

Approaches adopted for the numerical modeling of the local seismic response in the volcanic area of mount Etna

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Abstract

Seismic Microzonation studies carried out in 23 municipalities of the Catania province (Italy), within the volcano Etna area, have further highlighted how the complexities of geological systems, particularly those related to geostructural configuration and the heterogeneity of geological bodies, can affect the reliability of numerical modelling analyses aimed at calculating seismic amplification effects. In particular, the small scale heterogeneities and the varying degree of uncertainty affecting both geological setting and respective seismo-geotechnical characterization suggested the adoption of approaches differentiated to account for the local information level. Outcomes of these approaches are considered to provide an extensive estimate of 1D seismic amplification effects at the considered municipalities and reveal the presence of large lateral variations of expected effects. The results obtained, summarized here for several case studies, demonstrate the complementarity of the proposed approaches even within the same study area and, above all, emphasize their adaptability to the differing levels of knowledge inherent in the territorial contexts examined. This makes them a valuable tool for managing seismic microzonation studies in analogous geological contexts.

Keywords: Seismic microzonation; Numerical modelling; Amplification factor; Mount Etna

1. Introduction

Seismic Microzonation (SM) studies aim at evaluating the impact on the seismic ground motion of morphostratigraphic configurations at the scale from hundreds to few thousands of meters (Albarello, 2017; Moscatelli et al., 2020).

The guidelines and criteria for SM studies (ICMS), published by the National Civil Protection Department (SM-WG, 2015), currently represent the reference document for the preparation of microzonation maps at the national scale and, consequently, for the delineation of zones in which different co-seismic effects are expected.

However, the original version of the ICMS did not provide an in-depth analysis of cases characterized by marked geo-structural complexity, such as highly tectonized areas or areas with significant compositional and geometric heterogeneity of geological bodies, as is typically the case in volcanic regions.

In the years following the publication of the ICMS, a wealth of experience was gathered from fieldwork carried out after major seismic events that occurred in Italy, such as the 2009 L'Aquila earthquake, the 2012 Emilia earthquake, and the 2016-2017 Central Italy seismic sequence. These experiences contributed to updating the ICMS through operational protocols that provide more advanced and detailed guidance, particularly regarding the treatment of parametric and/or geostructural uncertainties, instabilities, and approaches to numerical modelling in geologically complex contexts. In particular, the data acquisition and processing protocols (<https://www.cnr.it/sites/default/files/public/media/attivita/editoria/978-88-8080-407-9-Microzonazione_Sismica_in_Italia_Centrale.pdf>), published by a working group of the Center for Seismic Microzonation and its Applications and coordinated by the Extraordinary Commissioner for the Reconstruction of the 2016 earthquake, following the extensive microzonation activities carried out for the reconstruction of the areas affected by the 2016-2017 seismic events in 138 municipalities of Lazio, Abruzzo, Marche, and Umbria (as per the Prime Ministerial Decree OPCM24-2017), provided new guidelines for managing the epistemic variability of base data through stochastic approaches. These were accompanied by recommendations concerning the heterogeneity and variability of geological bodies, which are often difficult to conceptualize and address using deterministic approaches. These protocols also demonstrated the influence of such uncertainties on the calculation of seismic amplification effects through numerical analysis.

These evaluations are expected to support local Authorities in developing land planning and prevention strategies to reduce seismic risk. Differently from common site response studies supporting anti seismic design of single buildings, SM is extensive in character by providing outcomes relative to wide areas (the Seismically Homogeneous Microzones – SHM) where seismic effects are expected to be similar, given that the level of heterogeneity within the single SHM is lower than that relative to the other surrounding SHMs. This implies that the modelling of seismic effects must account for the presence of moderate lateral heterogeneities within the single SHM. In particular, the present study focuses on ground motion amplification effects induced by seismic impedance heterogeneities (e.g. Kramer, 1996). In this context, due to the possible presence of non linear soil behaviour, the choice of reference ground motion representative of the local seismic hazard at the seismic bedrock plays an important role. As concerns the first element, ground motions characterized by an exceedance probability of 10% for an exposure time 50y and any rigid half space ($V_s > 800$ m/s) are conventionally considered as reference. However, this implies that both these data must be assessed and the relevant choice will be on its turn affected by significant uncertainty. Moreover, since the relevant parameterization concerns relatively large subsoil volumes, and that funds devoted to this kind of studies are relatively scarce, one cannot expect that information actually available (borehole data, laboratory measurements of dynamic soil properties, etc.) will be exhaustive enough to allow the application of advanced computational tools. In this context, 1D modelling in the linear equivalent approach (Schnabel et al., 1972) represents the main tool, while 2D approaches are considered where necessary only, i.e., where the seismic bedrock outcrops and morphological heterogeneities are expected to play a main role.

In the microzonation maps the results of the quantitative analyses, performed through numerical modelling, are expressed in terms of synthetic Amplification Factors (AF) defined as:

$$AF(T_1, T_2) = \frac{\int_{T_1}^{T_2} Sa_o dT}{\int_{T_1}^{T_2} Sa_b dT} \quad (1)$$

where Sa_a and Sa_b respectively represent spectral ordinates of the estimated response spectrum as function of the natural period T of buildings (assuming a 5% of damping) at the outcrop and at the outcropping engineering bedrock; the upper and lower integration limits (T_1 and T_2) respectively identify short (0.1-0.5 s), intermediate (0.4-0.8 s) and long period (0.7-1.1 s) ranges. This parametrization has been adopted by the Italian Guidelines for SM (SM Working Group, 2015) to optimize the application of microzonation outcomes for emergency and land planning, and seismic risk assessment (Mori et al., 2020).

The additional contribution of this study, compared with the aforementioned data acquisition and processing protocols, is to propose a flexible combination of approaches aimed at compensating for uncertainties inherent in the study cases or resulting from the limited availability of direct data. These approaches allow the treatment of

such uncertainties in proportion to their degree of indeterminacy. What is shown here is that these methodologies can also be applied to neighbouring areas without generating interpretational inconsistencies, while enabling a graduated treatment of uncertainty, an aspect that, in the future, could be made more explicit in reporting the computed AF value (Eq. 1), by associating it with the adopted methodological approach.

Whatever numerical approach is considered, many ground motion scenarios result compatible with available information and the choice of any reference outcome within the range of possibilities is mandatory. This last issue represents a key aspect of SM. When a conservative perspective is adopted, the full propagation of the whole range of inherent uncertainty on the resulting outcome may produce ‘inflative’ effects providing unrealistically high estimates. All these aspects are enhanced when SM concerns complex geological settings, which is the case of the present study.

This is part of the project “Support Activities for the Regional Department of Civil Protection for the Prevention and Reduction of Seismic Risk within the Regional Seismic Microzonation Plan (pursuant to Regional Council Resolution No. 138 of March 20, 2017) for the implementation of SM studies pursuant to the National Seismic Risk Prevention Program (pursuant to Article 11 of Law 77/2009)” coordinated by the Center for Seismic Microzonation and its Applications of the CRN IGAG. The project aims at providing advanced SM studies relative to 23 municipalities in the volcanic Etna area in the Sicilian province of Catania.

In fact, the sector covered by this study corresponds to the area where the volcanic edifice of Mount Etna is growing and, consequently, encompasses municipalities whose geology is essentially linked to the volcano’s eruptive and effusive activity. Being still active, this leads to a constant updating of the geometric and stratigraphic structure of the deposits attributable to it, by making this area particularly different in the context of the SM studies referred to sites with complex geological conditions of the subsoil (Salameh et al., 2017; Hakimov et al., 2024; Fiorucci et al., 2025).

The intrinsic heterogeneity of Etna’s volcanic deposits is expressed in alternating and irregular geometries of lithological terms, including lava, scoria, and ash. Furthermore, the volcanic deposits are juxtaposed with continental deposits, such as debris, talus and alluvial covers, hosted in paleo-valley systems often reused by lava flows to emplace their deposits or covered by fallout deposits associated with explosive eruptive phases.

Another peculiarity of the study area is that the volcanic edifice overlies a faulted sedimentary substrate consisting of cemented deposits, which are in direct contact with the volcanic deposits. These deposits are part of successions attributable to the Apennine-Maghrebien paleogeographic domain, including pre-orogenic deposits (limestones, marls and calcarenites), syn-orogenic deposits (conglomeratic flysch and scaly clays) and post-orogenic deposits (stiff clays, gypsum, marls, and calcarenites). Such a geological setting poses the further challenge of identifying a reference seismic bedrock in a substrate, which can be considered as compatible with the elastic behavior of the deposits (i.e., their S-wave velocity exceeding 800 m/s) but also with its notion of infinite half-space. Indeed, lava deposits often reach the first characteristic even at shallow depths, but due to both their limited thickness and their discontinuous structure, they cannot be considered an infinite half-space to be assumed as the basis for seismic wave propagation models. On the contrary, these deposits are often interspersed with thick bodies at significantly lower velocities and frequently generate significant contrasts in the seismic impedance and reversals already in the first few tens of meters of depth.

Depending on the specific stratigraphic setting of the sectors analysed, the notion of seismic bedrock has therefore been reduced to: i) deeper lava deposits of significantly greater thickness than the more superficial ones, as in the case of the succession of ancient volcanics (such as the basal tholeiites and super-synthems of the Timpe, Valle del Bove and Stratovolcano); ii) syn- or post-orogenic sedimentary deposits (such as the conglomeratic Capo d’Orlando flysch and the stiff Blue-Grey Clays); iii) cemented conglomeratic deposits ascribable to ancient alluvial deposits.

The 23 localities considered in the aforementioned microzonation study are characterized by different situations both as concerns the relevant geological setting and the amount of information available relative to the subsoil configuration. To face the specific difficulties met in the studies and to take the most possible advantage of available information, three different methodological approaches were designed to address the complexity of the geological and stratigraphic context discussed. The validity of the three approaches presented here must be commensurate with the nature of the underlying data and, if considered as a comprehensive tool, should be understood as a versatile and adaptive strategy for the feasibility of an extensive microzonation study in an area of high geological complexity.

Ultimately, this study aims at demonstrating how a versatile approach to quantitative analysis of local seismic response can represent an effective strategy for managing the intrinsic complexity and uncertainty of complex geological systems. Compared to previous extensive microzonation studies in volcanic areas, such as those carried out in the municipalities of Ischia island (Martino et al., 2020; Mancini et al., 2021) following the 2018

Casamicciola earthquake which were essentially based on a deterministic approach and whose results often remained affected by a significant margin of residual uncertainty, this study aims to restore greater versatility, enhancing the generalizability of advanced microzonation study (known as ‘third level’ seismic microzonation studies in Italy) and their adaptability to highly complex geological-structural systems. This, however, has not to be considered as a preclusive approach to reduce uncertainty levels in the Etna’s area following future studies, through the production of new direct or indirect investigation data.

In the following, after a brief geological overview of the study area, the technical aspects of the approaches proposed in different municipalities for the 1D numerical modeling of the local seismic response will be presented and compared through a methodological synoptic framework aimed at guiding the choice of the most suitable method, taking into account the reliability and availability of the knowledge data.

2. Geological setting

Mount Etna is a Quaternary composite volcano (Fig. 1), characterized by Na-alkaline magmatism, which has grown to its present elevation of 3320 m by accumulation of lavas and pyroclastics, erupted during the last 200 ka (Monaco et al., 2010). It is located in central-eastern Sicily at the front of the Maghrebian thrust belt. The eastern and southern sectors of the volcano lie mostly on an Early-Middle Pleistocene foredeep clayey succession deposited on the flexured margin of the Pelagian block (Lentini, 1982).

