



# Soil-building resonance effect in the urban area of Villa d'Agri (Southern Italy)

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## Abstract

This study aims to evaluate the possible occurrence during seismic shaking of interaction effects between the shallow subsoil and the overlying buildings of the Villa d'Agri town (Southern Italy). From the geological and building heritage points of view, the investigated area represents a typical town along the Apennines chain and therefore the obtained results could be easily exported to similar urban areas. A total of 239 single-station seismic ambient noise measurements were thus performed, 154 on the urban soils and 85 within buildings. Both subsets of measurements were planned to cover the main outcropping lithologies and building typologies. By means of the Horizontal-to-Vertical Noise Spectral Ratio technique, isofrequency and isoamplitude maps have been reconstructed for the whole area. The results evaluated on the 65 tested buildings allowed to infer the empirical relationship between the first vibrational period,  $T(s)$ , and their height,  $H(m)$ . Using this relationship and available information on the height of each building, the first vibrational frequency was estimated for 659 buildings belonging to the urban area of Villa d'Agri. Finally, in order to assess the possible occurrence of the double resonance phenomenon, we compared the main frequency of each building with that interpolated for the underlying foundation soil. The results show that the probability of being affected by the double resonance effect is very high only for a couple of buildings, high for about 16% of the buildings, moderate for the 23% and practically null for most buildings (60%).

**Keywords** Soil-building interaction · HVNSR · First vibrational frequency · Resonance effect

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## 1 Introduction

About 60% of Italian citizens live in small and medium-sized towns of inestimable historical and architectural value highly exposed to catastrophic events (e.g., earthquakes, landslides, volcanic eruptions, etc.) and extreme climatic events. Site seismic amplification and soil-foundation-structure interaction effects are among the most important effects that can cause increased damage following an earthquake. For seismic risk mitigation, having information on urban soils and structural characteristics for a large number of buildings, is crucial to investigate the influence of each parameter on the building dynamic response (i.e. the fundamental frequency of the building-soil system) and subsequent damage caused by earthquakes. This aspect is of particular interest for Italy, where historical masonry buildings have suffered substantial damage in the last decades (e.g., Valensise et al. 2017; Sextos et al. 2018; Sorrentino et al. 2019; Penna et al. 2022). So far, most studies were devoted to evaluating the dynamic behavior of individual buildings, without extending the results to assess the behavior of the overall built environment. Some studies have focused on evaluating the dynamic behavior of a selected masonry building and the interaction with its foundation soil (Piro et al. 2019). Recent works showed that the correct estimation of fundamental vibrational periods for different building typologies can support the near real-time seismic damage assessment (e.g., Scaini et al. 2021). At present, urban ground motion and building response are evaluated separately and treated as independent; in Italy there are in force two legislative tools for seismic risk mitigation: the National Seismic Code (NTC 2018) and the Guidelines for Seismic Microzonation (GSM; MS working group 2015). Thanks to microzonation studies, it is possible to know the area susceptible to seismic amplification (seismotectonic, litho-stratigraphical and geotechnical aspects of shallow soils) and instabilities (landslides, rockfalls, liquefaction, etc.); however, there is no information about city areas where the soil-building interaction effect could take place thus increasing the damage during earthquakes. Several studies (Ganev et al. 1995; Mucciarelli and Monachesi 1998; Castro et al. 1998, 2000; Gallipoli et al. 2004; Mucciarelli et al. 2004; Gallipoli et al. 2006; Mucciarelli et al. 2011; Castellaro et al. 2012; Ditommaso et al. 2013; Petrovic et al. 2018; Varone et al. 2019) support the hypothesis that the soil-building resonance phenomenon can produce a significant damage increase on buildings during earthquakes; whenever the main vibration frequency of a building is very close to that of the underlying soil, the soil-building resonance phenomenon is triggered. During seismic events, when the interaction involves the entire built environment and shallow urban soils, then it is called site-city interaction. Up to now the site-city interaction effect has been evaluated through numerical simulation approaches (e.g., Kham et al. 2006; Ghergu and Ionescu 2009; Padrón et al. 2009; Schwan et al. 2016). Recently, Agea-Medina et al. (2020) evaluated the probability of resonance effect in several districts of the Alicante and Elche municipalities, while Pinzón et al. (2019) and Tallini et al. (2020) and have produced soil-building resonance level maps based on numerical relations provided by seismic regulations, and Gallipoli et al. (2020) and Tragni et al. (2021) by an extensive collection of experimental data on urban soils and buildings.

