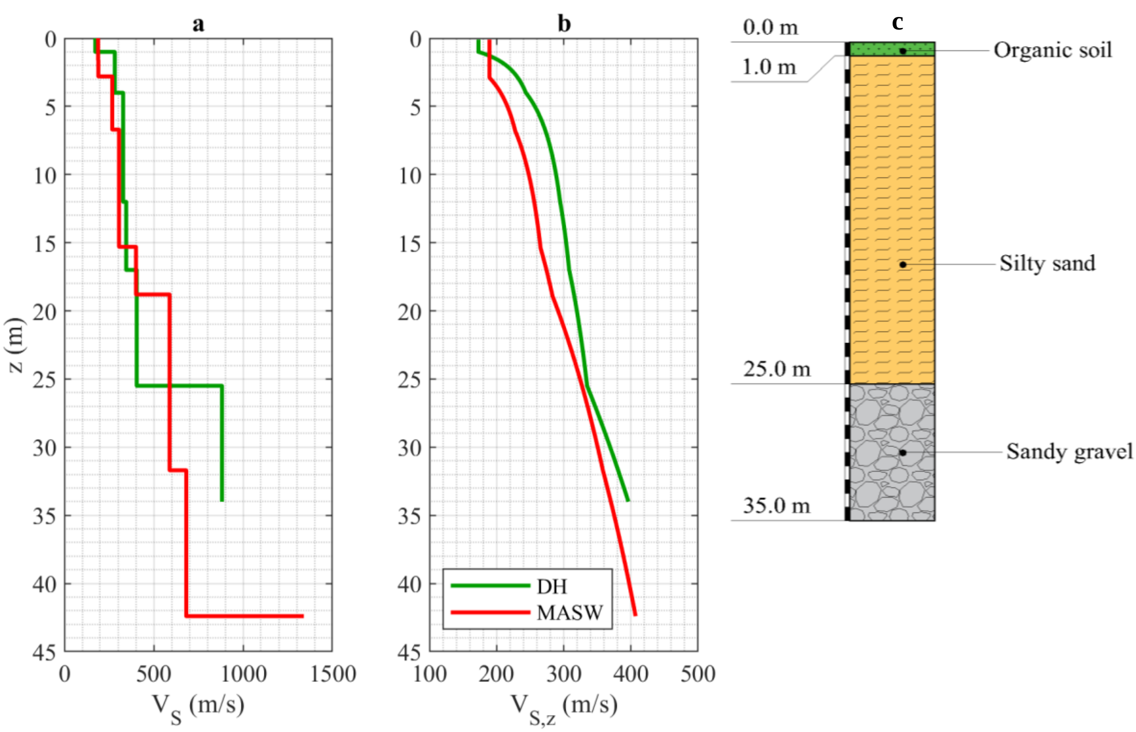


Figure 7 a) V_S profiles obtained from the MASW and the DH survey; b) $V_{S,z}$ profiles obtained from the MASW and the DH survey; c) Simplified stratigraphic profile at the DH borehole.

study followed two parallel analyses based on the two V_S profiles in Figure 8. Then, the results are compared in order to obtain a measure of the effect likely due to spatial variability on the site response.

The stratigraphy obtained from the borehole indicates the presence of a thin layer of organic soil over a 25 m-thick stratification of silty sands, lying over a formation of sands and gravels, which develops down to the bottom of the investigated depth. Figure 8.c shows the simplified stratigraphic model. The deepest layer was identified as the seismic bedrock since it is located in correspondence of a large impedance contrast, where the V_S becomes higher than 800 m/s. Some relevant properties for the GRAs (i.e., the plasticity index *PI*, the unit weight γ, the over-consolidation ratio *OCR* and the at-rest lateral pressure coefficient K_0) were derived through literature relationships (Hunter 2003, Massarsh 1979) and Table 3 lists their values.

With regard to the MRD curves, the study adopted the model proposed by Ciancimino et al. (2019), which is a specialized version of the Darendeli (2001) model, adapted to capture the specific behavior of silty and clayey soils from the Central Italy area.

Table 3. Geotechnical parameters of the Roccafluvione subsoil model.