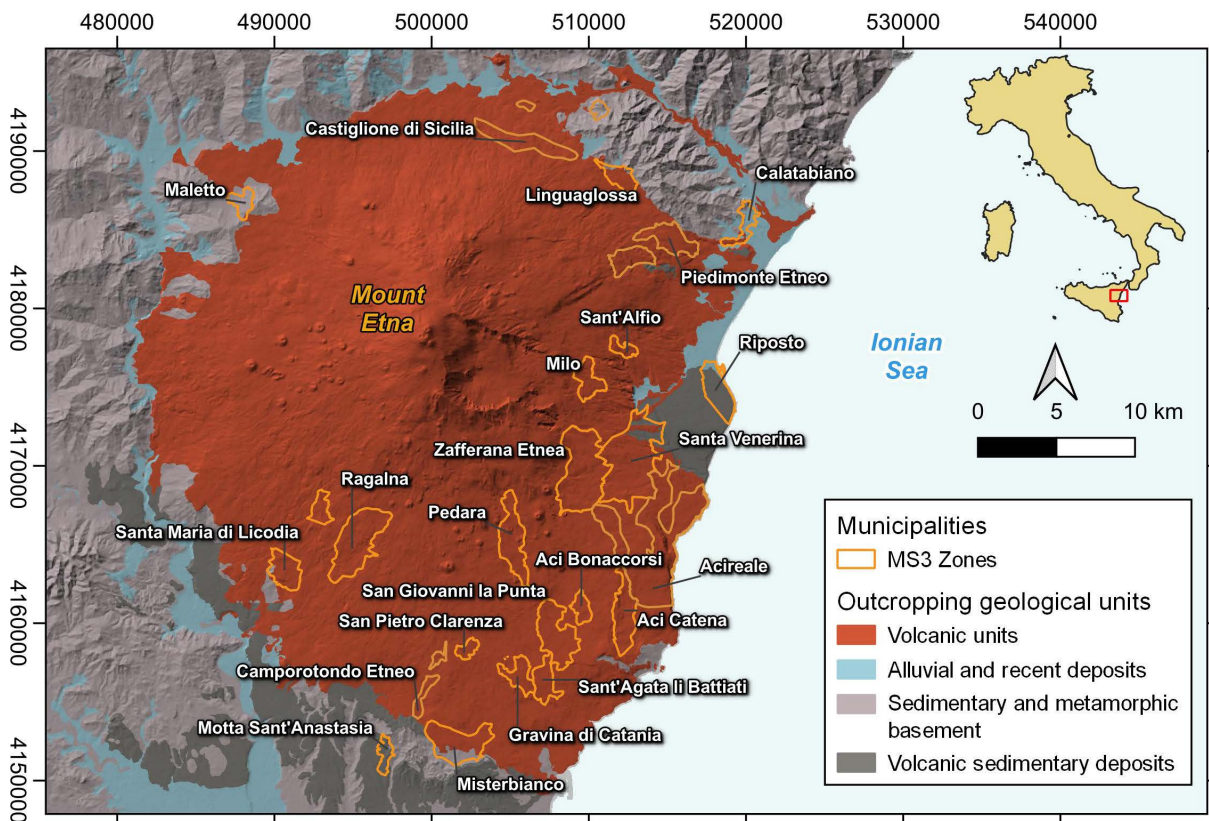


Figure 1. Study area (modified from Branca et al., 2011b).

More in particular, the Etna volcano is a composite basaltic stratovolcano characterized by four main evolutionary phases of eruptive activity (Branca et al., 2011a) started about 500 to 330 ka with scattered fissure-type eruptions occurring initially in the foredeep basin and then in a subaerial environment which increased about 200 ka in the eruptive activity up to 110 ka ago when the Valle del Bove volcanic deposits were erupted. Effusive activity is presently documented since the last 15 ka built the Mongibello volcano whose eruptive activity is mainly concentrated in three weak zones in which the recurrent magma intrusion generates flank eruptions down to low altitude.

Mount Etna's geological substratum (Fig. 1) consists of a complex mix of deep marine sediments and older volcanic rocks, lying atop the African plate being subducted beneath the Eurasian plate, creating a thick, folded sedimentary foundation (foredeep) of Miocene turbidites and Pleistocene clays, over which the volcano has grown for ~500,000 years, influencing its alkaline magmatism and active faulting, with basement rocks deformed by regional tectonics. Overall, taking into account the aforementioned geological mapping of the Etna area (Branca et al., 2011a), all the municipal territories considered for the present study are characterised by deposits consisting of volcanic covers of Etna superimposed on the Meso-Cenozoic sedimentary substrate of the Apennine-Maghrebian domain, attributable to mountain range units and to the foreland-foredeep system.

The Apennine-Maghrebian is formed by Mesozoic sedimentary successions detached from both continental and oceanic basements, and Tertiary terrigenous covers (Carbone and Lentini, 2015).

The deposits of the Apennine-Maghrebian domain are overlapped by a Neogene-Quaternary sedimentary succession, mostly characterized by marine clay deposits containing the Messinian evaporite transition represented by gypsum and the overlying Trubi Formation. At the top of this succession there are the stiff blue clays of the Lower-Middle Pleistocene.

Over the centuries, Mount Etna has been the site of numerous lava flows that have profoundly affected the landscape and the towns on its slopes, sometimes covering older alluvial deposits as well as older lava flows. Among the most famous is the 1669 eruption, the most devastating in the Etna volcano's history: lava destroyed entire towns such as Nicolosi, Misterbianco and Mascalucia, reaching the city of Catania and the sea. Another highly impactful event was the 1928 eruption, which led to the almost total destruction of Mascali, which was subsequently rebuilt in a safer location. Among modern eruptions, the 1991-1993 eruption stands out, one of the longest ever recorded, during which a flow seriously threatened Zafferana Etnea, necessitating lava diversion works. In recent decades, the eruptions of 1983, which affected the area of Nicolosi and Belpasso, and those of 2001 and 2002-2003, which caused extensive damage to infrastructure, tourist centers and settlements on the eastern side, involving municipalities such as Linguaglossa, Santa Venerina and Zafferana Etnea, have also become famous. These historic lava flows testify the central role of Etna volcano in the history and geography of eastern Sicily, demonstrating how volcanic activity has continually shaped the landscape and influenced the lives of local communities.

Mount Etna is also internationally renowned for the significant deformations affecting its flanks (Bonforte et al., 2011), which arise from the interaction between regional tectonics (Azzaro, 1999), magma ascent and the gravitational instability of the eastern flank (Sottili et al., 2007; Bozzano et al., 2013). These deformational processes have significantly influenced the volcano's geostructural framework, leading to the formation of sometimes complex lateral contacts between the deposits that make up the volcanic edifice.

3. Seismic and geotechnical parameterization of Engineering Geological Units (EGU)

By following the Italian guidelines of seismic microzonation (SM-WG, 2015), the characterization of the geological stratigraphical representative of each SHM is expressed in terms of standard Engineering Geological Units (EGU). Each unit is considered as a flat laterally homogenous layer characterized in the terms of thickness, representative shear wave velocity value (V_s), density, and curves relative to the effect of strain on shear modulus decay and damping.

In order to define the nonlinear mechanical properties of soils and rocks present in all the municipalities of the Etna area covered by this study, given the absence of specific laboratory tests on samples taken at the site, decay curves (Fig. 2 and Table 1) representative of the dynamic behavior of the geomaterials were chosen, extracted from databases currently available for Italy (Gaudiosi et al., 2023; Naso et al., 2004) or from technical reports. As it regards the use of decay curve for travertines in the case of volcanic scoria it was preferred with respect to the use of literature data on pyroclastic deposits (i.e., Pagliaroli et al., 2014; Verrucci et al., 2015) as these last ones are generated by volcanic flows and typically generate cemented weak rocks whose porosity is significantly lower if compared with the one of the scoriaceous volcanic deposits which characterise the volcanostrato edifice of Mt. Etna. The application of this classification in the Etna region was primarily based on compositional, textural (density and porosity), and mechanical (stiffness and strength) criteria. Where possible, as in the case of the over consolidated clay units (referred to as CO in Table 1), a stratigraphically based transposition was used to refer samples collected in other geostructural domains to that of the specifically considered contexts.

Furthermore, given the impossibility of finding curves capable of representing the different structural compositions and stiffnesses of the numerous existing lava flows, a proportional parameterization approach for the mechanical properties, previously applied by Bozzano et al., 2013, was used for a stress-strain numerical modelling of the stability conditions of Mount Etna's slopes under both static and seismic loads. The adopted logic consists of measuring, in percentage terms, the specific mechanical properties of each of the different compositional components of the volcanic rocks. The feasibility of this approach has been tested by numerical simulations (Fabozzi et al., 2022).

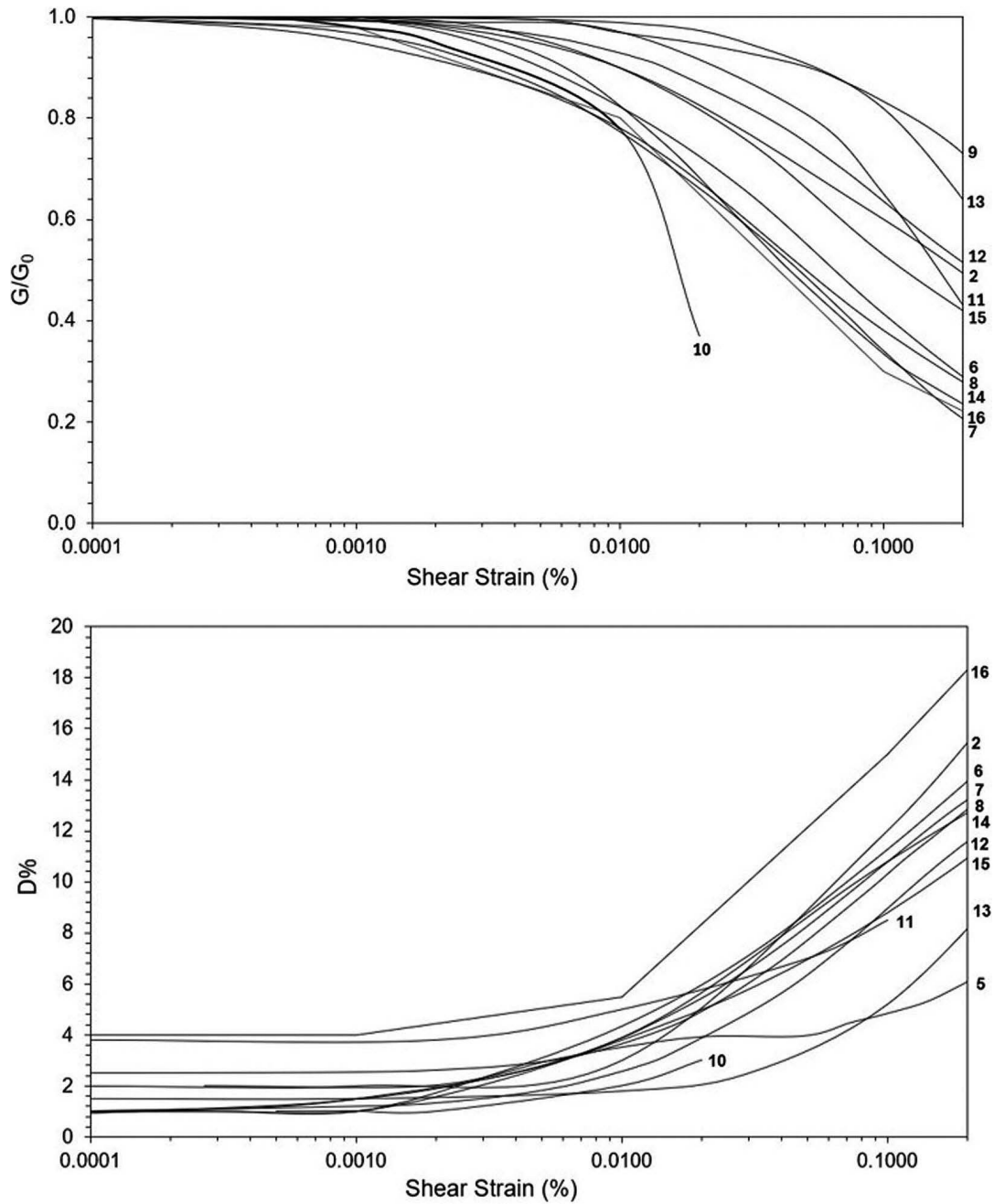


Figure 2. Decay curves (G/G_0 and $D\%$ vs. γ) for the adopted engineering-geological units. The ID of the units are referred to Table 1.

