

Sensitivity of Seismic Amplification to Shear-Wave Velocity Variability and Lithological Complexity: Insights from the Mt. Etna Volcanic Area (Italy)

Michele Punzo¹, Giuseppe Cavuoto^{*,1}, Francesco Pavano², Edoardo Peronace³, Daniela Tarallo¹, Giuseppe Tortorici³, Vincenzo Di Fiore¹

⁽¹⁾ Consiglio Nazionale delle Ricerche, Istituto di Scienze del Patrimonio Culturale, Napoli, Italy

⁽²⁾ Università degli Studi di Napoli Federico II, Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse, Napoli, Italy

⁽³⁾ Consiglio Nazionale delle Ricerche, Istituto di Geologia Ambientale e Geoingegneria, Roma, Italy

Article history: received May 25, 2026; accepted July 29, 2026

Abstract

Seismic microzonation in volcanic environments is strongly affected by epistemic uncertainty due to the marked heterogeneity of volcanic deposits and the complex stratigraphic architecture of the shallow subsurface. In these contexts, simplified parameters such as equivalent shear-wave velocity (V_{SE}) or VS30 are commonly adopted for seismic site classification, although they often fail to adequately represent the internal variability and impedance contrasts controlling local seismic response.

This study investigates the relationship between equivalent shear-wave velocity (V_{SE}), its associated variability, such as the standard deviation (Sd), and the seismic amplification factor (AF) in the Mt. Etna volcanic area (eastern Sicily, Italy). The analysis is based on ten high-resolution down-hole seismic surveys collected within the framework of the Regional Seismic Microzonation activities of the Mt. Etna area and distributed across different geological sectors of the volcanic edifice, including lava-dominated successions, volcanoclastic deposits, and sedimentary-volcanic transition zones. Shear-wave velocity data were analyzed using statistical indicators and lithological classification based on Engineering Geological Units (EGUs), while amplification factors were estimated through 1D equivalent-linear numerical simulations for different spectral period intervals.

The results show that sites characterized by similar V_{SE} values may exhibit significantly different amplification behavior, demonstrating that V_{SE} alone is not sufficient to describe the seismic response of heterogeneous volcanic successions. In contrast, the standard deviation of V_S (Sd) represents an effective indicator of internal velocity variability and provides complementary information for interpreting amplification effects. The relationship between Sd and AF is non-linear and strongly dependent on the spectral period range. Moderate heterogeneity tends to enhance amplification through the development of impedance contrasts and resonance effects, whereas highly heterogeneous profiles tend to reduce coherent amplification due to wave scattering and stratigraphic complexity. Distinct heterogeneity thresholds were identified for different VSE classes, beyond which amplification behavior becomes increasingly site-specific and no longer predictable through simplified equivalent-velocity approaches.

Although the proposed Sd-AF relationship is specific to the investigated geological setting, the methodology can also be applied to other volcanic and heterogeneous geological environments to better constrain seismic amplification effects.

Keywords: Seismic microzonation; Volcanic environments; Down-hole; Shear-wave velocity; Mt. Etna

1. Introduction

Seismic microzonation in active volcanic areas represents a major challenge due to the extreme geological heterogeneity and the distinctive seismological behavior of these environments. Unlike tectonically stable sedimentary basins, volcanic regions are commonly characterized by shallow seismicity, where earthquake sources are located within the uppermost kilometers of the crust and may interact directly with highly heterogeneous near-surface materials (Blong, 1984; Zollo et al., 1996; Patanè et al., 2006; Azzaro et al., 2012a). This proximity to urbanized areas significantly increases epistemic uncertainty in the estimation of site response, further complicated by the difficulty in distinguishing between primary depositional structures and secondary post-depositional processes such as weathering, hydrothermal alteration, and fracturing.

The shallow subsurface in volcanic settings is typically composed of a highly heterogeneous and discontinuous succession of lava flows, scoriaceous and brecciated horizons, pyroclastic deposits, volcanoclastic sediments, and paleosols (Del Negro and Napoli, 2002; Branca et al., 2011; Panzera et al., 2017; Di Giulio et al., 2019). These materials exhibit strong contrasts in mechanical and elastic properties due to differences in vesicularity, welding, fracturing, and alteration processes (Gudmundsson, 2020; Panzera et al., 2020). Therefore, seismic velocities display highly variable and non-monotonic trends with depth, often including velocity inversions and sharp impedance contrasts within the upper tens of meters (Wathelet et al., 2008; Di Fiore et al., 2020).

Previous studies have demonstrated that such heterogeneity strongly influences seismic wave propagation. Internal discontinuities within volcanic deposits – such as lava flow boundaries, blocky structures, and differential welding – can generate complex wave phenomena, including scattering, diffraction, and localized resonance effects, significantly modifying both the amplitude and duration of ground motion (Bard and Bouchon, 1985; Kawase, 1996; Bais et al., 2003; Wu and Aki, 1988). In these environments, seismic response cannot be adequately interpreted using simplified stratigraphic models.

In Italy, several studies have investigated seismic site response and subsurface characterization in volcanic and tectonically active areas (Nunziata et al., 1999, 2004; Barani et al., 2020; Rapolla et al., 2002; Mancini et al., 2021; Cavallaro et al., 2022). These studies highlight the strong heterogeneity of near-surface conditions and the complexity of seismic response in areas such as Mt. Etna and the Phlegraean Fields. In these environments, seismic velocities can also exhibit temporal variations associated with volcanic unrest and changes in physical conditions.

Shear-wave velocity (V_S) is a fundamental parameter for seismic microzonation, particularly for defining equivalent shear-wave velocity (V_{SE}) and evaluating site response. However, in volcanic environments, the relationship between velocity and depth is highly non-linear and strongly controlled by lithology and internal structure. Lava flows, for instance, may exhibit markedly different velocities depending on vesicularity, cooling history, and degree of fracturing, regardless of depth.

In this context, the widespread use of simplified parameters such as V_S , although essential for engineering classification, has important limitations. V_{SE} represents an averaged property that cannot capture internal layering, velocity inversions, or localized impedance contrasts, which are key drivers of seismic amplification (Boore, 2004; Castellaro et al., 2008). This limitation is particularly critical in volcanic environments, where seismic response is governed by stratigraphic complexity rather than by monotonic stiffness gradients.

Recent studies have highlighted the importance of statistical approaches to quantify velocity variability and its implications for seismic response (Phoon and Kulhawy, 1999; Rodriguez-Marek et al., 2001; Rathje et al., 2010). In parallel, Amplification Factors (AF) derived from V_S models provide a direct link between subsurface properties and ground motion amplification (Borcherdt, 1994; Pitilakis et al., 2013). However, the relationship between velocity variability, lithology, and amplification remains poorly constrained in volcanic environments (Mancini et al., 2021; Cavallaro et al., 2024).

In this perspective, velocity variability directly controls the spatial distribution of impedance contrasts, which represent a primary factor governing seismic amplification in heterogeneous volcanic stratigraphies.

This study aims to address this gap by integrating velocity analysis, statistical variability indicators, lithological classification, and amplification factors within a unified framework. In particular, the analysis focuses on the variability of VS within individual lithological units, evaluating the extent to which V_{SE} values can be considered representative of specific lithologies. Within this framework, the statistical analysis of V_{SE} variability within individual lithological units is used to evaluate the reliability of average velocity parameters as representative descriptors of subsurface conditions.

By combining down-hole measurements (DH), statistical descriptors, and numerical amplification analysis, the study investigates how vertical heterogeneity and impedance contrasts control seismic response in complex volcanic stratigraphies.

The underlying hypothesis is that seismic amplification in volcanic environments is not controlled by average stiffness alone, but by the combined effect of velocity variability and stratigraphic architecture, which together define the distribution and intensity of impedance contrasts within the shallow subsurface.

The statistical analysis performed on the dataset, as a function of the mean equivalent shear-wave velocity (V_{SE}) and its variability expressed as standard deviation (Sd), allows the identification of threshold conditions under which VS variability within lithological units does not produce significant variations in the amplification factor (AF).

2. Study area

The study area is located in the Mt. Etna region, eastern Sicily (Italy), and includes one of the most active and structurally complex basaltic stratovolcanoes of the Mediterranean region, rising up to ~3400 m a.s.l. (Lanzafame et al., 2003; Branca et al., 2011b; Azzaro et al., 2012b). The volcanic edifice (Fig. 1) is located at the front of the Sicilian thrust belt and north of the Malta Escarpment, marking the transition between the African and European plate domains (Ben-Avraham and Grasso, 1990; Finetti et al., 2005; Polonia et al., 2011, 2016).

Mt. Etna is characterized by persistent eruptive activity, frequent volcano-tectonic earthquakes, and intense shallow seismicity associated with both magmatic and tectonic processes (Barberi et al., 1994; Patanè et al., 2006; Azzaro et al., 2012b). The present geodynamic framework results from the interaction between regional tectonics, dyke intrusion, flank instability, and gravitational spreading processes, which strongly control magma ascent pathways and deformation patterns (Borgia et al., 1992; Borgia, 1994; Neri and Acocella, 2006; Bonforte et al., 2011; Gross et al., 2016). As a result of this long-lasting evolution, the shallow subsurface of Mt. Etna consists of a highly heterogeneous and diachronous volcanic succession, characterized by lava flows with variable internal structure (massive, vesicular, and scoriaceous) interbedded with pyroclastic deposits, volcanoclastic horizons, and locally with marine terraced deposits and alluvial terrains (Branca and Ferrara, 2013; Panzera et al., 2017; Porchia et al., 2026).

The volcanic edifice developed above the sedimentary deposits of the Gela-Catania foredeep and the frontal sector of the Apennine-Maghrebic chain (Fig. 2) (Branca et al., 2011). The pre-volcanic basement exhibits strong lateral variability reflecting the complex morphostructural setting of eastern Sicily (Finetti et al., 2005). Along the northern and western margins of the volcanic edifice, the substratum mainly consists of Mesozoic-Tertiary flysch-type units belonging to the Apennine-Maghrebic Chain, whereas along the southern and southeastern sectors it is predominantly represented by Early-Middle Pleistocene marly clay deposits related to the Gela-Catania foredeep (Lentini et al., 1995; Di Stefano and Branca, 2002). In the central sector of the volcano, the sedimentary basement is buried under several hundreds of meters of volcanic units. Conversely, along the peripheral sectors, where the volcanic cover progressively thins except within deeply incised paleovalleys, the substratum crops out discontinuously along major tectonic lineaments (Branca and Ferrara, 2001; 2013). This morphostructural framework exerts a first-order control on the geophysical heterogeneity of the shallow subsurface and on the spatial variability of seismic velocities. Accordingly, the volcanic edifice can be subdivided into three main structural sectors characterized by distinct geological and geophysical conditions (Table 1).

The geological, geotechnical, and down-hole (DH) seismic dataset analyzed in this study derives from investigations carried out within the framework of the ETNA FAC Working Group activities (ETNA FAC, 2024), developed under the agreement between the Department of Civil Protection of the Sicily Region and the CNR Institute of Environmental Geology and Geoengineering (IGAG-CNR) for seismic risk prevention and reduction within the Regional Seismic Microzonation Plan. The investigated boreholes are mainly located in the eastern sector of Mt. Etna because

