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Identification of realistic geotechnical subsoil models from the integration of HVSR data and 2D site response analyses

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ABSTRACT: The seismic risk assessment should rely on the accurate prediction of the seismic site response of the area of interest, which is strictly related to the proper definition of the geotechnical subsoil model. Especially for natural slopes characterized by buried morphologies, for which the vertical and lateral heterogeneity of the subsoil setting may exacerbate the seismic site amplification, the identification of the geotechnical subsoil model may become challenging. Indeed, when dealing with not well-characterized sites, non-invasive and expeditive site investigations, such as seismic seismic ambient noise measurements and geophysical surveys, could be useful for a first interpretation of preliminary geotechnical subsoil models. Recently, a relatively simple and expeditive methodological procedure, based on the joint interpretation of non-invasive geophysical investigations and parametric 2D numerical analyses of the seismic site response, has been proposed to develop reliable geotechnical subsoil models. The paper illustrates an application of the procedure to identify the preliminary subsoil models of an area characterized by complex topography and subsoil conditions. The site studied is the Costa del Canneto slope (Ferrandina, Matera) in Southern Italy, characterized by uneven topography and complex subsoil setting, potentially including lithological bodies of uncertain morphology causing geological and geomechanical heterogeneity. The procedure proves to be a useful tool to reduce the uncertainties associated with the presence of complex subsoil settings, including potential buried morphologies. Indeed, among several hypothesized geotechnical models, only for few of them the numerical analyses provide amplification profiles of the fundamental frequency reasonably comparable with data from seismic ambient noise measurements, allowing to reduce the number of possible slope models. These findings can be adopted to guide the design of additional in-situ geotechnical investigations, needed to better characterize the stratigraphy of the area and constrain the geometry of the expected buried morphologies.

KEYWORDS: HVNSR measurements, 2D FE site response analyses, buried morphologies, complex topographic conditions.

1 INTRODUCTION

Within the broader context of seismic risk assessment, the accurate prediction of the dynamic response of natural slopes represents one of the fundamental aspects to be dealt with. This process critically relies on the accurate definition of the geotechnical subsoil model, which encompasses the morphology of stratigraphic contacts, the location of the seismic bedrock, the dynamic properties of the soils, and the succession of soil layers. A particular challenge arises when dealing with slopes characterized by buried morphologies, as their inherent vertical and lateral heterogeneities can predispose them to increased risks during seismic events.

In scenarios where the subsoil setting is not well-characterized, the adoption of non-invasive and expeditive site investigations has proven to be highly beneficial for the initial definition of preliminary geotechnical subsoil models (Falcone et al., 2025). This approach can enable a reduction in uncertainties and guide more detailed subsequent investigations. Among the various surface site tests available, the seismic ambient noise measurements analyzed through the Horizontal-to-Vertical Noise Spectral Ratio (HVNSR) technique have been extensively employed for diverse applications, including large-area seismic microzonation and local site conditions investigations (Giallini et al., 2024; Moscatelli et al., 2020). For instance, HVNSR measurements, often supported by geological data, have been utilized in microzonation studies to identify areas exhibiting similar seismic behavior during earthquakes without necessitating deep, site-specific investigations. These measurements have also been adopted as an effective tool for providing a preliminary interpretation of geological and geo-mechanical models by indicating the depth of the seismic bedrock and assisting the interpretation of the shear wave velocity profile at depth. Moreover, seismic ambient noise measurements have been widely adopted to highlight site effects induced by complex subsoil and topographic settings characterized by stratigraphic heterogeneity. Beyond simply identifying resonance frequencies, HVNSR data can also be leveraged to study the directivity of ground motion induced by either uneven topography or buried morphologies, such as sediment-filled valleys or sliding bodies composed of softer soils. Several studies have demonstrated their utility in identifying the shape of buried valleys and abrupt changes in seismic impedance related to landslide boundaries (Sgattoni & Castellaro, 2020). In other cases, seismic ambient noise measurements have been combined with other geophysical tests to characterize landslide-prone areas (Calamita et al., 2019, 2023).