With reference to Table 1, the EGUs with identified as IDs 11, 12, and 13 were considered in specific cases as seismic bedrock in the modelled columns, due to their correspondence with geological formations belonging to the sedimentary basement of the Apennine-Maghrebide domain (such as the stiff Blue-Grey Clays, the Capo d'Orlando flysch, and the ancient lavas of the Basal Tholeiitic Super-synthem).

Table 1. Association between lithotechnical units and geological formations derived from the 1:50.000 geological map 612 (Randazzo), 613 (Taormina), 624 (Monte Etna), 625 (Acireale), 633 (Paternò), 634 (Catania).

ID	Geological formation			Lythotechnical unit	Engineering-geological unit code (EGU – ICMS 2008)	Dynamic behaviour reference
	Acireale	Piedimonte Etneo, Castiglione di Sicilia	Camporotondo Etneo			
1	Colata del 1329, Monte Ilice (mi), Salto del Cane (sd), Monte Gorna (mg), Piano d’Api (ay), Trecastagni (tr), Timone (ti), Mangano (ma), Passopomo (pa)/Fleri (fe), Castelluccio (ts), Pozzillo (pz), Vallone Pozzillo (vp), Vallone Vincenzina (vv), Madonna delle Grazie (22c)/Valverde (8)		Colata del 1669, colata di Camporotondo Etneo (ce), colata di Piano Tavola (ta), colata di Masseria Cisternazza (mc), colata di Misterbianco (mi)	Lapideous lavas	LCla	Elastic-linear behaviour D = 2%
2	Monte Ilice (mi), Monte Gorna (mg), Passodomo (pa)/Fleri (fe), Vallone Pozzillo (vp), Aci Platani (at)		Colata del 1669, colata di Camporotondo Etneo (ce), colata di Piano Tavola (ta), colata di Masseria Cisternazza (mc), colata di Misterbianco (mi)	Volcanic scorias	LCsc	Pergalani et al., 1999
3		Colata di Piano Pernicana (pp); colata di Casa Paradiso (22cd); deposito vulvanoclastico (23b); colata di Vallone S. Venera (22vs); colata di Verzella (22Vr)		75% lava-25% scorias	LCsc-LCla (75%)	Reconstructed
4		Colata di Crisimi (cr), colata di Micucco (ml); colata di Feudrogrande (fd); colata di Vallone Fogliarino (vf); colata di Casa morabito (cm1); colata di Diana (dd); colata di Vena (vn1); colata di passopisciario (psi); colata di Villa Santo Spirito (vsi); colata di Solicchiata (sl1); colata di Rovitello (ro); colata di Pantano (pn1)		50% lava-50% scorias	LCsc-LCla (50%)	Reconstructed
5		Colata di Civi (ci); colata di Piedimonte (ie-di); colata del 1879 (1879); colata del 1809 (1809); colata del 1566 (1566); colata C. da Muganazzai (mu1)		25% lava-75% scorias	LCsc-LCla (25%)	Reconstructed
6		Depositi alluvionali (b2)	Depositi alluvionali recenti (bb)	Silty sands	SM – SMec – SMtf	Vucetic and Dobry, (PI = 15), 1991
7	Caduta 25a			Sands	SW – SWpc	Rollins et al. (average), 1998
8	Chiancone 26a, terrazzo (S)/Vulcanoclastiti (5a)	Alluvioni attuali (b); ghiaie profonde; depositi conoide Monte Dolce (dc1)	Depositi alluvionali recenti (bb)	Gravels	GW – GP – GCcz – GM	Pergalani et al., 2000
9			Depositi alluvionali recenti (bb)	Organic clays	OH	Bozzano et al., 2008
10		Terreni di riporto (tr), (tv)		Fill materials	RI	Bozzano et al., 2008
11	Argille grigio-azzurre (Qa)	Argille grigio-azzurre (Qa)	Argille grigio-azzurre	Stiff clays	CO – COS – SFCO	Lo Presti et al., 1998
12	Timpe (4a)	(Oia); Flysch di Capo d’Orlando (Omar)		Arenaceous-pelitic flysch	SFLP – SFALS	Modoni and Gazzellone, 2010
13				Cemented conglomerates	SFGR – GRS – IS – ISS – SClh	Marcellini et al., 1995
14			Depositi alluvionali recenti (bb)	Silts	ML	Gaudiosi et al., 2023
15				Soft clays	CL	Vucetic and Dobry, PI = 30, 1991
16				Sandy-clays	SC	Anastasiadis et al., 2001

3.1 Definition of seismic input

In order to perform numerical analyses to assess site effects, it was necessary to have accelerograms to be used as seismic inputs. This project used appropriately selected recorded accelerograms. To obtain these inputs, we relied on the results of the study conducted by Azzaro et al., 2026, which used the outcomes of the Working Group MPS (2004), to determine the seismic hazard map. These maps report, for different return periods, the expected maximum acceleration (a_{max}) values and the spectral ordinates of the acceleration response spectra on a regular grid of points. The return period considered is 475 years, as it is the value conventionally used for SM studies.

The recorded accelerograms were selected using the databases developed by INGV (<https://www.mi.ingv.it/index.php/it/banche-dati>). Specifically, the selection was based on consistency in terms of:

- spectrum compatibility with the target spectrum corresponding to the response spectrum expected for subsurface category A (NTC, 2018) by following the Italian reference Hazard map (<https://esse1-gis.mi.ingv.it/>), within prescribed tolerance;
- historical seismicity: magnitude-distance pair from the source (Mw 5.5-6.6; distance 0-50 km);
- maximum expected horizontal acceleration;
- site conditions: records were selected primarily from stations classified as class A, when necessary records from classes B and C were also considered with the following criteria:
 - no scaling of the records was applied in the selection procedure, in order to preserve the original characteristics of the ground motions;
 - no constraints were imposed on the focal mechanism;
 - no scaling of the records was applied in the selection procedure, in order to preserve the original characteristic of the ground motions.

Considering the characteristics delineated above, and particularly the expected response spectra, the municipalities were divided into three groups, each associated with one set of accelerograms (7 in total) compatible with the reference target spectra. The grouping was performed by ensuring that the deviation between each individual code-based spectrum and the corresponding target spectrum does not exceed approximately 10% over the period range of interest, reducing the number of input conditions while preserving the main difference in seismic characteristics.

Specifically, the set ‘Target 1’ was assigned to the municipalities of Aci Catena, Acireale, Milo, Riposto, S. Alfio, S. Venerina, Zafferana Etnea, Aci Bonaccorsi, S. Giovanni la Punta, Linguaglossa, Piedimonte Etneo, Ragalna; the set ‘Target 2’ was assigned to the municipalities of Camporotondo Etneo, Gravina di Catania, S. Pietro Clarenza, Pedara, S. Agata li Battiati, Castiglione di Sicilia, Calatabiano; the ‘Target 3’ was assigned to the municipalities of S. Maria di Licodia, Maletto, Motta S. Anastasia, Misterbianco. The average response spectra relative to the three sets are reported in Fig. 3.

In addition to these accelerograms, Azzaro et al., 2026 conducted a study to identify a characteristic event that could represent volcanic seismicity (‘Scenario event’). This event, with a magnitude of 5.0 and a distance of 3 km, is characterized by a reference response spectrum that was used to select 7 further accelerograms, in this case the magnitude-distance pair from the source was Mw 4.5-6.0; distance 0-20 km; the corresponding average response spectrum is reported in Fig. 3. This was made to address the additional challenge posed by the treatment of a local hazard strongly influenced by a volcanic environment, where the associated non-negligible seismic activity does not always make the nationally standardized hazard, derived from normative products and defined on stiff soil at the national scale, fully representative of local conditions. These ‘scenario’ accelerograms were also considered for numerical simulations at the municipalities of Acireale, S. Venerina, Ragalna, S. Maria di Licodia and Zafferana Etnea.

A more explicit and reproducible description of the selection of seismic input motions is reported in Azzaro et al., 2026.

To obtain reference AF estimates at each SHM the 84th percentile of the distribution of AF estimates relative to each considered input motions (Target and eventually scenario accelerograms) was considered to provide a conservative estimate. The AF values relative to each SHM were obtained by considering the linear equivalent approach implemented in the open-source software STRATA (Kottke and Rathje, 2008).

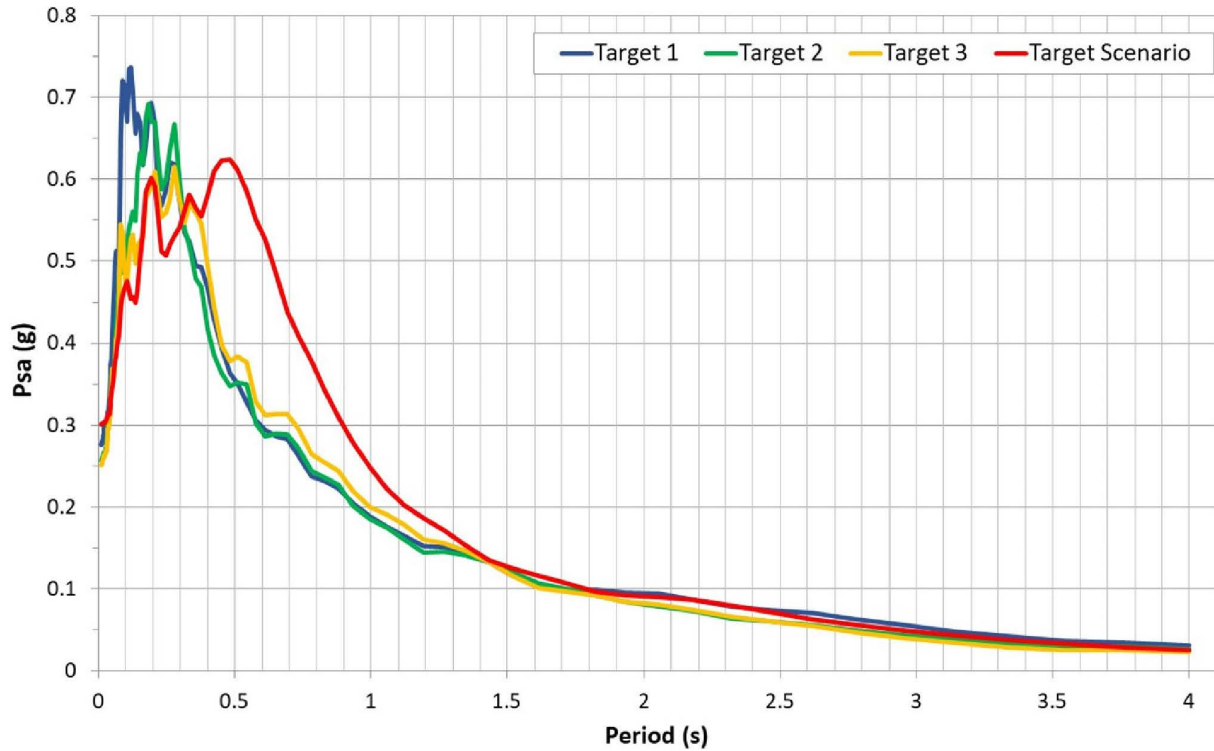


Figure 3. Mean of the acceleration response spectra of the selected accelerograms for the different Targets (1, 2, 3) and for the Target Scenario.

4. Methodological approaches

The need to adopt different approaches for assigning parameters and defining the seismo-stratigraphic characteristics of the columns to be subjected to 1D numerical modelling essentially derives from the geological-stratigraphic complexity of the Etnean area, which includes the municipalities involved in the here considered seismic microzonation studies.

The workflow adopted for all the methodologies proposed here does not differ from that directed by ICMS but rather different solutions are adopted, for each of the approaches, in relation to the parameterization of the rheological behaviors of the soil columns. Consequently, the commonly adopted workflow includes: 1) reconstruction of a seismic stratigraphy with associated rheological behaviors, transposed from direct (boreholes) or indirect (geophysical) site data; 2) identification of soil columns representative of each SHM to be considered to estimate the respective AF values; 3) numerical estimate of AF values relative to 1D seismotratigraphical effects by considering an equivalent linear approach, providing, where possible, a validation phase in a linear-elastic configuration in comparison with instrumental site data.

