

Empirical amplification factors for seismic microzonation studies in volcanic regions: the study case of Mt. Etna (Italy)

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Abstract

Quantifying local seismic amplification is essential for seismic microzonation (SM) and risk mitigation. Volcanic regions are particularly challenging due to complex stratigraphy, pronounced lateral heterogeneities, and topographic effects that strongly influence seismic wave propagation. We present an empirical characterization of site amplification across the Mt. Etna region (Sicily, Italy) that integrates two independent approaches and complementary datasets. The first approach derives site-to-site residuals ($\delta S2S$) from a non-ergodic Ground Motion Model (GMM) using 200 volcano-tectonic earthquakes ($M_L \geq 3.0$, 2008-2023) recorded by the permanent network installed on Mount Etna and its surrounding areas. This dataset is restricted to volcano-tectonic events over a long time span to ensure the repeatability of site effects. The second approach applies the Generalized Inversion Technique (GIT) to 125 events of both tectonic and volcano-tectonic origin (2022-2024), combining permanent with a temporary network, deployed *ad hoc* on the volcano, and exploiting a denser dataset over a short time window corresponding to the operation period of the temporary network. We further compare these results with single-station spectral ratios: namely horizontal-to-vertical ratios from earthquakes (EHV) and from ambient noise (NHV). The two main methods ($\delta S2S$ and GIT) provide broadly consistent amplification functions when referenced to a common site, while EHV and NHV provide complementary constraints on resonance features. Amplification factors (AF) are evaluated over selected period ranges relevant for engineering applications and seismic microzonation purposes and used to produce regional amplification maps. Results indicate generally low-to-moderate amplification with respect to the adopted reference site, with most AF values below 2 and locally higher amplifications observed at some stations. The integration of different datasets, temporary and permanent seismic networks, combined with these complementary approaches, enabled a robust empirical characterization of site amplification across the Mt. Etna region and can be applied to other seismic contexts, both volcanic and crustal.

Keywords: Site Effects; $\delta S2S$; GIT; Microzonation; Volcanic Areas; Mt. Etna; Amplification Factors

1. Introduction

Quantifying local seismic response is a key component of seismic microzonation, as ground motion amplification strongly influences earthquake-induced damage. Volcanic regions, however, present unique challenges due to their complex structural and topographic settings, pronounced lateral heterogeneities, and variable near-surface deposits, all of which can significantly affect seismic wave propagation.

These issues have been documented in volcanic contexts worldwide. Contrary to the common assumption that competent volcanic rocks are generally expected to produce low amplification – given their high shear-wave velocities and stiffness compared to soft sediments – medium to high amplification levels have frequently been observed. Such effects are often associated with weathered volcanic formations, strong lithological contrasts, and complex near-surface structures. For instance, volcanic deposits on Mayotte Island exhibit strong site effects due to thick, low-velocity superficial layers resulting from weathered volcanic outcrops, with amplification further enhanced by topographic features such as slopes and relief (Roullé et al., 2023). Similarly, significant amplification phenomena can arise from the geophysical contrast between stiff lava flows and underlying soft sediments, as demonstrated by Bessason and Kaynia (2002), who documented pronounced site amplification effects in Iceland using empirical spectral ratio techniques. Tramelli et al. (2010) highlighted strong spatial variability in seismic response in the Campi Flegrei area, linked to complex stratigraphy, caldera-related structures, and shallow low-velocity deposits. Their results show that highly heterogeneous volcanic settings can exhibit localized, frequency-dependent amplification regardless of the apparent competence of the rocks.

Mount Etna, Europe's most active volcano, provides a natural laboratory for investigating site response in volcanic settings. The juxtaposition of lava flows and volcanoclastic sediments, often disrupted by lateral heterogeneities, complicates site response. The region experiences both shallow volcanic and deeper tectonic earthquakes across a wide range of magnitudes and focal depths. Even moderate-magnitude events ($M_L \leq 4.8$) at shallow depths (< 3 km) have historically caused substantial damage to infrastructure and settlements (Pessina et al., 2021; D'Amico et al., 2025). Additionally, the high population density and urban development underscore the need for high-resolution microzonation to support Civil Protection planning and risk mitigation strategies. Accurate assessment of site effects in this context is therefore crucial for reliable seismic hazard evaluation.

The complexity of seismic site response in the Etna region has long been recognized, particularly in the urban area of Catania, where lava flows overlie a highly heterogeneous sedimentary substratum. Early NHV studies (Priolo et al., 2001; Lombardo et al., 2001) showed that seismic amplification is strongly controlled by the alternation of volcanic and sedimentary deposits. While massive lava flows generally exhibit weak amplification, weathered or fractured basalts and alluvial sediments produce distinct resonance patterns, highlighting the strong lateral variability of site response. Subsequent studies integrating ambient-noise measurements, earthquake recordings, and numerical modelling further demonstrated that amplification is governed by the combined effects of lithological contrasts, weathering, geomorphology, and structural complexity, with directional effects locally associated with the interaction between lava flows and sedimentary units (Panzera et al., 2011, 2015). Panzera et al. (2015) further highlighted that basaltic lava flows may overlie softer sedimentary deposits, generating velocity inversions capable of amplifying the vertical component of motion and influencing HVSR estimates.

More recent studies have further examined seismic site response at Mount Etna using dense ambient-noise surveys, earthquake recordings, and advanced processing techniques. These investigations confirmed the highly heterogeneous behaviour of the volcanic area, with strong lateral variations in site amplification related to the alternation of lava flows, volcanoclastic deposits, and structural discontinuities (Panzera et al., 2017, 2020; Grasso and Sammito, 2025). The recent compilation of a harmonized HVSR database for the Mt. Etna region (Gaudiosi et al., this issue), integrating more than 1,000 ambient-noise measurements from multiple institutions, further contributes to the characterization of local site effects and provides a valuable benchmark for seismic microzonation studies. Paratore et al. (2018) and Cavallaro et al. (2024) further highlighted the complexity of site response in fault-affected urban areas, focusing on seismic amplification and soil-structure interaction near the Tremestieri and Trecastagni faults (Fig. 1). Using ambient noise and polarization analyses, they identified azimuth-dependent resonant frequencies and directional amplification effects, which may be influenced by fault-zone geometry and local stiffness variations. Similarly, Di Giulio et al. (2009) and Pischiutta et al. (2013) observed directional variations of resonance across the Pernicana fault (Fig. 1), likely associated with local heterogeneities and structural anisotropy. These findings collectively underscore the role of lateral heterogeneity and structural complexity in modulating seismic wave propagation in volcanic formations.

In this study, local site response across the Mt. Etna region is evaluated using earthquake recordings from multiple datasets, collected by both permanent and temporary seismic networks. A temporary network was deployed *ad hoc* in the municipalities targeted for seismic microzonation (SM) to enhance spatial coverage and complement long-term recordings from permanent stations.

Site amplification is empirically characterized through two independent approaches: site-to-site residuals ($\delta S2S$) derived from a non-ergodic Ground Motion Model (Lanzano et al., 2025), and the Generalized Inversion Technique (GIT; Andrews, 1986) applied to distinct earthquake datasets. The results are further constrained through comparison with single-station spectral ratios (EHV and NHV), allowing joint characterization of broadband amplification and resonance features. In addition, empirical amplification functions are compared with available one-dimensional (1D) numerical site-response analyses based on site-specific V_s profiles, providing an independent assessment of the

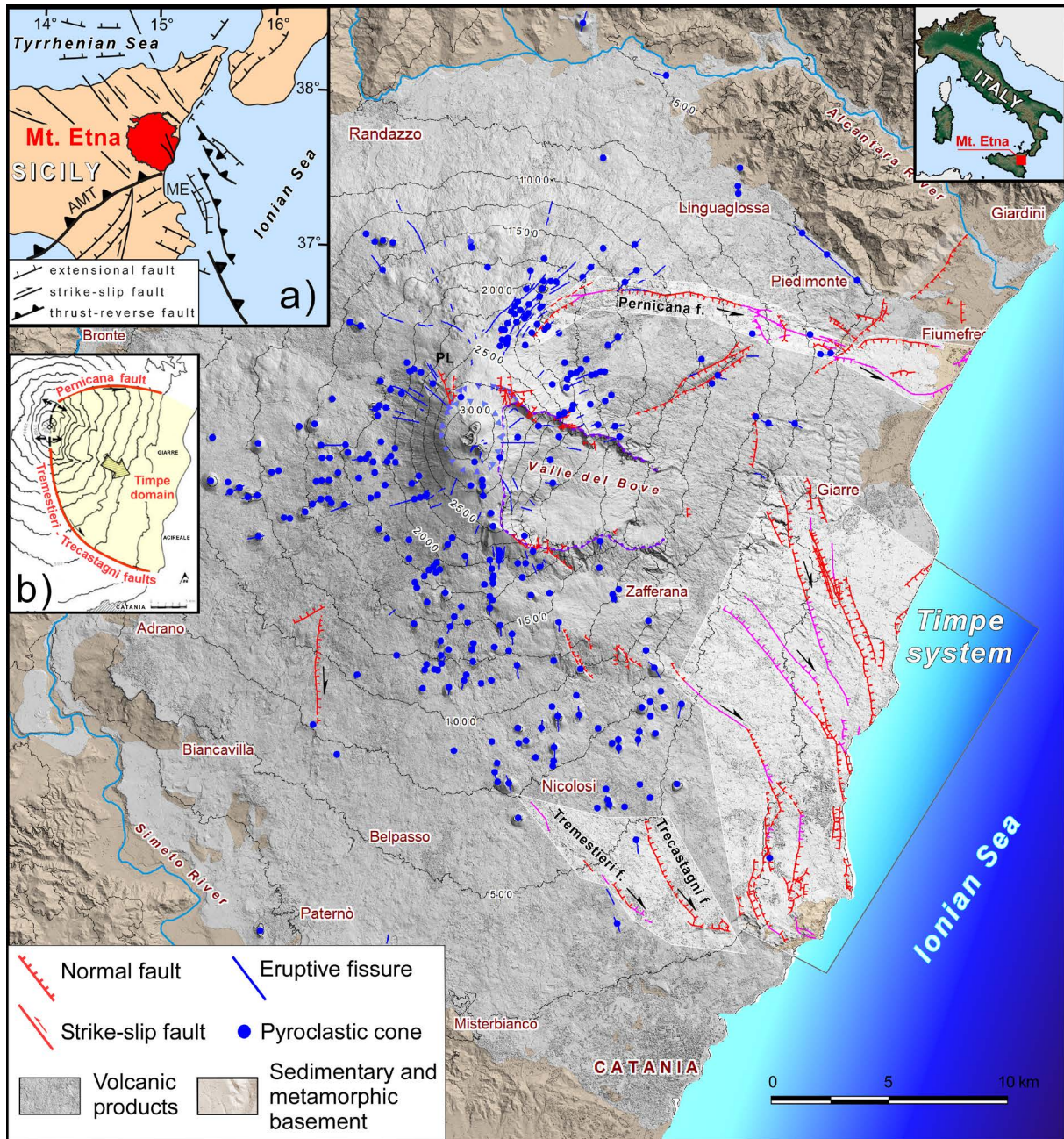


Figure 1. Main volcano-tectonic features of Mt. Etna (modified from Azzaro et al., 2012). Inset map (a) illustrates the major regional tectonic structures (simplified from Lentini et al., 2006): AMT, front of the Appennine-Maghrebian thrust belt; ME, Malta Escarpment. Inset (b) shows the conceptual model of the seaward sliding of the eastern flank; the unstable sector is highlighted in yellow.

ability of standard microzonation approaches to reproduce the observed amplification patterns. Finally, amplification factors (AF) are evaluated over the period ranges adopted in the Italian seismic microzonation guidelines and analysed as a function of EC8 site classes, in order to investigate the extent to which standard $V_{S,30}$ -based classifications explain the observed variability of site response in the complex volcanic environment of Mt. Etna.

2. Volcano-tectonic and seismological background of Mt. Etna

2.1 Geological and structural features

Standing at an elevation of approximately 3,350 m, Mount Etna volcano is the largest and most active stratovolcano in Europe, representing a complex response to the regional geodynamics of the Central Mediterranean. The volcanic edifice is located at the complex transition zone between the Apenninic-Maghrebian fold-and-thrust belt and the Hyblean Plateau, the latter representing the northern margin of the African foreland (Doglioni et al., 2001; Barreca et al., 2020) (Fig. 1a).

The structural evolution of the area is governed by the northward flexure of the Hyblean carbonate succession beneath the Plio-Pleistocene foredeep sediments, in a context of active plate convergence (e.g., Lentini et al., 2006). The long-term evolution of the volcanic district of Etna is marked by a progressive north-west migration of the volcanic centres, shifting from the early tholeiitic basalts of the Pre-Etnean stage to the complex alkaline activity of the current Etna edifice (Branca et al., 2011). The volcanic products rest on a basement of different nature and elevation, from flyschoid/metamorphic terrains to the North and West, to a more recent clayey-sandy sedimentary succession to the South. The geological complexity of the area is expressed by an extremely variable lithological diversity, determined by the superimposition of the different geological formations (Branca et al., 2015). The main volcanic units are represented by products of different ages and emplacement mechanisms, including lava-flows, pyroclastic deposits, and volcanoclastic sequences. Lava flows generally consist of compact to highly fractured basaltic rocks, whose mechanical behaviour is strongly influenced by the degree of fracturing. Pyroclastic deposits, on the other hand, range from loose ash and lapilli to weakly cemented tuffs, typically exhibiting lower density and stiffness. Volcaniclastic deposits, typically heterogeneous and reworked, show highly variable geotechnical properties depending on grain size, sorting, and degree of consolidation and weathering. The sedimentary substratum underlying the volcanic edifice contributes, at a different degree depending on the thickness of the volcanic pile (up to 900 m), to further first-order heterogeneities. This variability in lithological and geotechnical characteristics indeed plays a key role in controlling local site response in this volcano area.