Lithotype	Organic soil	Silty sand
***PI* (%)**	40	15
γ (kN/m^3)	12	15
***OCR* (-)**	1	1
K_0 (-)	0.64	0.493

The model was calibrated on a database of 72 cyclic tests carried out on low and normal active clays and silts of low plasticity with *PI* ranging from 0 to 45%. The tests were carried out under effective confining pressures, σ_m', ranging from 30 to 440 kPa. The model also provides information about the statistical dispersion of the results, which can be used as indicator of the uncertainty affecting the MRD curves. Specifically, two relationships were obtained on the basis of the model residuals to estimate the standard deviation as a function of the predicted values (i.e., MRD curves). Figure 9 shows the superposition for the silty clay layer between the distribution of the theoretical MRD curves, represented by the interval defined by one standard deviation, and the experimental points sharing common conditions in terms of plasticity index and confinement level.

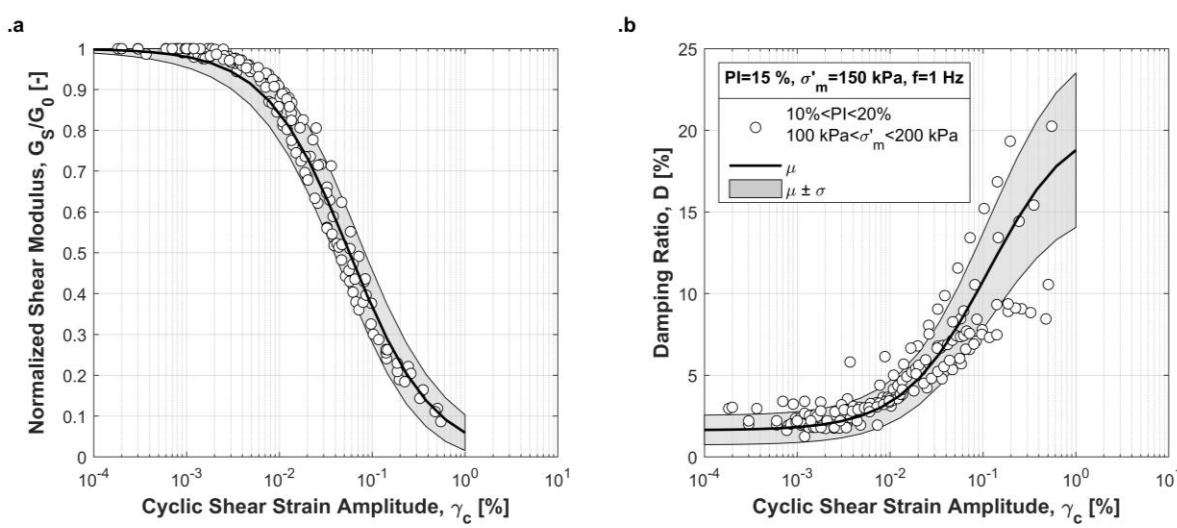


Figure 9 Theoretical distribution and experimental points for a) the MR curve and b) the D curve.

A special remark should be mentioned for the soil small-strain damping ratio D_{min}. Some studies questioned the applicability of a laboratory-based damping measurement to field conditions (Stewart et al. 2014) and proposed alternative approaches for its determination, based on the study of weak motions (e.g., Thompson et al. 2012, Zalachoris and Rathje 2015). On the other side, Stewart and Kwok (2008) observed that the damping-related misfit between theoretical and real response may not be relevant in some shallow soil profiles and the laboratory value is adequate in such situations. Due to the lack of information about the definition of D_{min} and its role on the ground response, the present study assumes as D_{min} the values obtained from the model proposed by Ciancimino et al. (2019).

3.2 Input motions

The input motions consist of seven unscaled seismologically and spectrum-compatible acceleration time histories selected with the web service REXELite (Iervolino et al. 2010). The tool extracts ground motion records from the Italian strong motion database ITACA (itaca.mi.ingv.it/, Luzi et al. 2017), taking into account the compatibility with the expected magnitude and epicentral distance intervals. Then, it checks for an adequate match between the average spectrum and the target Uniform Hazard Spectrum (return period of 475 years) for reference conditions, as provided by the Italian Building Code (NTC, MIT 2018). The average ordinate has to fall between 0.9 and 1.3 times the corresponding value of the code spectrum in the considered interval of vibration periods, ranging from 0.1 to 1.1 s (Figure 10).