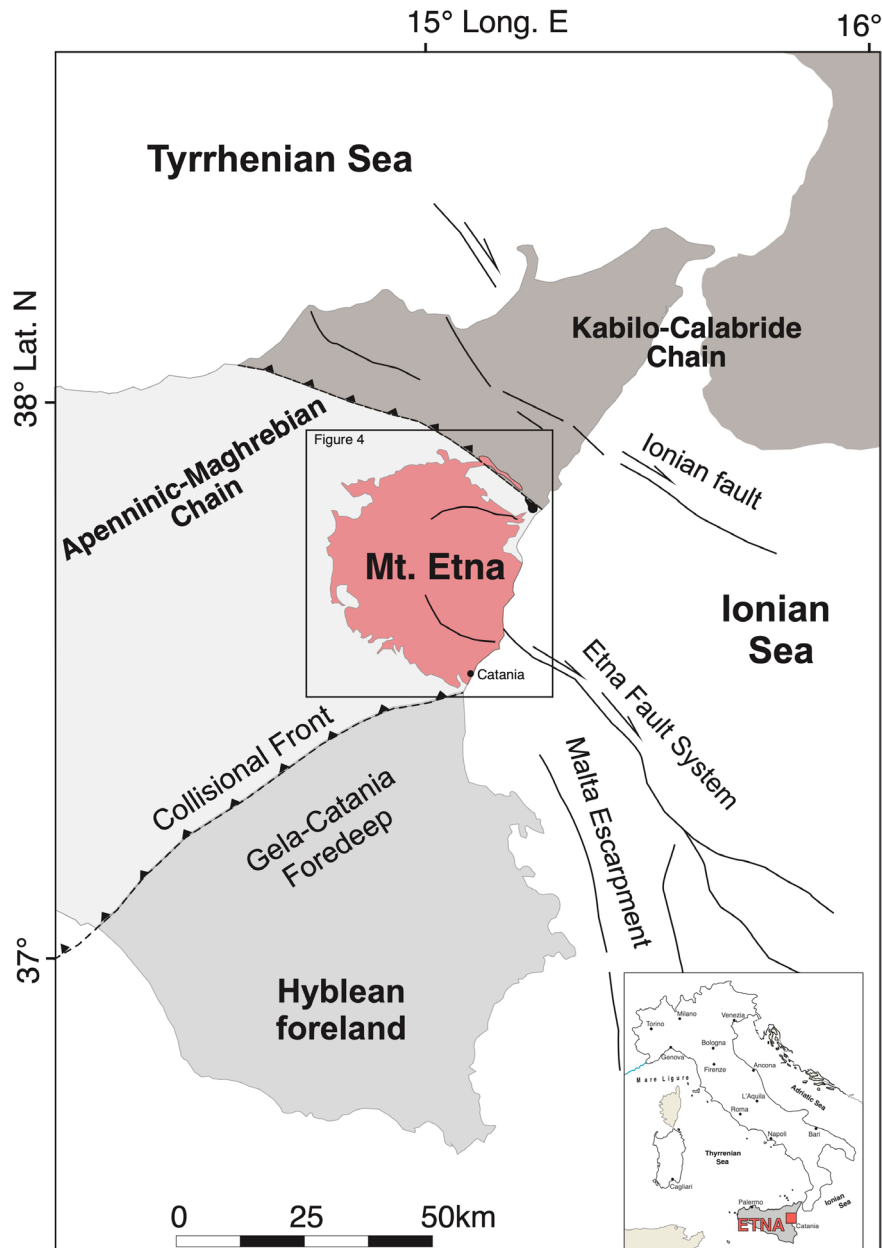


Figure 1. Simplified tectonic map showing the main geodynamic setting of eastern Sicily where Mt. Etna is located. The inset map indicates the location of the study area within the central Mediterranean. The black rectangle identifies the area detailed in Fig. 4.

they correspond to the municipalities included in the Level 3 Regional Seismic Microzonation programme. Their distribution therefore reflects the spatial coverage of the regional investigation rather than an attempt to obtain a homogeneous sampling of the entire volcanic edifice. The investigated sites span proximal lava-dominated sectors, intermediate zones characterized by interbedded lava flows and pyroclastic deposits, and distal sectors where volcanic units progressively interact with sedimentary formations and the pre-volcanic basement. In particular, the DH surveys of Maletto and Castiglione di Sicilia intercept shallow flysch-type substrata, whereas those of Gravina di Catania and San Giovanni La Punta are characterized by the presence of Pleistocene marly clays at relatively shallow depth. The remaining sites mainly investigate heterogeneous volcanic successions related to the Ellittico and Mongibello phases. This distribution captures the progressive transition from purely volcanic to mixed volcanoclastic-sedimentary environments, as reflected by the spatial variability of lithological classes. Such heterogeneity makes the Mt. Etna area an ideal natural laboratory for investigating the relationships between shear-wave velocity (VS), lithological-engineering units (EGUs), and amplification factors (AF).

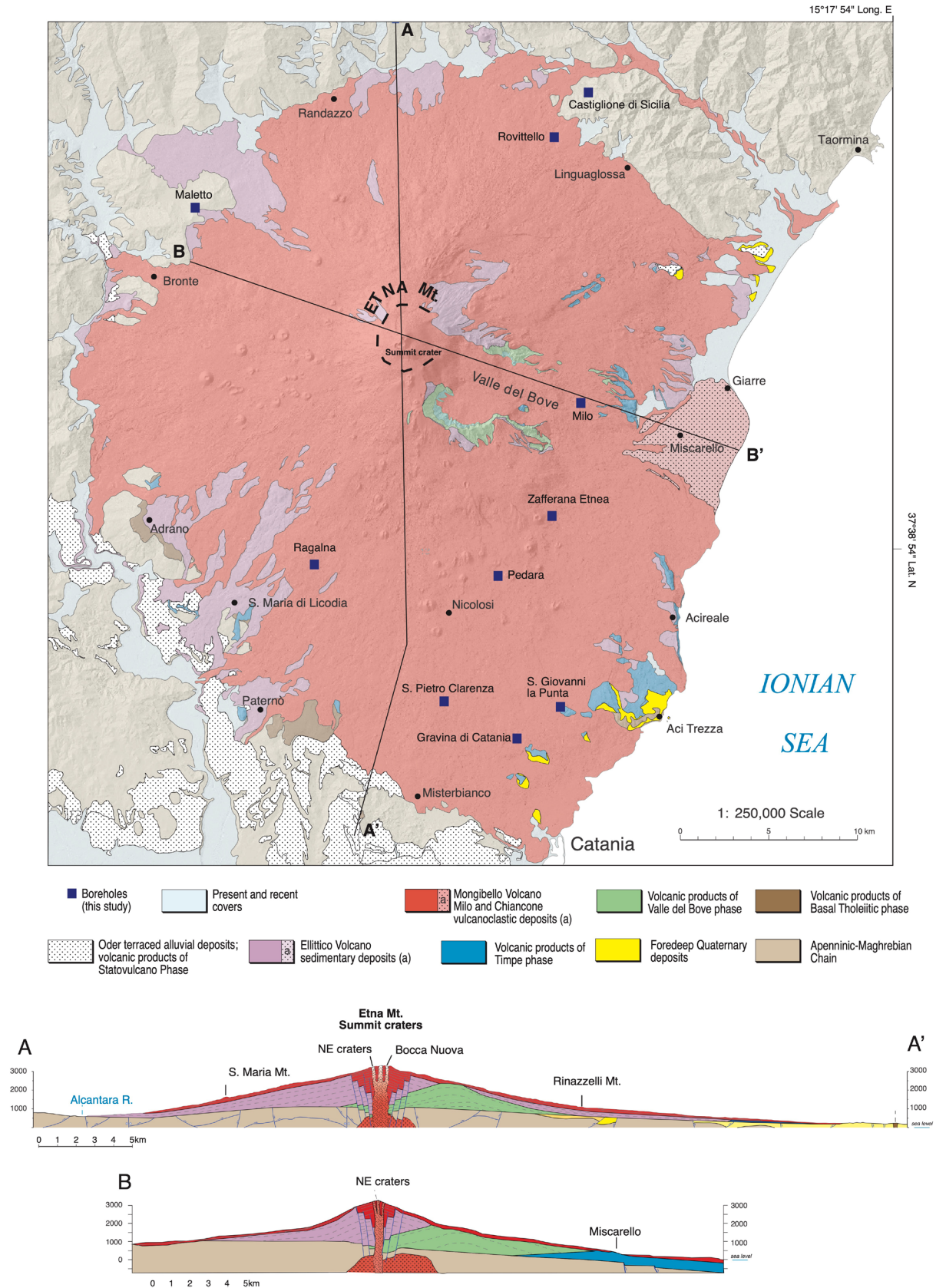


Figure 2. Geological map of Mt. Etna (modified from Branca et al., 2011; 2013) and location of the investigated down-hole seismic surveys, together with representative geological cross-sections (A-A' and B-B'). The map illustrates the distribution of the main volcanic units, sedimentary deposits, and structural features of the Etnean edifice, including the Valle del Bove depression and the Ionian coastal sector. Borehole locations analyzed in this study are indicated by blue squares.

Table 1. Schematic subdivision of Mt. Etna into the main structural sectors, highlighting differences in volcanic evolution, lithology, and subsurface architecture.

Zone	Distance from summit	Representative sites	Dominant lithologies	Subsurface characteristics
Proximal volcanic core	0-10 km	Pedara, Ragalna	Massive to vesicular basaltic lava flows with subordinate scoriaceous horizons	Thick lava-dominated volcanic pile; strong vertical heterogeneity controlled by vesicularity, fracturing, and cooling facies
Intermediate mixed volcanic zone	10-20 km	Milo, San Pietro Clarenza, Zafferana Etnea	Alternating lava flows, pyroclastic deposits, paleosols, and volcaniclastic layers	Layered volcanic sequences with rapid facies variations and frequent impedance contrasts
Distal volcaniclastic-sedimentary transition	20-30 km	Gravina di Catania, San Giovanni La Punta	Pyroclastic deposits overlying marly clay substratum	Transition from volcanic to sedimentary control; shallow stratigraphic contrasts and mixed mechanical behavior
Distal sedimentary-basement domain	20-30 km	Maletto, Castiglione di Sicilia	Flysch units and cohesive clayey formations with thin volcanic cover	Shallow sedimentary basement; reduced volcanic influence; strong lithological contrasts
Distal lava-sedimentary mixed domain	~20-25 km	Rovittello	Lava bodies interbedded with volcaniclastic and coarse detrital deposits	Mixed volcanic-detrital system with discontinuous lava bodies and high lateral heterogeneity

3. Data and Methods

The dataset analyzed in this study comprises ten high-resolution DH surveys conducted within the framework of the Regional Seismic Microzonation Program in eastern Sicily (Regione Siciliana, 2017). These investigations were performed as part of institutional activities aimed at improving seismic hazard assessment and land-use planning in the highly urbanized areas surrounding Mt. Etna.

The surveys were distributed across ten different municipalities (Castiglione di Sicilia, Gravina di Catania, Maletto, Milo, Pedara, Ragalna, Rovittello, San Giovanni La Punta, San Pietro Clarenza, and Zafferana Etnea) providing a representative sampling of the volcanic edifice's geological complexity. Each DH test reached a depth of approximately 30 m, ensuring a consistent characterization of the shallow subsurface volumes that most significantly influence local seismic response and soil classification (e.g., V_{SE} definition). This spatial distribution allows for a comprehensive evaluation of various lithological units, including diverse lava flow sequences, pyroclastic deposits, and varying degrees of fracturing and hydrothermal alteration.

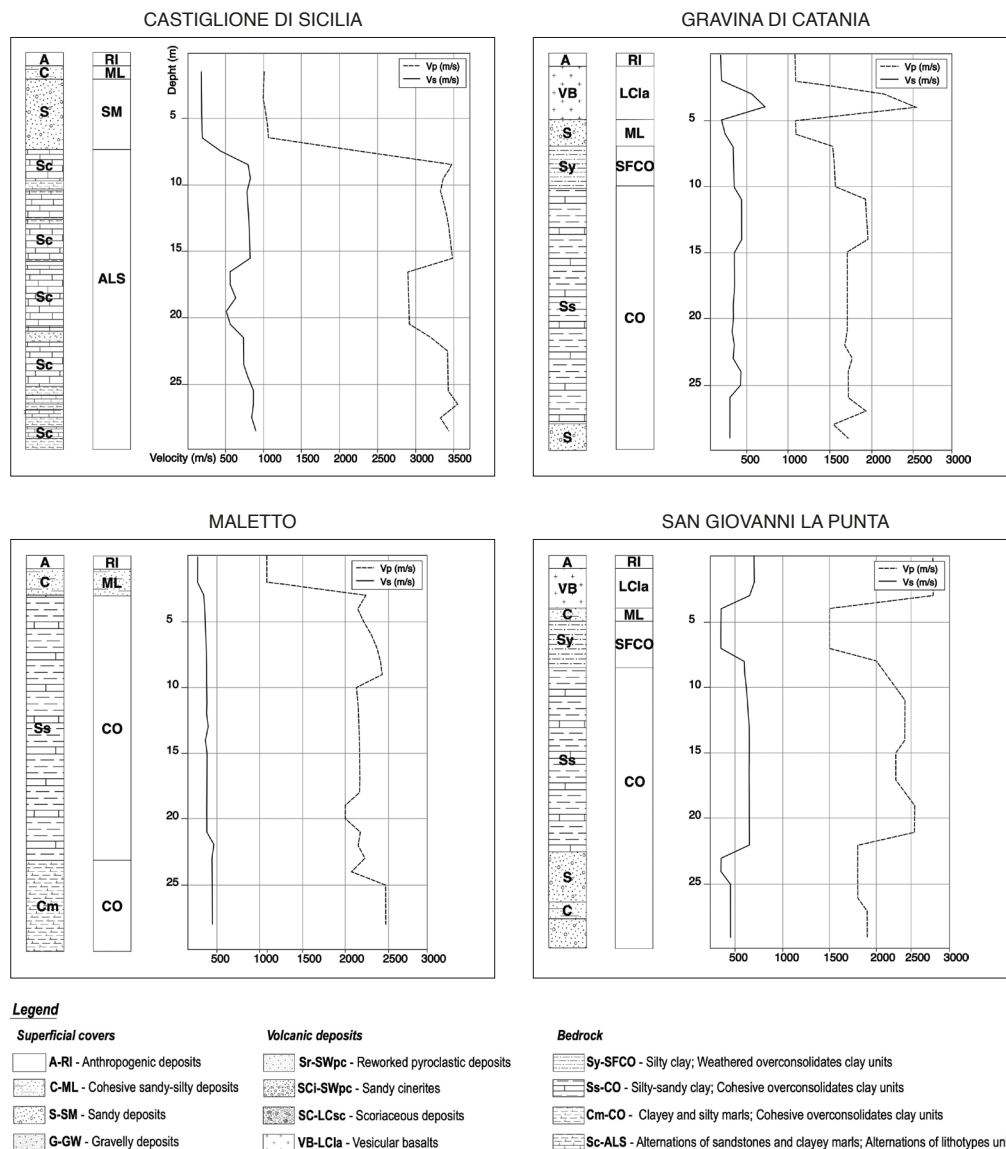
The survey geometry and acquisition parameters are summarized in Table 2. For each receiver position, a minimum of three shots were recorded and stacked to improve the signal-to-noise ratio and prevent errors caused by occasional external noise or instrumental artifacts. A window time of 1.0 s was selected, providing a sufficiently large temporal window to capture late arrivals or reflections from deeper discontinuities. DH measurements were performed using standardized acquisition and processing protocols widely adopted in seismic microzonation studies (e.g., Di Fiore et al., 2020) with a surface seismic source and a three-component geophone lowered inside the borehole at fixed 1-m depth intervals. Both compressional (P) waves and horizontally polarized shear (SH) waves were generated at the surface and recorded.