Bearing in mind this research perspective, the built environment of the town of Villa d'Agri has been characterised by considering the main characteristics of the urban soils, overlaying buildings and their mutual interactions according a holistic approach, that is, considering the built environment as a whole soil-building system. This approach was developed and applied for the first time to the city of Matera (Gallipoli et al. 2020), and we propose to validate it in the town of Villa d'Agri since it has a different urban structure than

Matera and Villa d'Agri is representative (in terms of geological-geotechnical settings, seismic hazard context and the building heritage) of many urban centers located in the Apennines mountain chain. Indeed, historical centers are typically located on top of morphological reliefs commonly located on outcropping bedrock, urban sprawl areas frequently expand on nearby poorly consolidated alluvial and/or colluvial deposits. Accordingly, the principal aim of this study was to evaluate the possible occurrence of the double resonance phenomenon between the first vibrational frequency of all buildings and the underlying urban soil for the whole town of Villa d'Agri based on an experimental approach. Therefore, we performed 239 single-station seismic ambient noise measurements, 154 on the urban soil and 85 inside selected buildings, trying to regularly and entirely cover the investigated area and to sample the different geological settings in terms of outcropping lithology, shallow sedimentary thickness and stratigraphy as well as geotechnical characteristics. Also for the measurements inside the buildings, we firstly classified them in terms of (1) built typology, (2) year of construction, (3) number of floors and (4) foundation soil, and then selected some of them as representative of each recognized class.

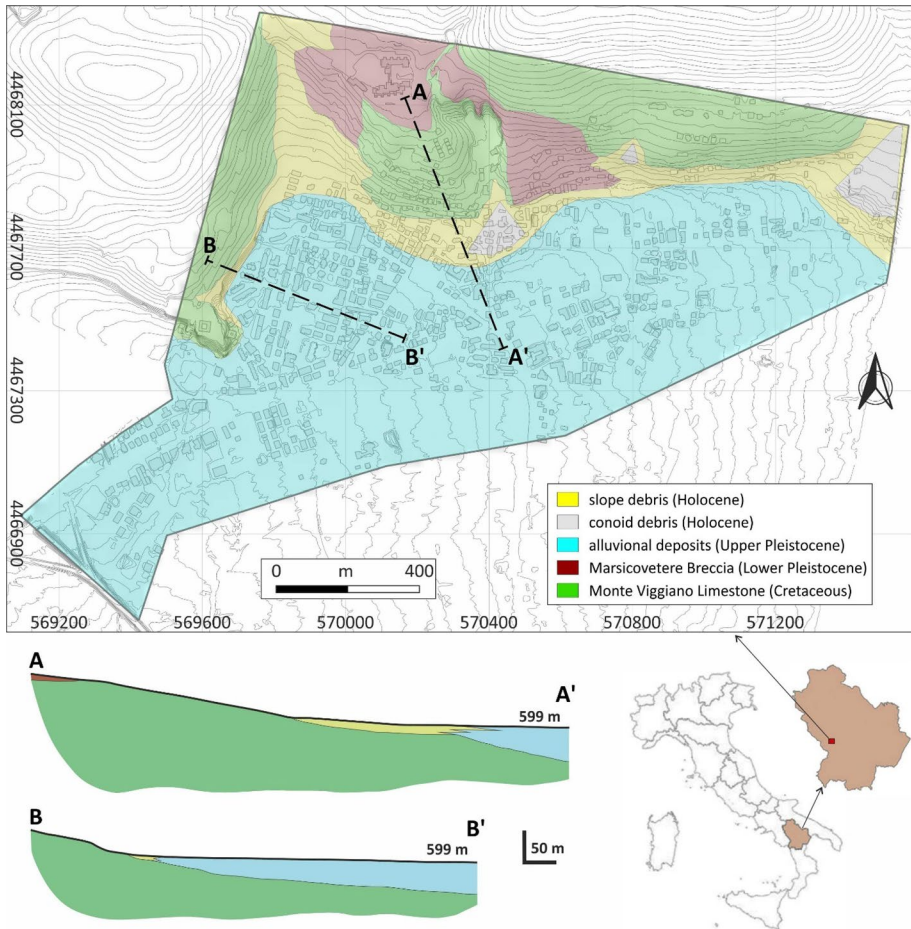
The implementation and interpretation of the isofrequency map of the whole urban soils has been made possible by both the large seismic survey carried out during the present research and the availability of data from previous studies, i.e. the detailed geological map and a large number of geophysical and geotechnical tests. Furthermore, the 85 recordings acquired inside the main building typologies allowed to estimate a relationship between the first vibrational period  $T$ (s) and the corresponding height  $H$ (m) in the form  $T = a * H$ . By using this empirical relationship and knowing the height of each building, it has been possible to infer the first vibrational frequency of the 659 buildings of the town of Villa d'Agri. Finally, by comparing the frequencies of these buildings with the interpolated frequency of the underlying soil, it was possible to classify the urban area according to different levels of probability of occurrence of soil-building resonance effect in elastic domain.