More details about the selection process are reported in Luzi et al. (2019).

3.3 Generation of the ground models

The Monte-Carlo generation of the ground models consists in the extraction of two samples of 1000 V_S profiles, each one assuming the resulting profile for the single survey as base-case (Figure 7.a-b). The randomization has been obtained with the geostatistical model proposed by Passeri (2019), which represents an upgrade of the one introduced by Toro (1995). This new geostatistical model provides a physically-based and well-constrained population of soil models, compatible with the common geological features and the experimental site signatures (Passeri et al. 2019). The generation of the layer thicknesses refers to a non-homogeneous Poisson distribution. As for the generation of V_S values, the procedure randomizes the cumulated travel-times from a lognormal distribution, whose statistical parameters derive from a database of geophysical surveys by the Politecnico di Torino (Passeri et al. 2019). The choice of the randomization of the cumulated travel-times (or, equivalently, the harmonic average V_S profiles) is at the same time the most simple and the most crucial innovation of the model. The reader can refer to Passeri et al. (2019) for further details about the model architecture and parameters.

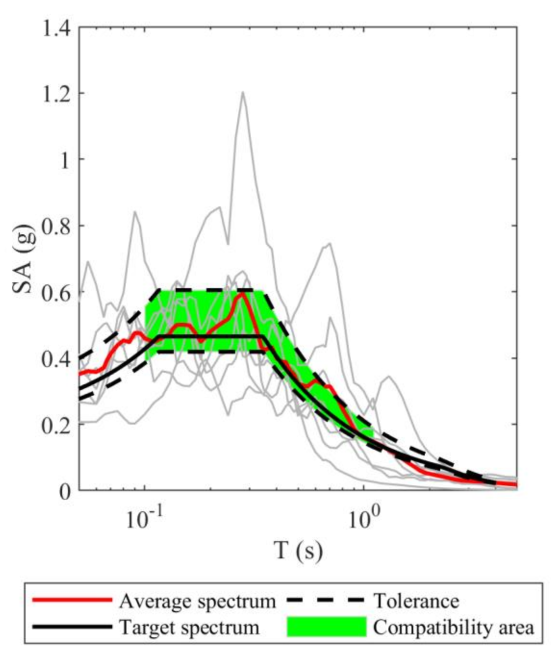


Figure 10. Spectral compatibility of the selected input motions.

Then, the procedure assigns the MRD curves. Thanks to the presence of information about their statistical dispersion, it is possible to simulate different MRD curves for each synthetic ground model, thus incorporating the uncertainties in the soil nonlinear behavior. The generation assumes a negative correlation between the G/G_0 curve and the D curve, by introducing a default correlation coefficient equal to -0.5 (Kottke and Rathje 2008). Furthermore, to avoid physically inconsistent MRD curves, there are some restraints on the possible values: the normalized modulus should not be smaller than 0.05, whereas the damping ratio should be bounded between 0.45% and 24.5% (i.e., the extreme values observed in the laboratory tests on the soils from Central Italy, normalized to a reference frequency of 1 Hz in order to account for the rate-dependence of this parameter, Ciancimino et al., 2019). Note that the defined minimum value of D_{min} suits the recommendations prescribed in Stewart et al. (2014).

3.4 Results

For each ground model, results are averaged through logarithmic mean with respect to the input motions, obtaining a representative response for every soil profile under the reference ground motion. In order to have synthetic indicators for the distribution of the results, the mean and the standard deviation of the spectral