This geological complexity is mirrored by the structural setting of the volcanic edifice (Fig. 1), deeply influenced by the interaction between magma-induced stresses, flank instability processes (Fig. 1b) and regional tectonics (Azzaro et al., 2013). In particular, the eastern and southern sectors of the volcano are affected by a continuous seaward sliding which is accommodated by major active fault systems. Among these, the Pernicana fault system represents a key structural boundary to the north, characterized by high rates of creep and very frequent seismicity (Alparone et al., 2013). The eastern flank is of special interest for the highly seismogenic Timpe tectonic system, which is morphologically well expressed by several prominent fault scarps crossing these densely urbanised areas of Etna (Azzaro et al., 2012). Other important active faults are those located in the southern flank of the volcano, separating the unstable sector from the stable domain to the South, and in the south-western sector.

2.2 Seismic input

The identification of reference ground motion represents a key step for the selection of spectrum-compatible accelerograms to be used in the evaluation of site response (e.g., transfer functions, site response spectra, and GIT analysis). In standard practice, the target spectrum is based on the seismic hazard map for a 475-year return period prescribed by the NTC18 (MIT, 2018) code (MPS04, Stucchi et al., 2011), referring to a flat and unamplified site on rock. However, in volcanic areas such as Etna, several municipalities are affected not only by regional-scale tectonic seismicity but also by local volcano-tectonic events, which can produce ground motions with different spectral characteristics. Taking these elements into account, Azzaro et al. (this issue) defined the seismic input by identifying the most significant events for each municipality through a critical assessment of site seismic histories,

based on the analysis of more than 400 years of historical macroseismic records from the CMTE catalogue (Azzaro and D'Amico, 2026).

In particular, volcano-tectonic earthquakes are typically characterized by higher amplitudes at short periods, rapidly attenuating with distance, and by a relatively stronger low-frequency content compared to tectonic events (Milana et al., 2008; Panzera et al., 2011; Tusa and Langer, 2016; Lanzano and Luzi, 2020; Tusa et al., 2020; Ramadan et al., 2023). For this reason, in addition to the code-based spectrum, scenario spectra representative of local volcanic seismicity were defined for areas where local events may significantly contribute to the seismic hazard. These conditions were identified by integrating site-specific macroseismic data, instrumental seismicity, and seismotectonic considerations.

The local reference spectrum was defined using the ground-motion model of Lanzano and Luzi (2020) for a representative scenario with magnitude $M_W = 5.0$ and hypocentral distance $R = 3$ km, consistent with shallow near-field volcanic sources. This magnitude is consistent with that observed for the 26 December 2018 earthquake ($M_W \approx 5.0$), which produced strong near-field shaking (PGA up to ~ 0.5 – 0.6 g within a few kilometres). The volcano-tectonic spectrum exhibits higher amplitudes at short periods compared to the code-based target spectra, followed by a rapid decay with increasing period, highlighting the distinctive high-frequency content of volcanic ground motion.

Accordingly, the selection of spectrum-compatible accelerograms follows current guidelines based on the 475-year hazard level (MPS04), complemented by an additional set of seven records introduced as a precautionary measure to account for these spectral features. Full details on the selection criteria are provided in Azzaro et al. (this issue).

3. Seismological Networks and Dataset

Local site response was evaluated using two complementary approaches, each applied to distinct datasets. Figure 2 summarizes the main characteristics of the two datasets in terms of magnitude, focal depth, and hypocentral distance. Dataset 1 includes 200 volcano-tectonic earthquakes with $M_L \geq 3.0$, recorded by permanent networks over a long-time span providing dense waveform coverage and enabling robust identification of repeatable site effects through the analysis of site-to-site residuals (δS_2S).

Dataset 2 consists of 125 volcano-tectonic and tectonic earthquakes recorded between November 2022 and October 2024 by both temporary and permanent stations. Due to the shorter recording duration of the temporary network, site effects at these locations were estimated using the Generalized Inversion Technique (GIT), applied to a multi-event dataset spanning a wide range of distances to constrain attenuation and separate source, path, and site contributions.

Together, these datasets enable the analysis of site response over a broad range of magnitudes, depths, and distances, combining the temporal continuity of permanent networks with the improved spatial coverage provided by temporary deployments. Further details on the seismic networks and datasets are provided below.

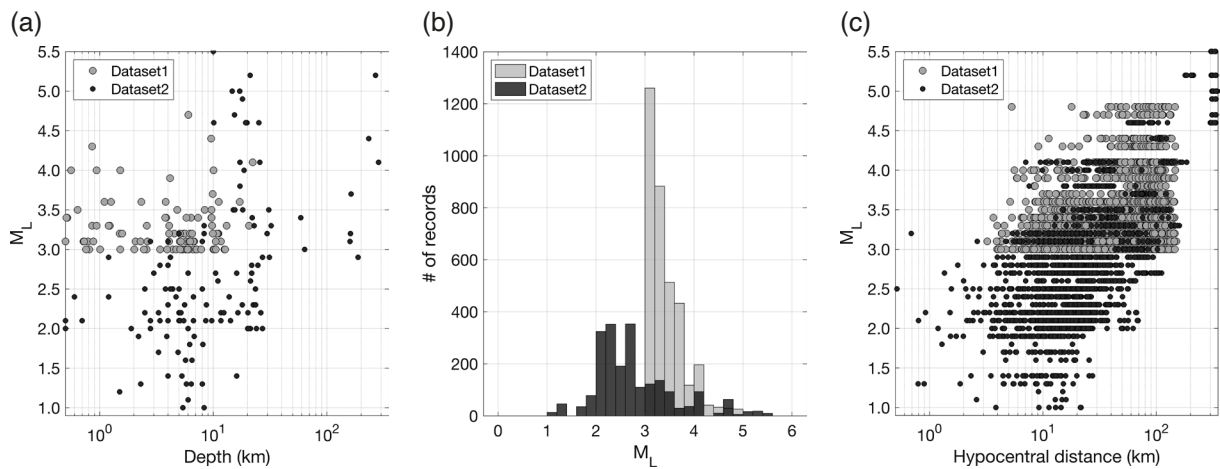


Figure 2. Comparison between Dataset 1 (light grey circles/bars) and Dataset 2 (black circles/bars). (a) Scatter plot of local magnitude (M_L) versus focal depth; (b) frequency distribution of magnitudes; (c) local magnitude M_L versus hypocentral distance.

3.1 Permanent and temporary networks in the Mt. Etna area

The permanent and temporary seismic networks, already installed and operational around Mt. Etna, comprise 40 stations (Fig. 3, green triangles) belonging to four main networks:

- 1) Italian National Seismic Network (INSN), code IV (INGV, 2005), which includes all the permanent and several temporary stations (both accelerometers and velocimeters), managed by the INGV;
- 2) Rete Accelerometrica Nazionale (RAN), code IT (DPC, 1972) composed by accelerometric instruments and managed by the Italian Department of Civil Protection;
- 3) the temporary network with code 1J (“FocusX temporary land-network, FXland, Southern Italy”), managed by the INGV as well (Moretti et al., 2021);
- 4) the temporary network with code 7C (“Urban Seismic Network”), managed by INGV.

Together, these networks ensure a dense spatial coverage and long-term monitoring of seismic activity associated with both volcanic and tectonic processes. The full list of stations is reported in Table S1.

3.2 Temporary network installed for MZS activities

In addition, a temporary seismic network (MZ, Fig. 3, blue triangles) was deployed from November 2022 to October 2024 within a seismic microzonation support project for the Sicilian Civil Protection Department (see Acknowledgements). The network corresponds to the ETNA Microzonation Temporary Network (FDSN code 15, 2022-2024), operated by OGS and consisting of 18 temporary stations installed in 18 municipalities around Mt. Etna. The network metadata are available through the FDSN network registry (<https://doi.org/10.7914/gmfh-g622>), whereas the waveform data are not currently publicly available. Continuous ground-motion recordings were collected over approximately two years to create a database of earthquake waveforms. The deployment strategy prioritized urban areas lacking permanent seismic stations, to improve spatial coverage for site-response evaluation. Each mobile station was equipped with three-component velocimetric sensors (Lennartz LE-3D/1s), 24-bit Reftek RT130 data loggers operating at a sampling rate of 100 Hz, GPS antennas, and battery-based power systems, supplemented by photovoltaic panels where mains power was unavailable. Data acquisition was performed locally and periodically retrieved with support from INGV Catania. Ambient noise conditions varied significantly across sites: some stations were affected by traffic and other anthropogenic sources, while others exhibited low noise levels, allowing detection of low-magnitude seismic events.

3.3 Dataset 1 (volcano-tectonic, 2008-2023)

Dataset 1 (Fig. 4) is based on a seismic dataset consisting of about 4,700 recordings of 200 earthquakes with $M_L \geq 3.0$, occurring in the Mt. Etna volcanic region between January 2008 and July 2023. These events are exclusively associated with volcano-tectonic processes and the earthquake catalogue, including high precision locations and M_L estimates, was derived from the Etnean Observatory (INGV-OE) catalogues (Alparone et al., 2015; Barberi et al., 2020). The largest event is the M_L 4.8 Fleri earthquake, which occurred on 26 December 2018, with maximum Peak Ground Acceleration (PGA) observed of about 0.6 g at Santa Venerina station (code SVN, network IT). For each seismic event, the following procedure was implemented:

- Waveform collection. Recordings from stations within a 150 km radius were extracted from EIDA dataset (Strollo et al., 2021) for IV and other public permanent and temporary networks. Recordings from IT network were added offline;
- Phase picking. P- and S-phase arrival times were initially determined using automated picking algorithms (Spallarossa et al., 2014, 2021; Scafidi et al., 2016) and subsequently underwent rigorous manual visual inspection for quality control;
- Spectral Analysis. Both Fourier Amplitude Spectra (FAS) and Response Spectra (SA) were computed. FAS were derived from S-wave acceleration windows of variable length, selected according to an energy-based criterion defined on the cumulative Arias Intensity (AI) of each record. Each S-wave window starts 0.1 s before the manually picked S-wave onset and ends when a prescribed fraction of the cumulative AI is reached; the fraction decreases

with hypocentral distance R_{hyp} , so as to limit the contribution of the increasingly long coda at larger distances: 90% of AI for $R_{hyp} \leq 25$ km, 80% for $25 < R_{hyp} \leq 50$ km, and 70% for $R_{hyp} > 50$ km. Two bounds are imposed on the resulting window length: windows longer than 25 s are truncated, and a minimum length of 4 s is enforced for near-source records, which would otherwise be too short to guarantee an adequate spectral resolution below 1 Hz. This criterion applies to the computation of the Fourier Amplitude Spectra. SA were instead computed on fixed-length 30 s S-wave windows.

- Quality check. Consistency check by analysing the ground motion residuals to identify any outliers in the data.

As also reported in Tarchini et al. (this issue), all traces, velocimetric and accelerometric waveforms, were processed through the same scheme (after Pacor et al., 2016), so that the resulting ground-motion parameters are homogeneous

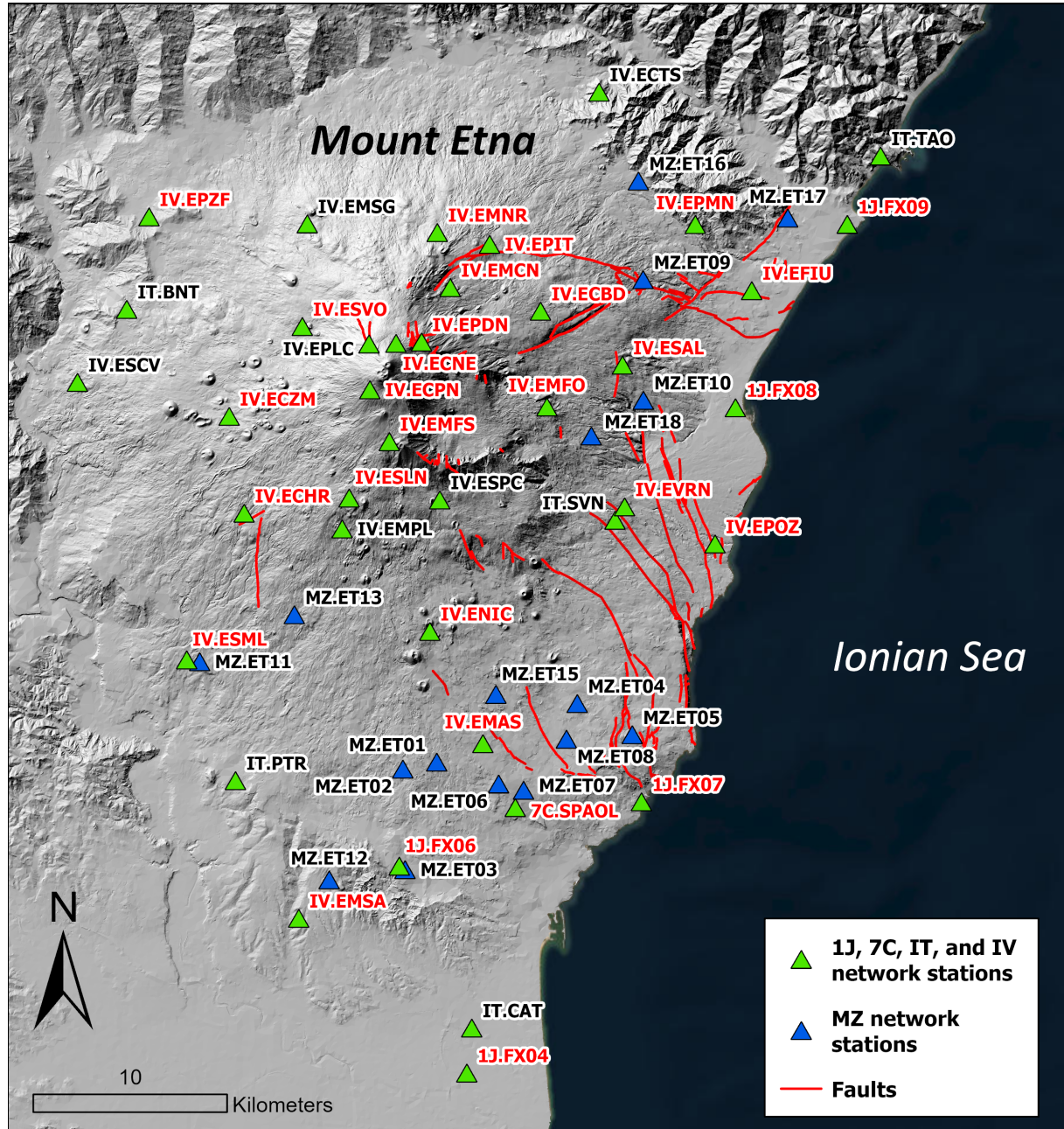


Figure 3. Distribution of seismic stations in the Etna area, including the temporary MZ network installed between November 2022 and October 2024, together with stations from the 1J, 7C, IT, and IV networks. Station labels shown in red identify the stations for which amplification factors were derived using both the δS_2S and GIT approaches. Red lines indicate mapped faults.