In the following three approaches are presented, as they were applied to different municipalities according to criteria related to data heterogeneity, with specific reference to the complexity of layering and the definition of individual layer thicknesses as well as to the data availability of geognostic and geophysical data used to constrain the seismo-stratigraphic columns.

4.1 Approach A

This approach was applied to nine municipalities located on the south-eastern flank of Mount Etna: Aci Bonaccorsi, Camporotondo Etneo, Gravina di Catania, Misterbianco, Motta Sant'Anastasia, Pedara, Sant'Agata li Battiati, San Giovanni la Punta, San Pietro Clarenza. For each municipality and each SHM, a representative column has been defined based on expert judgement in considering both geotechnical, geomorphological and geophysical

data. To compensate the scarcity of data, a detailed geological and geomorphological survey was carried out by expert field geologists: this expertise allowed to better define the extension of the more scoriaceous lava (LCsc) and the lapideous ones (LCla), that were thus distinguished also in terms of mechanical behaviour, even within the same lava flow. Preliminary 1D numerical simulations were performed also by considering minimum and maximum thicknesses for units with uncertain extension and by varying V_s velocities according to the ranges observed from geophysical data. By comparing the results with simulation performed assuming average V_s values and average thickness of the unit, a very low deviation in terms of AF values was observed. Therefore, the 1D simulations were performed by assuming the average values for the units presenting a range in terms of thickness and V_s .

4.2 Approach B

This approach was applied in the municipalities of Calatabiano, Castiglione di Sicilia, Maletto, Ragalna, Piedimonte Etneo, Linguaglossa and Santa Maria di Licodia, on the base of the following assumptions: 1) many areas subjected to advanced seismic microzonation studies did not have site-specific investigations capable of accounting for the considerable variability of the subsurface physical-mechanical characteristics; 2) the geological complexity of the subsurface (both in terms of lateral and vertical variations between volcanic and sedimentary deposits) does not facilitate the assumption of a representative column, even within a single SHM; 3) the compositional nature of volcanic deposits (both flow-based, such as lava flows, and fall-based, such as pyroclastics and fall deposits) often makes the assumption of a column in which lithological terms (formational units identified on a volcanological basis) can correspond to specific lithotechnical units irrelevant. This, for example, is most evident in the case of repeated alternations of lavas and pyroclastic deposits within the same formational unit.

For these reasons, for each SHM of the studied municipal areas, the stratigraphic succession was tentatively established based on geological and volcanological considerations. The variability of the layering inherent in the composition of each volcanological unit was treated by attributing a mechanical behaviour expressed not by a determined damping stiffness variation curve, but rather by a synthetic curve obtained by dosing, proportionally to the presence of compositional terms, the normalized stiffness values and the absolute damping values.

More in particular, as concerns volcanic Etna deposits, the three synthetic decay curves as the shear deformation varies were mathematically reconstructed on the basis of the stiffness (G/G_0) and damping (D) values of the end member curves, “dosing” the percentage contributions of lavas and complementarily of scoria according to the pre-established percentages. At this aim, two end members were adopted: lavas and pyroclastics. Based on literature curves, lavas were characterized by emphasizing their high stiffness and low primary porosity, while pyroclastics, on the other hand, were characterized by emphasizing their high primary porosity (presence of voids) and lower stiffness. Specifically, a linear elastic behaviour curve with constant damping set at 2% was attributed to compact lavas (LCla), considering their maximum presumed stiffness, while a literature curve referring to lithologies with similar mechanical behaviour (travertines in Pergalani et al., 1999) was attributed to vacuolar pyroclastics (e.g. scoria) (LCsc). The result is a parameter weighted on the lithological composition that responds to the need to take into account the intrinsic heterogeneity of each formational unit that makes up the volcanic edifice and which does not necessarily, among other things, correspond to a regular alternation (i.e., geometric arrangement) of compositional terms. For this study, therefore, three lithotechnical units were defined resulting from the mix of two compositional end members (Fig. 4) represented by the lava component (LCla) and the scoriaceous component (LCsc); in particular, three dosages were established corresponding respectively to 75%, 50% and 25% of lavas in proportion to the scoria (LCsc-LCla (75%), LCsc-LCla (50%) and LCsc-LCla (25%) which complement them. Therefore, considering the maximum presumed stiffness, a curve with linear elastic behaviour with constant damping set at 2% was attributed to the compact lavas (LCla), while a literature curve referable to lithologies with mechanical behaviour (vacuolar lithoid travertines) was attributed to the vacuolar volcanic scoria (LCsc).

To support the choice of the dosage for different geological formations ascribable to both sedimentary and volcanic rocks (such as lavas dating back to different eras or pyroclastic deposits present at different stratigraphic heights), we relied on evidence from stratigraphic columns associated with the aforementioned stratigraphic units, not necessarily pertaining to the SHM under consideration. Thus, a geological and stratigraphic criterion was preferred for selecting the most appropriate rheological behavior in terms of equivalent continuum material.

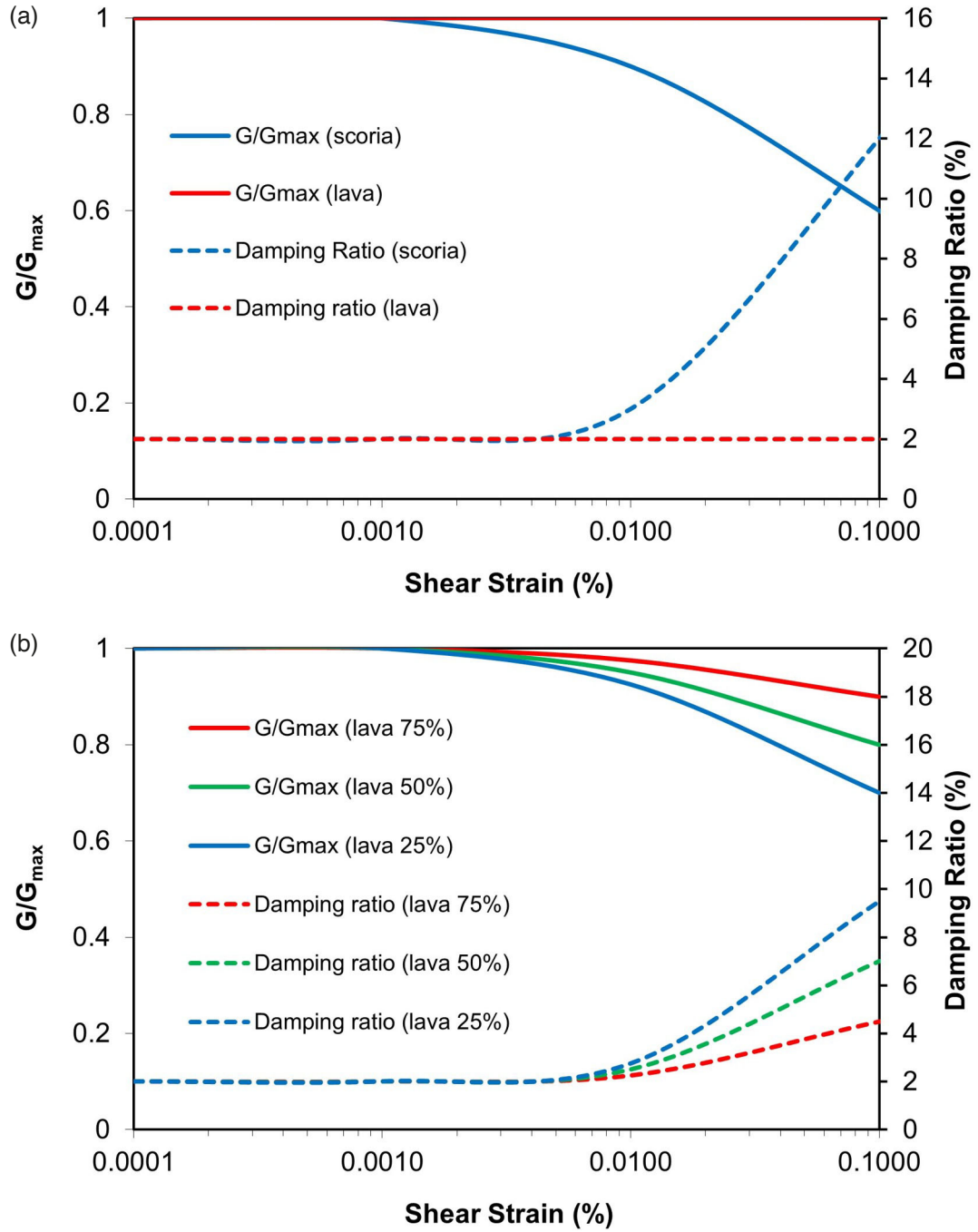


Figure 4. (a) End member decay curves for compact lavas LCl (top) and pyroclastics LCsc (bottom); (b) decay curves obtained by “dosing” the percentage contributions of lavas and complementarily of scoria.

With reference to the Vs, for each municipality the most representative values for each lithotechnical unit were adopted based on any on-site surveys (with priority given to Down Hole data). An average value was also assumed if there was a maximum deviation of 250 m/s between the minimum and maximum measured values (Table 2).

The aforementioned approach has, in effect, led to addressing the epistemic variability associated with the compositional nature of volcanic lithological features by optimizing information from available field surveys and geophysical investigations (such as MASW and Down Hole) and no longer limited to their correspondence with the specific SHM being addressed.

The Approach B tested in this study, however, was not deemed sufficiently constrained by stratigraphic data to be applied to 2D models due to extrapolation limits and uncertainty in geometrical features as well. Therefore, it was applied only to 1D simulations of columns representing specific SHM.

Table 2. Examples of attribution of the different volcanic and sedimentary geological units, in Piedimonte Etneo and Castiglione di Sicilia Municipalities, in lithotechnical units according to the proposed mixed decay curves; the dynamic behaviour has been also defined by the different Vs velocities.

Municipality	Geological Formation	Density (kg/m ³)	EGU	Vs (m/s)
Piedimonte Etneo	Colata di Crisimo	2000	LCsc-LCla (50%)	475
	Colata di Milicuccio	2000	LCsc-LCla (50%)	475
	Colata di Vallone Fogliarino	2000	LCsc-LCla (50%)	475
	Colata Casa di Morabito	2000	LCsc-LCla (50%)	475
	Colata di Vena	2000	LCsc-LCla (50%)	475
	Colata Casa di Diana	2000	LCsc-LCla (50%)	475
	Colata di Feudogrande	2000	LCsc-LCla (50%)	475
	Colata di Piedimonte	1900	LCsc-LCla (25%)	300
	Colata di Civi	1900	LCsc-LCla (25%)	300
	Colata di Casa Paradiso	2100	LCsc-LCla (75%)	725
	Colata di Piano Pernicana	2100	LCsc-LCla (75%)	725
	Colata Vallone San Venera	2100	LCsc-LCla (75%)	725
	Depositi alluvionali attuali e antichi	2000	GW	278/713
	Depositi ghiaiosi	2000	GM	360
	Sabbie	1850	SW	200
	Argille grigio-azzurre degradate/compatte	1950	SFCO	475/800
	Depositi vulcanoclastici	2100	LCsc-LCla (75%)	725
Castiglione di Sicilia	Colata del 1809	1900	LCsc-LCla (25%)	300
	Colata del 1879	1900	LCsc-LCla (25%)	300
	Colata del 1566	1900	LCsc-LCla (25%)	300
	Colata da C. Muganazzi	1900	LCsc-LCla (25%)	300
	Colate di Passopisciaro e Villa Santo Spirito	2000	LCsc-LCla (50%)	460
	Colata di Solicchiata	2000	LCsc-LCla (50%)	460
	Colata di Rovitello	2000	LCsc-LCla (50%)	460
	Colata di Pantano	2000	LCsc-LCla (50%)	460
	Colata di Verzella	2100	LCsc-LCla (75%)	714
	Depositi alluvionali b2	1850	SM	295
	Depositi di conoide di Monte Dolce	2000	GW	350
	Flysch di Capo d'Orlando	2000	SFALS	1050

4.3 Approach C

This approach was applied to the municipalities located on the eastern flank of Mount Etna (Aci Catena, Acireale, Milo, Riposto, Sant’Alfio, Santa Venerina, and Zafferana Etnea). The first activity consisted in defining the criteria for analysis and representation of the subsurface geological model, with the aim of reproducing the main characteristics of the local stratigraphic successions.