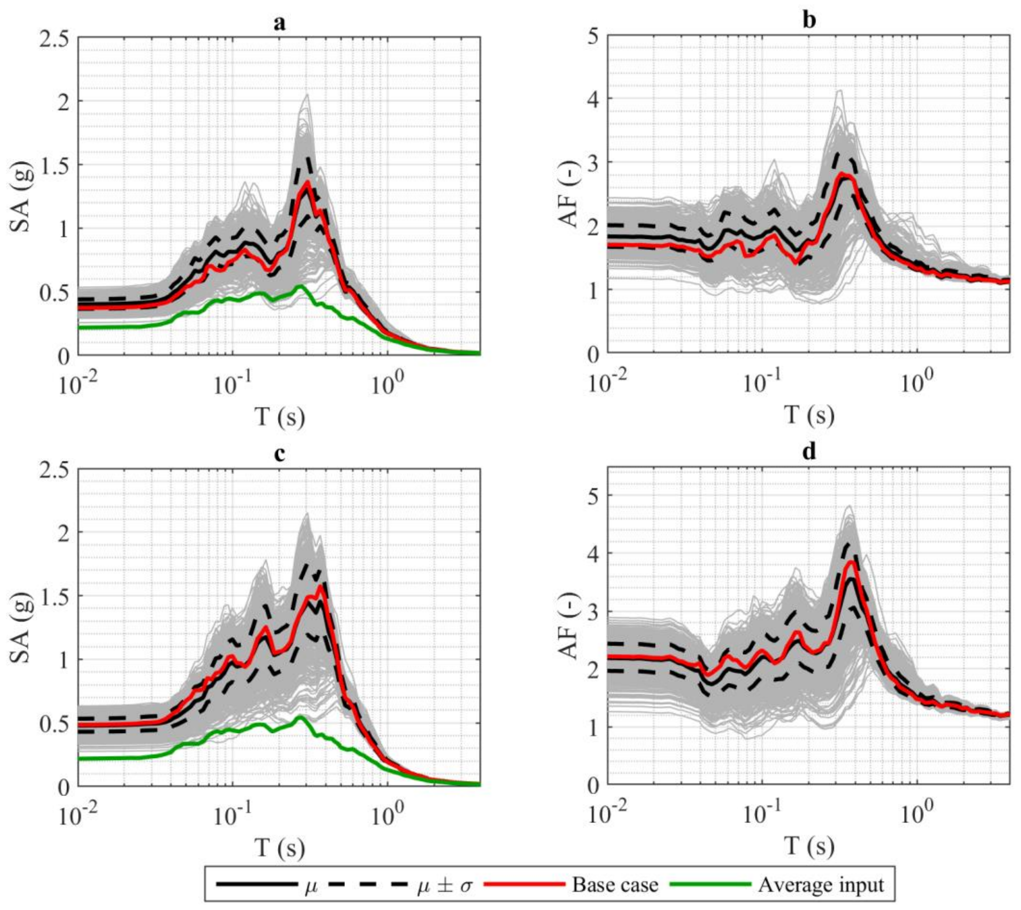


Figure 11 SAs of the a) DH- and c) MASW-based samples, compared with the average spectrum of the input motions; AFs of the b) DH- and d) MASW-based samples.

ordinates with respect to the ground models are computed, assuming lognormal distribution of the data. The procedure is applied for the two populations of ground models. Moreover, the study also reports the ground response of the base-case profile, assuming the mechanical parameters reported in Table 3 and the average MRD curves. This strategy allows for the comparison between the original soil profiles and the distribution of the results.

Figure 11 shows the results in terms of surface SA and AF for the DH-based samples (Figure 11.a and Figure 11.b, respectively) and the ones for the MASW-based models (Figure 11.c and Figure 11.d, respectively). Generally, there is an amplification of the design ground motion at almost all the vibration periods of interest, with a peak at 0.25 s.

On the other side, the response of the two groups of ground models is not the same, as shown in Figure 12.a. The MASW-based models undergo a larger amplification of the spectral ordinates for all the vibration periods of interest and the difference rises up to 20-30% at short vibration periods and close to 0.25 s (i.e., where the amplification is higher). Moreover, there is a deviation between the two curves for vibration periods ranging between 0.08 s and 0.3 s, since the MASW-based samples exhibit an amplification monotonically increasing together with the period, whereas the amplification function of the DH-based models decreases down to a minimum at 0.15 s. Figure 12.a reports also the AFs obtained from the ground response analyses performed on the DH and MASW base-case profiles, which might be taken as reference. Comparing these results with the mean curves of the samples, a good consistency is observed. The MASW base case exhibits larger amplification with respect to the randomized models, in correspondence of the peak and in the interval of vibration periods between 0.03 s and 0.2 s. Conversely, the amplification observed in the DH-based models is higher than in the correspondent base-case, especially at small vibration periods.