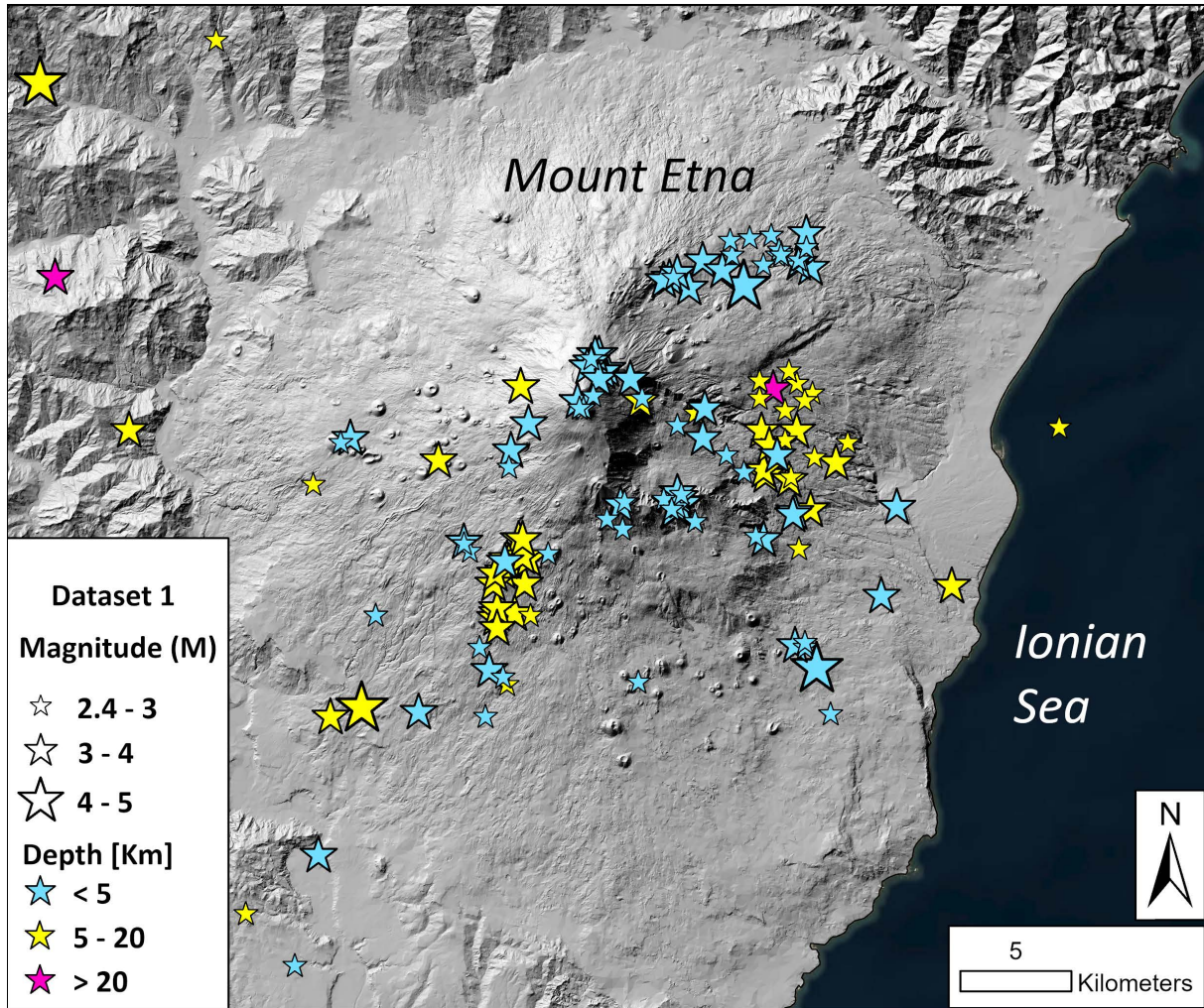


Figure 4. Earthquake Dataset 1. Symbol size is proportional to event magnitude, and colour scale represents hypocentral depth.

regardless of the sensor type. After manual picking of the P- and S-wave onsets, each trace was band-pass filtered with a Butterworth filter whose low-cut corner frequency was determined record by record from the signal-to-noise ratio, within the range 0.04-0.6 Hz and satisfying $\text{SNR} > 2.5$, while the high-cut corner was fixed at 48 Hz. Filtering was applied before the deconvolution, to avoid amplifying long-period noise when removing the instrument response. After filtering, the instrument response was removed to obtain waveforms in displacement physical units. The displacement time series were corrected through linear detrending, offset removal, and cosine tapering. Velocity and acceleration records were obtained by successive differentiation of the tapered displacement traces.

After the processing and quality checks, the high-quality waveforms were used for the estimation of site amplification factors of 147 recording stations. The estimates of the time-averaged shear-wave velocity in the upper 30 meters ($V_{S,30}$) were obtained from the Italian ACcelerometric Archive (ITACA; Felicetta et al., 2023) or from *ad hoc* geophysical surveys (Tarchini et al., this issue). In particular, $V_{S,30}$ values were derived following a hierarchical approach based on publicly available ITACA information: (i) direct geophysical measurements, where available; (ii) estimates from topographic slope proxies (Mascandola et al., 2021); and (iii) geological information when neither measurements nor slope-based estimates were available. This hierarchy was adopted consistently for both $V_{S,30}$ and EC8 site classification. In addition, for stations in the Etna area, slope-based classifications were further reviewed using the lithological classification of Brunelli et al. (2026) and the detailed geophysical/geotechnical studies of Gresta and Langer (2002), leading to the reclassification of several stations and updated $V_{S,30}$ values where appropriate. Although the original dataset includes recordings from many more recording stations, our focus was restricted to the 40 stations in the study area (Fig. 3).

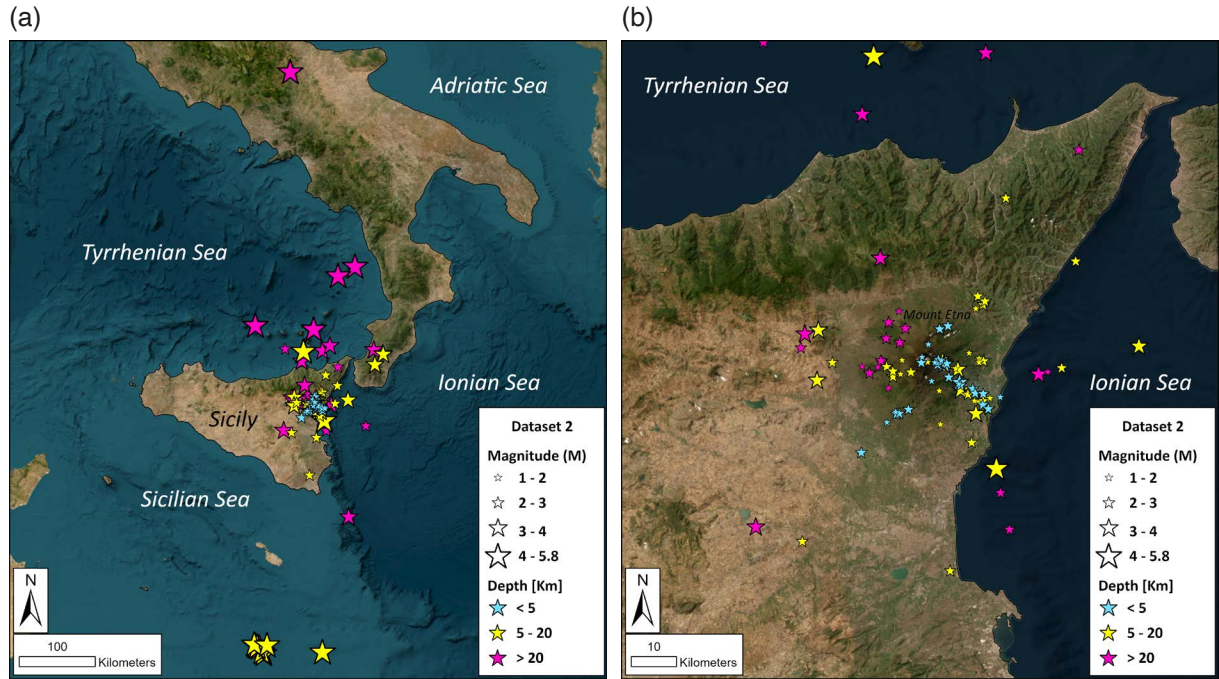


Figure 5. Earthquake Dataset 2. The (b) panel shows a zoomed-in view focused on central-northern Sicily. Symbol size is proportional to event magnitude, and colour scale represents hypocentral depth.

3.4 Dataset 2 (tectonic and volcano-tectonic, 2022-2024)

Dataset 2 (Fig. 5) consists of 125 seismic events recorded by both temporary and permanent velocimetric stations between November 2022 and October 2024. The dataset includes both local volcano-tectonic earthquakes and regional tectonic events, with magnitudes ranging from 1.0 to 5.5 and epicentral distances up to 300 km. Overall, it provides broad coverage in terms of magnitude, depth, epicentral distance, and azimuth.

Earthquake recordings were extracted from the continuous waveform archive according to the list of events reported by the INGV earthquake monitoring service (<https://terremoti.ingv.it/>). Data were processed by removing the mean and linear trend, applying a band-pass filter between 0.3 and 50 Hz, and correcting for the instrument response using poles and zeroes to obtain velocity time series. Subsequently, all recordings underwent visual quality control, and those affected by high noise levels, spikes, overlapping seismic events, or signal saturation were discarded.

In the analysed period, in the region surrounding Mount Etna, seismic activity exhibited lower magnitudes (Fig. 5b). Earthquakes on the eastern flank are typically shallow, with focal depths usually less than 10 km, as seen in a cluster of four events ($1.0 \leq M_L \leq 2.5$) that occurred between Sant'Alfio and Giarre on 7 December 2022, all with focal depths less than 8 km (Barberi et al., 2020). In contrast, the western sector experiences deeper seismic events. Further north, in the Aeolian area (Fig. 5a), earthquakes show larger magnitudes and greater focal depths. A notable seismic sequence occurred south of Malta in December 2022, featuring several events with magnitudes around 5 and focal depths generally below 20 km.

Figure 6 shows, as an example, the vertical velocity components of the $M_L = 2.5$ earthquake from the aforementioned cluster, located about 2 km east of both Sant'Alfio municipality and station ET10, as recorded at seven stations from the permanent and temporary networks, situated at progressively increasing epicentral distances. Notable differences in amplitude are observed, with signal durations unusually long for a low-magnitude event, lasting several tens of seconds. These variations are not clearly related to source-to-station distance and likely reflect a combination of radiation pattern and local site effects, although propagation effects may also contribute to the observed variability, given the heterogeneous nature of the Mt. Etna volcanic edifice.

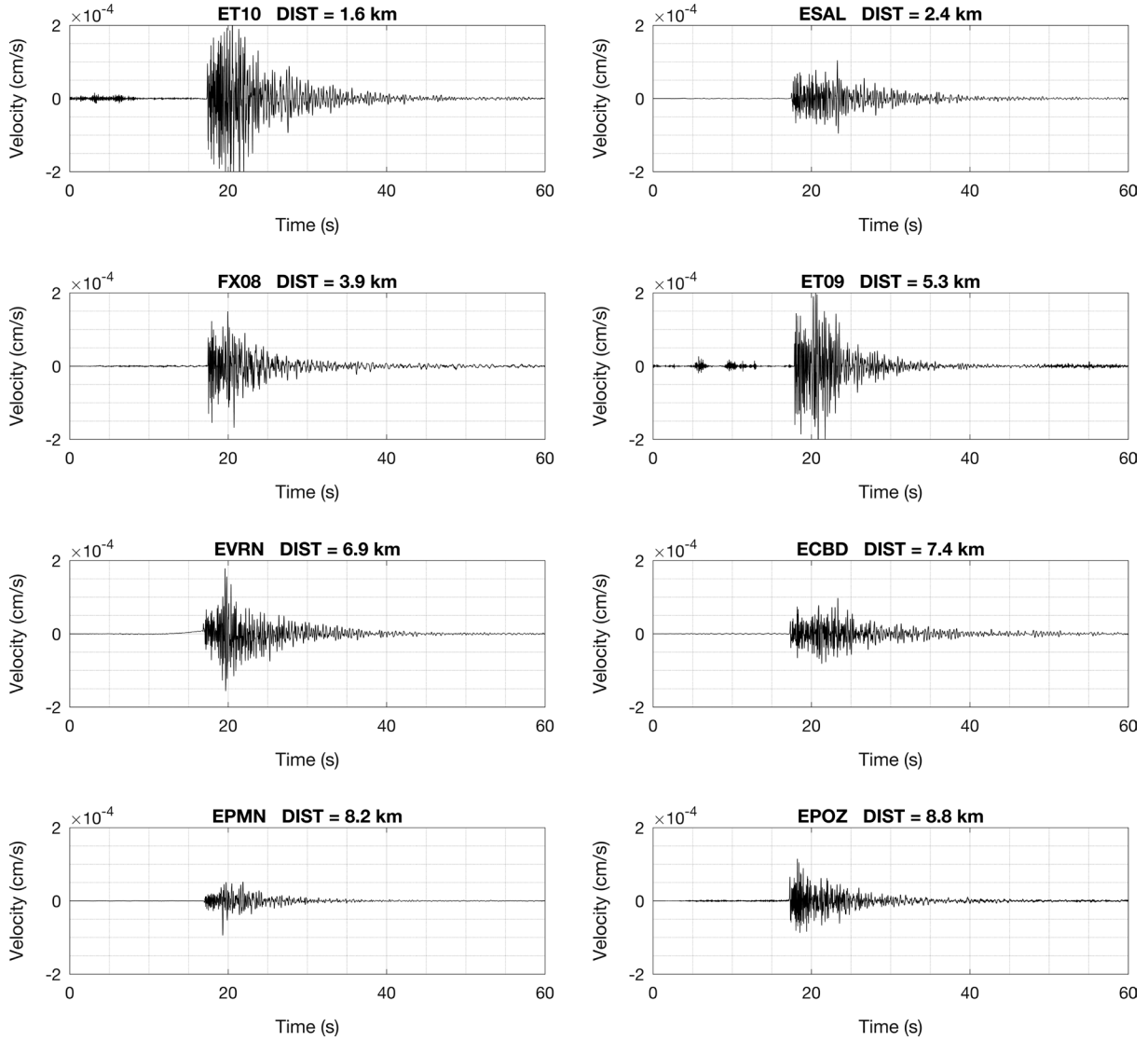


Figure 6. Seismograms (vertical component) of the M_L 2.5 earthquake of 7 December 2022, 2 km east of Sant’Alfio, recorded at eight stations from both the permanent and temporary networks, located at progressively increasing epicentral distances.