Several scientific investigations have underlined the importance of integrating information from seismic ambient noise measurements, geophysical surveys, and site response analyses for the construction of reliable soil deposit models, especially those with high impedance contrasts. Based on a parametric numerical investigation of ideal slope models, Falcone et al. (2023) have demonstrated that the presence of a shear band confining a landslide body, or more generally, a subsoil buried morphology, represents an impedance contrast that strongly affects the seismic response. This influence has been observed not only in terms of resonance frequency, but mainly in terms of seismic amplification patterns along the ground surface. Inspired by these numerical findings on ideal cases, Falcone et al (2025) proposes a relatively simple and expeditive methodological procedure to develop reliable geotechnical subsoil models, through the joint interpretation of non-invasive geophysical investigations and parametric two dimensional (2D) numerical analyses of the seismic site response.

In this paper, the proposed procedure has been adopted to identify a plausible geotechnical subsoil model of a prototype area, the Costa del Canneto slope in Southern Italy, which is characterized by uneven topography and a complex subsoil setting, potentially including lithological bodies causing geological and geomechanical heterogeneity. The proposed procedure serves as a foundation for a cost-effective and less invasive approach to design in-depth site investigations specifically tailored for the targeted area. More broadly, the outcomes of this research offer engineers, planners, and decision-makers valuable tools and guidelines to reduce uncertainties in the geotechnical and geomorphological assessment of slopes with complex subsurface settings, including potential buried morphologies.

2 METHODOLOGY

Figure 1 provides a structured overview of the methodological procedure proposed by Falcone et al. (2025) for developing reliable geotechnical subsoil models for slopes, particularly those characterized by complex settings and potential buried morphologies.

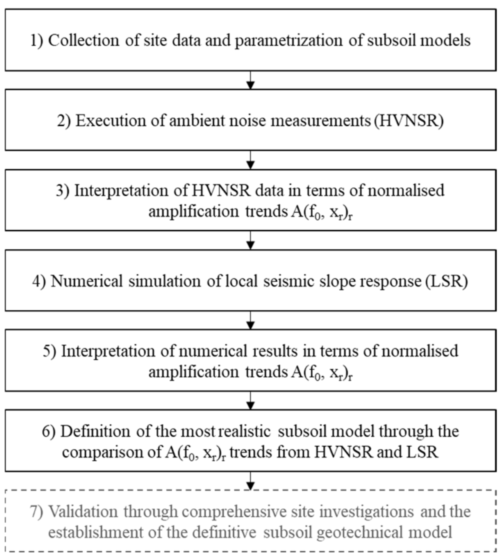

Figure 1. Simplified workflow for subsoil model definition (modified after Falcone et al, 2025).

The workflow outlines a systematic approach that integrates field measurements with numerical simulations. It is structured into six primary stages, culminating in a critical validation phase:

1. <u>Collection of site data and parametrization of subsoil models.</u> This initial and fundamental step consists in gathering all available geological, geomorphological, and geotechnical information from historical archives and literature. This data is then used to hypothesize preliminary subsoil models, which may include vertical and lateral heterogeneities, and possibly buried morphologies.
2. <u>Campaign of seismic ambient noise measurements</u>. This stage involves conducting non-invasive single-station seismic seismic ambient noise measurements analyzed using the Horizontal-to-Vertical Noise Spectral Ratio (HVNSR) technique. These measurements provide crucial in-situ data about the dynamic response of the site.
3. <u>Interpretation of HVNSR data in terms of normalized amplification trends $A(f_0, x_r)_r$</u>. The recorded HVNSR data are processed and interpreted in terms of $A(f_0, x_r)_r$, which represents the amplitude value at the fundamental frequency f_0 for a given location x_r along the slope, i.e., $A(f_0, x_r)$, normalized by the maximum amplitude value observed along the slope area, i.e., max[$A(f_0)$].
4. <u>Numerical simulation of local seismic slope response (LSR)</u>. This step consists in performing dynamic simulations of the slope seismic response using numerical methods, such as Finite Element Method (FEM), with reference to a set of plausible subsoil models and adopting weak input motions.
5. <u>Interpretation of LSR numerical results in terms of normalized amplification trends $A(f_0, x_r)_r$</u>. The numerical outputs are processed to derive the normalized amplification trends, to be compared to those obtained from HVNSR data.
6. <u>Definition of the most realistic subsoil model through the comparison of $A(f_0, x_r)_r$ trends from HVNSR and LSR</u>. This is a pivotal stage where the normalized amplification trends derived from HVNSR measurements are directly compared with those from the LSR numerical simulations. The goal is to identify the subsoil models that provide the best agreement between the field data and the numerical predictions, thus representing the most realistic subsoil configuration.