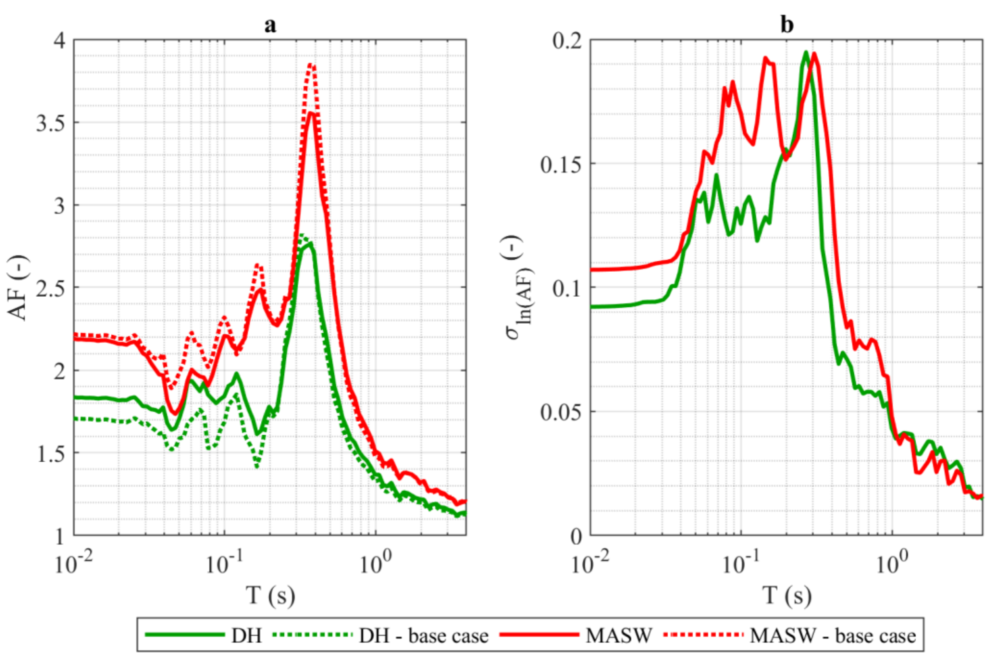


Figure 12 a) Mean AFs of the DH and MASW-based samples and AF of the corresponding base-cases; b) standard deviation (in logarithmic scale) of the AFs of the DH and MASW-based samples.

As for the uncertainty in the ground response of the two sets of samples, the logarithmic standard deviation of the AF is close to 0.1 at small vibration periods, it grows up to a peak a bit smaller than 0.2 for periods close to 0.4 and it gradually decreases at high periods (Figure 12.b). The MASW-based models assume a higher degree of dispersion and the standard deviation keeps its maximum value on a broad range of vibration periods between 0.08 s and 0.2 s, whereas the DH-based models show only a narrow peak.

The observed differences in the response of the two collections highlight the effect of the spatial variability of soil conditions in the site response: the mean value and the uncertainty of the response exhibited by models generated from two surveys performed close to each other and giving similar V_S profiles is not the same and disregarding this discrepancy might lead to errors in the estimate of the seismic action.

4 CONCLUSIONS

The evaluation of seismic hazard at a site requires a detailed assessment of seismic site response to account for the modification of ground motion that are expected as a consequences of the mechanical and geometrical characteristics. In the paper, the main features of site specific and urban scale studies have been considered to show how the two approaches are to be considered complementary rather than alternative. Specifically, urban scale studies allow the adoption of 2D and 3D models, which are most often not feasible at the scale of the single ordinary building.

One of the main issues related to reliability of the results is due to uncertianties in model parameters, which are inevitably propagated into the final assessment of site response. An example of a consistent approach for the identification, quantification and management of the uncertainties is presented with an example based on a recent geostatistical randomization model and a Montecarlo approach for accounting for uncertainties in laboratory tests. Taking into account that an a-priori selection of conservative values of model parameters in dynamic analyses is not possible, these type of approaches are expected to be widely adopted in the future not only for site response analyses, but also for soil-foundation-structure interaction.

5 ACKNOWLEDGEMENTS

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