4. Methods

In the following, we describe the two approaches used in this study. The first approach, based on site-to-site residuals of a non-ergodic Ground Motion Model ($\delta S2S$), was applied exclusively to Dataset 1, which comprises only volcano-tectonic earthquakes recorded by EIDA networks. The second approach is the Generalized Inversion Technique (GIT), and was applied to Dataset 2, comprising tectonic and volcano-tectonic earthquakes recorded by stations of both temporary and permanent networks. For comparison, we also evaluate site response using two well-known techniques that do not require a reference site: namely, the earthquake horizontal-to-vertical spectral ratio (EHV) and the ambient-noise horizontal-to-vertical spectral ratio (NHV). These methods provide additional constraints on the area’s resonance frequencies and help validate the amplification patterns inferred from $\delta S2S$ and GIT.

4.1 $\delta S2S$ from non-ergodic GMM residual

The first method for empirical estimation of the amplification functions is based on the decomposition of the residuals in the framework of the calibration of the non-ergodic Ground Motion Models (GMMs) (Lanzano et al., 2025).

The residuals R_{es} are generally computed as the difference between the (natural) logarithm of the observed ground motion parameter $\log(Y)_{\text{obs}}$ and the corresponding prediction $\log(Y)_{\text{pred}}$, from a reference GMM. After that, according to the Al Atik et al. (2010) notation, the residuals R_{es} are basically decomposed into repeatable terms referring to event and site, as:

$$R_{es} = \delta_0 + \delta B_e | \text{event} + \delta S2S_s | \text{site} + \delta W_{es} \quad (1)$$

where δ_0 is the total residuals offset, δB_e is the between-event residual, $\delta S2S_s$ is the site-to-site residual, and δW_{es} is the event- and site-corrected residual, obtained by removing the event and station errors from total R_{es} . In this study, we focus on the $\delta S2S_s$ term that quantifies the systematic deviations between the observed ground-motion and the GMM median predictions at a given site, representing de-facto the peculiar site-effect of the recording station. Advanced residual decompositions are possible by also introducing terms related to source and propagation (see Sgobba et al., 2024), with the advantage of obtaining $\delta S2S_s$ estimates as free as possible from trade-offs with propagation effects (Lanzano et al., 2025). However, the estimates in this study refer to stations and events located in the same area, which consist of very short source-to-site paths and result in a strong limitation of the distortion effects due to the trade-off.

In the case of Mt. Etna seismicity, the recent Ground Motion Model (GMM) of Ramadan et al. (2023) was selected, which provides the horizontal and vertical median prediction and associated variability for the peak ground acceleration, PGA, the peak ground velocity, PGV and spectral amplitudes SA in the period interval $T = 0.01\text{--}5$ s. The residual components were routinely computed using the mixed-effect modeling (Stafford, 2014; Bates et al., 2015).

4.2 Generalized Inversion Technique (GIT)

The Generalized Inversion Technique (GIT) (Andrews, 1986) is a robust and widely used method for estimating site response and can be viewed as an extension of the classical Reference Site Spectral Ratio (RSSR) approach (Borcherdt, 1970). GIT relies on a standard parametrization in which the shear-wave amplitude spectrum recorded at site s for event e is expressed as the product of three independent contributions:

$$A_{e,s}(f) = S_e(f) G(R_{e,s},f) H_s(f) \quad (2)$$

where:

- $S_e(f)$ is the source spectrum of the e -th event,
- $H_s(f)$ is the site response function at station s ,
- $G(R_{e,s},f)$ represents the path term, which accounts for geometrical spreading and anelastic attenuation as a function of hypocentral distance $R_{e,s}$ and frequency f .

In this study, GIT was applied using the one-step generalized inversion approach described by Oth et al. (2011), implemented via an enhanced version of the GITANES (GIT ANalysis of Earthquake Spectra) software package (Klin et al., 2018, 2021). To ensure a stable and unique solution to the overdetermined linear system, additional constraints were imposed on both the propagation and site terms. Source spectra, attenuation characteristics, and site response functions are estimated using the minimum constraints necessary to solve the inversion problem, without assuming any a priori functional form for the source or attenuation terms. For the propagation term, constraints included the definition of a reference distance at which the path effect is set to zero, and the application of a smoothing condition to prevent abrupt variations between adjacent distance intervals (Castro et al., 1990). For the site term, a reference station assumed to be unaffected by local site effects was specified (see next section).

To account for differences in recording quality among stations and events, the GIT inversion was formulated as a weighted least-squares problem. The weighting coefficients were determined on the basis of the signal-to-noise ratio (SNR) of each seismic recording. The SNR was computed as the ratio between the power spectrum of the S-wave signal window and that of a pre-event noise window. Consequently, recordings characterized by lower SNR values had a reduced influence on the inversion, whereas higher-quality records contributed more strongly to the final solution.

4.3 Generic-to-reference ground-motion scaling

One of the most complex tasks in seismic engineering and engineering seismology is to correctly define seismic motion with respect to a reference level (Lanzano et al., 2022). In the residual analysis, $\delta S2S$ values are typically computed with respect to a fixed, common reference for all sites, corresponding to the GMM prediction for a generic rock site, usually represented by EC8 soil category A according to the Eurocode 8 (European Committee for Standardization (CEN), 2005; hereafter EC8), where the time-averaged shear-wave velocity in the upper 30 m ($V_{s,30}$) is equal to 800 m/s. Hereafter, $\delta S2S_A$ refers to the site-to-site residuals relative to this generic rock reference. In the Ramadan et al. (2023) GMM, the site term is represented as a dummy variable ($F_S = s_i$ with $i = 1, 2, 3$) according to the EC8 subsoil classes, where $i = 1$ corresponds to rock sites (class A, $s_1 = 0$), $i = 2$ to stiff soils (class B) and $i = 3$ to soft soils (classes C and D). To scale the model relative to subsoil category A, $\delta S2S_A$ must be calculated as:

$$\delta S2S_A(IM) = \delta S2S_s(IM) + F_S(IM) \quad (3)$$

where F_S is the coefficient obtained from the regression of the reference model for the subsoil category of the given site, with $F_S = 0$ for class A, and non-zero for the other categories and IM is the acronym of Intensity Measure (PGA or SA ordinates).

In contrast, the Generalized Inversion Technique (GIT), requires the definition of a reference site assumed to be free of site amplification (unit response). In volcanic environments such as Mt. Etna, no site fully satisfies the criteria of an ideal rock reference (Lanzano et al., 2020), due to the presence of weathered layers, fractured materials, and possible topographic effects. Moreover, the eastern and northern sectors of the volcano are characterized by intense faulting and structural discontinuities, which may induce directional amplification and polarization effects, as documented by previous studies (Rigano et al., 2008; Di Giulio et al., 2009; Pischiutta et al., 2013; Panzera et al., 2016).

To address these issues, a reference station was selected on the western-southwestern flank of the volcano to reduce the influence of strong structural complexities. The selection was based on its central location within the study area, data quality and availability, and evidence of weak site amplification. ESML (Santa Maria di Licodia) fulfils these requirements: it is located on the southwestern flank of Mt. Etna, ensuring a balanced sampling of source-receiver geometries, and exhibits limited amplification as indicated in the NHV curve (generally below 2 over the 0.1-10 Hz range; Fig. S1, black curve). Although it corresponds to class B conditions ($V_{s,30} \approx 500$ m/s; Tarchini et al., this issue), it represents the best available approximation to a reference site and was therefore adopted for the GIT analysis.

To make the results of the two methods comparable, the $\delta S2S_A$ estimates for all stations must be scaled with respect to the median motion of the ESML station, i.e., $\delta S2S_{ref}$ is calculated as follows:

$$\delta S2S_{ref,i}(IM) = \delta S2S_{A,i}(IM) - \delta S2S_{A,ESML}(IM) \quad (4)$$

where the index i refers to the generic station and IM is the acronym of Intensity Measure (PGA or SA ordinates). Figure 7 shows the $\delta S2S_A$ and $\delta S2S_{ref}$ values for the ESML station, compared with an independent estimate of $\delta S2S$ from the study by Lanzano et al. (2025), derived from a dataset of crustal earthquakes and scaled to a $V_{s,30}$ of 800 m/s (referred to briefly as $\delta S2S_{800}$). The first point to note is that the estimates of $\delta S2S_A$ and $\delta S2S_{800}$ are consistent for the ESML station, even though the datasets are different and the ground motion prediction models are equally different (a specific GMM is used for crustal earthquakes). Secondly, compared to $\delta S2S_{ref}$, which is obviously flat and equal to 1, $\delta S2S_A$ of ESML is negative at short periods (approximately -0.5 natural logarithmic units for $T < 0.7$ s, indicating de-amplification) and slightly amplified at long periods (with maximum values not exceeding 0.5 natural logarithmic units). This behaviour indicates that the site, although with a response sufficiently flat for seismological analyses, differs from the average of A-class sites in Italy, exhibiting more pronounced attenuation at high frequencies (higher near-site high frequency attenuation parameter κ_0) and slight amplification at low frequencies, consistent with the fact that the site falls into subsoil category B.

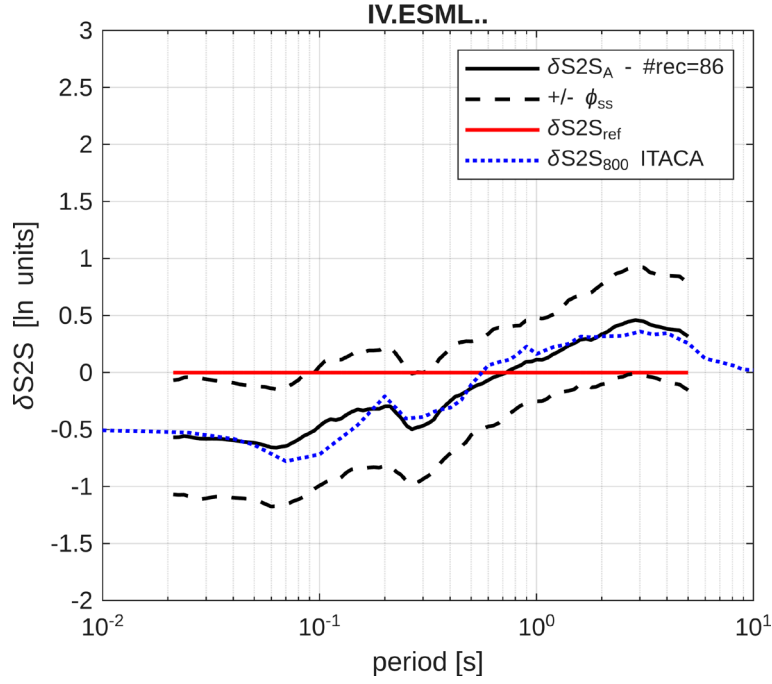


Figure 7. Site-to-site term vs period for IV.ESML station.

4.4 Single-station spectral ratios (EHV, NHV)

In addition to the two reference-based approaches ($\delta S2S$ and GIT), we also employ two widely used single-station techniques that do not require the identification of a reference site. The first method, the horizontal-to-vertical spectral ratio (HVSr) from earthquake recordings (hereafter EHV), originally proposed by Lermo and Chávez-García (1993), is computed from the ratio between the horizontal and vertical components of the S-wave portion of earthquake recordings. The method relies on the assumption that the vertical component is only weakly affected by local site amplification. Under this assumption, the horizontal-to-vertical ratio provides a proxy for a reference-site spectral ratio, allowing the identification of resonance peaks and their relative amplitudes. However, this assumption is not always valid (Parolai and Richwalski, 2004), and it is generally recognized that although the method reliably captures the fundamental resonance frequency of a site, it does not necessarily provide an accurate estimate of absolute amplification. EHV were evaluated from the Fourier Amplitude Spectra computed for the same S-wave windows of earthquake recordings extracted for the GIT analysis. For each event, the horizontal-to-vertical spectral ratio was calculated by combining the two horizontal components through the vector summation of the Fourier amplitude spectra.