In these areas, the surface geology is dominated by volcanic deposits of different nature, which almost completely replace the sedimentary lithologies commonly observed in other sectors. The surface lava blanket (LC unit) is composed of a scoriaceous portion (LCsc) and a massive portion (LCla). The subsurface model was therefore developed using a one-dimensional approach, in order to associate a “Significant Stratigraphic Column” with each SHM, from which local seismic response parameters could be derived.

Given the extreme lateral variability of volcanic facies within the LC unit, a strong fragmentation of SHM would normally be expected. The size of each SHM is, in fact, directly related to the level of detail adopted in the stratigraphic column: the greater the detail, the smaller the area over which stratigraphic homogeneity can be assumed. To avoid excessive fragmentation the approach is based on the preliminary definition of a “Municipal Stratigraphic Matrix” (MSC), which includes the different geological formations associated with the corresponding EGU, together with the variability of their thicknesses, geotechnical and geophysical properties (Fig. 5).

Starting from the MSC and adopting a modular composition, a set of “Synthetic Stratigraphic Columns” was constructed. These columns are composed of different EGU arranged in various stratigraphic positions. Four modules were defined. Three modules (I, II, and III) represent the surface lava flow, while the fourth module (IV) refers to older geological units characterized by greater lateral continuity.

Module IV is always present and represents the bedrock. Modules I, II, and III are included only under specific conditions, when they may produce impedance contrasts at shallow depths and one or more velocity inversions within the stratigraphic column.

Module I was considered when one of the LC units was overlain by LCsc units or when thin, loose geotechnical units were present at the surface. Module II represents the presence of the first velocity inversion, located at the base of the shallowest LCla unit. This module becomes the starting module when the massive lava unit directly outcrops at the surface. Module III accounts for the occurrence of a second velocity inversion, associated with particular stratigraphic configurations in which high-Vs and low-Vs units alternate at depth. Based on the configurations defined in the MSC, velocity inversions may occur individually or in pairs at depths of approximately 10-15 m, 15-30 m, or 30-40 m.

Parametric numerical analyses were carried out by varying the thicknesses, geophysical properties, linear and nonlinear behaviour of the EGU composing each module of the “Synthetic Stratigraphic Columns”. The results were expressed in terms of AF, calculated for three period ranges (0.1-0.5 s, 0.4-0.8 s, and 0.7-1.1 s) (Pergalani et al., 2019).

These results allowed the construction of the final subsurface model by identifying in SHM among different “Synthetic Stratigraphic Columns” and by evaluating the limited influence of some of the considered modules. On this basis, the “Significant Stratigraphic Columns” were finally defined and associated with the corresponding EGU, significantly improving the clarity and readability of the final product.

In the following section, some of the parametric data used in the numerical analyses are reported in Table 3. Table 4 shows two examples of “Synthetic Stratigraphic Columns” together with the results of the parametric numerical analyses, referring to the municipality of Acireale.

The municipality of Acireale represents a particularly significant case study due to the presence of several features that distinguish it from the other municipalities, including:

- the size of the area and the wide variety of outcropping units;
- the high number of available subsurface investigations;

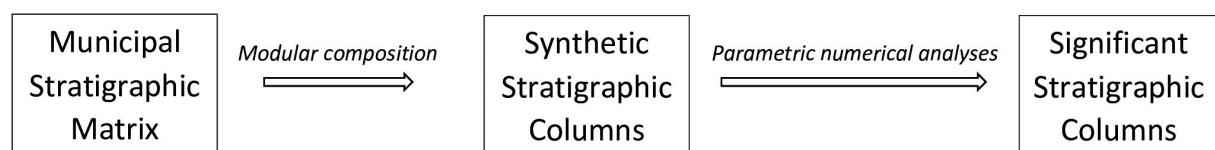


Figure 5. Workflow followed in Approach C.

- the presence of seismic bedrock at the surface or at shallow depth;
- the occurrence of three different subsurface conditions, controlled by active fault systems in the area.

Table 3. Data used in parametric analysis.

Module	EGU	Density (kg/m ³)	Thickness (m)	Vs (m/s)
I	LCsc	1700	6-14	300-570
	LCla	1900	10-40	480-780
II	LCla	1900	10-40	480-780
III	LCsc	1700	5-20	300-570
	LCla	1900	5-20	480-780
IV	SFALS	1900	100	480-800
	CO	2200	half-space	800

The following considerations can be made from the analyses performed.

For the module IV outcropping, in cases of medium stiffness (V_s in the order of 500 m/s), low amplifications are observed at low periods ($AF_{0.1-0.5}$ ranging from 1.1 to 1.3) and medium-high amplifications at high periods ($AF_{0.7-1.1}$ ranging from 1.6 to 1.7) both considering linear and nonlinear behaviours; in the stiffer cases, amplification phenomena are negligible at low periods and very low amplifications at high periods ($AF_{0.7-1.1}$ – between 1.0 and 1.1).

The superposition of Module II does not produce significant changes in the seismic response when linear material behaviour is considered. In contrast, when nonlinear behaviour is assumed for medium-stiffness conditions ($V_s \approx 500$ m/s), an increase in thickness results in greater energy dissipation and a shift of amplification effects towards periods longer than 1.1 s. In these cases, amplification at short periods becomes negligible for “Synthetic Stratigraphic Columns” thicker than approximately 120 m, while amplification at longer periods (0.7-1.1 s) ranges between 1.4 and 1.6.

The further superposition of Module I does not lead to appreciable variations in the stiffest conditions. Conversely, in lower-stiffness cases (V_s of the order of 300 m/s), changes in the surface seismic response are negligible for minimum LCsc thicknesses (approximately 5-10 m), whereas they become significant for maximum thicknesses (10-15 m). In these latter cases, low-period amplification phenomena occur, with $AF_{0.1-0.5}$ values ranging between 1.5 and 1.7.

Based on the parametric results a feedback loop analysis was performed and the “Significant Stratigraphic Columns” were identified by selecting only those modules and EGU that exert a significant influence on the seismic response. Dedicated numerical analyses were then performed for these columns, and the results were used to characterize the SHM on which the MS map was developed.

For each identified “Significant Stratigraphic Column”, the V_s values, density and thickness were defined for the different EGU. These parameters for Acireale, as an example, are shown in Table 5.

The final analyses were carried out considering the variability of the “Significant Stratigraphic Columns” in terms of velocity and thickness. For each case, the most conservative AF values were selected.

Table 4. Examples of “Synthetic Stratigraphic Columns” of Acireale (n. 1 – only module IV with the presence of EGU SFALS/CO; n. 2 – modules I, II, IV with the presence of EGU LCsc/LCla, LCla, SFALS/CO) and relative results in terms of Amplification Factors AF.

Parametric condition	AF 0.1-0.5 s		AF 0.4-0.8 s		AF 0.7-1.1 s	
	Non linear	Linear	Non linear	Linear	Non linear	Linear
Synthetic Stratigraphic Columns n. 1						
Min Vs	1.1	1.3	1.3	1.5	1.6	1.7
Max Vs	1.0	1.0	1.1	1.1	1.1	1.1
Synthetic Stratigraphic Columns n. 2						
Min thickness Min Vs	1.2	1.3	1.2	1.3	1.4	1.5
Max thickness Min Vs	1.5	1.7	1.4	1.5	1.3	1.5
Min thickness Max Vs	1.0	1.0	1.1	1.1	1.1	1.1
Max thickness Max Vs	1.1	1.1	1.1	1.1	1.1	1.1

Table 5. Parameters used in the analyses of the “Significant Stratigraphic Columns” for Acireale.

EGU	Density (kg/m ³)	Thickness (m)	Vs (m/s)
RI	1700	0/5	150
LCsc	1700	5/10/15	350/450
SW	1700	5/10/15	350/450
GM/SM	1700	10/20	360
LCla	2000	5/15/20/40	570/700
	2100	5/10/15/25/30	700/1000
GW	1900	10/20/40	450
	2000	30	550
	2100	10/30/80	650

5. Case studies

5.1 Approach A

In approach A, the 1D modeling of 3 seismo-stratigraphic columns, representative of 3 adjacent SHM in the municipality of Camporotondo Etneo, is presented. Simulations were performed by assuming the average values in terms of thicknesses and Vs for each EGU. Columns 2001 and 2002 are quite similar presenting a cover of 5 m thickness of lapideous lava (LCla) above a layer of clays (OH); further down, gravel intercalations (GW) of the column 2001 are in continuity with a deposit of scoriaceous lava (LCsc) within the column 2002. Finally the stratigraphy is completed by a 5–10 m thickness layer of silts (ML) above a sedimentary overconsolidated clays (CO) deposit. Column 2003, adjacent to the column 2002, is composed of a cover layer of clays (OH) overlying an alternating sequence of scoriaceous (LCsc) and lapideous (LCla) lava above a sedimentary overconsolidated clays (CO) deposit.

Table 6. Seismo-stratigraphic columns reconstructed for Camporotondo Etneo municipality.

Thickness (m)	EGU	Density (kg/m ³)	Vs (m/s)
Column 2001			
5.0	LCla	2200	400
10.0	OH	1700	200
25.0	GW	2000	440
7.5	ML	2000	325
32.5	CO	2200	500
half-space	CO	2200	800
Column 2002			
5.0	LCla	2200	400
10.0	OH	1700	200
25.0	LCsc	1800	440
7.5	ML	2000	325
32.5	CO	2200	500
half-space	CO	2200	800
Column 2003			
3.0	OH	1700	200
15.0	LCsc	1800	440
13.5	LCla	2200	590
26.5	LCsc	1800	430
22.0	CO	2200	500
half-space	CO	2200	800

By using the decay curves presented in Fig. 2 for the lithotechnical units, the 1D simulations provided the reference AF values relative to the three period ranges shown in Table 7.

Table 7. Amplification Factors (AF) for the 1D seismo-stratigraphic columns of Camporotondo Etneo with Approach A, reported for the three ICMS (2008) period ranges.

Column	AF 0.1-0.5 s	AF 0.4-0.8 s	AF 0.7-1.1 s
2001	1.4	1.7	2.0
2002	1.4	1.8	2.0
2003	1.2	1.4	1.6

5.2 Approach B

Some examples, representative of peculiar and complex geological-technical contexts of the subsoil of the Etna's area, are referred to the municipalities of Piedimonte Etneo and Castiglione di Sicilia and are presented below. First, the validation of the reconstructed seismo-stratigraphic columns is illustrated; specifically, for each seismo-stratigraphic column, the amplification functions obtained from linear-elastic 1D modelling were compared with the H/V spectral ratios from seismic noise measurement (HVSNR) available in the areas from which the columns were extracted. Subsequently, the proposed decay curves, together with the seismic inputs defined for the municipalities under consideration, are employed to derive the AF of the different microzones through 1D equivalent-linear modelling.

5.2.1 Piedimonte Etneo

The municipal area of Piedimonte Etneo is predominantly mantled by extensive volcanic deposits composed of lava flows and scoriaceous materials resting on a marly-clayey substratum (SFCO) or on the conglomeratic units of the Piedimonte Formation (SFLAS). Within this framework, 17 seismo-stratigraphic columns were identified, nine pertaining to the main urban sector and eight to the Vena district. In addition to the volcanic cover, locally thin alluvial layers are present, consisting of sands (SW), gravels (GM), anthropogenic fill (RI) and thick gravelly intercalations (GW) embedded within the volcanic sequence. These deposits overlie a seismic bedrock that typically occurs at depths exceeding 100 m across most of the study area.