Table 2. Acquisition parameters for the DH seismic surveys.

Number of Shots (No)	Sampling rate (dt)	Record Length (WT)	Offset (D)	Depth Interval (d)
3	0.125 ms	1.0 s	175 cm	100

3.1 Engineering geological classification (EGUs and stratigraphic grouping)

To interpret the seismic velocity data in relation to lithological variability, the investigated materials were classified into Engineering Geological Units (EGUs), in accordance with the Italian Graphic and Data Archiving Standards for Seismic Microzonation v. 4.2 (Technical Commission for Seismic Microzonation, 2020). These units were defined by integrating stratigraphic data with physical-mechanical parameters and shear-wave velocity profiles (VS). This approach involves a systematic translation of lithostratigraphic units into engineering-geological classes (e.g., A → RI), where each EGU is characterized by homogeneous seismic behavior, facilitating the identification of areas prone to local amplification or ground instability. The superficial cover includes anthropogenic deposits (A-RI), cohesive soils (C-ML), and granular materials such as sandy and gravelly eluvio-colluvial deposits (S-SM; G-GW). These units are generally characterized by low to moderate shear-wave velocities and high variability related to compaction and heterogeneity. Figure 3 shows the stratigraphic columns, the corresponding EGU classification, and the corresponding VS profiles.



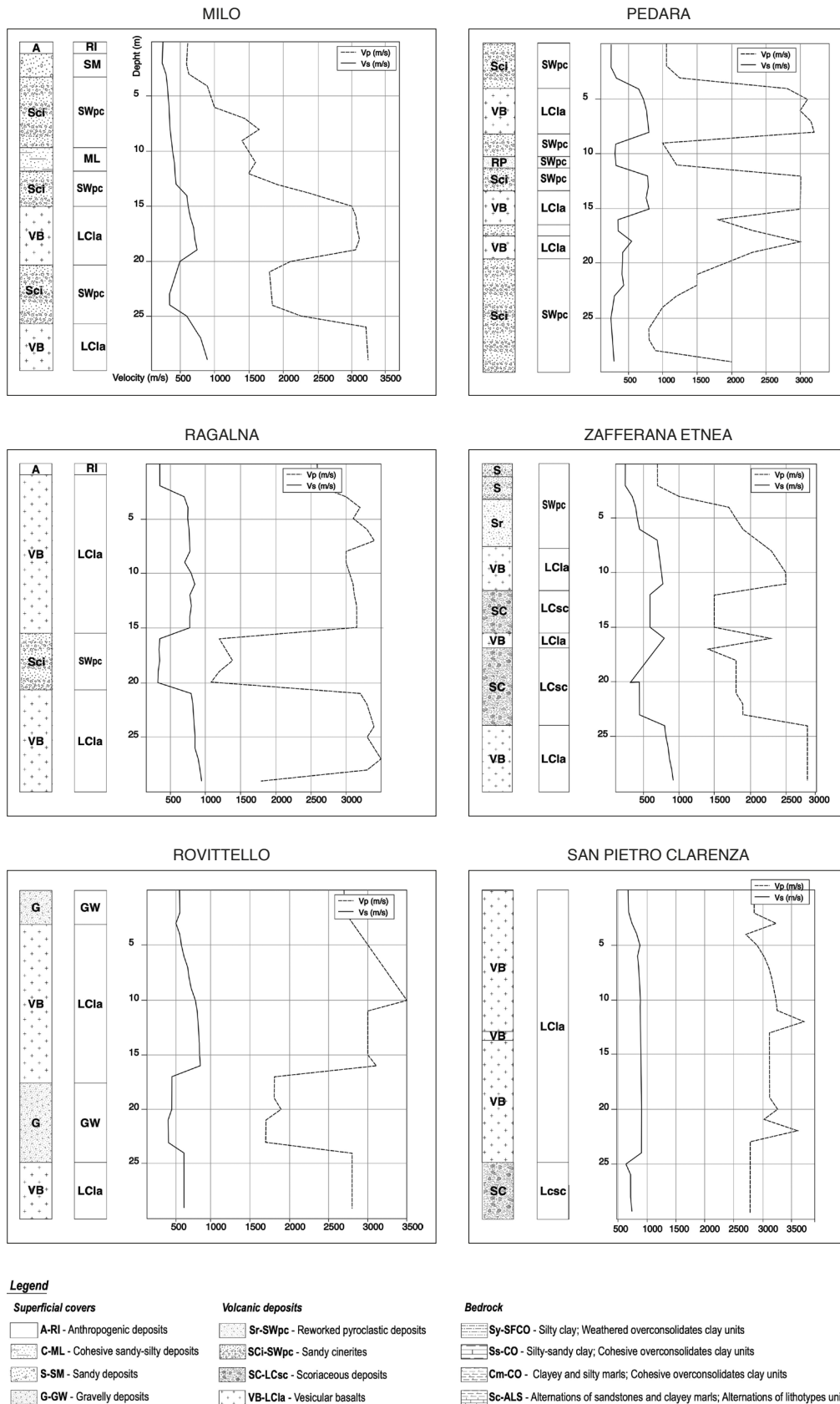


Figure 3. Representative down-hole seismic profiles for the investigated municipalities on Mt. Etna, showing the vertical distribution of stratigraphy, engineering geological units (EGUs), and seismic velocities (V_p and V_s) within the first ~30 m of the subsurface. The sites are grouped according to the dominant geological framework, highlighting differences between (i) sectors characterized by shallow sedimentary bedrock, (ii) areas with alternating volcanic and sedimentary units, and (iii) lava-dominated sequences with absent exposure of the substratum.

and the VP and VS profiles. The EGU columns summarize the lithological groupings defined according to common geological and engineering characteristics.

Building upon this geological framework, a concentric zonation of the volcanic edifice can be defined based on borehole stratigraphy and engineering geological classification (EGUs). Proximal sectors are dominated by massive and vesicular lava flows (LCla), forming a thick and relatively stiff volcanic pile. Intermediate zones are characterized by a highly heterogeneous alternation of lava flows and pyroclastic deposits (SWpc + LCLa), with frequent impedance contrasts and strong vertical variability. Distal sectors show increasing influence of sedimentary formations (CO, ALS) and volcanoclastic deposits, with a thinner volcanic cover and a shallower bedrock. Locally, mixed volcanic-detrital domains (e.g., GW + LCLa) further increase lateral heterogeneity.

Table 3 summarizes all the EGUs identified in Fig. 3, grouped into superficial soils, pyroclastic deposits, and geological bedrock.

Volcanic deposits were subdivided into pyroclastic units, including sandy cinerites (SCi-SWpc), scoriaceous deposits (SC-LCsc), and reworked pyroclastic deposits (Sr-SWpc). These materials exhibit highly variable seismic properties due to differences in grain size, degree of welding, and post-depositional alteration.

Lava flows were mainly classified as vesicular basalts (VB-LCLa), representing the most competent volcanic units within the shallow subsurface. These deposits, identified at specific sites (e.g. Milo, Pedara, Zafferana Etnea, Ragalna, Rovittello, S. Pietro Clarenza) typically show high shear-wave velocities and relatively limited dependence on depth, although local variability may occur due to fracturing and vesicularity.

The former (CO) consist predominantly of overconsolidated clayey formations, including the “Argille Azzurre Formation” (Foredeep Quaternary deposits in Fig. 2) and the chaotic “Argille Varicolori” or “Numidian Flysch” (Apennine-Maghrebian chain in Fig. 2) (Lentini, 1982; Branca et al., 2011a), while SFCO represents their weathered and altered counterparts. In contrast, the “Capo d’Orlando Flysch” (ALS) (Apennine-Maghrebian chain in Fig. 2) is characterized by a well-stratified alternation of competent sandstone and pelitic layers, whereas SFALS corresponds to its altered and degraded portions, where weathering processes reduce mechanical competence and increase heterogeneity. These distinct geological frameworks result in divergent mechanical behaviors (Panzera et al., 2017): while the clay-rich formations exhibit moderate seismic velocities, the flysch units provide significantly higher stiffness and overall rock-mass competence (Mineo et al., 2019; Panzera et al., 2017). To reduce data dispersion and improve the interpretation of velocity trends, the EGUs were further grouped into broader stratigraphic classes: superficial soils, pyroclastic deposits, lava flows, and geological bedrock. This grouping allows a more robust analysis of the relationships between seismic velocities, depth, and lithology, overcoming the limitations of purely depth-dependent approaches. These groups were used as the reference framework for the statistical analysis and for the interpretation of VS-depth relationships presented in the following sections.

Table 3. Representative shear-wave velocity (V_s) ranges for the engineering geological units (EGUs), grouped into broader stratigraphic classes (superficial soils, pyroclastic deposits, lava flows, and geological bedrock). This classification reduces data dispersion and enhances the interpretation of velocity trends by emphasizing lithological control over depth-dependent variability. Values are derived from the analyzed dataset and supported by literature for volcanic environments.

Stratigraphic Group	EGUs	Description	V_s range (m/s)	Expected lithological heterogeneity	Interpretation
Superficial soils	RI	Anthropogenic deposits	100-250	Very high	Unconsolidated, highly heterogeneous
	ML	Cohesive soils (clays/silts)	150-350	High	Controlled by consolidation and water content
	SM	Sandy deposits	200-450	High	Density-dependent, poorly sorted
	GW – GP – GCcz – GM	Gravelly deposits	200-450	High	Density-dependent, poorly sorted

Stratigraphic Group	EGUs	Description	V _s range (m/s)	Expected lithological heterogeneity	Interpretation
Pyroclastic deposits	SWpc	Sandy cinerites	200-400	Very high	Weakly cemented, highly variable
	LCsc	Scoriaceous deposits	250-500	Very high	Strong influence of vesicularity
	SWpc	Reworked pyroclastics	200-450	Very high	Mixed materials, strong heterogeneity
Lava flows	LCla	Vesicular basalts	400-800	Moderate-High	Controlled by fracturing and cooling structures
Geological bedrock	CO	Clayey bedrock (undisturbed)	300-600	Moderate	Overconsolidated formations
	SFCO	Clayey bedrock (weathered)	200-450	High	Weathering reduces stiffness
	ALS	Flysch (undisturbed)	600-1000	Moderate	Competent layered sequences
	SFALS	Flysch (weathered)	400-700	High	Degradation increases heterogeneity

3.2 Seismic site response analyses

In this study, seismic amplification is measured with an amplification factor (AF) derivation, computed as the ratio of response spectra at the soil surface to response spectra at the outcropping reference rock. $SA(T)_s$ and $SA(T)_b$ are the 5% damped spectral accelerations at the soil surface and outcropping reference bedrock, respectively. For 1D seismic site analysis we used the NC92 Soil software (Acunzo et al., 2024). The assumption based on the equivalent-linear site response was adopted for 1D analysis. NC92 Soil software performs an equivalent-linear site response analysis which assumes linear-elastic wave propagation with strain compatible properties. The analysis is an iterative procedure which changes the properties in the layer such that properties use the previously computed effective strain for the layer. The extensive evaluation of the impact of local seismo-stratigraphic configurations on seismic ground motion presents significant challenges due to the necessity of considering the combined effects of uncertainty and small-scale lateral variability of the relevant parameters. With respect to existing software, the code introduces new pre and post-processing features, which also meet the specific requirements of seismic microzonation studies. Within the code, the complete spectrum of uncertainties related to local seismo-stratigraphic configurations, including lithotype successions, layer thicknesses, and seismic and geotechnical properties for the considered lithotypes, is managed by considering user-defined constraints and statistical properties of the relevant parameters.