The second technique, indicated with NHV, computes the spectral ratio between the horizontal and vertical component from environmental seismic noise at the same station (Nogoshi and Igarashi, 1970, 1971; Nakamura, 1989; Bard, 1999; Field and Jacob, 1995). NHV is widely used due to its simplicity, low operational cost, and independence from earthquake recordings, and is recognized as an efficient and reliable technique for identifying the fundamental resonance frequency of a site (Molnar et al., 2022). NHV was calculated following the criteria defined by the SESAME project recommendations (Bard, 2008). Ambient noise recordings were divided into 60-s windows, and the spectra were smoothed using the Konno-Ohmachi smoothing function. A minimum of 30 min of seismic noise recording was used for each station.

4.5 Amplification factors (AF1-AF2-AF3)

Following the Italian Seismic Microzonation (SM) Guidelines (Working Group SM, 2015), spectral amplification factors (AF) were computed as the ratio of averaged 5%-damped SA at the site and at outcropping rock over three period bands representative of the building stock: $\Delta T1 = 0.1-0.5$ s (AF1), $\Delta T2 = 0.4-0.8$ s (AF2), $\Delta T3 = 0.7-1.1$ s (AF3).

Although averaging over predefined period intervals may partially smooth local resonance features and mask some site-specific effects, especially in complex volcanic environments where site response can be characterized by broad spectral peaks, these intervals were adopted to ensure consistency with the Italian SM framework.

The approaches adopted for calculating AF also differ between the two methods:

- For GIT, 5%-damped SA are estimated by applying the spectral amplification functions to the seismic input compatible with the Uniform Hazard Spectrum (UHS), calculated for a 10% exceedance probability level in 50 years (475-year return period), as defined by the Italian seismic code NTC18 (MIT, 2018). In more detail, first, the site-specific time histories were obtained through the simple multiplication of the GIT spectral amplification function in the Fourier domain by the Fourier amplitude spectrum of the seismic input, while preserving the original phase information (Priolo et al., 2020; Lanzano et al., 2025). The amplified (site-specific) time histories were then used to compute the 5%-damped SA.
- For $\delta S2S_{ref}$, amplification relative to the reference site at generic IM can be computed as $\exp(\delta S2S_{ref}(IM))$. AF values for period ranges are obtained by averaging the scaled spectral ordinates across each ΔT . In particular, we approximated the integrals of 5% damped acceleration response spectra at site, S_a , and at bedrock, S_b , to mean spectral values over the period intervals of interest (see Priolo et al., 2020; Lanzano et al., 2025). In this way, AF was simply calculated as the exponential of the average of scaled $\delta S2S$ estimates over the interval of reference periods, as:

$$AF_{T1-T2} = \frac{\langle S_b \rangle \langle \exp(\delta S2S_{ref}) \rangle}{\langle S_b \rangle} = \langle \exp(\delta S2S_{ref}) \rangle \quad (5)$$

Lanzano et al. (2025) noted that this approximation compared with the rigorous formulation results in very small variations in the amplification factor, well below the range of variability associated with the median value of the empirical amplification.

It is worth noting that, although AF values are derived through different procedures in the GIT and $\delta S2S$ approaches, recent comparisons performed on large Italian datasets have shown that the two methods provide highly consistent amplification factors once referred to a common reference ground-motion level (Hailemichael et al., submitted to BEE). This finding suggests that the reference condition represents the dominant source of systematic differences, whereas the specific AF computation procedure has only a secondary impact.

5. Results

5.1 Spectral amplification functions and HV ratios

The spectral amplification functions evaluated using the two approaches – $\delta S2S$ and GIT – are compared with the single-station techniques EHV and NHV (HV ratios), to assess the consistency of site response across the Etna region (Fig. 8 and Fig. S1). Although $\delta S2S$ estimates (dashed magenta curves) are defined in the response spectra domain, they are included in the plots to enable a qualitative comparison of overall trends, mainly in terms of amplification frequency bands. It should be noted that $\delta S2S$ and GIT quantify horizontal amplification relative to a reference site, whereas EHV and NHV rely on the vertical component at the same station as a reference. As a result, discrepancies may occur where the vertical component is subject to local amplification, influencing the corresponding spectral ratios.

The two EHV curves, computed from Dataset 1 and Dataset 2, are remarkably consistent across the entire frequency band, except for one site, ENIC, where differences in amplitude are observed, although the overall shape remains very similar. This agreement indicates that EHV estimates are stable with respect to differences in event magnitude, focal depth, and source-to-site geometry and provide robust and stable estimates of the amplification frequency. This finding is consistent with previous studies, starting from the pioneering work of Lermo and Chávez-García (1993) and subsequently confirmed by several investigations (e.g., Yang et al., 2019).

As shown in Figs. 8 and S1, the EHV estimates exhibit relatively large standard deviations at low frequencies. This increased variability reflects the significant dispersion among the individual EHV curves, which can be attributed to the contribution of multiple seismic sources with different azimuthal distributions, as well as to the effects of

different wave propagation paths. Similar behaviour has been widely documented in the literature and is observed irrespective of whether EHV ratios are computed using Fourier amplitude spectra or 5%-damped response spectra of the horizontal and vertical ground-motion components (see Zhu et al., 2022, for a review).

NHV curves (black) also closely match EHV ratios, with nearly identical amplitudes, spectral shapes, and resonance frequencies (except a few cases, e.g., FX04, FX06, FX08 in Fig. S1). This agreement is consistent with previous studies, which show that ambient noise can reliably reproduce EHV, with discrepancies mainly occurring in the presence of strong velocity inversions (Mucciarelli and Gallipoli, 2004) or specific wavefield conditions (La Rocca and Chiappetta, 2022). However, as detailed stratigraphic or geophysical information is not available for these sites, these explanations should be regarded as plausible hypotheses.

Examining the general trend of the NHV and EHV curves, the Etna stations show a heterogeneous site-response behaviour. Many curves exhibit significant amplification over broad frequency bands, often with amplitudes exceeding 2, but the amplification pattern is not always characterized by sharp and isolated peaks. A subset of stations displays clearer and more stable peaks, for which f_0 can be more reliably identified. This behaviour is consistent with Tarchini et al. (this issue), who computed both EHV and NHV for 40 stations in the Etna area and, following the SESAME (2004) reliability criteria, identified f_0 only where stable and well-defined HV ratios peaks were observed, whereas flat curves or curves lacking a clear peak were classified as having no identifiable f_0 . Therefore, the absence of sharp peaks in HV ratios at some stations should not be interpreted as a total lack of site amplification. Rather, it indicates the absence of a sharp, single impedance contrast, suggesting instead that the amplification may be distributed across a broader frequency band due to gradual velocity variations or complex volcanic stratigraphy.

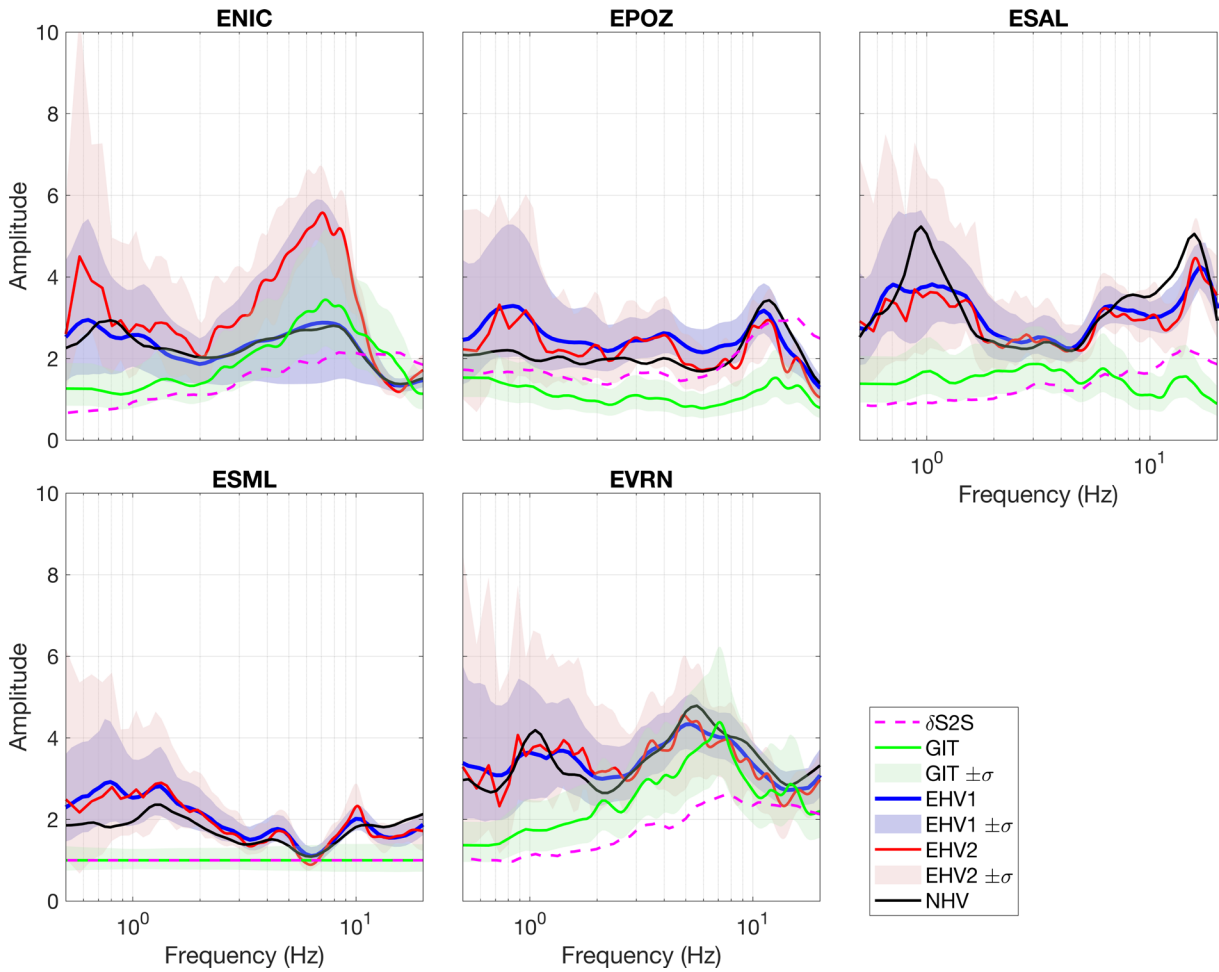


Figure 8. Comparison of spectral curves from $\delta S2S$ (dashed magenta curves), GIT (green curves), and HVSR methods at five selected sites. Blue and red curves represent EHV results obtained from Dataset 1 and Dataset 2, respectively (shaded areas indicate one standard deviation), while black curves correspond to NHV derived from seismic noise recordings.

At many sites, the GIT spectral ratios (green curves) follow the same overall trend indicated by HV ratios, capturing the broad-band amplification pattern and the gentle frequency-dependent variations. At a limited number of stations (i.e., ECHR, EFIU, EMSA, EPMN, EPOZ, EPZF, FX06, FX07, FX09, and SPAOL in Fig. S1), GIT shows deviations in terms of lower amplitudes and, in some cases, even de-amplification – especially in the higher-frequency band.

In volcanic environments, basaltic lava flows overlying softer sedimentary or pyroclastic deposits may generate velocity inversions and significant vertical-motion amplification, as documented by Panzera et al. (2015). Under such conditions, horizontal-to-vertical ratio amplitudes may be biased because the vertical component is no longer a neutral reference. However, the amplification factors considered in this study are derived from the GIT and $\delta S2S$ approaches, which are based on horizontal ground-motion amplitudes and are consistent with the requirements of the Italian seismic microzonation guidelines, where amplification is evaluated on the horizontal component. Although vertical amplification may represent an important feature of site response in volcanic environments, especially in the presence of velocity inversions, it was not explicitly quantified in the present work.

Although not directly comparable, the GIT and $\delta S2S$ curves identify amplification within the same frequency band and consistently highlight the same sites characterized by low amplification, and, in some cases de-amplification (i.e., EMSA, FX06, FX07, FX08, FX09, and SPAOL in Fig. S1), thereby confirming the weak site response inferred at these locations.

5.2 Amplification factors

Figure 9 shows the comparison of empirical amplification factors obtained through the two independent approaches, GIT (red symbols) and $\delta S2S$ (black symbols), for the three period intervals considered. In this figure, only the sites common to both approaches are shown (in red on the map in Fig. 3), i.e., those evaluated using both

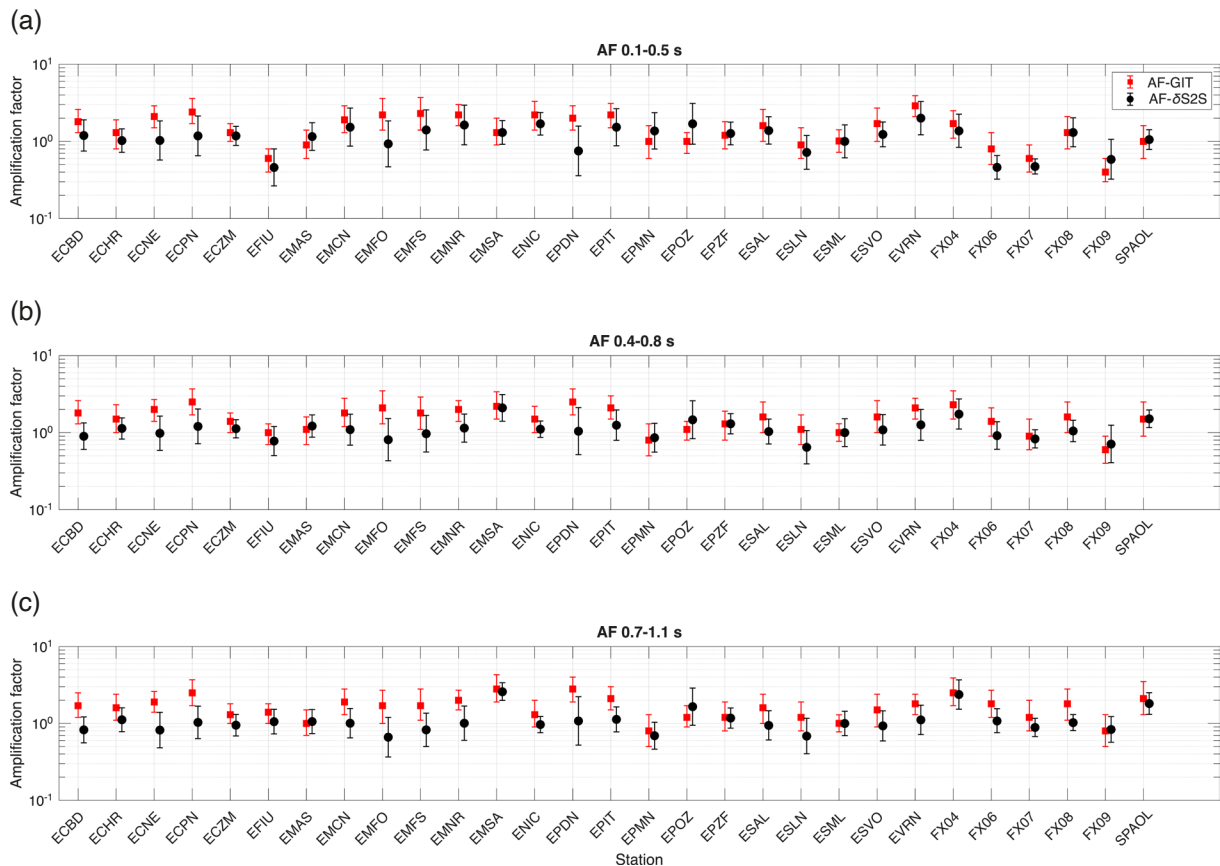


Figure 9. Empirical amplification factors at common sites obtained using the two methodologies, $\delta S2S$ (black) and GIT (red) for the three period intervals: $T = 0.1-0.5$ s (a), $T = 0.4-0.8$ s (b) and $T = 0.7-1.1$ s (c).