In this context, the various lava flows were grouped into three units exhibiting distinct dynamic behaviours (Table 1), based on their prevailing structural and lithological composition, following the continuous-equivalent approach adopted for assigning the corresponding decay curves (Fig. 2) and the S-wave velocity values derived from available geophysical surveys.

Based on ambient noise measurements collected across the municipal area, a comparison was carried out between the HVNSR curves and the linear-elastic amplification functions obtained through one-dimensional modelling performed with the STRATA software. The comparison refers to seismo-stratigraphic column 8, which consists of two volcanic geo-technical units with variable composition (LCsc-LCLa 50% and LCsc-LCLa 75%) overlying the seismic bedrock represented by the conglomerates of the Piedimonte Formation (SFLAS) (Fig. 6).

The two available noise measurements for the area corresponding to column 8 reveal a first resonance peak between 4 and 5 Hz, which closely matches the fundamental frequency of approximately 5 Hz derived from the linear-elastic amplification function (Fig. 6). This agreement validates the reconstruction of the seismo-stratigraphic column in terms of unit thicknesses and associated Vs values.

The application of the mixed decay curves assigned to the two units, together with the input motion defined for the Piedimonte Etneo area (Target 1 in Fig. 3), subsequently allowed equivalent-linear modelling to be performed, yielding AF for the three period ranges specified by the ICMS 2008 standards (Table 9), with values representative for a low-medium amplification in the entire examined area.

Table 8. Seismo-stratigraphic columns reconstructed for Piedimonte Etneo municipality.

Seismostratigraphic Column	EGU	Thickness (m)
1	SW	4,5
	SFALS (half-space)	
2	LCsc-LCla (50%)	30
	SFALS (half-space)	
3	LCsc-LCla (25%)	10
	LCsc-LCla (50%)	30
	LCsc-LCla (75%)	26
	GW	10
	LCsc-LCla (75%)	46
	GW	18
	SFALS (half-space)	
4	LCsc-LCla (75%)	20
	LCsc-LCla (50%)	30
	LCsc-LCla (75%)	26
	GW	10
	LCsc-LCla (75%)	46
	GW	18
	SFALS (half-space)	
5	LCsc-LCla (25%)	10
	LCsc-LCla (50%)	40
	LCsc-LCla (75%)	75
	GW	60
	SFALS (half-space)	
6	GM	10
	LCsc-LCla (25%)	10
	LCsc-LCla (50%)	40
	LCsc-LCla (75%)	75
	GW	60
	SFALS (half-space)	
7	LCsc-LCla (25%)	24
	LCsc-LCla (50%)	11
	LCsc-LCla (75%)	64
	GW	20
	LCsc-LCla (75%)	20
	GW	20
	SFALS (half-space)	
8	LCsc-LCla (50%)	4
	LCsc-LCla (75%)	30
	SFALS (half-space)	

Seismostratigraphic Column	EGU	Thickness (m)
9	LCsc-LCla (50%)	12
	SFCO	40
	SFCO (half-space)	
10	RI	3
	LCsc-LCla (50%)	11
	LCsc-LCla (75%)	14
	SFCO	40
	SFCO (half-space)	
11	LCsc-LCla (50%)	15
	LCsc-LCla (25%)	18
	LCsc-LCla (75%)	22
	GW	12
	SFALS (half-space)	
12	LCsc-LCla (50%)	13
	LCsc-LCla (50%)	16
	LCsc-LCla (25%)	15
	LCsc-LCla (75%)	36
	SFALS (half-space)	
13	LCsc-LCla (25%)	15
	LCsc-LCla (50%)	15
	LCsc-LCla (75%)	50
	GW	15
	SFALS (half-space)	
14	LCsc-LCla (50%)	22
	LCsc-LCla (75%)	70
	GW	20
	SFALS (half-space)	
15	LCsc-LCla (75%)	20
	LCsc-LCla (50%)	30
	SFALS (half-space)	
16	LCsc-LCla (50%)	20
	LCsc-LCla (75%)	20
	LCsc-LCla (50%)	30
	LCsc-LCla (75%)	26
	GW	10
	LCsc-LCla (75%)	46
	GW	18
	SFALS (half-space)	
17	SFCO	20
	SFCO (half-space)	

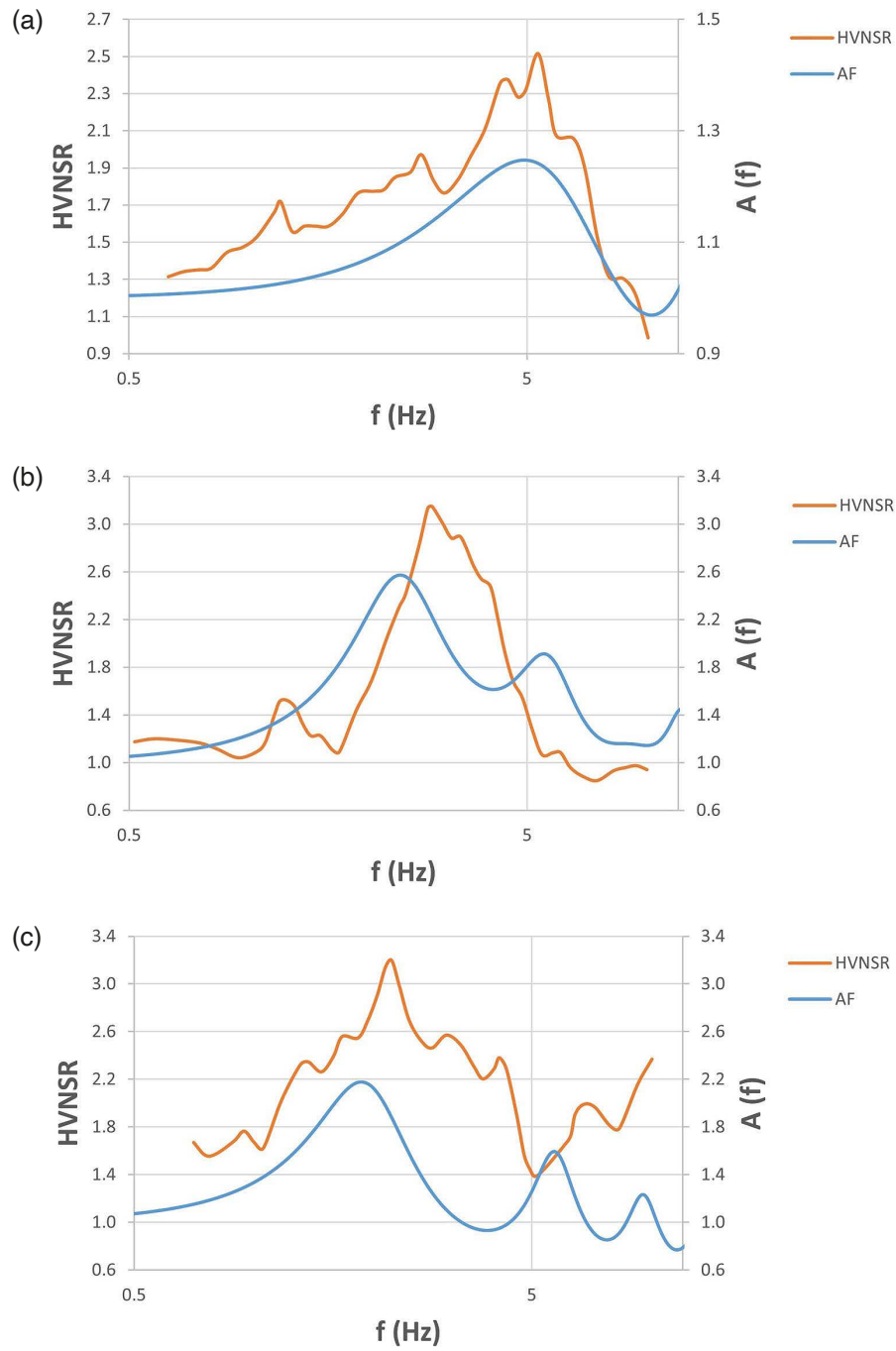


Figure 6. (a) Comparison between the amplification function (AF) obtained from 1D linear-elastic numerical modelling and the horizontal-to-vertical spectral ratio (HVNSR) from ambient-noise measurements for the Piedimonte Etneo area, represented by seismo-stratigraphic column 8. (b, c) Comparison between the amplification function (AF) obtained from 1D linear-elastic numerical modelling and the horizontal-to-vertical spectral ratio (HVNSR) from ambient-noise measurements for the Castiglione di Sicilia area, represented by seismo-stratigraphic columns 2 and 8.

Table 9. Amplification Factors (AF) for the modelled seismo-stratigraphic columns derived from equivalent-linear 1D seismic response analyses for the 17 seismo-stratigraphic columns, reported for the three ICMS (2008) period ranges.

Seismostratigraphic Column	AF 01-0.5 s	AF 0.4-0.8 s	AF 0.7-1.1 s
1	1.5	1.1	1.0
2	1.6	1.3	1.1
3	1.7	1.5	1.5
4	1.1	1.4	1.4
5	1.6	1.6	1.4
6	1.6	1.9	1.6
7	1.8	2.1	1.7
8	1.2	1.1	1.0
9	1.5	1.7	1.4
10	1.9	1.7	1.6
11	1.6	1.6	1.4
12	1.5	1.8	1.5
13	1.4	1.4	1.4
14	1.3	1.3	1.3
15	1.3	1.6	1.4
16	1.1	1.3	1.5
17	1.4	1.1	1.1

5.2.2 Castiglione di Sicilia

In the municipality of Castiglione di Sicilia, 17 seismo-stratigraphic columns were reconstructed, two of which refer to the main settlement, where pelitic-arenaceous deposits of the Capo d'Orlando Flysch Formation (SFALS) crop out either in altered conditions (column 17) or beneath a thin sandy cover (SM) (column 16). In the remaining hamlets of the municipal area, seismo-stratigraphic columns were reconstructed in which volcanic cover deposits, lavas and scoriae of varying composition, predominate. In some cases (columns 7 and 10), these units overlie a weak sedimentary cover of sandy-gravelly type (SM/GW) and rest on the sedimentary substratum (SFALS) at depths reaching up to 90 m (Table 10).

In this area, the various lava flows have likewise been grouped into three units with different dynamic behaviour (Table 1), based on their structural and lithological characteristics. The validation of seismo-stratigraphic columns 2 and 8 is presented here. Column 2 consists of three possible engineering-geological lava units with mixed compositions: LCsc-LCla 25% (18 m), LCsc-LCla 50% (22 m), and LCsc-LCla 75% (20 m), all overlying the pelitic-arenaceous sedimentary substratum. Column 8, characterised by a simpler succession, consists of 60 m of the LCsc-LCla 50% unit, also resting upon the same sedimentary substratum.

Table 10. Seismo-stratigraphic columns reconstructed for Castiglione di Sicilia municipality.

Seismostratigraphic Column	EGU	Thickness (m)
1	LCsc-LCla (50%)	30
	LCsc-LCla (75%)	20
	SFALS (half-space)	
2	LCsc-LCla (25%)	18
	LCsc-LCla (50%)	22
	LCsc-LCla (75%)	20
	SFALS (half-space)	
3	LCsc-LCla (25%)	12
	LCsc-LCla (50%)	65
	LCsc-LCla (75%)	20
	SFALS (half-space)	
4 & 5	LCsc-LCla (50%)	50
	LCsc-LCla (75%)	20
	SFALS (half-space)	
6	LCsc-LCla (25%)	10
	LCsc-LCla (50%)	60
	LCsc-LCla (75%)	20
	SFALS (half-space)	
7	GW	40
	LCsc-LCla (50%)	50
	LCsc-LCla (75%)	20
	SFALS (half-space)	
8	LCsc-LCla (50%)	60
	SFALS (half-space)	
9	LCsc-LCla (25%)	12
	LCsc-LCla (50%)	60
	SFALS (half-space)	

Seismostratigraphic Column	EGU	Thickness (m)
10	SM	5
	LCsc-LC1a (50%)	60
	SFALS (half-space)	
11	LCsc-LC1a (50%)	70
	SFALS (half-space)	
12	LCsc-LC1a (50%)	60
	SFALS (half-space)	
13	LCsc-LC1a (25%)	10
	LCsc-LC1a (75%)	20
	SFALS (half-space)	
14	LCsc-LC1a (50%)	20
	LCsc-LC1a (75%)	20
	SFALS (half-space)	
15	LCsc-LC1a (75%)	25
	SFALS (half-space)	
16	SM	6
	SFALS	20
	SFALS (half-space)	
17	SFALS	20
	SFALS (half-space)	

For both cases, the available seismic-noise measurements exhibit a frequency peak in the HVSNR function between 2.6 and 2.9 Hz for column 2, and around 2.2 Hz for column 8. In each case, these peaks correspond closely to the fundamental frequencies, approximately 2.3 Hz and 1.8 Hz, respectively, identified in the amplification functions derived from 1D linear-elastic modelling of the two seismo-stratigraphic columns (Fig. 6). The consistency between observed and modelled response demonstrates the reliability of the reconstructed seismo-stratigraphic columns for the municipality of Castiglione di Sicilia when adopting the continuous-equivalent approach. The subsequent 1D equivalent-linear modelling, by applying the corresponding seismic input (Target 2, Fig. 3) and the decay curves, enabled the computation of AF values, summarised in Table 11 which quantify the amplification values of the seismic input up to approximately 2 in several areas of this municipality.