The final step 7 "Validation through comprehensive site investigations and the establishment of the definitive subsoil geotechnical model" condenses the iterative and fundamental validation process of the proposed methodology (Falcone et al., 2025), consisting in verifying and refine the subsoil model, once a set of plausible subsoil models is identified. This process implies the design and the execution of new, in-depth site-specific investigations, in order to assess the reliability of the preliminary subsoil model(s) or to modify it (them). The entire process should be repeated iteratively, adjusting the subsoil model parametrization, until the numerical results consistently achieve the best possible fit with the HVNSR data, and the interpretation of the new site investigations constrains the updated model.

The proposed approach has been applied up to Stage 6 for the selected case study, and the identified models can now guide site-specific investigations to validate or confute the assumed subsoil models.

3 CASE STUDY

3.1 *Geology and geomorphology of the prototype slope*

The Costa del Canneto slope is situated in the Basilicata Region of Southern Italy (Figure 2a), specifically within the Bradanic Foredeep. The area is characterized by steep slopes with ground surface inclinations often exceeding 50%, making it susceptible to both seismic topographic amplification and slope failures. Geomorphological features indicate the plausible presence of buried morphologies due to past and present landslide phenomena.

From a geological perspective, the area primarily features outcropping formations of yellow clay, blue-grey clay, and alluvial deposits of the Basento River. The sedimentary sequence in the upper part consists of middle-low Pleistocene open-shelf muddy deposits, commonly known as Sub-Apennine Clays, referred to in the paper as blue-grey clays. These blue-grey clays can reach thicknesses of about 500 m and may be interlayered with very thin sand strata. The shallowest part of the blue-grey clays, typically 20-30 m thick, is composed of yellow clays, which are the result of weathering or alteration processes. In the Basento valley, an alluvial layer, consisting of sands, silty sands, and coastal conglomerates, with a maximum thickness of 90 m, overlies the blue-grey clay layer.

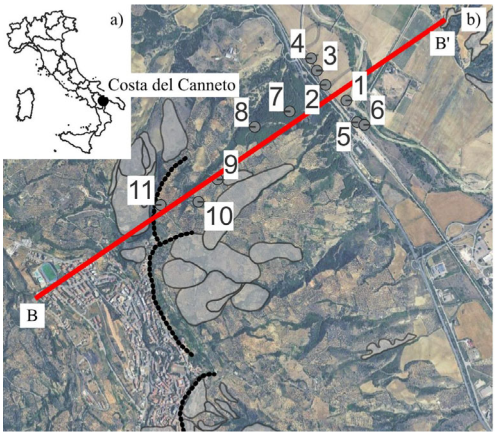

Figure 2. a) Location of Costa del Canneto and b) in-situ investigations and landslide features overlaid on Google earth photo.

The geological and geomorphological analyses, largely based on the available literature (due to a lack of direct geognostic investigations in this specific area) revealed the presence of deep slope instability phenomena. Landslides identified from the IFFI (2023) Italian catalogue (see grey areas in Figure 2b) and a geomorphological reconstruction by Melidoro et al. (1996) are mapped in the area. Historical investigations by Cotecchia (1985) for a nearby railway line also identified potential sliding bodies composed of remolded clays, with maximum depths of sliding surfaces between 30 and 80 m on the left side of the Basento River valley. Melidoro et al. (1996) suggested a deeper sliding body (over 100 m deep) for the area of interest on the right side of the valley. Crowns of these landslides are sketched with black dashed lines in Figure 2b. These findings strongly support the presence of buried morphologies, which serve as a starting point for the parametric analyses performed in the study. The site complex topographic conditions and subsoil settings make it a representative case study for the proposed methodological approach. Electrical resistivity tomography (ERT) data and HVNSR measurements further support the interpretation of complex subsurface lithological bodies and vertical discontinuities (for further details, see Falcone et al., 2025), suggesting less compact material overlying stiffer soil, consistent with the presence of remolded clays and buried features.