the GIT and δS_2S methods across the two datasets, for a total of 29 sites. A consistent trend is visible across the period bands: the two methods produce similar patterns, with stations showing comparable amplification behaviour, although GIT values are slightly higher at several sites. Overall, the relative amplification factors rarely exceed 2 with respect to the adopted reference station with little variation among the three AF metrics. However, a few locations exhibit a large difference between them. At these sites, AF3 values are higher than AF1 values, though none exceed 2. These specific locations (such as SPAOL, FX09, FX07, and FX06) lie on the lower slopes of Mt. Etna, where deeper soils are expected.

5.3 Comparison with 1-D numerical modeling

In addition to the empirical approaches, one-dimensional (1D) numerical analyses were carried out for five sites where IV recording stations are installed. Ambient seismic noise surveys were carried out using two-dimensional (2D) seismic arrays, and the shear-wave velocity (V_S) profiles were retrieved from the dispersive properties of surface waves. The analysed IV stations are EPOZ (Pozzillo), ESML (Santa Maria di Licodia), ENIC (Nicolosi), ESAL (S. Alfio) and EVRN (Santa Venerina). The stations were selected based on the availability of high-quality seismic recordings, whose preliminary analysis revealed peculiar features in the site response, motivating a dedicated investigation of local site conditions. However, the interpretation of the results requires some caution due to the marked lateral heterogeneity of volcanic lithologies.

The shear wave velocity profiles (Figs. 10 and S2), V_S , were used as input data for the 1D simulation using the STRATA numerical code (Kottke and Rathje, 2009). The resulting V_S models consistently show a very soft shallow layer ($V_S = 77\text{--}149$ m/s), about 1.0–1.4 m thick, overlying stiffer lithological units. Below this shallow cover, EPOZ, ESML, ENIC, and ESAL show V_S values of about 245–420 m/s down to depths of approximately 9.0–11.5 m, before a marked increase to stiffer materials. In contrast, EVRN shows lower V_S values (158–331 m/s) persisting down to about 25 m depth. At greater depth, all investigated sites are underlain by markedly stiffer materials, with V_S values generally ranging from about 570 to 710 m/s. In terms of EC8 classification, EPOZ, ESML, ENIC, and ESAL fall within class B, with $V_{S,30}$ values between 386 and 505 m/s, while EVRN is the only softer site, classified as EC8 class C with $V_{S,30} = 298$ m/s. Overall, the derived models indicate recurrent shallow impedance contrasts, consistent with thin soft surficial deposits overlying stiffer volcanic materials, although with appreciable site-to-site variability in layer thickness and velocity structure (see results of HV ratios in Tarchini et al., this issue).

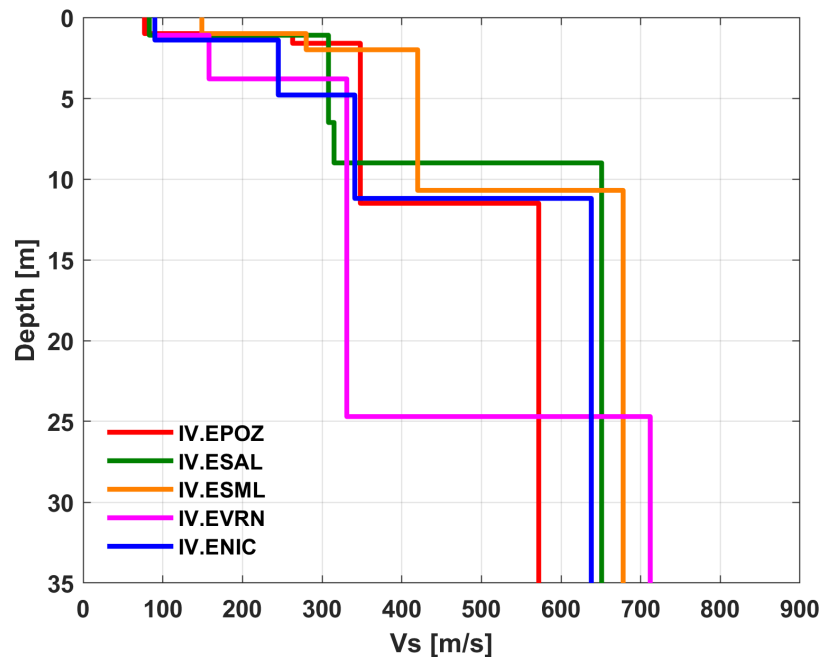


Figure 10. Shear wave velocity profiles of five recording stations of the IV network. The full profiles, down to bedrock depth, are available in the electronic supplementary material (Fig. S2).

To simulate the local seismic response, we applied the accelerograms selected on purpose to represent the ground motion characteristics in the Mt. Etna volcanic context by Azzaro et al. (this issue). A deterministic linear elastic model was chosen, to model similar conditions as the empirical analyses¹.

Figure 11a shows the frequency transfer function and the ratio between the acceleration spectra at the surface and at bedrock for three selected sites (the remaining 2 are in Fig. S3). To have an empirical benchmark, the transfer functions were compared with the curves obtained from GIT from Dataset 2 and the literature empirical $\delta S2S_{800}$ curves, obtained using the ITA18 model (Lanzano et al., 2019) from a dataset of shallow active crustal recordings. In Fig. 11b, the comparison is made with the $\delta S2S$ curves obtained from Dataset 1, using both subsoil category A and the ESML station as references.

Overall, the numerical simulations reproduce the main amplification frequency bands identified by the empirical approaches, although the degree of agreement varies among the investigated sites. At several stations, the numerical model captures the dominant impedance contrasts and the overall spectral shape, whereas local discrepancies are observed in the amplitude and sharpness of individual resonance peaks. These differences are expected given the deterministic one-dimensional representation adopted in the numerical analyses and the geological complexity of the Mt. Etna volcanic environment, characterized by lateral heterogeneity, fractured lava flows, irregular interfaces, and active fault systems. In addition, uncertainties in the available V_s profiles and unresolved shallow impedance contrasts

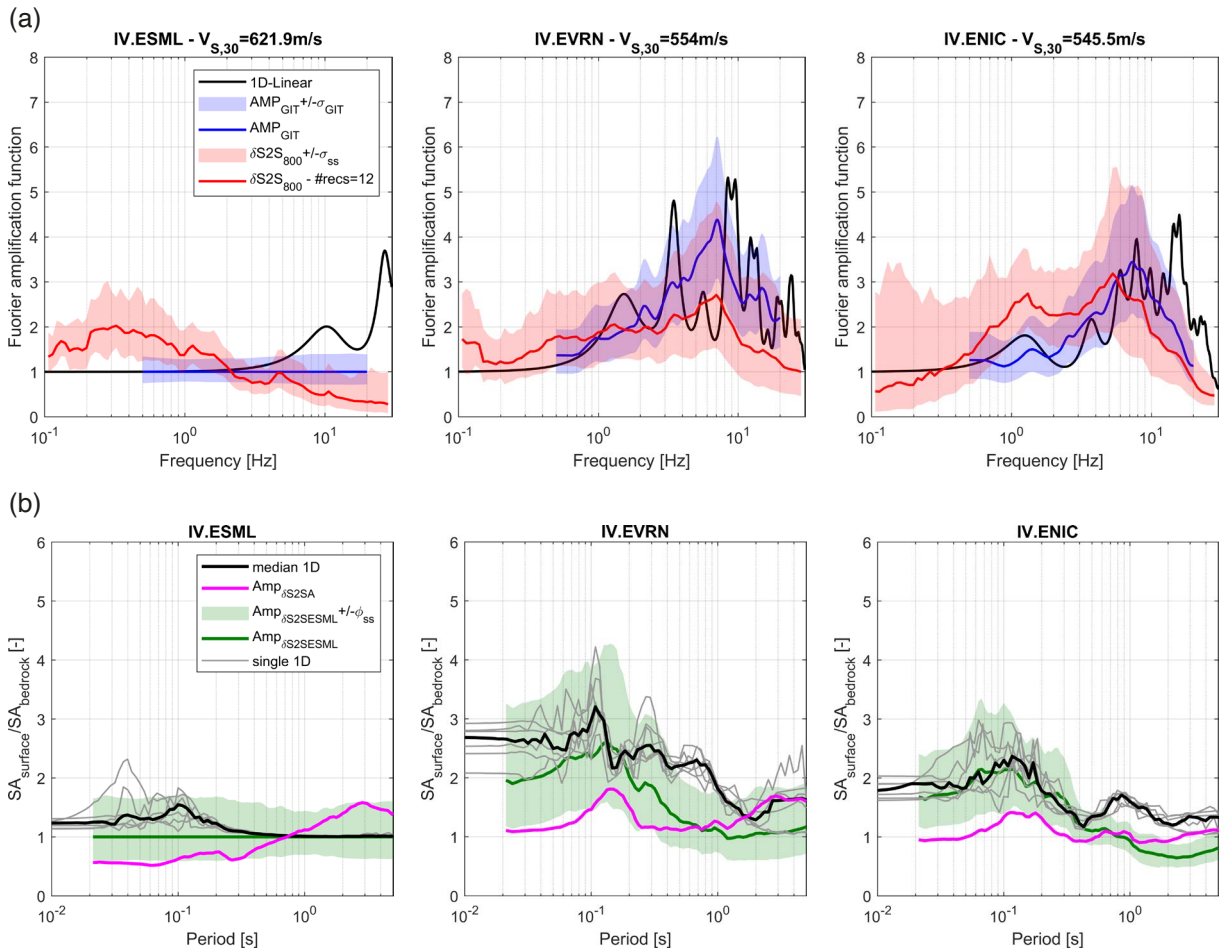


Figure 11. Comparison of empirical results and 1D analyses for three stations in the IV network. (a) Comparison of numerical and empirical amplification curves in FAS; (b) spectral ratios between the surface and bedrock from 1D analyses and $\delta S2S$ values derived from recordings in the Etna area. Left: ESML; middle: EVRN; right: ENIC.

¹ Among the required STRATA input data, we assumed typical values for the specific weight ρ and the elastic damping ratio D_0 . The specific weight was assumed in the range 16-22 kN/m³ and is proportional to V_s according to the Keçeli (2009) relationship: $\rho = 0.44V_s^{0.25}$. Three elastic damping D_0 values were therefore chosen, also depending on the V_s values in the respective layer: 3% for layers with $V_s < 360$ m/s; 2% for layers with $360 \text{ m/s} < V_s < 800$ m/s; 1% for layers with $V_s \geq 800$ m/s.

may also contribute to the observed differences. Using ESML as the reference station generally provides a better match in terms of amplification amplitudes. ENIC and EVRN exhibit pronounced high-frequency amplification in both the empirical and numerical results ($f > 3$ Hz). The numerical simulations reproduce the main amplification frequency band, although they predict sharper and larger resonance peaks than the empirical estimates, particularly for EVRN. Conversely, ESML exhibits an almost flat empirical response over the entire frequency range, whereas the numerical model predicts moderate high-frequency amplification, likely associated with shallow impedance contrasts that may be overemphasized by the simplified deterministic representation. The EPOZ and ESAL stations (Fig. S3) show larger discrepancies between numerical and empirical amplification functions, which are likely related to simplifications in the adopted V_s profiles together with the intrinsic limitations of one-dimensional modelling in such a complex volcanic environment.

6. Discussion

The integration of multiple empirical and numerical approaches provides a coherent and mutually reinforcing picture of seismic site response across the Etna region, despite the pronounced geological and structural heterogeneity typical of volcanic environments. The two main empirical methods adopted in this study – $\delta S2S$ from non-ergodic GMM residuals and GIT – show a high degree of consistency in the frequency-dependent amplification patterns they retrieve, suggesting that the observed spatial variability is primarily controlled by local site conditions rather than by methodological artifacts. This result is particularly relevant because the two methods rely on different datasets, earthquake populations, and inversion strategies, yet converge toward a similar picture of the dominant amplification behaviour.