Figure 4 shows the location of the boreholes where the down-hole surveys were performed. The boreholes were drilled with continuous coring and were distributed across the investigated municipalities to sample the main lithological units occurring in the study area.

The parameters adopted in the 1D analysis are reported in Table 4 and were derived from previous studies conducted in the Mt. Etna area, as also reported in the reference list. The variation of normalized shear modulus (G/G_{max}) and damping ratio (D) was derived from literature data, as summarized in Table 4.

As regards the input motions, seven accelerograms recorded at permanent seismic stations installed around the Mt. Etna area were selected. Table 5 reports the main characteristics of each record, while Fig. 5 shows the corresponding response spectra.

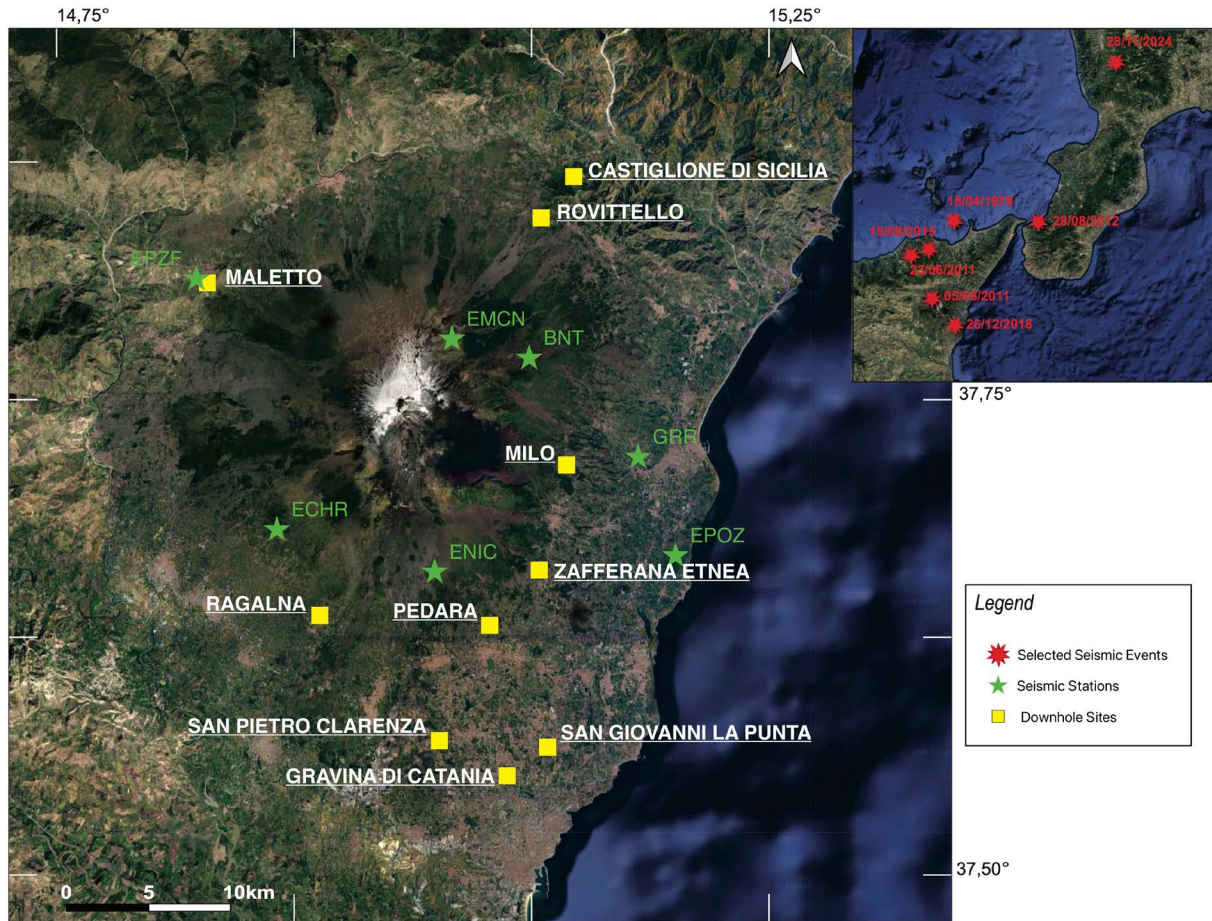


Figure 4. Location of the investigated sites on the Mt. Etna volcanic edifice (eastern Sicily, Italy). Yellow squares indicate the down-hole survey sites analyzed in this study, while green stars represent the seismic stations used for input motion selection. The inset shows the regional location of the selected seismic event. Coordinates are expressed in decimal degrees.

Table 4. Mechanical and dynamic parameters adopted for the equivalent-linear seismic response analyses, including representative V_s ranges, modulus reduction and damping reference curves, and unit weight values for the investigated lithological classes, assigned according to literature data and site-specific geological interpretation.

Stratigraphic Group	EGU	Description	V_s (m/s)	Seismic Bedrock	G(g)-D(g) Reference	Unit weight (kN/m ³)	Unit weight Reference
Superficial soils	RI	Anthropogenic deposits	100-250	—	Pagliaroli et al., (2014)	15.5	Lengkeek and Brinkgreve, 2022
	C	Cohesive soils (clays/silts)	150-350	—	Vucetic, M., and Dobry, R. (1991)	16.0	Lengkeek and Brinkgreve, 2022
	SM – SMec – SMtf	Granular deposits (sands, gravels)	200-450	—	Vucetic, M., and Dobry, R. (1991)	18.0	Banna et al., 2016

Stratigraphic Group	EGU	Description	V _s (m/s)	Seismic Bedrock	G(g)-D(g) Reference	Unit weight (kN/m ³)	Unit weight Reference
Pyroclastic deposits	SW – SWpc	Sandy cinerites	200-400	—	Rollins et al., 1998	15.5	Di Traglia et al., 2026
	LCsc*	Scoriaceous deposits	250-500	—	Naso et al. (2001)	15	Di Traglia et al., 2026
	SW – SWpc	Reworked pyroclastics	200-450	—	Rollins et al., 1998	17	Di Traglia et al., 2026
Lava flows	LCla*	Vesicular basalts	400-800	x	Linear	27	Corsaro and Miraglia, 2022
Geological bedrock	CO	Clayey bedrock (undisturbed)	300-600	x	Naso et al. (2001)	20	Wiesmaier et al., 2015
	SFCO	Clayey bedrock (weathered)	200-450	x	Naso et al. (2001)	18	Wiesmaier et al., 2015
	LP – ALS	Flysch (undisturbed)	600-1000	x	Modoni and Gazzelloni (2010)	24	Wiesmaier et al., 2015
	SFLP – SFALS	Flysch (weathered)	400-700	x	Modoni and Gazzelloni (2010)	20	Wiesmaier et al., 2015

Table 5. Input ground motions selected for the 1D seismic response analyses and associated response spectra (see Fig. 4 for location of selected seismic events and seismic stations; ITACA-INGV database, Felicetta et al., 2023). Legend: ML = Local Magnitude; DE = distance station site-epicenter; dt = time residual.

Permanent Seismic Station			Seismic event						
Name	Latitude	Longitude	Latitude	Longitude	ML	DE	dt	Date	Time
ENIC	37.6860	14.9130	37.8040	14.9430	4.0	13.3	0.005	05/06/2011	15:12:35
ECHR	37.6863	14.9129	38.0990	14.9190	4.4	45.8	0.005	15/08/2015	23:04:58
BNT	37.7805	14.8444	38.0640	14.7840	5.2	31.9	0.005	23/06/2011	22:02:46
EMCN	37.7910	15.0340	37.6440	15.1160	4.8	17.9	0.005	26/12/2018	02:19:14
GRR	37.7261	15.1628	38.2700	15.1100	5.2	60.5	0.005	15/04/1978	23:33:47
EPZF	37.8240	14.8570	39.2107	16.3585	4.2	202	0.005	28/11/2024	23:54:53
EPOZ	37.6719	15.1885	38.2600	15.7500	4.7	81.8	0.005	28/08/2012	23:12:16

Since the investigated down-hole sites do not generally coincide with the locations of the available permanent seismic stations, the selected accelerograms were not intended to reproduce the local site response at the recording stations. Instead, they were selected as representative input motions for the regional seismic hazard affecting the Mt. Etna area and subsequently scaled to a common target response spectrum according to the Italian Technical Standards for Construction (NTC, 2018).

Therefore, the adopted procedure allows the numerical analyses to isolate the influence of the geological and geotechnical characteristics of the investigated down-hole profiles on seismic amplification, while minimizing differences related to the original spectral characteristics of the recorded motions. Although the spatial separation between recording stations and investigated sites represents an intrinsic limitation of the available dataset, the selected stations are all located within the Mt. Etna volcanic region and provide representative strong-motion records for the considered seismotectonic setting.

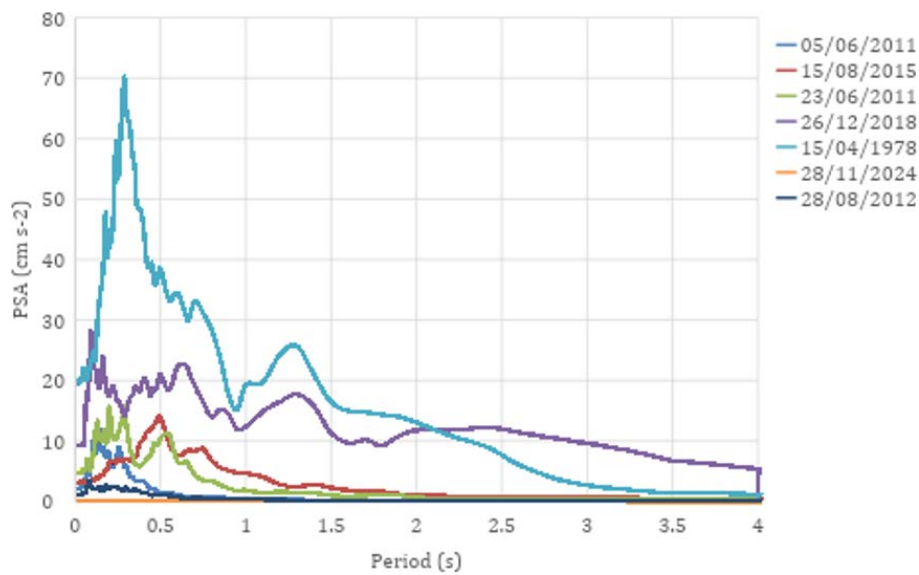


Figure 5. Acceleration response spectra of the selected input ground motions adopted for the 1D seismic response analyses (see Table 5). Each curve represents the response spectrum of one selected accelerometric record acquired at the corresponding seismic station. The figure shows the superimposed spectra before the spectral scaling procedure.

Figure 6 reports the SA that were scaled using the software InSpector (Acunzo et al., 2014), spectrum-compatible with elastic target response spectrum built on the indication of NTC (Italian technical standards for construction, 2018) and considering the site's coordinates with the highest reference hazard. All response spectra show different peak periods (Fig. 5).

The seismic bedrock was assumed at a depth of 30 m, corresponding to the maximum depth of the DH surveys. Although this assumption is not strictly representative of actual geological conditions, it allows the evaluation of the effect of VS variability within each lithology on the amplification function (AF). For $G(y)$, $D(y)$ and density, we adopted the data as reported in Table 4.

These parameters were also adopted in previous third-level seismic microzonation studies carried out in several municipalities of the Mt. Etna area (ETNA FAC, 2024). The analysis considered the ten stratigraphic columns derived from the down-hole (DH) surveys, for which amplification factors (AF) were calculated while maintaining constant thicknesses for the different lithological units. Within this framework, a sensitivity analysis was performed to evaluate the influence of shear-wave velocity variations within each lithology on the resulting seismic amplification. Table 6 summarizes, for each investigated site, the number of generated VS models (mn) adopted for the 1D numerical simulations.

To directly investigate the influence of shallow subsurface heterogeneity on seismic response, AF values were computed for each site using equivalent shear-wave velocity (VSE) profiles derived from DH measurements. The seismic response was estimated assuming vertically propagating shear waves within horizontally layered media.