This detailed characterization of geological and geomorphological settings, though derived from existing literature and non-invasive surveys, is crucial for developing plausible geotechnical subsoil models that account for the observed heterogeneities and potential buried structures.

3.2 *Geotechnical properties*

The geotechnical characterization of the Costa del Canneto slope has been focused on defining the dynamic properties of the encountered soils (i.e., blue-grey clay, yellow clay and remolded clay within the soil body). Since site-specific dynamic data were scarce, the dynamic behavior of these clays at very low shear strains has been assumed to be similar to that of Montemesola clay (Cafaro and Cotecchia, 2001), whose initial shear stiffness modulus (G_0) profile may be described by the empirical relationship (Eq. 1) modified after Cafaro and Cotecchia (2001):

$$\begin{cases} G_0(z) = A^* \cdot p'^{n^*} \cdot R_0^{m^*} \\ A^* = 10^{a \cdot e^{\mathrm{Log}(S_\sigma) \cdot b}} \end{cases} \qquad (1)$$

This relationship, rooted in concepts from Viggiani and Atkinson (1995), allowed for the estimation of G_0 as a function of various soil parameters.

In this study, the coefficients *a* and *b* have been assumed equal to 3.0969 and 0.1834, respectively, according to what suggested by Falcone et al. (2025); m^* and n^* have been set equal to 0.225 and 0.78, respectively, based on the correlation with plasticity index (PI) provided by Viggiani and Atkinson (1995) for PI = 26%. R_0 and S_σ are the overconsolidation ratio and the stress sensitivity, respectively, assumed equal to 1.5 and 2.5 for Soil_2 (Figure 3a) and both equal to 1 for Soil_3 (Figure 3b), this latter representative of a normally consolidated reconstituted soil. It is worth noting that since no in-depth data were available for this case study, these two V_S profiles represent a sounding attempt to account for soil heterogeneity in the parametrization of the numerical models.

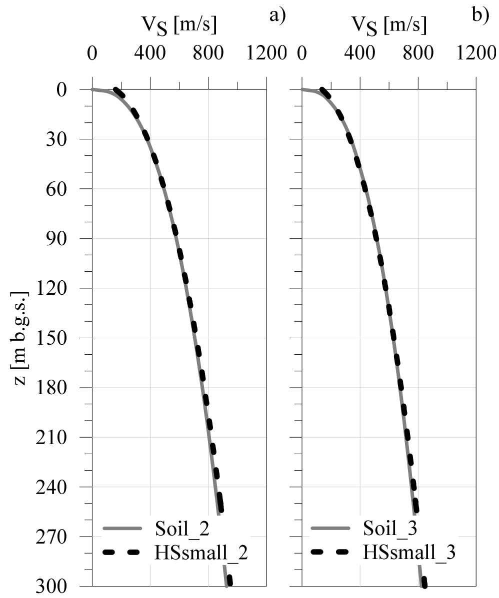

Figure 3. Reference $V_S(z)$ profiles compared with those predicted by the HSsmall model for a) Soil_2 and b) Soil_3.

3.3 *Geophysical data*

Figure 4 shows the plan view of the section BB' with the location of the single-station seismic ambient noise measurements, along with the geological section proposed by Melidoro et al. (1996), including the presence of a buried morphology. Moreover, panel c) to h) displays the HVNSR elaborated curves corresponding to each single-station measurement. It should be noted that the fundamental frequency (f_0), approximately equal to 0.22 Hz, is almost constant along the slope. Furthermore, the largest amplitude value at f_0 is gained at the middle of the slope (HVNSR #8, likely corresponding to the center of the landslide area according to the subsoil model provided by Melidoro and co-authors) rather than at the crest, as would be expected in the presence of purely topographic amplification (Bouckovalas & Papadimitriou, 2005; di Lernia et al., 2024; Falcone et al., 2023).