Systematic discrepancies are observed in terms of absolute amplitude, with GIT generally yielding slightly higher amplification levels than $\delta S2S$, especially in the short-period range. Although ESML is not an ideal EC8 Class A site, its frequency-dependent response is independently quantified through the $\delta S2S$ analysis (Fig. 7) and accounted for through Eq. (4), so that both methods ultimately refer to the same reference condition. Therefore, the response of ESML affects both datasets consistently. The observed discrepancies are more likely related to the different sensitivity of the two approaches to residual source- and path-related effects, as well as to the different statistical stability of the estimates, with $\delta S2S$ being based on a larger number of recordings. Dataset 1, used for $\delta S2S$, consists exclusively of local volcano-tectonic earthquakes with short source-to-site distances, whereas Dataset 2, used for GIT, includes both volcanic and regional tectonic earthquakes spanning a broader range of distances and azimuths. Under these conditions, residual propagation effects not fully captured by the attenuation model may contribute to the generally higher GIT amplification factors, particularly at short periods.

In the context of seismic microzonation, where a single map of amplification factors is required for operational use, reconciling these methodological differences becomes essential. To build an integrated dataset of amplification factors for the Etna area, the estimates from the two methods were therefore combined into a unified dataset. Using $\delta S2S$ as the reference dataset and correcting GIT estimates through the average offset observed at common stations represents a pragmatic solution that maximizes spatial coverage while preserving consistency with the more stable dataset. This procedure inevitably assumes that the offset between the two methods is sufficiently uniform within each period band; therefore, the final dataset should be regarded as a homogeneous but still approximate representation of site amplification, particularly where only GIT estimates are available. The offset is evaluated for each of the three considered period ranges by the difference between the two estimates at the stations common to both datasets as:

$$AF_{\delta S2S} - AF_{GIT} \quad (6)$$

Subsequently, for each period range, the mean difference was estimated as:

$$DFA = \text{mean} (AF_{\delta S2S} - AF_{GIT}) \quad (7)$$

where the mean was computed exclusively over the stations shared by the two datasets.

For stations where an AF from $\delta S2S$ was available, the final amplification factor was taken directly from $\delta S2S$. For stations lacking an AF from $\delta S2S$ but having an AF from GIT, the final value was obtained by correcting the GIT estimate using the mean offset DFA, according to the relation:

$$AF_{\text{final}} = AF_{\text{GIT}} + \text{DFA} \quad (8)$$

The mean offset introduced in Eq. (7) is not intended to correct the response of the reference station, which is already accounted for through Eq. (4). Instead, it is applied separately within each period range to account for the average residual differences observed between GIT and $\delta S2S$ estimates at common stations. This approach represents a pragmatic harmonization aimed at improving spatial coverage while preserving consistency between the two datasets, resulting in a homogeneous set of amplification factors across the study area. The distributions of the differences between the AF estimates obtained from the $\delta S2S$ and GIT methods, computed for the 29 stations common to both datasets, are shown in Supplementary Fig. S4. The boxplots show that the offset distributions are consistently shifted toward negative values for all three period ranges, with the offset becoming progressively more negative from short to long periods. The resulting values for each period range are shown in Fig. 12.

The empirical amplification factors show widespread amplification effects across the study area, which generally tend to decrease with increasing period. In the short-period range (0.1-0.5 s, Fig. 12a), 41 out of 57 stations show $AF > 1$, with 21 stations exceeding $AF = 1.5$ and 8 stations showing $AF > 2$. In the intermediate range (0.4-0.8 s, Fig. 12b), the number of amplified sites decreases to 37 out of 57, and only 13 stations show $AF > 1.5$. In the longer-period range (0.7-1.1 s, Fig. 12c), 32 out of 57 stations still exhibit $AF > 1$, but most of them fall within the lower amplification classes, indicating a general decrease in amplification at longer periods. Spatially, moderate-to-high AF values tend to cluster mainly along the coastal and eastern parts of the study area, whereas inland areas more commonly show low or near-unity values. This general pattern is visible across all three period ranges, although with local differences related to the considered interval. Finally, amplification is more widespread and locally stronger at short periods, with several stations reaching $AF > 2.5$, while some stations show persistent amplification over multiple period bands, as observed at ET10. In contrast, the southern sector of the study area, including stations on the Catania Plain (CAT and FX04) and near the Etna foothills (ET12 and EMSA), shows higher amplification values at longer periods.

This behaviour suggests that shallow impedance contrasts and near-surface layers play a major role over much of the study area.

However, the persistence of amplification at longer periods in some stations, particularly in the southern sector and in the Catania Plain, indicates that deeper geological structures or thicker sedimentary/volcanoclastic successions may locally control the response. The spatial concentration of moderate-to-high AF values in the coastal and eastern sectors is consistent with this interpretation and suggests that these areas may be more prone to significant local amplification during earthquakes.

Figure 13 compares spectral amplification curves obtained using GIT and $\delta S2S$ at nearby stations, providing insight into the consistency of site-response estimates at short spatial scales. In most cases (panels a, b, d), the two methods show a good agreement within the main amplification frequency band (1-10 Hz), identifying similar spectral features and trends. Larger differences are observed at the low- and high-frequency ends of the spectra, where the amplitudes may diverge more significantly. At high frequencies (typically >10 Hz), these discrepancies may reflect very shallow site conditions, which can vary substantially over short distances. Figure 13c highlights the two previously mentioned stations, EMSA and ET12. The two stations exhibit generally similar spectral behaviour, particularly in the 1-3 Hz frequency range; however, ET12, located a few kilometres to the north, shows moderately higher amplification levels over the same frequency band. Both stations are not located within the volcaniclastic Etna succession but lie on the Pleistocenic alluvial terraces.

Part of the discrepancies observed at short periods (previously noted also in Fig. 9) may also reflect differences in station installation conditions. Most temporary MZ stations were installed inside small low-rise buildings in urban environments, where recordings may be affected by soil-structure interaction and building response (Castellaro et al., 2022). However, previous studies (Ditommaso et al., 2010) indicate that the influence of such structures is generally concentrated at frequencies higher than about 5-10 Hz. Therefore, although a contribution

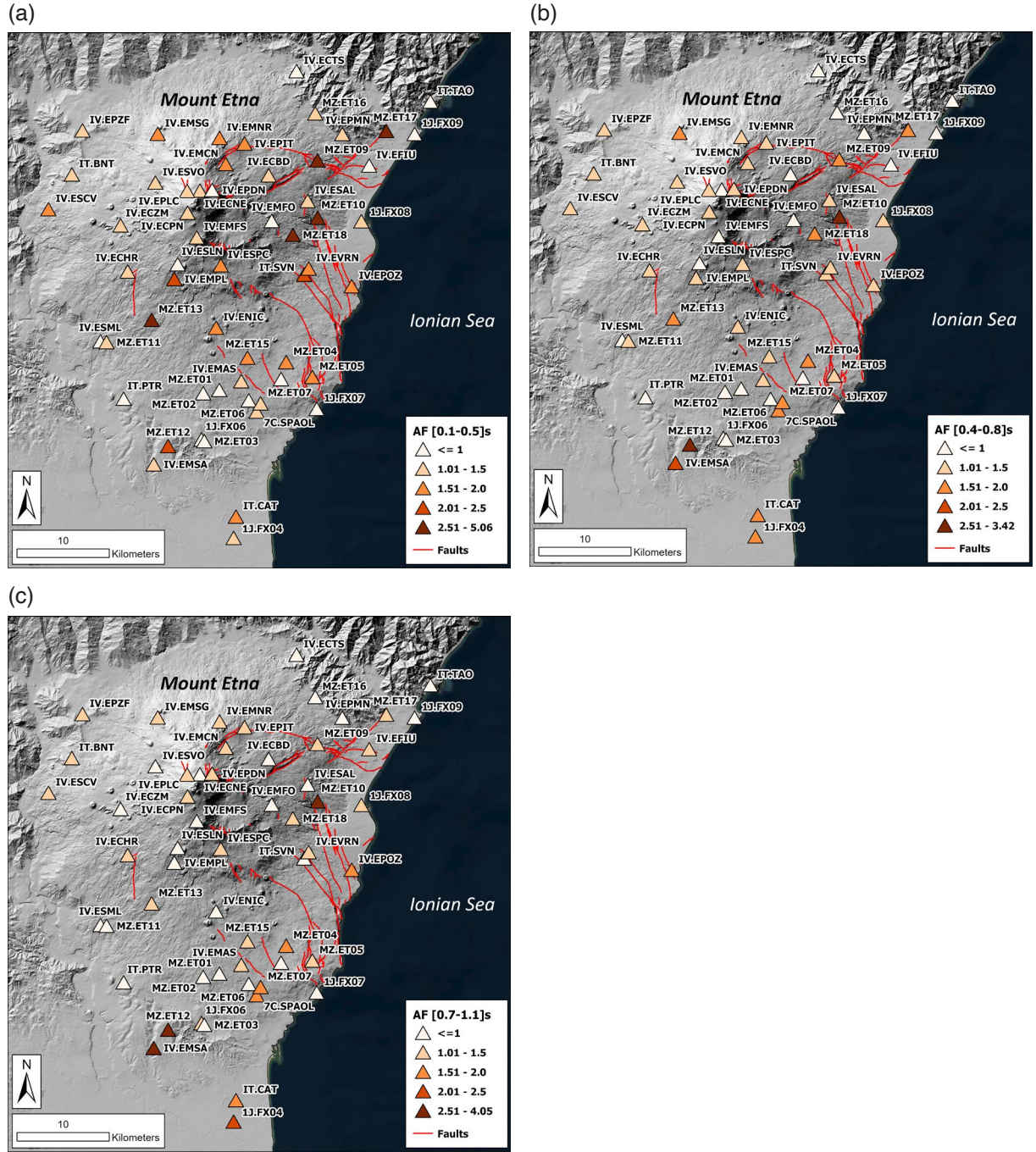


Figure 12. Empirical amplification factors (AF) derived for the study area. (a) AF estimates for the period interval $T = 0.1-0.5$ s. (b) AF estimates for the period interval $T = 0.4-0.8$ s. (c) AF estimates for the long-period interval $T = 0.7-1.1$ s. Red lines indicate mapped faults.

from soil-structure interaction cannot be completely excluded, its impact on the broad-band amplification patterns discussed in this study is expected to be limited. Moreover, the overall consistency between the amplification patterns retrieved from the temporary and nearby permanent stations suggests that any building-related contribution is secondary with respect to the spatial variability associated with local site conditions and does not significantly affect the regional trends highlighted by the amplification maps.

In Fig. 14, the boxplots grouped according to the EC8 (2005) site class of the stations show an overall consistent trend across the three period ranges. Class B, which represents the largest group, exhibits the highest dispersion of AF values, although with median values generally close to or slightly above unity. This indicates that stations belonging to the same $V_{s,30}$ -based class may experience substantially different levels of amplification. Compared

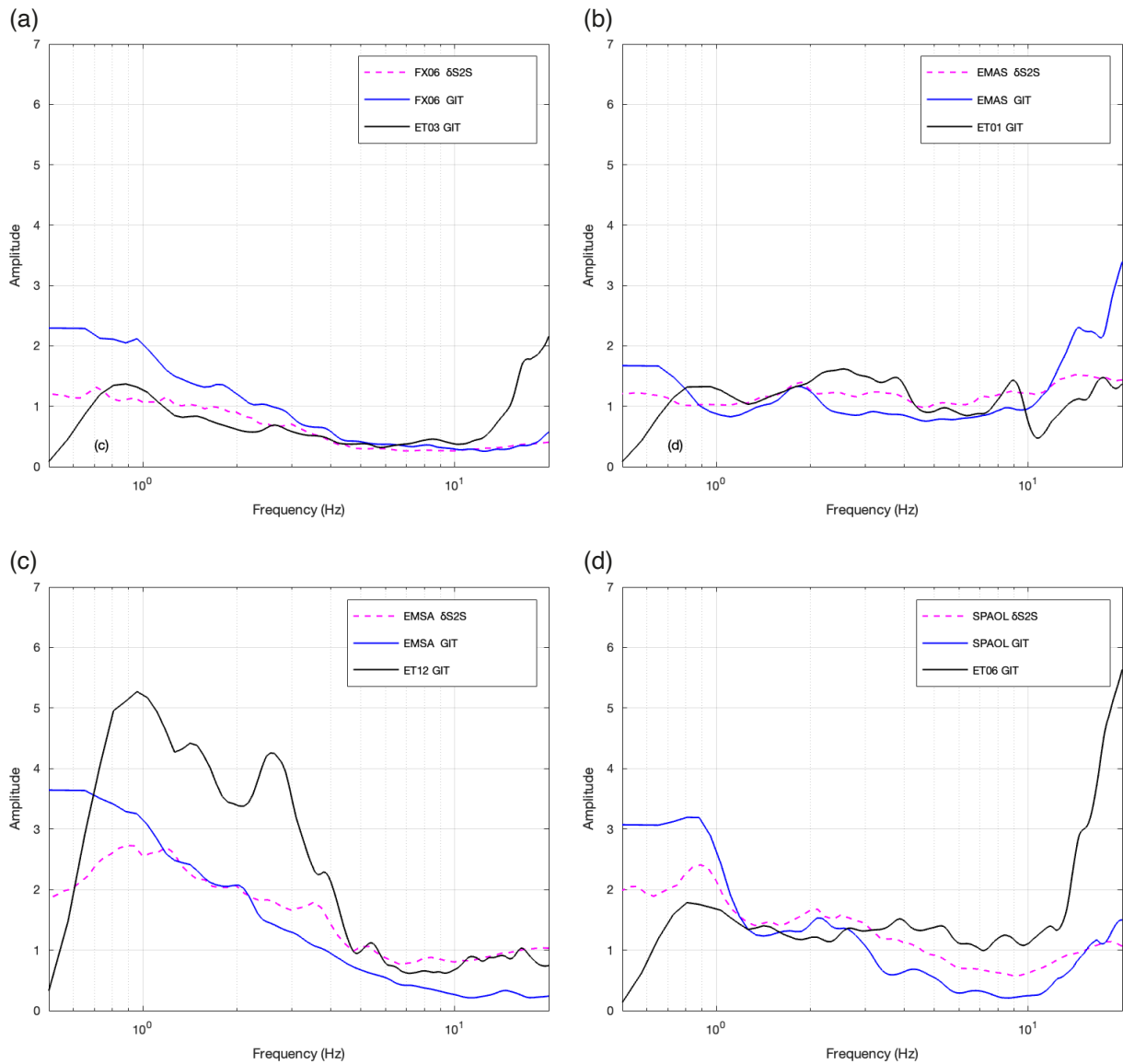


Figure 13. Comparison of spectral curves obtained at nearby stations from $\delta S2S$ (dashed magenta curves) and GIT (blue and black curves).

with Class B, Class C generally exhibits higher median amplification values across all three period ranges. For both Classes B and C, however, the median amplification is highest in the short-period range ($T = 0.1\text{--}0.5$ s) and decreases progressively towards the intermediate- and long-period ranges. It is also important to emphasize that Classes A and D are each represented by a single station, so no general conclusions can be drawn for these site classes. Although Class C is represented by more stations, its sample size remains limited; therefore, the observed trends should be interpreted with caution. It is also worth noting that an EC8 class based on measured $V_{S,30}$ could only be determined for 23 out of the 57 stations, whereas for the remaining sites it was assigned from $V_{S,30}$ inferred from slope following Wald and Allen (2007). Overall, these results suggest that EC8 site classes alone cannot fully explain the large variability in AF values observed within the same site class, particularly in the complex volcanic setting of the Etna region, as evidenced by the large dispersion of AF values within Class B.