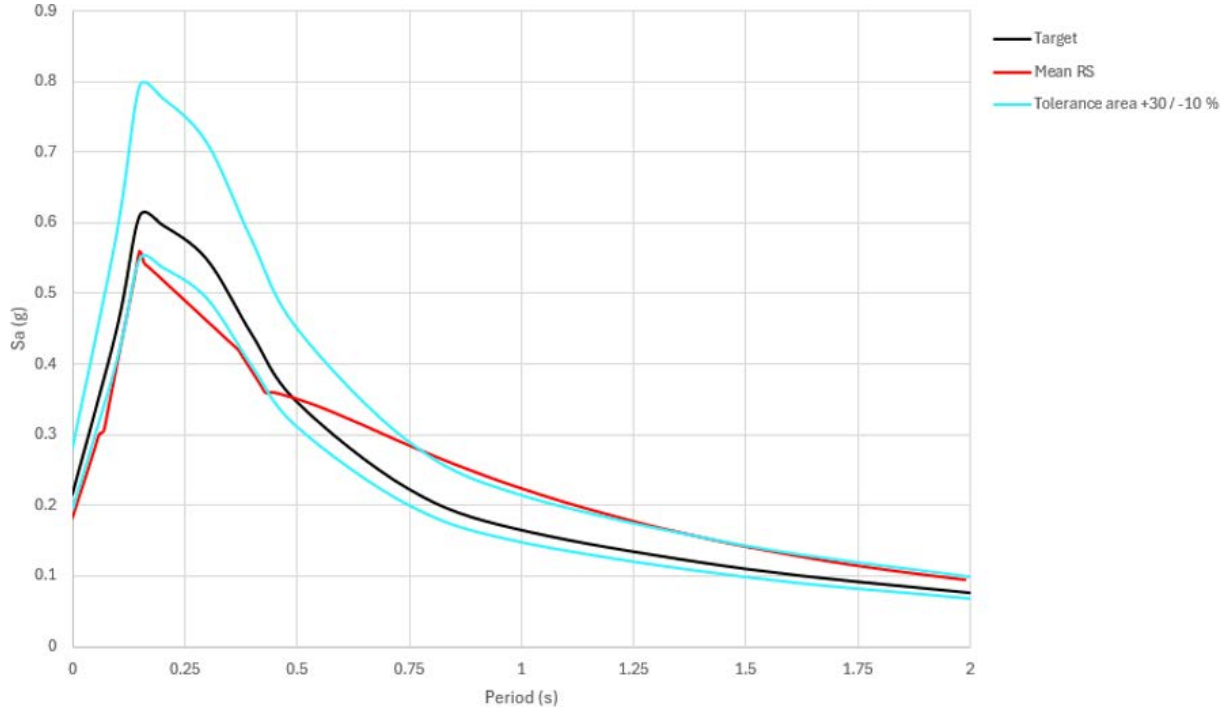


Figure 6. Acceleration spectral response selected and scaled using the software InSpector (Acunzo et al., 2014). Spectrum compatible target response (solid black line) by NTC, 2018 is reported. The return period of 475 years (probability of exceedance of 10% in 50 years) was considered. Solid red line: mean SA; solid light blue line: tolerance area +30/-10%.

To evaluate the frequency-dependent behavior of site response, AF values were averaged over three spectral period intervals: short periods (0.1–0.5 s), intermediate periods (0.4–0.8 s), and long periods (0.7–1.1 s). Short-period response is generally more sensitive to the mechanical properties and localized impedance contrasts of the shallower portion of the profile, whereas intermediate- and long-period response tends to reflect the broader vertical organization of the investigated stratigraphic succession.

3.3 Influence of the V_S variability on the AF

The variation of V_S within each lithological unit can be significant. The analyzed DH data show that V_S variability within individual lithologies is non-negligible, leading to potentially inconsistent AF estimates. Equivalent Velocity (V_{SE}) alone does not provide a unique indication of expected amplification, due to the principle of equivalence, since similar V_{SE} values may correspond to significantly different AF values. In this study, we propose an approach to estimate AF variability by considering not only V_{SE} , but also the dispersion around the mean value (V_{SEM}). To achieve this, for each stratigraphic profile a set of EGU-based models was generated according to the V_S variability within each lithology. The $V_{S,eq}$ value was computed for each model using Eq. (1), where h_i and $V_{S,i}$ are the thickness and shear-wave velocity of the i -th layer, respectively, and n is the total number of layers within the investigated 0–30 m depth interval. The mean equivalent velocity (V_{SEM}) and the corresponding standard deviation (Sd) were then calculated using Eqs. (2) and (3), respectively.

$$V_{se} = \frac{\sum_{i=1}^n h_i}{\sum_{i=1}^n \frac{h_i}{V_{Si}}}; \quad (1)$$

$$V_{sem} = \frac{1}{mn} \sum_{i=1}^n V_{se} \quad (2)$$

Equivalent Velocity Limits in Volcanic Site Response

$$Sd = \sqrt{\frac{1(V_{se} - V_{sem})^2}{mn - 1}} \quad (3)$$

Table 6 summarizes the number of generated models (mn); the V_{SEM} and the corresponding standard deviation (Sd) for the investigated sites.

The obtained values indicate markedly different levels of internal heterogeneity among the analyzed stratigraphic successions. The highest variability is observed at Zafferana (Sd = 108 m/s), Ragalna (Sd = 97 m/s), and Pedara (Sd = 71 m/s), reflecting the strong lithological complexity of these sectors (proximal/intermediate zone), characterized by alternating lava flows, pyroclastic horizons, reworked volcanoclastic deposits, and variable weathering conditions. In contrast, Maletto exhibits the lowest variability (Sd = 10 m/s), suggesting a comparatively more homogeneous subsurface configuration controlled by shallow sedimentary basement conditions (Distal sedimentary-basement domain).

Table 6. Study sites and number of generated V_S models (mn), mean equivalent shear-wave velocity (V_{SEM}), and standard deviation (Sd) adopted for the 1D seismic response analyses.

Sites	mn	V_{SEM} (m/s)	Sd (m/s)
Castiglione	50	353	28
Gravina di Catania	40	316	38
Maletto	40	363	10
Milo	50	426	25
Rovittello	50	570	31
San Giovanni La Punta	40	570	31
San Pietro Clarenza	50	690	18
Ragalna	60	659	97
Pedara	60	377	71
Zafferana	40	360	108

4. Discussion

The resulting AF values show a wide variability both within individual sites and across different municipalities, highlighting the strong influence of subsurface heterogeneity. In particular, AF does not exhibit a simple dependence on V_{SE} values. Sites with similar V_S may display significantly different amplification levels, indicating that internal layering and velocity contrasts play a dominant role.

To further investigate this aspect, the “standard deviation of V_S ” (Sd) was computed for each profile as a quantitative indicator of velocity variability.

Figure 7 (a-j) shows the ordered distributions of V_{SE} derived from the generated stochastic models. Beyond the absolute variability values, the morphology of the distributions provides important information on the internal organization of the shallow subsurface and on the relative influence of lithological heterogeneity on V_{SE} . The observed

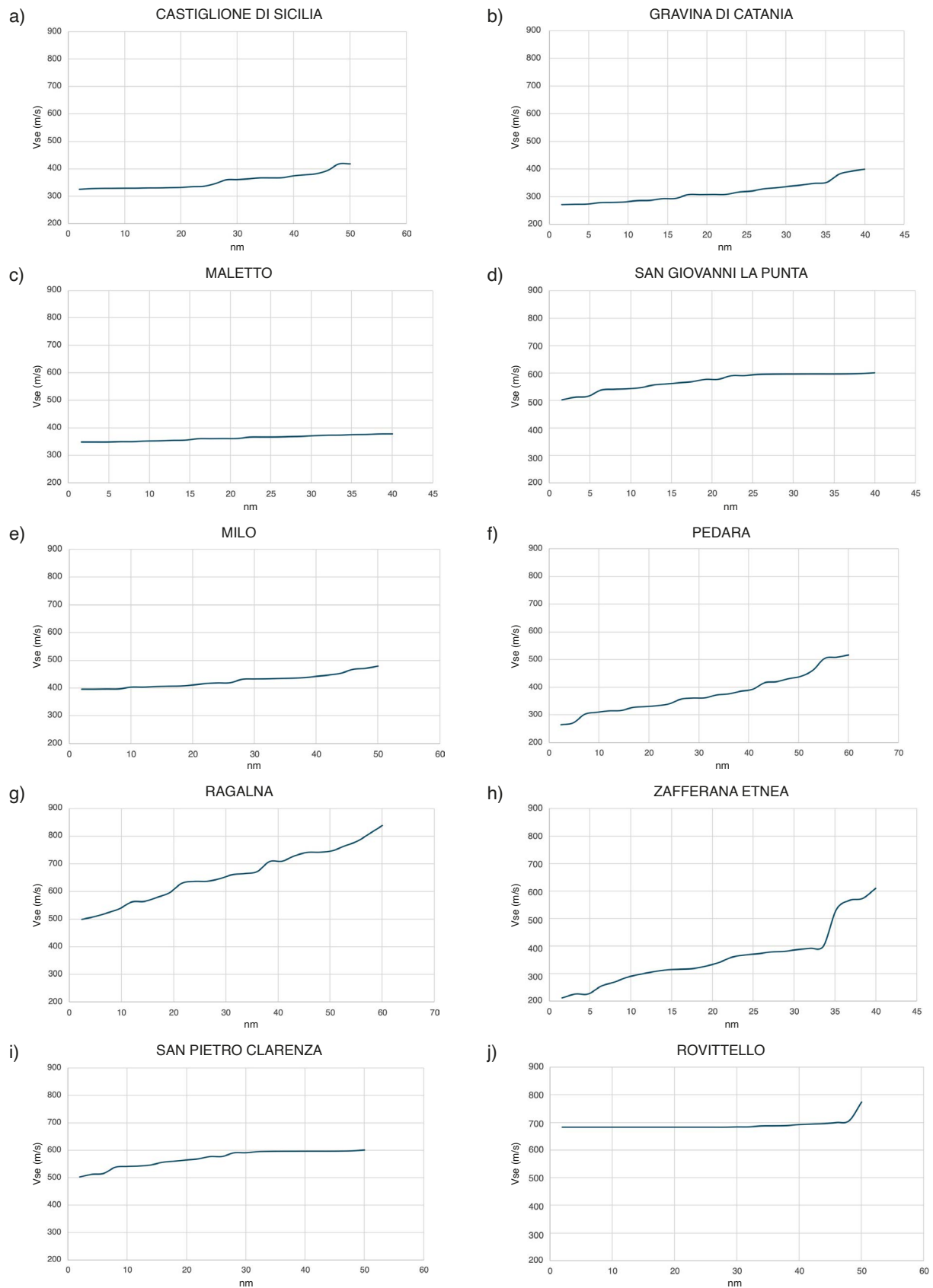


Figure 7. (a-j) Distribution of equivalent shear-wave velocity values (V_{se}) derived from the generated V_s models for the investigated sites: (a) Castiglione di Sicilia, (b) Gravina di Catania, (c) Maletto, (d) San Giovanni La Punta, (e) Milo, (f) Pedara, (g) Ragalna, (h) Zafferana Etnea, (i) San Pietro Clarenza, and (j) Rovittello. The progressive variation of V_{eq} highlights the different levels of internal V_s variability and stratigraphic heterogeneity characterizing the analyzed volcanic and sedimentary successions.

trends can be directly related to the dominant engineering geological units (EGUs) characterizing the investigated stratigraphic successions.

Castiglione di Sicilia, Gravina di Catania, and Maletto exhibit gently increasing distributions characterized by limited dispersion and smooth gradients. These patterns suggest relatively stable subsurface configurations, where the V_{SE} is only moderately affected by internal lithological variability. In Castiglione di Sicilia and Maletto, this behavior is mainly associated with the predominance of cohesive and lithified sedimentary units (ALS, CO), represented by flysch-type formations and clayey substrata, locally covered by thin volcanic deposits. The relatively limited variability reflects the persistence of mechanically coherent sedimentary successions with reduced vertical contrasts. In Gravina di Catania, the smoother trend is instead related to the prevalence of pyroclastic and cohesive units (SFCO, CO), where soft volcanoclastic deposits overlie marly clay formations, generating gradual stiffness transitions rather than abrupt impedance contrasts.

Rovittello and San Giovanni La Punta display convex-shaped distributions characterized by an initially rapid increase followed by progressive stabilization toward higher velocity values. This behavior reflects mixed stratigraphic configurations where relatively stiff volcanic units progressively dominate the equivalent response. At Rovittello, the alternation of lava units (LCla) with coarse volcanoclastic and gravelly deposits (GW) produces a mixed volcanic-detrital system in which the contribution of rigid lava bodies becomes increasingly dominant at higher V_{SE} . A similar trend is observed at San Giovanni La Punta, where pyroclastic and cohesive deposits are locally interbedded with stiffer volcanic layers, leading to progressive stabilization of the equivalent stiffness.

A markedly different behavior is observed at Ragalna, Pedara, and Zafferana Etnea, where strongly ascending distributions indicate high sensitivity of equivalent velocity to internal stratigraphic variability. These sites are dominated by lava units (LCla) interbedded with scoriaceous horizons (LCsc), pyroclastic deposits (SWpc), and weathered volcanoclastic levels. The resulting alternation of mechanically contrasting EGU classes generates strong impedance contrasts and rapid vertical stiffness variations. In these sectors, relatively small modifications in layer thickness or velocity produce substantial changes in equivalent stiffness, resulting in highly dispersed and strongly ascending distributions. Zafferana Etnea, in particular, exhibits the highest variability, reflecting the complex alternation of lava flows, pyroclastic horizons, paleosols, and reworked volcanoclastic deposits typical of the eastern flank of Mt. Etna.