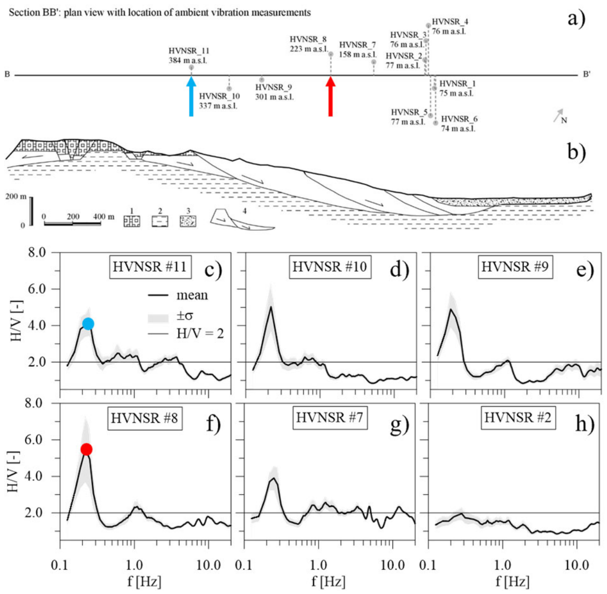

Figure 4. Section BB': a) plan view showing the location of the single-station seismic ambient noise measurements; b) geological section proposed by Melidoro et al. (1996); c-h) the HVNSR elaborated curves corresponding to the single-station measurement. In panel b): 1) conglomerates and sands, 2) clay, 3) alluvium, and 4) soil body.

3.4 *Numerical models*

Based on the observations derived from the first two stages, the plausible numerical subsoil models have been constructed, as synthetized in Figure 5. Specifically, the 4 numerical models considered in this study are:

- Model #0, characterized by a simplified topography and outcropping seismic bedrock;
- Model #6, upgrading the previous model by implementing the real topography;
- Model #10, which includes both a vertical heterogeneity (i.e. two layered subsoil), and a buried morphology, with each soil layer having a constant V_S with depth;
- Model #13, which is characterized by a two-layered subsoil and a buried morphology and incorporates the variation of V_S with depth within each soft layer.

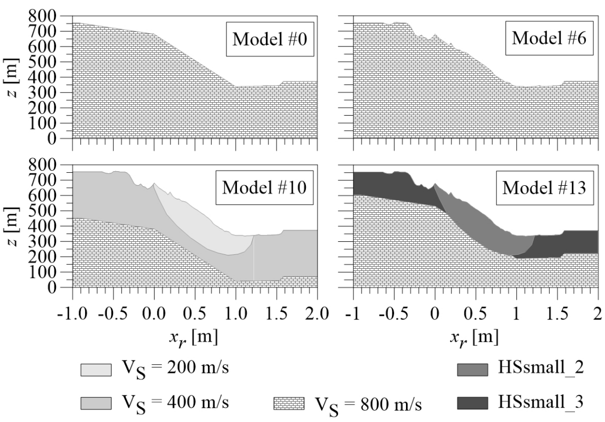

Figure 5. Geotechnical models implemented in the FE simulations.

The seismic bedrock has been assumed to behave as a linear visco-elastic material, characterized by $V_S = 800$ m/s and damping ratio (D) of 0.1%. Rayleigh damping has been implemented for all materials, with the target damping specified for each material and controlling frequencies set at 0.1 Hz and 1.0 Hz. Furthermore, the linear visco-elastic constitutive model has been employed for the materials in Models #0, #6, and #10, while the elasto-plastic hysteretic model HSsmall (Benz et al., 2009; Schanz et al., 1999), has been adopted in FE model #13 for the soil in the buried morphology (HSsmall_2) and the outcropping soil overlying the seismic bedrock (HSsmall_3).