Table 11. Amplification Factors (AF) for the modelled seismo-stratigraphic columns derived from equivalent-linear 1D seismic response analyses for the 17 seismo-stratigraphic columns, reported for the three ICMS (2008) period ranges.

Seismostratigraphic Column	AF 01-0.5 s	AF 0.4-0.8 s	AF 0.7-1.1 s
1	1.8	1.6	1.3
2	2.2	2.4	1.7
3	1.9	1.9	2.1
4 & 5	1.6	2.0	1.6
6	1.7	2.0	2.0
7	1.4	1.8	2.5
8	1.5	2.0	1.8
9	1.7	2.1	2.0
10	1.6	2.0	1.8
11	1.4	1.9	1.9
12	1.5	2.0	1.8
13	2.1	1.2	1.1
14	1.8	1.3	1.1
15	1.3	1.1	1.0
16	1.7	1.2	1.1
17	1.3	1.1	1.0

5.3 Approach C

Within the framework of the Approach C, the following example shows the results for the municipality of Acireale, where 29 “Significant Stratigraphic Columns”, object to one-dimensional (1D) numerical analysis, using the open-source STRATA software, were identified.

Below, in Table 12 for two of “Significant Stratigraphic Columns” (n. 1 e n. 2) analysed, the thickness, the EGU, the density and the Vs velocity are reported.

An additional analysis was conducted regarding the presence of fill deposits or very poor geotechnical materials (RI).

Although the thickness and extent of these materials are not considerable, ranging from 5-7 m, a one-dimensional analysis was performed on the previously analysed columns (n. 3 in Table 12), decreasing the velocity of Vs of the surface units, to assess the influence of these materials on the final result (n. 4 in Table 12).

Table 12. Some seismo-stratigraphic columns reconstructed for Acireale municipality.

Thickness (m)	EGU	Density (kg/m ³)	Vs (m/s)
Significant Stratigraphic Column 1			
15	LCsc	1700	350
15	LClā	2100	1000
10	GW	1900	450
half-space	CO	2200	800
Significant Stratigraphic Column 2			
30	LClā	2100	700
15	LCsc	1700	350
15	LClā	2000	570
40	GW	1900	450
30	GW	2000	550
30	GW	2100	650
half-space	SFALS	2200	800
Significant Stratigraphic Column 3			
15	LClā	2100	700
15	LCsc	1700	350
15	LClā	2100	1000
10	GW	1900	450
half-space	CO	2200	800
Significant Stratigraphic Column 4			
5	RI	1700	150
15	LClā	2100	700
15	LCsc	1700	350
15	LClā	2100	1000
10	GW	1900	450
half-space	CO	2200	800

In Table 13 the results in terms of AF, in the 3 period intervals ($AF_{0.1-0.5}$, $AF_{0.4-0.8}$, $AF_{0.7-1.1}$) regarding the four “Significant Stratigraphic Columns” are shown.

Table 13. Amplification Factors (AF) for some 1D seismo-stratigraphic columns of Acireale reported for the three ICMS (2008) period ranges.

Stratigraphic Column	AF 0.1-0.5 s	AF 0.4-0.8 s	AF 0.7-1.1 s
1	1.5	1.5	1.3
2	0.7	1.0	1.2
3	1.3	1.8	1.6
4	1.7	1.9	1.6

6. Discussion

In principle, site effects can be reasonably determined by deterministic approaches based on physical modelling of seismic waves propagation effects. However, reliability of modelling outcomes strictly depends on the quality of data available for the model parametrization at the scale of interest (of the order of tens to hundreds of meters). When estimates are expected to concern wide areas, which is the case of seismic microzonation studies, availability of sufficient information becomes a crucial issue to obtain reliable outcomes. On the other hand, cost limitations prevent extensive experimental characterization of the subsoil in the study area. This aspect is particularly critical when strong small-scale lateral and vertical heterogeneities are expected to exist, which is the case of the volcanic environment. In this case, any reasonable compromise must be reached based on the full exploitation of information actually available by also relying on geological interpretations and expert judgements to compensate for the lack of experimental data. As an example, in the case of the area under study, only a gross characterization of lateral heterogeneities is performed based on geological interpretations. On that basis, the study area is partitioned in homogenous microzones (SHMs) each characterized by a ‘representative’ 1D subsoil configuration. This choice is mandatory but also represents a main limitation for the possible outcomes.

In this situation, the use of advanced physical models appears wishful thinking and a linear equivalent numerical approach is considered making relevant outcomes to some extent ‘conventional’. When parameter uncertainty is of main concern, a prudent approach is generally considered by searching for a reasonable upper bound of expected effects (e.g., corresponding to fixed exceedance probability). However, when the range of uncertainty cannot be effectively explored (how to parameterize the possible effect on unknown lateral heterogeneities?), this approach will provide unreasonably overconservative estimates. Thus, the focus will be on the expectation more than on this possible upper bound, which is the approach here considered. The three approaches described above represent three possible strategies to estimate such expectation by taking the maximum possible advantage of available information relative to compositional heterogeneity and irregularity (both vertical and lateral) of each geological formation and availability of geognostic and geophysical data, to constrain variability of subsoil layering and lithologies.

The methodological approach (Fig. 7) can be sequenced into three steps for parameter values attribution which, taken together, represent the procedure for assigning properties. The only step that does not vary among the three procedures concerns the assignment of V_s profile, which is always based on the average V_s values derived from geophysical surveys extrapolated to the reference site for the modelled column.

The substantial differences between the three approaches concerns the parameterization of the soil columns used for modeling, both in terms of layering definition (layer juxtaposition and thickness) and in terms of mechanical behavior and related decay curves of the stiffness and damping parameters. Following these different attribution methods, however, the approaches for modeling and attribution of seismic inputs, as well as the restitution and use of AF values for SHMs, do not present any differences, effectively aligning with what is indicated in the guidelines for SM studies.

Selection criteria		Approach choice	Parameterization			1D Numerical Modelling	
Heterogeneity	Data Availability	Adopted approach	STEP1 – soil column layering	STEP2 – mechanical behaviour	STEP3 – geophysical properties	Seismic input selection	Modelling output vs. SHM
Medium variability of layering and thickness for sedimentary and volcanic deposits	Geological surveys to better constrain data from log-stratigraphy and geophysical investigation	Approach A	From specific log-stratigraphy: detailed geological layering, thickness of EGU, depth of EGU	G/G0(g) and D(g) from association of each Geological Formation to EGU	Average values of Vs attributed to each layer from geophysical investigations	Application of 7 to 14 selected accelerograms based on local seismic hazard	Modelled seismo-stratigraphic column corresponds uniquely to already defined SHM; Output Response Spectrum for AF computing considered as 84 th percentile of the ones derived from 7 to 14 input accelerograms
High variability of layering (lavas vs. scoria) for different and juxtaposed volcanic deposits	Poorly constrained data from log-stratigraphy and geophysical investigation	Approach B	From extrapolated log-stratigraphy: dosage of geological layering, thickness of EGU, depth of EGU	G/G0(g) and D(g) from association of each Geological Formation to EGU including the ones reconstructed by dosage			
High variability of layering and layer thickness for sedimentary and volcanic deposits		Approach C	From extrapolated log-stratigraphy: geological layering with variability, thickness of EGU with variability, depth of layers with variability, feedback loop analysis	G/G0(g) and D(g) from association of each Geological Formation to EGU, feedback loop analysis			

Figure 7. Synopsis of the methodological approach discussed in this study.

In order to check the robustness of the outcomes relative to the three approaches, results relative to the three municipal areas (Ragalna, Pedara, and Zafferana Etnea) where similarities in their engineering-geological structures are present were evaluated. In all the cases, the subsoil is characterized by superficial gravels and/or scoriae (up to approximately 30 m thick with Vs ranging from 360 up to 475 m/s) overlying a substantial sequence of lapideous lava and scoriae up to 120 meters thick with Vs ranging from 600-700 m/s, resting on a seismic bedrock composed of ancient lavas above sedimentary-metamorphic basement units with Vs higher than 750 m/s. The three municipalities are located at an elevation between 600 and 850 meters above sea level, in the southern sector of the Etna volcano edifice, which partly explains the similar thickness of volcanic cover present above the basement. The comparison of AF values is shown in Table 14, considering that for the municipalities of Pedara, Ragalna and Zafferana Etnea, approach A, B and C were respectively adopted.

Table 14. Comparison among case studies managed by different approaches in terms of AF.

Municipality	Approach	AF 0.1-0.5 s	AF 0.4-0.8 s	AF 0.7-1.1 s
Pedara	A	1.2	1.4	1.9
Ragalna	B	1.3	1.4	1.5
Zafferana Etnea	C	1.2	1.4	1.4

The comparison was made across the three period bands (0.1-0.5 s; 0.4-0.8 s; 0.7-1.1 s) used for microzonation and assuming reference seismo-stratigraphic columns representative of the aforementioned lithotechnical sequence. The results show uniformity in the values and coherence in their variation across the higher period bands, confirming that the three approaches, although associated with different levels of confidence in the underlying data, can be flexibly used in the evaluation of AF values relative to a broad territory. For the longer period band only (0.7-1.1 s), significant differences exist due to different possible choices relative to deeper layers (>100 m), badly constrained by available information.

7. Conclusions

Seismic microzonation studies carried out in recent years over a wide area of the Catania province in Sicily Italy, belonging to the complex geological system of Mount Etna, required the adoption of quantitative approaches for assessing seismic amplification factors which, in some cases, deviated from the guidelines and criteria proposed by the National Civil Protection Department and from the operational protocols introduced in subsequent years. Such deviations were necessary to address significant uncertainties concerning key parameters, namely: i) the geo-structural and geotechnical characteristics of geological bodies; ii) uncertainties related to the definition of the seismic bedrock; and iii) uncertainties regarding the representativeness of the seismic input in a context where seismic hazard is influenced both by the regional geodynamic framework and by local volcanic processes. Consequently, three approaches were adopted for the quantitative analysis of local seismic response through numerical simulations and, in particular, for layering definition and mechanical behaviour attribution to the strata, encompassing two methodological “end members” (Approach A vs. Approach C) and an “intermediate” approach based on continuous-equivalence criteria applied to the mechanical behaviour of geomaterials.

A comparison among the proposed approaches highlights the substantial robustness of the considered approaches and their feasibility also in a complex context such as the Etnaean one. This, however, should not mask the inherent limitation of the results obtained. Moreover, only the comparison with experimental observations (e.g., accelerometric data during representative earthquakes) or for seismic response analysis at well documented sites can actually validate outcomes described here. A basic limitation should be clearly stated in that, since the range of uncertainty affecting outcomes has not been explored, resulting AF evaluations cannot be considered as representative of a prudential conservative approach. On the other hand, since providing hazard estimates to local Authorities is anyway mandatory also where few subsoil data are available, what has been presented here can be considered at least a guideline for a preliminary seismic microzonation approach in complex areas. Such a preliminary estimate could be also considered as a starting point for identifying most critical situations where future and more costly investigations are required to provide more detailed parameterization of the subsoil configurations.