Finally, Milo and San Pietro Clarenza show nearly sub-horizontal distributions with limited dispersion around the mean values, suggesting relatively persistent stratigraphic configurations and reduced sensitivity of equivalent velocity to local variability. In Milo, the alternation of lava flows and pyroclastic deposits (LCla + SWpc) appears sufficiently regular to produce progressive but controlled stiffness variations. San Pietro Clarenza is instead characterized by the predominance of compact lava units (LCla), whose mechanical continuity limits the variability of equivalent seismic velocities despite the volcanic nature of the succession.

Overall, the observed distribution patterns demonstrate that the morphology of the V_{SE} curves is strongly controlled by the spatial organization of EGU classes within the shallow subsurface. Sites dominated by persistent and mechanically homogeneous units tend to exhibit stable or weakly dispersed distributions, whereas profiles characterized by frequent alternations of contrasting volcanic and volcanoclastic units produce highly variable and non-linear equivalent velocity patterns. This confirms that V_{SE} in volcanic terrains are controlled not only by average stiffness conditions but also by the internal stratigraphic architecture and persistence of impedance contrasts within the investigated successions.

The resulting AF values exhibit strong variability both within individual sites and across different geological domains, confirming that amplification does not depend exclusively on V_{SE} . Sites characterized by similar V_{SE} may exhibit substantially different amplification levels, indicating that internal layering and impedance contrasts exert a primary control on seismic response.

An interesting analysis consists in plotting S_d versus AF for different V_{SE} classes, considering all the models adopted in the 1D numerical simulations as the reference dataset.

Figures 8-11 show the variation of the amplification factor (AF) as a function of S_d for representative V_{SE} classes ($V_{SE} = 300, 350, 400$, and 500 m/s). The results indicate that the S_d -AF relationship exhibits a non-linear behavior for specific ranges of S_d , and that these threshold S_d values vary according to the corresponding V_{SE} class.

The most heterogeneous response is observed for soft-to-intermediate profiles ($V_{SE} = 300$ m/s), where AF shows strong sensitivity to increasing S_d . Intermediate- and long-period AF values progressively increase with heterogeneity up to critical thresholds ($S_d = 140$ - 160 m/s), after which amplification rapidly decreases. This behavior likely reflects a transition from coherent resonance-controlled amplification to increasingly scattered and dissipative wave

propagation associated with highly heterogeneous volcanic structures. A markedly different behavior is observed for $V_{SE} = 300$ m/s (Fig. 8), AF increases within the 0.4-0.8 s and 0.7-1.1 s period ranges up to Sd values of approximately 150 m/s, beyond which AF decreases almost to unity. For the 0.1-0.5 s period range, a nearly constant and slightly de-amplifying trend is observed. This behavior likely reflects a transition from AF controlled by coherent resonance phenomena to increasingly diffusive and dissipative wave propagation associated with highly heterogeneous volcanic structures.

Figure 9 shows AF as a function of Sd for $V_{SE} = 350$ m/s. In this case, for Sd values up to 75 m/s, AF remains nearly constant for all three reference period ranges. Beyond this threshold, while AF values for the 0.1-0.5 s and 0.4-0.8 s period ranges remain nearly unchanged around 1.3, the 0.7-1.1 s range, corresponding to lower frequencies, exhibits

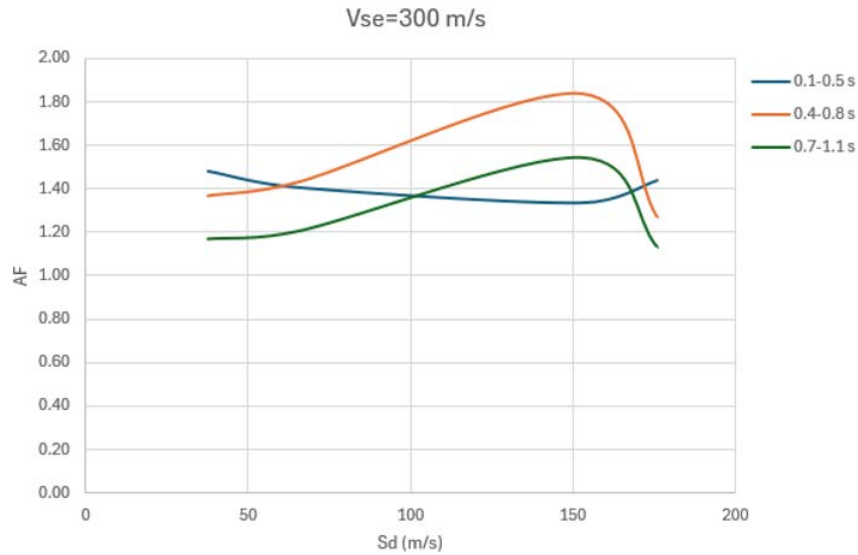


Figure 8. Variation of amplification factor (AF) as a function of shear-wave velocity standard deviation (Sd) for $V_{SE} = 300$ m/s. The observed non-linear trends indicate that amplification does not depend exclusively on equivalent velocity values, but is strongly influenced by the spatial organization of velocity contrasts and period-dependent resonance effects.

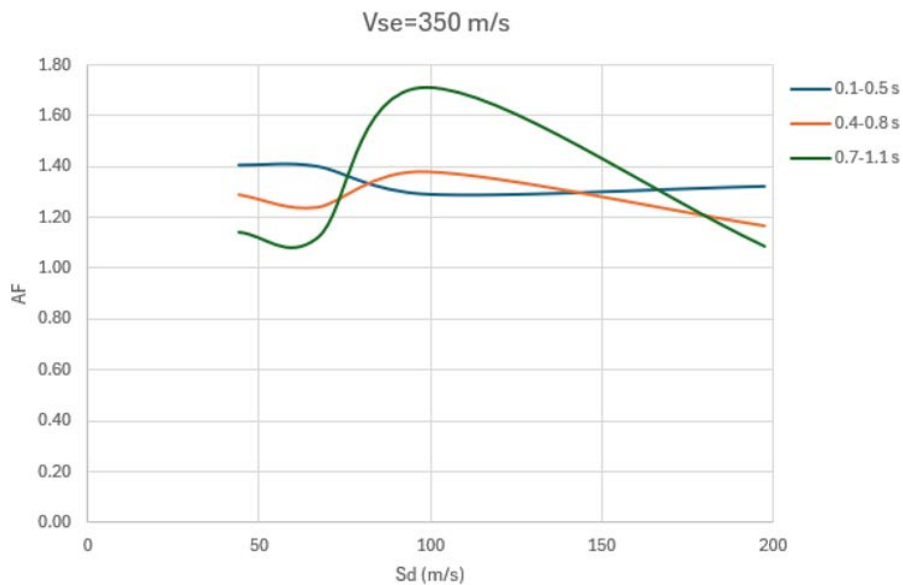


Figure 9. Relationship between amplification factor (AF) and shear-wave velocity variability (Sd) for $V_{SE} = 350$ m/s. The marked amplification peak observed within the long-period interval (0.7-1.1 s) highlights the strong sensitivity of seismic response to internal velocity heterogeneity and impedance distribution.

Equivalent Velocity Limits in Volcanic Site Response

a marked increase up to $S_d \approx 100$ m/s, followed by a progressive decrease toward unity for $S_d = 190$ m/s. This behavior suggests the existence of optimal heterogeneity conditions capable of enhancing resonance phenomena within layered volcanic successions at lower frequencies.

Profiles characterized by $V_{SE} = 400$ m/s (Fig. 10) exhibit the most stable behavior, with limited AF variability over the entire S_d range. In this case, moderate heterogeneity appears insufficient to significantly modify the overall AF of the stratigraphic sequence.

For relatively stiff profiles ($V_{SE} = 500$ m/s, Fig. 11), AF remains nearly constant at approximately 1.05-1.17 for S_d values lower than about 120 m/s. Beyond this threshold, AF progressively increases, although not markedly,

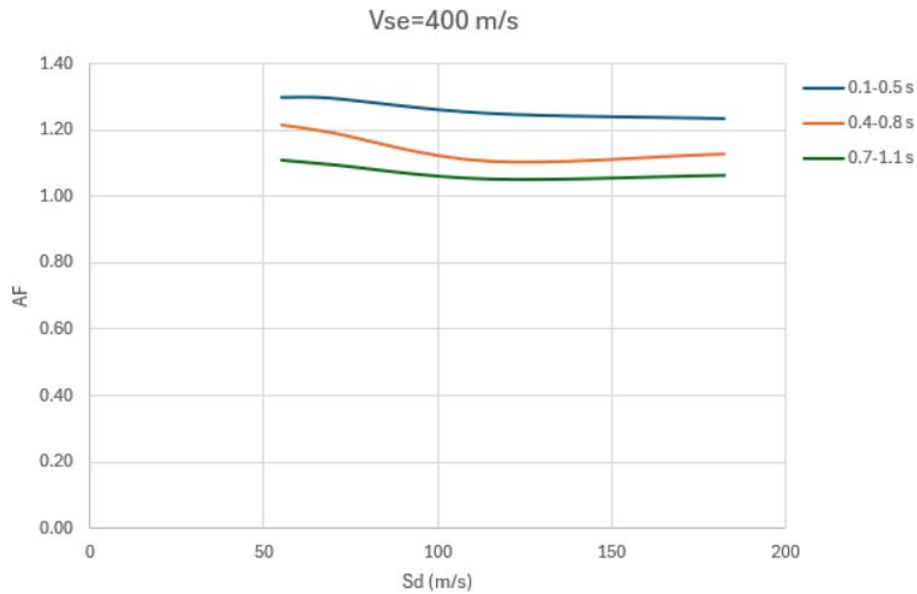


Figure 10. Variation of amplification factor (AF) with increasing shear-wave velocity standard deviation (S_d) for $V_{SE} = 400$ m/s. The relatively stable AF values observed across the investigated period ranges indicate limited sensitivity of seismic amplification to distributed velocity variability under intermediate stiffness conditions.

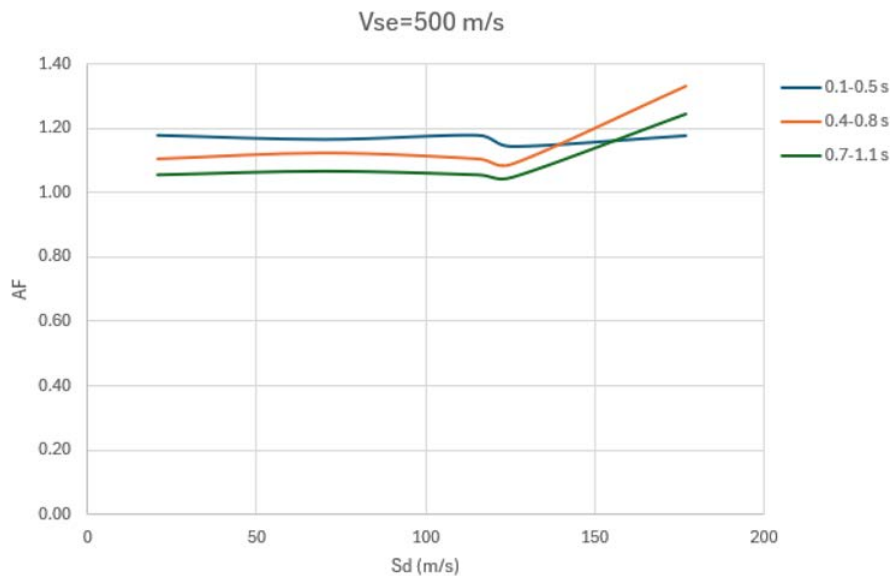


Figure 11. Variation of amplification factor (AF) as a function of shear-wave velocity standard deviation (S_d) for equivalent shear-wave velocity $V_{SE} = 500$ m/s. AF values are reported for three spectral period intervals (0.1-0.5 s, 0.4-0.8 s, and 0.7-1.1 s). The results show a progressive increase in amplification at intermediate and long periods for high S_d values, indicating the influence of increasing internal heterogeneity on seismic response.

especially within the 0.4-0.8 s and 0.7-1.1 s period ranges, indicating that strong heterogeneity ($S_d > 120$ m/s) begins to control AF through the development of significant impedance contrasts.

A further feature emerging from Figs. 8 and 11 is that the S_d -AF curves for the 0.1-0.5 s period interval are consistently flatter than those for the intermediate- and long-period ranges. This behaviour does not reflect the original differences among the earthquake spectra, but is mainly a consequence of the scaling procedure and the way AF is computed.