The HSsmall model is capable of predicting the nonlinear cyclic soil response and accounts for the depth-dependent initial shear stiffness via Equation (2).

$$G_0(z) = G_0^{ref} \cdot \left(\frac{c' \cos\varphi' - \sigma_3' \sin\varphi'}{c' \cos\varphi' + p^{ref} \sin\varphi'} \right)^m \tag{2}$$

G_0^{ref} denotes the reference shear modulus at very small strains, c' represents the effective cohesion, φ' is the effective friction angle, p^{ref} is the reference stress for stiffness (equal to 100kPa), σ'_3 is the lowest principle effective stress, and m is the power parameter for the stress-level dependency of stiffness.

The HSsmall model parameters have been calibrated based on the V_S profile assumed for Soil_2 and Soil_3 (Figure 3). Rayleigh damping has also been implemented for HSsmall materials to account for damping at very low strain levels, where HSsmall is characterized by zero damping. A summary of the material properties and the constitutive model parameters is reported in Table 1.

Table 1. Material properties and HSsmall parameters

Parameter	Description	HSsmall_2	HSsmall_3
γ	Unit weight (kN/m^3)	20	20
c'	Cohesion (kPa)	5	5
φ'	Friction angle (°)	22	22
G_0^{ref}	Reference shear modulus (MPa)	97.1	73.4
m	Power for the stress-level dependency of stiffness	0.86	0.86
ν_{ur}	Poisson's ratio	0.2	0.2

Dynamic boundary conditions (Falcone et al., 2025) have been implemented by establishing free-field boundaries along the vertical sides of the finite element models, complemented by fixed vertical displacements. At the base of the mesh, a compliant boundary (i.e., an absorbing boundary) has been imposed to emulate wave dissipation into the deeper soil layers, ensuring minimal reflection at the lower boundary. This compliant base approach has involved applying only the upward-propagating component of the reference signal at the FE model's base. Consequently, the input signal has undergone conversion by the FE code into a shear stress time history. Additionally, the lateral extension of the FE meshes has been set to five times the height of the model. This configuration has been chosen to mitigate any potential interference from the vertical boundaries with the slope area. To guarantee numerical accuracy, the coarseness of the FE mesh has been optimized. This has involved ensuring a distance between two consecutive nodes that is smaller than approximately one-eighth of the wavelength associated with the maximum frequency content (f_{max}) of the input wave. For this specific case study, f_{max} has been selected as 1 Hz. Prior to initiating the dynamic phase, a gravity loading procedure has been implemented to establish the initial stress state within the FE slope models.

3.5 *Input motion*

All numerical simulations have been carried out using a simple Ricker pulse, Equation (3), as the reference outcrop signal, with a maximum acceleration of 0.01g (Figure 6). A central frequency (f_c) of 0.4 Hz has been chosen to produce broadband energy within the 0.2-0.6 Hz frequency range, which is consistent with the fundamental frequencies of the subsoil in the area of interest (i.e., 0.19-0.25 Hz as shown in Figure 4).

$$a(t) = (1 - 2 \cdot \pi^2 \cdot f_c^2 \cdot t^2) \cdot exp(-\pi^2 \cdot f_c^2 \cdot t^2) \qquad (3)$$

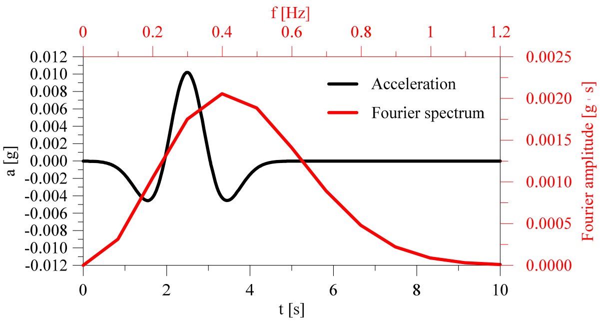

Figure 6. Ricker reference signal.