The grouping based on the aggregated lithological classification of Brunelli et al. (2026) at 1:100,000 scale (Fig. 15) also shows a coherent pattern across the three period ranges, although the scale of the map is not able to capture local detail. The LIDO class (Limestone and Dolomites) tends to show low AF values or values close to unity, in agreement with the expected behaviour of more competent lithologies. The EMR class (Effusive Magmatic Rocks), which constitutes the largest group, shows significant dispersion but overall moderate values, with a few isolated

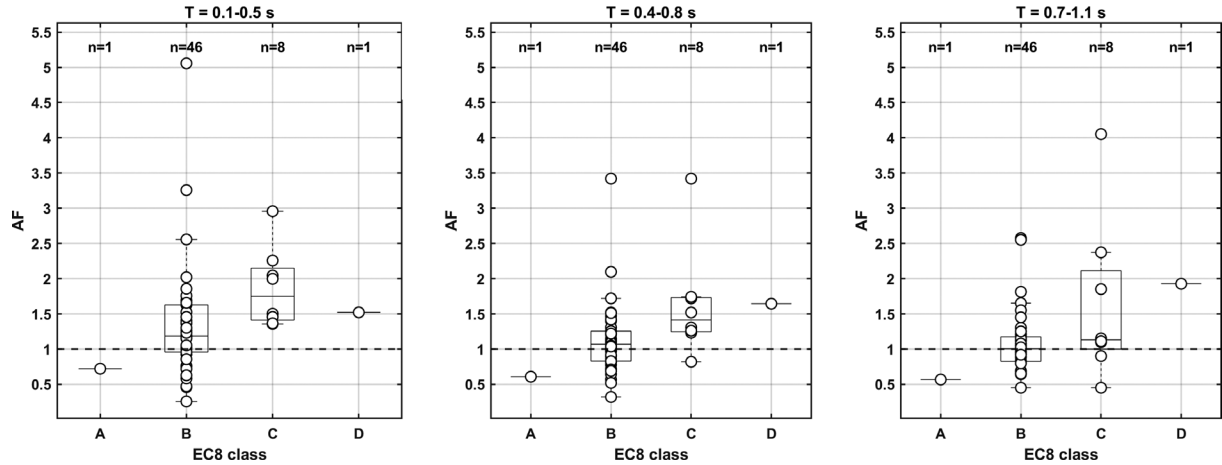


Figure 14. Distribution of amplification factors (AF) for the different EC8 site classes in the three investigated period ranges. Boxplots display the median, interquartile range, and outliers. The sample size (n) for each site class is indicated above each boxplot.

cases of high amplification. The ASM class (Argillites, Siltstones, Marls) exhibits generally higher AF values than LIDO and EMR, especially at intermediate-to-long periods. Finally, the SMG class (Coarse-to-medium-grained soils) generally shows the highest AF values, particularly in the 0.7-1.1 s interval, as expected for less rigid site conditions. Overall, the lithological grouping provides a useful indication of the average amplification behaviour, but the large variability of AF values within individual classes shows that surface lithology at 1:100,000 scale alone cannot fully explain the observed site-response variability, especially in the complex volcanic stratigraphic setting of Mt. Etna.

The results suggest that empirical amplification in the Etna region is spatially heterogeneous, period-dependent, and only partly represented by standard site-classification schemes. This may have implications for seismic microzonation, supporting the potential use of locally calibrated amplification factors. More generally, the findings underline the importance of empirical approaches to better capture the variability of site response in complex volcanic settings such as Mt. Etna. Recently, a harmonized database of more than 1000 HVSr measurements has been developed for the Mt. Etna region (Gaudiosi et al., this issue), integrating ambient-noise surveys from multiple institutions following standardized acquisition, processing, and quality-control procedures. From a future perspective, the next step is the spatialization of these results at a finer scale, exploiting the dense coverage provided by the HVSr dataset to better resolve local variations in amplification and to improve the characterization of site effects across the volcanic edifice.

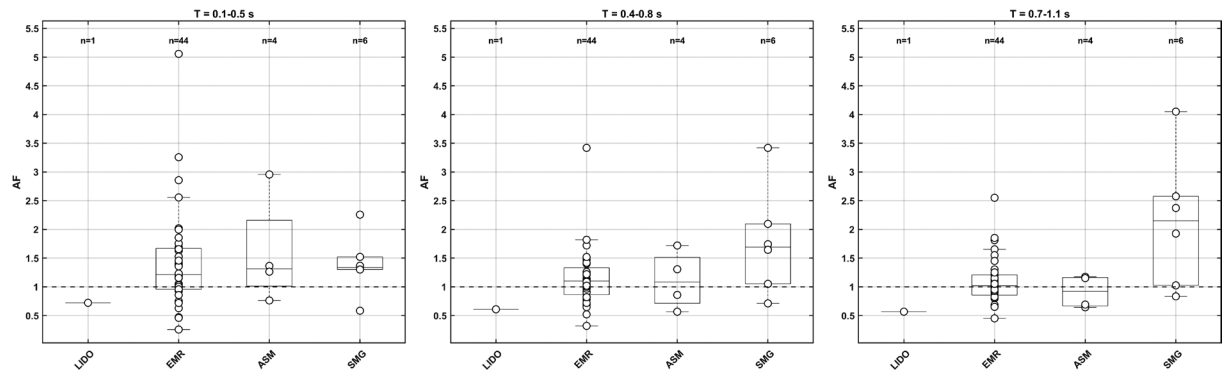


Figure 15. Boxplots representing the AF according to the aggregated lithological classification of Brunelli et al. (2026) for the three period ranges. EMR: Effusive magmatic rocks; LIDO: Limestone and Dolomites; ASM: Argillites, siltstones, marls; SMG: Coarse-to-medium-grained soils.

7. Conclusions

This study provides an empirical assessment of seismic site amplification in the Mt. Etna region by integrating complementary datasets from permanent and temporary seismic networks. Site amplification was evaluated using two independent reference-based approaches – site-to-site residuals ($\delta S2S$) from a non-ergodic Ground Motion Model and the Generalized Inversion Technique (GIT) – and supported by single-station spectral ratios (EHV and NHV).

Despite differences in datasets and methodologies, $\delta S2S$ and GIT yield consistent amplification patterns when referenced to a common site, identifying predominantly low to moderate amplification, with most amplification factors below 2 and locally higher values observed at selected stations. Horizontal-to-vertical spectral ratios confirm the main resonance features and support the robustness of the empirical results. The empirical AFs also reveal a clear period-dependent behaviour: amplification is generally more widespread and locally stronger at short periods, while amplification at longer periods is more localized, especially in the southern sector of the study area and in the Catania Plain. Spatially, moderate-to-high AF values tend to cluster mainly along the coastal and eastern sectors, whereas inland areas more commonly show low or no amplification.

It should be noted that the amplification factors derived in this study are relative to the adopted reference station rather than to an ideal engineering bedrock condition. Therefore, any amplification or de-amplification at the reference site may influence the estimated AF values. However, this effect is expected to be limited for ESML (Fig. 7), whose $\delta S2S$ response relative to EC8 Class A sites shows only slight de-amplification at short periods and modest amplification at longer periods. Consequently, although the reported AF values should be interpreted as relative to ESML, they are expected to remain broadly consistent with amplification factors referred to standard reference conditions, such as EC8 Class A sites or $V_{S,30} = 800$ m/s.

Furthermore, previous investigations on Mt. Etna have highlighted the presence of directional site effects related to faulting and structural heterogeneity (Rigano et al., 2008; Di Giulio et al., 2009; Pischiutta et al., 2013; Panzera et al., 2016). Therefore, amplification factors computed over predefined period intervals may partly smooth directional effects and locally underestimate the maximum amplification occurring along preferred directions. However, the reference station ESML does not appear to be affected by significant directional effects. Analyses of earthquake-based HVSRs available through the ITACA database (Felicetta et al., 2023) indicate stable spectral responses for different source azimuths, and the relatively uniform azimuthal distribution of the analysed events further supports the absence of marked directional amplification at this site. Therefore, the adopted reference condition is not expected to introduce significant bias related to wavefield polarization or azimuth-dependent site response. Nevertheless, the potential influence of directional effects on the estimation of amplification factors at individual stations was not explicitly investigated in this study and deserves dedicated analysis in future research.

To support the seismic microzonation study, empirical amplification factors were compared with deterministic 1D numerical site-response analyses performed for five representative sites. This comparison is relevant because 1D analyses represent the standard approach adopted in the Italian seismic microzonation guidelines. The result should be analysed considering the geological setting of Mt. Etna, characterized by strong lateral heterogeneity, irregular volcanic stratigraphy, fractured lava flows, active fault systems, and complex topography, all of which may produce three-dimensional wave-propagation effects that cannot be reproduced by a 1D model. Consequently, local discrepancies between empirical and numerical amplification functions are expected and do not necessarily indicate deficiencies in either the empirical observations or the subsurface characterization. Rather, the numerical analyses were included as an independent consistency check to assess whether the available V_s profiles capture the dominant impedance contrasts responsible for the observed amplification. Therefore, the comparison should not be interpreted as a validation of the 1D approach itself, but as an assessment of the ability of the available subsurface models to reproduce the main empirical amplification features. The overall agreement between the two approaches suggests that the dominant characteristics of the local site response are reasonably represented, while recognizing that more sophisticated two- or three-dimensional simulations would be required to investigate the effects of complex geological structures.

The comparison should also be interpreted within the assumptions adopted for the numerical analyses. Deterministic linear-elastic models were intentionally used to ensure consistency with the empirical observations and to avoid introducing additional variability associated with profile randomization. Under strong ground motions, however, nonlinear soil behaviour may become significant, leading to shear modulus degradation, increased damping, reduced short-period amplification, and a shift of the amplification towards longer periods. The resulting modification of the transfer function is frequency dependent, and linear amplification functions should therefore not be interpreted as

a universal upper bound over the entire frequency range. Investigating these effects requires dedicated nonlinear site-response analyses and falls beyond the scope of the present study.

Additional uncertainty may arise from soil-structure interaction at some temporary stations installed inside small buildings, although its effect is expected to be limited and mainly confined to high frequencies.

The amplification factors were then merged into a unified dataset (AF1-AF3), combining the statistical stability of $\delta S2S$ with the improved spatial coverage provided by GIT. This integration is particularly important for operational seismic microzonation, where a single map of amplification factors is required, and the consistency between $\delta S2S$ and GIT makes their joint use a robust strategy for deriving empirical amplification factors. One-dimensional numerical simulations performed at selected sites reproduce the main spectral trends observed empirically, providing additional support to the inferred site-response behavior.

The results also show that standard site-classification schemes provide only a partial description of the observed amplification pattern. EC8 site classes alone cannot fully explain the large variability in AF values observed within the same site class, particularly in the complex volcanic stratigraphic setting of the Etna region. Similarly, the aggregated lithological grouping provides a useful indication of the average amplification behaviour, but the large dispersion of AF values within individual classes shows that surface lithology at 1:100,000 scale alone cannot fully explain the observed site-response variability. This is especially evident for the effusive magmatic rocks (EMR), where different degrees of weathering, fracturing, lateral heterogeneity, and possible velocity inversions may produce markedly different amplification levels within the same broad lithological class.

Overall, the results highlight the effectiveness of a multi-method empirical strategy for characterizing site effects in complex volcanic environments. The amplification factors derived for the Mt. Etna area represent a reliable contribution for seismic microzonation enabling a robust empirical characterization of site amplification across the Mt. Etna region. The proposed empirical workflow is also replicable in other contexts, both volcanic and crustal, provided that sufficiently dense seismic datasets and a reliable reference site are available, allowing independent empirical approaches $\delta S2S$ and GIT to be compared and integrated into a unified set of amplification factors.

Future developments may focus on further improving both the physical interpretation and the predictive capability of the proposed approach. In particular, the integration of empirical amplification factors with detailed 3D geological and geophysical models of Mt. Etna would allow a better understanding of the role of complex stratigraphy, volcanic deposits, and lateral heterogeneities in controlling site response. Increasing the spatial resolution of the analysis, especially in urbanized areas, through high-density HVSR measurements, temporary stations and geophysical surveys, would further enhance the applicability of the results for advanced seismic microzonation.

Data availability statement. The data used in this study belong to the following networks: IV: Italian Seismic Network, doi:10.13127/sd/x0fxnh7qfy; IT: Italian Strong Motion Network, doi:10.7914/SN/IT; 1J: Seismic Network 2021/1J FocusX temporary land-network, doi:10.13127/sd/o5qwm6wjcd; 7C: Rete Sismica 2021/7C Urban Seismic Network, doi:10.13127/sd/o5nrhmp9n7; MZ(15): ETNA Microzonation Temporary Network, doi:10.7914/gmfh-g622.

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