Although the unscaled response spectra of the selected earthquakes show pronounced differences at short periods (Fig. 5), these differences were substantially reduced before the site-response analyses by scaling the accelerograms to a common NTC-compatible target spectrum (Fig. 6). Therefore, the variability of the original input spectra should not be directly compared with the S_d -AF trends obtained from the scaled motions.

Moreover, AF represents the relative modification of the input motion produced by each stratigraphic model rather than the absolute spectral amplitude of the input motion. Since AF values were averaged over the relatively broad 0.1-0.5 s period interval, differences occurring at individual spectral periods are further smoothed in the resulting band-averaged values. The comparatively flat short-period trends therefore indicate that, for a given V_{SE} class, increasing the overall velocity dispersion of the 0-30 m profile does not systematically modify the mean amplification within this period range.

This behaviour also suggests that S_d , being an integrated measure of shear-wave velocity variability over the entire investigated profile, is not equally sensitive to the stratigraphic features controlling amplification at different periods. Short-period amplification is likely to be more strongly influenced by localized shallow impedance contrasts, whereas the intermediate- and long-period ranges are more sensitive to the overall vertical organization of velocity contrasts within the investigated succession. Consequently, changes in S_d produce a stronger and more systematic effect on AF at intermediate and long periods than within the 0.1-0.5 s range.

Overall, the results demonstrate that subsurface heterogeneity does not systematically increase AF. Moderate heterogeneity may enhance resonance effects by increasing impedance contrasts, whereas excessive heterogeneity may progressively disrupt coherent wave amplification through scattering and stratigraphic complexity.

Profiles characterized by similar V_{SE} may exhibit substantially different amplification behavior depending on the internal organization of lithological contrasts and on the degree of vertical heterogeneity. Consequently, beyond specific S_d thresholds, simplified site classification schemes become insufficient and site-specific seismic response analyses become necessary.

5. Conclusions

This study investigates the sensitivity of seismic amplification to shear-wave velocity (V_s) variability within volcanic lithological units at Mt. Etna through the analysis of ten sites characterized by geognostic boreholes and down-hole (DH) seismic investigations. One-dimensional seismic response simulations were performed to evaluate the relationship between equivalent shear-wave velocity (V_{SE}), velocity variability (S_d), and amplification factor (AF).

The results highlight the strong heterogeneity of volcanic successions and demonstrate that equivalent velocity parameters alone, such as V_{SE} or VS_{30} , are insufficient to reliably predict seismic site response in volcanic environments. Significant variability of equivalent stiffness may occur within the same lithological unit, particularly in lava flows and pyroclastic deposits affected by fracturing, vesiculation, weathering, and reworking processes. Consequently, similar V_{SE} values may correspond to substantially different AF values depending on the internal stratigraphic architecture and distribution of impedance contrasts.

A statistical approach based on the combined use of mean equivalent shear-wave velocity (V_{sem}) and standard deviation (S_d) was adopted to quantify AF variability for each stratigraphic sequence. The analyses show that AF is controlled not only by V_{SE} , but also, and more significantly, by the dispersion of V_s values around the same equivalent velocity.

For $V_{SE} = 300$ m/s, AF increases with S_d within the intermediate- and long-period ranges up to threshold values of approximately 150 m/s, beyond which amplification decreases toward unity. This behavior suggests a transition from coherent resonance-controlled amplification to increasingly scattered and dissipative wave propagation in highly heterogeneous volcanic structures.

For $V_{SE} = 350$ m/s, AF remains nearly constant up to $S_d \approx 75$ m/s for all investigated period ranges. At higher S_d values, AF at long periods (0.7-1.1 s) increases significantly before progressively decreasing for $S_d > 100$ m/s,

indicating the existence of optimal heterogeneity conditions capable of enhancing low-frequency resonance effects within layered volcanic successions.

Profiles characterized by $V_{SE} = 400$ m/s exhibit the most stable behavior, with limited AF variability across the entire Sd range, indicating that moderate heterogeneity is insufficient to significantly modify the seismic response. Conversely, relatively stiff profiles ($V_{SE} = 500$ m/s) show nearly constant AF values up to $Sd \approx 120$ m/s, beyond which amplification progressively increases, particularly at intermediate and long periods, reflecting the growing influence of impedance contrasts associated with strong heterogeneity.

Overall, the study demonstrates that simplified site classification schemes based on VSE or Vs30 may not adequately capture the complexity of volcanic environments characterized by strong vertical and lateral heterogeneity. Direct in situ measurements from DH investigations, combined with stochastic approaches accounting for Vs variability, are therefore essential to improve the reliability of site response analyses and reduce epistemic uncertainty.

Although the proposed Sd-AF relationships are specific to the investigated geological setting, the adopted methodology can be extended to other volcanic and structurally complex environments to improve seismic microzonation and reduce epistemic uncertainty in local seismic response analyses.

Data availability statement. The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Acknowledgements. This work was carried out within the framework of the ETNA FAC Working Group activities (ETNA FAC, 2024), developed under the agreement entitled “Attività di supporto al Dipartimento Regionale della Protezione Civile per la prevenzione e riduzione del rischio sismico nell’ambito del Piano Regionale di Microzonazione Sismica” between the Department of Civil Protection of the Sicily Region and the CNR Institute of Environmental Geology and Geoengineering (IGAG-CNR), funded within the national seismic risk prevention program (art. 11, Law 77/2009). The authors gratefully acknowledge the professionals and technicians involved in field investigations and data acquisition activities, particularly M. Iavarone and A. Mercadante (ISMAR-CNR).

Author contributions. All authors contributed to the conception and development of the study. Di Fiore V., contributed to conceptualization, numerical modeling, software development, writing-original draft, and writing-review and editing. Cavuoto G. contributed to conceptualization, validation, writing-original draft, and writing-review and editing. Punzo M. contributed to data analysis, material preparation, and writing-review and editing. Tarallo D. contributed to methodology, formal analysis, supervision, and writing-review and editing. Peronace E. contributed to investigation, resources, data curation, and writing-review and editing. Pavano F. contributed to investigation, resources, and writing-review and editing. Tortorici G. contributed to investigation, resources, validation, and writing-review and editing. All authors read and approved the final manuscript.

References

- Acunzo, G., A. Pagliaroli and G. Scassera (2014). In-Spector: un software di supporto alla selezione di accelerogrammi naturali spettrocompatibili per analisi geotecniche e strutturali, Atti 33° Convegno Nazionale GNGTS, Trieste, 107-114.
- Acunzo, G., G. Falcone, A. di Lernia, F. Mori et al. (2024). NC92Soil: A computer code for deterministic and stochastic 1D equivalent linear seismic site response analyses, *Comput. Geotech.*, 165, 105857, doi:10.1016/j.compgeo.2023.105857.
- Armienti, P., M. D’Orazio, F. Innocenti and R. Petrini (1994). The long-standing 1991-1993 Mount Etna eruption: petrography and geochemistry of lavas, *Acta Vulcanol.*, 4, 15-28.
- Azzaro, R., A. Bonforte, S. Branca and F. Guglielmino (2012a). Geometry and kinematics of the fault systems controlling the unstable flank of Etna volcano (Sicily), *J. Volcanol. Geotherm. Res.*, 251, 5-15, doi:10.1016/j.jvolgeores.2012.10.001.
- Azzaro, R., S. Branca, K. Gwinner and M. Coltelli (2012b). The volcano-tectonic map of Mt. Etna (Sicily, Italy), *J. Maps*, 8, 3, 210-221.

- Bais, G., P. P. G. Bruno, V. Di Fiore and A. Rapolla (2003). Characterization of shallow volcanoclastic deposits by Turning Ray seismic tomography: an application to urban environments in Naples area (S. Italy), *J. Appl. Geophys.*, 52, 11-21, doi:10.1016/S0926-9851(02)00230-6.
- Banna, G., P. Capilleri, M. R. Massimino and E. Motta (2016). Geotechnical characterization of Mount Etna ash for its reuse preserving human health, in *Volcanic Rocks and Soils*, Rotonda et al. (eds.), Taylor and Francis Group, London, ISBN: 9781138028869.
- Barani, S., G. Ferretti and R. De Ferrari (2020). Incorporating results from seismic microzonation into probabilistic seismic hazard analysis: An example in western Liguria (Italy), *Eng. Geol.*, 267, 105479, doi:10.1016/j.enggeo.2020.105479.
- Barberi, F., M. Coltelli, A. Frullani and M. Rosi et al. (1994). Chronology and evolution of the eastern flank of Mt. Etna, *J. Volcanol. Geotherm. Res.*, 61, 3-4, 253-287, doi:10.1016/0377-0273(95)00017-8.
- Bard, P. Y. and M. Bouchon (1985). The two-dimensional resonance of sediment-filled valleys, *Bull. Seismol. Soc. Am.*, 75, 2, 519-541, doi:10.1785/BSSA0750020519.
- Ben-Avraham, Z. and M. Grasso (1990). Collisional zone segmentation in Sicily and surrounding areas in the central Mediterranean, *Ann. Tectonicae*, 4, 2, 131-139.
- Blong, R. J. (1984). *Volcanic Hazards: A Sourcebook on the Effects of Eruptions*, Academic Press, Sydney, 424, ISBN: 9780121064609.
- Bonforte, A., F. Guglielmino, M. Coltelli, A. Ferretti et al. (2011). Structural assessment of Mount Etna volcano from Permanent Scatterers analysis, *J. Geophys. Res.*, 116, B10, B10202, doi:10.1029/2010GC003213.
- Boore, D. M. (2004). Estimating VS30 (or NEHRP site classes) from shallow velocity models (depths <30 m), *Bull. Seismol. Soc. Am.*, 94, 2, 591-597, doi:10.1785/0120030105.
- Borcherdt, R. D. (1994). Estimates of site-dependent response spectra for design (methodology and justification), *Earthq. Spectra*, 10, 4, 617-653, doi:10.1193/1.1585791.
- Borgia, A. (1994). Dynamic basis of volcanic spreading, *J. Geophys. Res.*, 99, B9, 17791-17804, doi:10.1029/94JB00578.
- Borgia, A., L. Ferrari and G. Pasquarè (1992). Importance of gravitational spreading in the tectonic and volcanic evolution of Mount Etna, *Nature*, 357, 6375, 231-235, doi:10.1038/357231a0.
- Branca, S. (2003). Geological and geomorphologic evolution of the Etna volcano NE flank and relationships between lava flow invasions and erosional processes in the Alcantara Valley (Italy), *Geomorphology*, 53, 3-4, 247-261, doi:10.1016/S0169-555X(02)00315-X.
- Branca, S., M. Coltelli, G. Groppelli and F. Lentini (2011). Geological map of Etna Volcano, *Ital. J. Geosci.*, 130, 3, 265-291, doi:10.3301/IJG.2011.15.
- Branca, S., P. Del Carlo and M. Coltelli (2004). Eruptive history of Etna volcano, *J. Volcanol. Geotherm. Res.*, 132, 1-2, 1-22.
- Branca, S. and V. Ferrara (2001). An example of river pattern evolution produced during the lateral growth of a central polygenic volcano: the case of the Alcantara river system, Mt. Etna (Italy), *Catena*, 45, 2, 85-102, doi:10.1016/S0341-8162(01)00144-8.
- Branca, S. and V. Ferrara (2013). The morphostructural setting of Mount Etna sedimentary basement (Italy): Implications for the geometry and volume of the volcano and its flank instability, *Tectonophysics*, 586, 46-64, doi:10.1016/j.tecto.2012.11.011.
- Castellaro, S., F. Mulargia and P. L. Rossi (2008). VS30: Proxy for seismic amplification?, *Seismol. Res. Lett.*, 79, 4, 540-543, doi:10.1785/gssrl.79.4.540.
- Cavallaro, A., A. Fiamingo, S. Grasso, M. R. Massimino et al. (2024). Local site amplification maps for the volcanic area of Trecastagni, south-eastern Sicily (Italy), *Bull. Earthq. Eng.*, 22, 4, 1635-1676, doi:10.1007/s10518-023-01834-4.
- Cavallaro, A., S. Grasso and M. S. V. Sammito (2022). A seismic microzonation study for some areas around the Mt. Etna volcano on the east coast of Sicily, Italy, in *Proc. 4th Int. Conf. on Performance Based Design in Earthquake Geotechnical Engineering*, *Geotech. Geol. Earthq. Eng.*, 52, Springer, Cham, doi:10.1007/978-3-031-11898-2_61.
- CEN (2004). Eurocode 8: Design of structures for earthquake resistance. Part 1: General rules, seismic actions and rules for buildings, European Committee for Standardization, Brussels.
- Coltelli, M., P. Del Carlo and L. Vezzoli (2000). Stratigraphic constraints for explosive activity in the past 100 ka at Etna Volcano, Italy, *Int. J. Earth Sci.*, 89, 3, 665-677, doi:10.1007/s005310000117.
- Corsaro, R. A. and L. Miraglia (2022). Near real-time petrologic monitoring on volcanic glass to infer magmatic processes during the February-April 2021 paroxysms of the South-East Crater, Etna, *Front. Earth Sci.*, 10, 828026, doi:10.3389/feart.2022.828026.