4 RESULTS

The comparison between the normalized amplification trends, $A(f_0, x_r)_r$, derived from in-situ Horizontal-to-Vertical Noise Spectral Ratio (HVNSR) measurements and those obtained from two-dimensional (2D) finite element (FE) numerical simulations for various subsoil models is illustrated in Figure 7. This figure is crucial for discerning which geotechnical subsoil configurations represent most realistically the Costa del Canneto slope.

The $A(f_0, x_r)_r$ trends predicted by numerical simulations and in-situ data are shown in Figure 7a. Firstly, a comparative analysis between Model #0 (characterized by a simplified topography and outcropping seismic bedrock everywhere) and Model #6 (implementing the real topography while still assuming an outcropping seismic bedrock everywhere) has been performed to highlight the isolated effect of topography on the seismic response. The $A(f_0, x_r)_r$ trend for Model #6 appears more consistent with the HVNSR results than the trend for Model #0, suggesting an influence of the topography on surface site response. However, despite potentially yielding to comparable $A(f_0, x_r)_r$ trends with HVNSR data, these models cannot be accepted as plausible subsoil representations, since the geological evidence clearly indicates that the seismic bedrock is not outcropping at the ground surface in the area of interest.

The effect of the buried morphology is introduced through Model #10, for which the $A(f_0, x_r)_r$ trend notably shows a peak located approximately at the center of the buried valley. This observed amplification pattern could indicate the presence of a landslide body, which is typically characterized by reduced V_S compared to the surrounding and underlying material. However, this model totally misses the slope response for $x_r < 0.3$. Finally, the more sophisticated Model #13, incorporating minor stratigraphic modifications and crucially accounting for the variation of V_S with depth for each considered soil layer, provides an $A(f_0, x_r)_r$ trend more qualitatively similar to the HVNSR data. Specifically, it exhibits a local peak around $x_r = 0.2$, an absolute peak near $x_r = 0.6$, and a subsequent decreasing trend for $x_r > 0.6$.

To quantitatively assess the similarity between the numerical and experimental results, the error ($\varepsilon_{A(f0,\,xr)r}$) has been calculated according to Equation (4):

$$\varepsilon_{A(f_0)_r} = \left| \frac{A(f_0)_{r\_HVSR} - A(f_0)_{r\_FEM}}{A(f_0)_{r\_HVSR}} \right| \qquad (4)$$

In this equation, $A(f_0, x_r)_{r\_HVNSR}$ represents the normalized amplitude at the fundamental frequency derived from HVNSRs, while $A(f_0, x_r)_{r\_FEM}$ denotes the corresponding value obtained from FE simulations. This error metric provides a direct measure of the deviation of the numerical prediction from the experimental data. Figure 7b, representing the scatter plot of $A(f_0, x_r)_r$ and the median values of the error distribution, shows that among the models exhibiting satisfactory agreement (i.e., those with error below 15%), Model #13 yields a quantitatively significant comparison. In fact, the median value of the error distribution, $\varepsilon_{A(f0)r}$, equal to 5.7%, is the lowest one. This strong quantitative agreement further reinforces the potentiality of Model #13 to be a realistic representation of the subsoil conditions, especially given its ability to both qualitatively and quantitatively capture the observed amplification patterns.