References

- Albarello, D. (2017). Extensive application of seismic microzoning: methodological and socio-political issues in the Italian experience, *Boll. Geofis. Teor.*, 58, 4, 253-264, doi:10.4430/bgta0205.
- Anastasiadis A., D. Raptakis and K. Pitilakis (2001). Thessaloniki's detailed microzoning: subsurface structure as bias for site response analysis, *Pure Appl. Geophys.*, 158, 2597-2633.
- Azzaro, R. (1999). Earthquake surface faulting at Mount Etna volcano (Sicily) and implications for active Tectonics, *J. of Geodyn.*, 28, 193-213.
- Azzaro, R., S. D'Amico, T. Castelbarco, C. Felicetta, G. Lanzano, F. Pacor and G. Tusa (2026). Seismotectonic setting and seismic hazard in the Etna region: constraints for the definition of the seismic input for microzonation, (this volume).
- Bonforte, A., F. Guglielmino, M. Coltelli, A. Ferretti and C. Puglisi (2011). Structural assessment of Mount Etna volcano from Permanent Scatterers analysis, *Geochemistry, Geophysics, Geosystems*, 12, 2, Q02002, doi:10.1029/2010GC003213.
- Bozzano, F., A. Caserta, A. Govoni, F. Marra and S. Martino (2008). Static and dynamic characterization of alluvial deposits in the Tiber River Valley: New data for assessing potential ground motion in the City of Rome, *J. Geophys. Res.*, 113, B01303.
- Bozzano, F., M. Gaeta, L. Lenti, S. Martino et al. (2013). Modeling the effects of eruptive and seismic activities on flank instability at Mount Etna, Italy, *J. Geophys. Res.: Solid Earth*, 118, 1-22, doi:10.1002/jgrb.50377.
- Branca, S., M. Coltelli and G. Groppelli (2011a). Geological evolution of a complex basaltic stratovolcano: Mount Etna, Italy, *Ital. J. Geosci.*, 130, 3, 306-317, doi:10.3301/IJG.2011.13.
- Branca, S., M. Coltelli, G. Groppelli and F. Lentini (2011b). Geological map of Etna volcano, 1:50.000 scale, *Ital. J. Geosci.*, 130, 3, 265-291, doi:10.3301/IJG.2011.15.
- Carbone, S. and F. Lentini (2015). *Memorie Descrittive della Carta geologica d'Italia*, Vol. 98/2015, ISBN: 978-88-9311-008-2, ISSN: 0536-0242 (<https://www.isprambiente.gov.it/en/publications/technical-periodicals/descriptive-memories-of-the-geological-map-of-geological-map-of-etna-volcano>).

- De Beni, E., S. Branca, M. Coltelli, G. Groppelli and J. Wijbrans (2011). $^{39}\text{Ar}/^{40}\text{Ar}$ isotopic dating of Etna volcanic succession, *Ital. J. Geosci.*, 130, 3, 292-305, doi:10.3301/IJG.2011.14.
- Decreto Ministeriale 17 Gennaio 2018 (NTC 2018). Aggiornamento delle «Norme tecniche per le costruzioni», G.U. 20 febbraio 2018, n. 42, <https://www.mi.ingv.it/index.php/it/banche-dati>.
- Fabozzi, S., D. Albarello, A. Pagliaroli and M. Moscatelli (2022). The possible use of homogeneous subsoil models for 1D seismic response analyses in seismic microzonation studies, *Bull. Earthq. Eng.*, doi:10.1007/s10518-021-01273-z.
- Fiorucci, M., S. Martino, B. Antonielli, V. Charalampopoulou, P. Ciampi et al. (2025). Local seismic response in the historical centre of Nafplio (Greece) as a tool for seismic risk management, *Nat. Hazards* 121, 15581-1561, doi:10.1007/s11069-025-07403-z.
- Gaudiosi, I., G. Romagnoli, D. Albarello, C. Fortunato., P. Imprescia, F. Stigliano and M. Moscatelli (2023). Shear modulus reduction and damping ratios curves joined with engineering geological units in Italy, *Sci. Data* 10, 1, 625, doi:10.1038/s41597-023-02412-8.
- Hakimov, F., H. B. Havenith, A. Ischuk and K. Reicherter (2024). Assessment of site effects and numerical modeling of seismic ground motion to support seismic microzonation of Dushanbe City, Tajikistan. *Geosciences (Basel)*, 14, 5, 117.
- Kottke, A. and E. Rathje (2008). Technical manual for strata, Report No.: 2008/10, Pacific earthquake engineering research center, Berkeley: University of California, <https://github.com/arkottke/strata/>.
- Kramer, S. L. (1996). *Geotechnical Earthquake Engineering*, Prentice-Hall, New Jersey, 653.
- Lentini, F. (1982). The Geology of the Mt. Etna Basement, *Memorie della Società Geologica Italiana*, 23, 7-26.
- Lo Presti, D. C. F. (1998). Non-linear stress-strain relations of soils for cyclic loading, In 11th European Conference on Earthquake Engineering.
- Mancini, M., M. C. Caciolli, I. Gaudiosi, G. A. Alleanza et al. (2021). Seismic microzonation in a complex volcano-tectonic setting: the case of northern and western Ischia Island (southern Italy), *It. J. Geosci.* 140, f.3, 382-408, doi:10.3301/IJG.2021.10.
- Martino, S., P. Caprari, M. Della Seta, C. Esposito et al. (2020). Influence of geological complexities on local seismic response in the municipality of Forio (Ischia island, Italy), *It. J. Engin. Geol. Environ.*, 2, 43-62, doi:10.4408/IJEGE.2020-02.O-04.
- Marcellini, A., R. Daminelli, G. Franceschina and M. Pagani (1995). Proprietà dinamiche dei conglomerati di Benevento. In: *Atti del VII Convegno Nazionale "L'Ingegneria Sismica in Italia"* (ANIDIS), Siena, 25-28 settembre 1995, 1, 415-424.
- Modoni, G. and A. Gazzellone (2010). Simplified Theoretical Analysis of the Seismic Response of artificially compacted gravels, *V Int. Conf. on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, San Diego, USA, Paper No. 1.28a.
- Monaco, C., G. De Guidi and C. Ferlito (2010). The Morphotectonic map of Mt. Etna, *Ital. J. Geosci. (Boll. Soc. Geol. It.)*, 129, 3, 408-428, doi:10.3301/IJG.2010.11.
- Mori, F., I. Gaudiosi, E. Tarquini, F. Bramerini et al. (2020b). HSM: a synthetic damage-constrained seismic hazard parameter, *Bull. Earthq. Eng.*, 18, 12, 5631-5654, doi:10.1007/s10518-019-00677-2.
- Moscatelli, M., D. Albarello, G. Scarascia Mugnozza and M. Dolce (2020). The Italian approach to seismic microzonation, *Bull. Earthq. Eng.*, 18, 12, 5425-5440, doi:10.1007/s10518-020-00856-6.
- MS-AQ Working Group (2010). *Microzonazione sismica per la ricostruzione dell'area aquilana*, Regione Abruzzo – Dipartimento della Protezione Civile, L'Aquila, 3 vol. and CD-Rom, <https://www.protezionecivile.gov.it/it/pubblicazione/microzonazione-sismica-la-ricostruzione-dellarea-aquilana/>.
- Naso, G., M. Petitta and G. Scarascia Mugnozza (2004). *La Microzonazione Sismica: Banca dati delle curve di degrado dei terreni per analisi dinamiche [Dataset su CD-ROM]*, Allegato a *Geologia Tecnica e Ambientale*, 4/2004, Consiglio Nazionale dei Geologi.
- Pagliaroli, A., G. Lanzo, P. Tommasi and V. Di Fiore (2014). Dynamic characterization of soils and soft rocks of the Central Archaeological Area of Rome, *Bull. Earthq. Engin.*, 12, 1365-1381.
- Pergalani, F., R. Romeo, L. Luzi, V. Petrini, A. Pugliese and T. Sanò (1999). Seismic microzoning of the area struck by Umbria – Marche (Central Italy) Ms 5.9 earthquake of 26 September 1997, *Soil Dyn. Earth. Engineer*, 18, 279-296.
- Pergalani, F., L. Luzi and V. Petrini (2000). Definizione delle istruzioni tecniche e valutazione quantitativa degli effetti locali di alcune località della Garfagnana (Castelnuovo Garfagnana), *Rapporto tecnico*, Convenzione tra Regione Toscana e Istituto di Ricerca sul Rischio Sismico (IRRS), Milano.

- Pergalani, F., A. Pagliaroli, C. Bourdeau, M. Compagnoni et al. (2019). Seismic microzoning map: approaches, results and applications after the 2016-2017 Central Italy seismic sequence, *Bull. of Earthquake Engineering*, doi:10.1007/s10518-019-00640-1.
- Rollins, K. M., M. D. Evans, N. B. Diehl and W. D. Daily (1998). Shear Modulus and Damping Relationships for Gravels, *J. Geotech. Geoenviron. Engin.*, 124, 5), 396-405, doi:10.1061/(ASCE)1090-0241(1998)124:5(396).
- Salameh, C., P. Y. Bard, B. Guillier, J. Harb et al. (2017). Using ambient vibration measurements for risk assessment at an urban scale: from numerical proof of concept to Beirut case study (Lebanon), *Earth Planets Space*, 69, 1-17.
- Servizio Geologico d'Italia (2009). Carta Geologica d'Italia la scala 1:50.000, F. 625 Acireale, ISPRA, doi:10.15161/oar.it/143323.
- Servizio Geologico d'Italia (2009). Carta Geologica d'Italia alla scala 1:50.000, F. 634 Catania, ISPRA, doi:10.15161/oar.it/143335.
- Servizio Geologico d'Italia (2009). Carta Geologica d'Italia alla scala 1:50.000, F. 613 Taormina, ISPRA, doi:10.15161/oar.it/143307.
- Servizio Geologico d'Italia (2010). Carta Geologica d'Italia alla scala 1:50.000, F. 633 Paternò, ISPRA, doi:10.15161/oar.it/143331.
- Servizio Geologico d'Italia (2012). Carta Geologica d'Italia alla scala 1:50.000, F. 612 Randazzo, ISPRA, doi:10.15161/oar.it/143303.
- Servizio Geologico d'Italia (2014). Carta Geologica d'Italia alla scala 1:50.000, F. 624 Monte Etna, ISPRA, doi:10.15161/oar.it/143319.
- SM Working Group (2015) Guidelines for seismic microzonation. In: Conference of regions and autonomous Provinces of Italy – Civil Protection Department, Rome, <https://www.centromicrozonazioneismica.it/it/download/category/9-guide-ines-forseismic-microzonation>.
- SM Working Group (2015) Guidelines for seismic microzonation. In: Conference of regions and autonomous Provinces of Italy – Civil Protection Department, Rome, <https://www.centromicrozonazioneismica.it/it/download/category/9-guide-ines-forseismic-microzonation>.
- Sottili, G., S. Martino, D. Palladino, A. Paciello and F. Bozzano (2007). Effects of tidal stresses on volcanic activity at Mount Etna, Italy, *Geophysical Research Letters*, 34, L01311, doi:10.1029/2006GL028190.
- Verrucci, L., G. Lanzo, P. Tommasi and T. Rotonda (2015). Cyclic and dynamic behaviour of a soft pyroclastic rock, *Geotechnique*, 65, 5, 359-373.
- Vucetic, M. and R. Dobry (1991). Effect of soil plasticity on cyclic response, *J. Geotech. Engin.*, 117, 1, 89-117.
- Working Group MPS (2004). Redazione della mappa di pericolosità sismica prevista dall'Ordinanza PCM 3274 del 20 marzo 2003, Rapporto finale per il Dipartimento della Protezione Civile, INGV, Milano-Roma, 65, 5 appendici, <http://zonesismiche.mi.ingv.it/>.

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