- De Beni, E., S. Branca, M. Coltelli and J. Wijbrans (2011). 40Ar/39Ar dating of Etna volcanic succession, Ital. J. Geosci., 130, 3, 292-305, doi:10.3301/IJG.2011.14.
- Del Negro, C. and R. Napoli (2002). Ground and marine magnetic surveys of the lower eastern flank of Etna volcano (Italy), J. Volcanol. Geotherm. Res., 114, 3-4, 357-372, doi:10.1016/S0377-0273(01)00295-5.
- Di Fiore, V., D. Albarello, G. Cavuoto, R. De Franco et al. (2020). Downhole seismic wave velocity uncertainty evaluation by theoretical simulation and experimental data acquired during the seismic microzonation of Central Italy, Soil Dyn. Earthq. Eng., 138, 106319, doi:10.1016/j.soildyn.2020.106319.
- Di Giulio, G., M. Punzo, P. P. Bruno, F. Cara et al. (2019). Using a vibratory source at Mt. Etna (Italy) to investigate the wavefield polarization at Pernicana Fault, Near Surf. Geophys., 17, 4, 313-329, doi:10.1002/nsg.12051.
- Di Stefano, A. and S. Branca (2002). Long-term uplift rate of the Etna volcano basement (Southern Italy) from biochronological data of the Pleistocene sediments, Terra Nova, 14, 1, 61-68.
- Di Traglia, F., A. Falasconi and L. Borselli (2026). Explaining the origin of deposit-derived pyroclastic density currents, Bull. Volcanol., 88, 26, doi:10.1007/s00445-026-01948-y.
- ETNA FAC Working Group (2024). Linee Guida per lo studio delle Faglie Attive e Capaci (FAC) nell'area vulcanica etnea, Version 1.0, CNR-IGAG and Dipartimento Regionale della Protezione Civile della Regione Siciliana, Catania, 242.
- Felicetta, C., E. Russo, M. D'Amico, S. Sgobba et al. (2023). Italian Accelerometric Archive v4.0, Istituto Nazionale di Geofisica e Vulcanologia (INGV), doi:10.13127/itaca.4.0.
- Finetti, I. R., F. Lentini, S. Carbone, A. Del Ben et al. (2005). Geological outline of Sicily and lithospheric tectonodynamics of its Tyrrhenian margin from new CROP seismic data, in Deep Seismic Exploration of the Central Mediterranean and Italy, Elsevier, Amsterdam, 319-376.
- Foti, S., F. Hollender, F. Garofalo, D. Albarello et al. (2018). Guidelines for the good practice of surface wave analysis: a product of the InterPACIFIC project, Bull. Earthq. Eng., 16, 6, 2367-2420, doi:10.1007/s10518-017-0206-7.
- Gillot, P. Y., G. Kieffer and R. Romano (1994). The evolution of Mount Etna in the light of potassium-argon dating, Acta Vulcanol., 5, 81-87.
- Gross, F., S. Krastel, J. Geersen, J. H. Behrmann et al. (2016). The limits of seaward spreading and slope instability at Mt. Etna volcano at the continental margin offshore Mt Etna, imaged by high-resolution 2D seismic data, Tectonophysics., 667, 63-76, doi:10.1016/j.tecto.2015.11.011.
- Gudmundsson, A. (2020). Volcanotectonics – Understanding the Structure, Deformation and Dynamics of Volcanoes, Cambridge University Press, Cambridge, ISBN:9781107024953.
- Guest, J. E., D. K. Chester and A. M. Duncan (1984). The Valle del Bove, Mount Etna: its origin and relation to the stratigraphy and structure of the volcano, J. Volcanol. Geotherm. Res., 21, 1-2, 1-23, doi:10.1016/0377-0273(84)90013-1.
- Kawase, H. (1996). The cause of the damage belt in Kobe: "the basin-edge effect," constructive interference of the direct S-wave with the basin-induced diffracted/Rayleigh waves, Seismol. Res. Lett., 67, 5, 25-34, doi:10.1785/gssrl.67.5.25.
- La Delfa, S., G. Patanè, R. Clocchiatti and C. Centamore (2011). Geophysical imaging of the Chiancone fan (Mt. Etna), J. Volcanol. Geotherm. Res., 203, 1-2, 1-12.
- Lanzafame, G., M. Neri, V. Acocella, A. Billi et al. (2003). Structural features of the July-August 2001 Mount Etna eruption: evidence for a complex magma supply system, J. Geol. Soc. London, 160, 4, 531-544, doi:10.1144/0016-764902-151.
- Lengkeek, H. J. and R. B. J. Brinkgreve (2022). CPT-based unit weight estimation extended to soft organic clays and peat: an update, in Cone Penetration Testing 2022 G. Gottardi and L. Tonni (Editors), CRC Press, London, 503-508, doi:10.1201/9781003308829-71.
- Lentini, F. (1982). The geology of the Mt. Etna basement, Mem. Soc. Geol. Ital., 23, 7-25.
- Lentini, F., S. Catalano and S. Carbone (1995). Geological setting of the Peloritani-Nebrodi area and Etna basement, in F. Ferrucci and P. Gasparini (eds.), Mt. Etna: Five Years of Volcano Monitoring (1989-1993), Giardini Editori, Pisa, 11-21.
- Lo Presti, D. C. F., O. Pallara and A. Cavallaro (1998). Shear modulus of Italian clays, J. Geotech. Geoenviron. Eng., 124, 10, 1039-1049.
- Mancini, M., M. C. Cacioli, 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), Ital. J. Geosci., 140, 3, 382-408, doi:10.3301/IJG.2021.10.

- Mineo, S., G. Pappalardo, C. I. Casciano, A. Di Stefano, S. Catalano and M. Gagliano (2019). Insights on the Capo d'Orlando flysch (NE Sicily) by means of geomechanics and sedimentology, *Italian Journal of Geosciences*, 138, 3, 404-417, doi:10.3301/IJG.2019.13.
- Ministero delle Infrastrutture e dei Trasporti (2018). Aggiornamento delle «Norme tecniche per le costruzioni», *Gazzetta Ufficiale della Repubblica Italiana*, 42, Suppl. Ordinario n. 8.
- Naso, G., A. Pagliaroli, G. Lanzo and F. Silvestri (2001). Database geotecnico per le analisi di risposta sismica locale, ENEA, Roma.
- Neri, M. and V. Acocella (2006). The 2004-2005 Etna eruption: Implications for flank deformation and structural behaviour of the volcano, *Journal of Volcanology and Geothermal Research*, 158, 1-2, 195-206, doi:10.1016/j.jvolgeores.2006.04.022.
- Nunziata, C., R. Mele and M. Natale (1999). Shear wave velocities and primary influencing factors of Campi Flegrei – Neapolitan deposits, *Eng. Geol.*, 54, 3-4, 299-312.
- Nunziata, C., M. Natale and G. Panza (2004). Seismic characterization of Neapolitan soils, *Pure Appl. Geophys.*, 161, 5-6, 1285-1300, doi:10.1007/s00024-003-2492-z.
- 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. Eng.*, 12, 3, 1365-1381, doi:10.1007/s10518-013-9452-5.
- Panzerà, F., G. Lombardo, E. Longo et al. (2017). Exploratory seismic site response surveys in a complex geologic area: a case study from Mt. Etna volcano (southern Italy), *Natural Hazards*, 86, Suppl. 2, 385-399, doi:10.1007/s11069-016-2517-4.
- Panzerà, F., G. Lombardo and R. Rigano (2014). Seismic site effects in volcanic environments, *Soil Dyn. Earthq. Eng.*, 66, 303-315.
- Panzerà, F., G. Tortorici, G. Romagnoli, G. Marletta et al. (2020). Empirical evidence of orthogonal relationship between directional site effects and fracture azimuths in an active fault zone: The case of the Mt. Etna lower eastern flank, *Eng. Geol.*, 279, 105900, doi:10.1016/j.enggeo.2020.105900.
- Patanè, D., G. Barberi, O. Cocina, P. De Gori et al. (2006). Time-resolved seismic tomography detects magma intrusions at Mt. Etna, *Science*, 313, 5788, 821-823, doi:10.1126/science.1127724.
- Phoon, K. K. and F. H. Kulhawy (1999). Characterization of geotechnical variability, *Can. Geotech. J.*, 36(4), 612-624, doi:10.1139/t99-038.
- Pitilakis, K., E. Riga and A. Anastasiadis (2013). New code site classification, amplification factors and normalized response spectra based on a worldwide ground-motion database, *Bull. Earthq. Eng.*, 11, 4, 925-966, doi:10.1007/s10518-013-9429-4.
- Polonia, A., L. Torelli, A. Artoni, M. Carlini et al. (2016). The Ionian and Alfeo-Etna fault zones: New segments of an evolving plate boundary in the central Mediterranean Sea?, *Tectonophysics*, 675, 69-90, doi:10.1016/j.tecto.2016.03.016.
- Polonia, A., L. Torelli, P. Mussoni, L. Gasperini et al. (2011). The Calabrian Arc subduction complex in the Ionian Sea: Regional architecture, active deformation, and seismic hazard, *Tectonics*, 30, 5, TC5018, doi:10.1029/2010TC002821.
- Porchia, A., G. Tortorici, A. D'Agostino, E. Peronace et al. (2026). A GIS-based approach for planning investigations in seismic microzonation studies of Level 3: methodology and application in the Etnean area, Italy, *Ann. Geophys.*, 69, doi:10.4401/ag-9532.
- Rapolla, A., G. Bais, P. P. G. Bruno and V. Di Fiore (2002). Earth modeling and estimation of the local seismic ground motion due to site geology in complex volcanoclastic areas, *Ann. Geophys.*, 45, 6, 743-752, doi:10.4401/ag-3540.
- Rathje, E. M., A. R. Kottke and W. L. Trent (2010). Influence of input motion and site property variabilities on seismic site response analysis, *J. Geotech. Geoenviron. Eng.*, 136, 4, 607-619, doi:10.1061/(ASCE)GT.1943-5606.0000255.
- Regione Siciliana – DRPC (2017). Piano Regionale di Microzonazione Sismica, Deliberazione della Giunta Regionale n. 138 del 20 marzo 2017, Palermo.
- Rodríguez-Marek, A., J. D. Bray and N. A. Abrahamson (2001). An empirical geotechnical seismic site response procedure, *Earthq. Spectra*, 17(1), 65-87, doi:10.1193/1.1586167.
- Saccorotti, G., L. Zuccarello, E. Del Pezzo, J. M. Ibáñez et al. (2004). Quantitative analysis of the tremor wavefield at Etna volcano, Italy, *J. Volcanol. Geotherm. Res.*, 136, 3-4, 223-245, doi:10.1016/j.jvolgeores.2004.04.003.
- Telford, W. M., L. P. Geldart and R. E. Sheriff (1990). *Applied Geophysics*, 2nd ed., Cambridge University Press, Cambridge, ISBN:9780521339384.

- Technical Commission for Seismic Microzonation (2020). Standard di rappresentazione e archiviazione informatica per la microzonazione sismica, Version 4.2, Roma.
- Vucetic, M. and R. Dobry (1991). Effect of soil plasticity on cyclic response, *J. Geotech. Eng.*, 117, 1, 89-107, doi:10.1061/(ASCE)0733-9410(1991)117:1(89).
- Wathelet, M., D. Jongmans, M. Ohrnberger and S. Bonnefoy-Claudet (2008). Array performances for ambient vibrations on a shallow structure and consequences over Vs inversion, *J. Seismol.*, 12, 1, 1-19, doi:10.1007/s10950-007-9067-x.
- Wiesmaier, S., M. J. Heap, S. Branca, H. A. Gilg et al. (2015). Variability in composition and physical properties of the sedimentary basement of Mt Etna, Italy, *J. Volcanol. Geotherm. Res.*, 302, 102-116, doi:10.1016/j.jvolgeores.2015.06.008.
- Wu, R. S. and K. Aki (1988). Introduction: Seismic wave scattering in three-dimensionally heterogeneous earth, *Pure Appl. Geophys.*, 128, 1-2, 1-6, doi:10.1007/BF01772587.
- Zollo, A., P. Gasparini, J. Virieux et al. (1996). Seismic evidence for a low-velocity zone beneath Mount Vesuvius, *Science*, 274(5287), 592-594, doi:10.1126/science.274.5287.592.

***CORRESPONDING AUTHOR: Giuseppe CAVUOTO**

Institute of Heritage Science, National Research Council of Italy (CNR), Italy

e-mail: giuseppe.cavuoto@cnr.it

© 2026 the Author(s).

Open Access. This article is licensed under a Creative Commons Attribution 4.0 International License