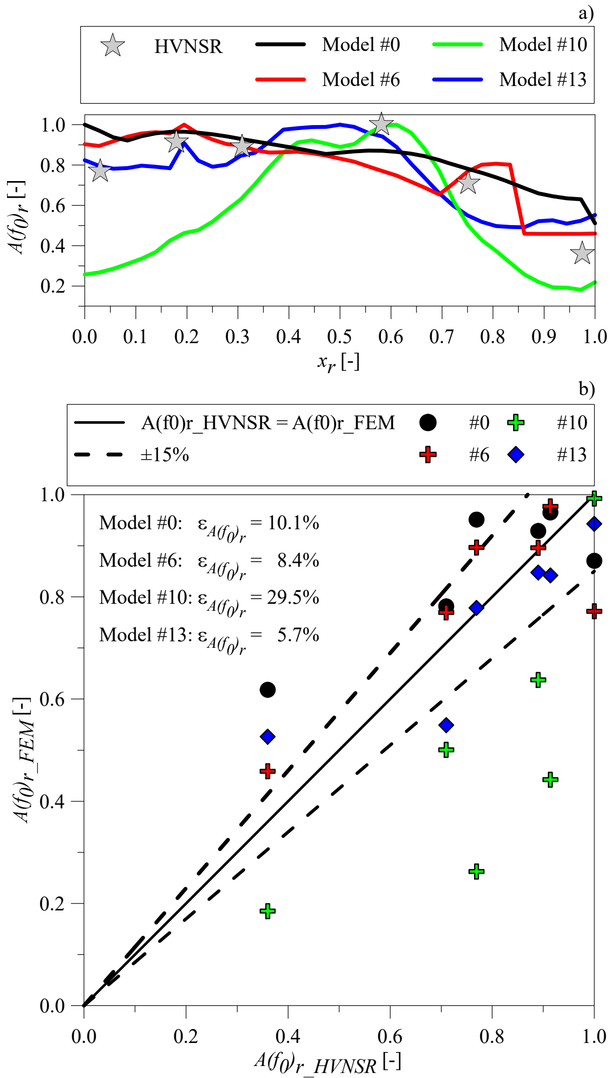

Figure 7. Comparison of HVNSR and numerical results: a) $A(f_0, x_r)_r$ trends and b) $A(f_0, x_r)_r$ scatter plot. The median values (briefly $\varepsilon_{A(f0)r}$) of the error distribution for each model are also displayed in panel b).

5 CONCLUSIONS

This paper presents an application of the novel methodological procedure for the identification of preliminary subsoil models, based on joint integration of HVNSR functions obtained from seismic ambient noise measurements and two-dimensional (2D) numerical analyses of the seismic site response of slopes. The approach has been conceived for the characterization of slope areas exhibiting uneven topography and complex subsoil conditions, including those with buried lithological bodies of uncertain morphology, particularly where direct geological and geotechnical data are scarce. In such scenarios, conventional deep site surveys, laboratory testing, and extensive in-situ monitoring, typically required for comprehensive subsoil characterization, can be prohibitively expensive.

The methodological approach has been applied to the prototype Costa del Canneto slope, resulting to be instrumental in demonstrating its utility. Through an iterative parametrization process the initial range of possible geotechnical subsoil models has been provided. It has been observed that the most credible model, in terms of normalized amplification profiles along the slope, includes both a buried morphology and the variation of shear wave velocity with depth. However, a conclusive definition of the actual subsoil setting of the investigated area cannot be derived solely from the performed analyses. A critical point of the current study is the acknowledged absence of deep in-situ investigations specifically executed to validate the proposed subsoil model. Therefore, the identified plausible model requires further confirmation through additional, properly designed, in-depth site investigations. Such future investigations, which could include continuous coring boreholes, inclinometers, and down-hole tests, are strongly recommended to reach depths of at least 100 m consistent with the buried morphology implemented in the most reliable model. Their primary aim would be to better constrain the lateral and vertical variation of soil mechanical properties within the deposit and to investigate the precise shape of any possible buried morphology.

The proposed methodology offers significant potential as a cost-effective and less invasive tool to reduce uncertainties inherent in the geological, geomorphological, and geotechnical characterization of such areas, thereby guiding the design of more focused in-depth site investigations. A paramount strength of this procedure lies in its capability to incorporate potential buried morphologies within 2D numerical models of slope areas.

As a crucial future development, the methodology could be extended to consider 3D models. Incorporating 3D numerical schemes in future analyses would allow for an even more comprehensive understanding of wave propagation, with results consistently extracted in terms of normalized amplification profiles. This would help in addressing potential disagreements between measured and predicted data that might arise from three-dimensionality in seismic wave propagation, particularly related to complex topographic and subsoil conditions. Ultimately, this procedure serves as a powerful tool to guide engineers toward designing targeted, in-depth site investigations for areas with complex subsoil conditions, leading to the establishment of definitive geotechnical models.

6 ACKNOWLEDGEMENTS

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