## 2 Data and Methods

### 2.1 Geological and geotechnical settings

The Villa d'Agri town is located in the upper reach of the Agri Valley representing a NW–SE trending intermontane basin (Fig. 1), which mainly developed during Quaternary draining a large sector of the Southern Apennines. The tectonic framework of the area is represented by a NE-vergence fold-and-thrust system developed between Early Miocene (D'Argenio et al. 1973) and Early Pleistocene (Carbone et al. 1991; Cinque et al. 1993). The terrains involved in the orogenic deformation are generally Mesozoic in age belonging to the Lagonegro units and the Campania-Lucania platform (Scandone 1967). In the eastern sector of the high Agri Valley, the Mesozoic bedrock is covered by the Miocene flysch deposits of the Gorgoglione and Albidona formations.

The high Agri Valley is affected and bounded by several post-orogenic faults striking WNW–ESE. The occurrence of loose slope deposits and palaeosols deformed during the last 40 ka (Giano et al. 2000; D'Addezio et al. 2006) clearly document a persistent latest Quaternary seismogenic activity. The High Agri Valley is a tectonically active area characterized by high seismic hazard related to fault systems capable of generating up to  $M=7$  earthquakes (i.e. the 1857  $M_w=7$  Basilicata earthquake; Rovida et al. 2019). Based on the



**Fig. 1** Geological map of the investigated area and representative geological sections. The built environment is represented by the gray polygons in the map

reconstructed macroseismic field, the estimated equivalent magnitude was ca. 7.0 (Gasparini et al. 1999). In particular, this sector of the valley was characterized by intensities up to X MCS (Guidoboni et al. 2007). In addition to the natural seismicity, the water loading and unloading operations in the Pertusillo artificial reservoir (the largest in Southern Italy) and the wastewater disposal at the Costa Molina 2 injection well cause two different and well recognized clusters of induced microseismicity (Stabile et al. 2020).

The town of Villa d'Agri is developed at the northeastern border of the Agri Valley at ca. 600 m asl. Some of the buildings in the northern sector of the town stand on the lower slope of the nearby relief, but most of the urbanized area is developed on a low-dipping to almost horizontal flat surface in correspondence of some alluvial cones associated with lateral tributaries and a major fluvial terrace. The latter surface is part of a staircase system of fluvial terraces characterizing the whole high Agri Valley and developed as a consequence of alternating periods of low-stand and high-stand water level of the palaeo-Pertusillo Lake (Bianca and Caputo 2003). Such hydraulic variations were induced by both Quaternary

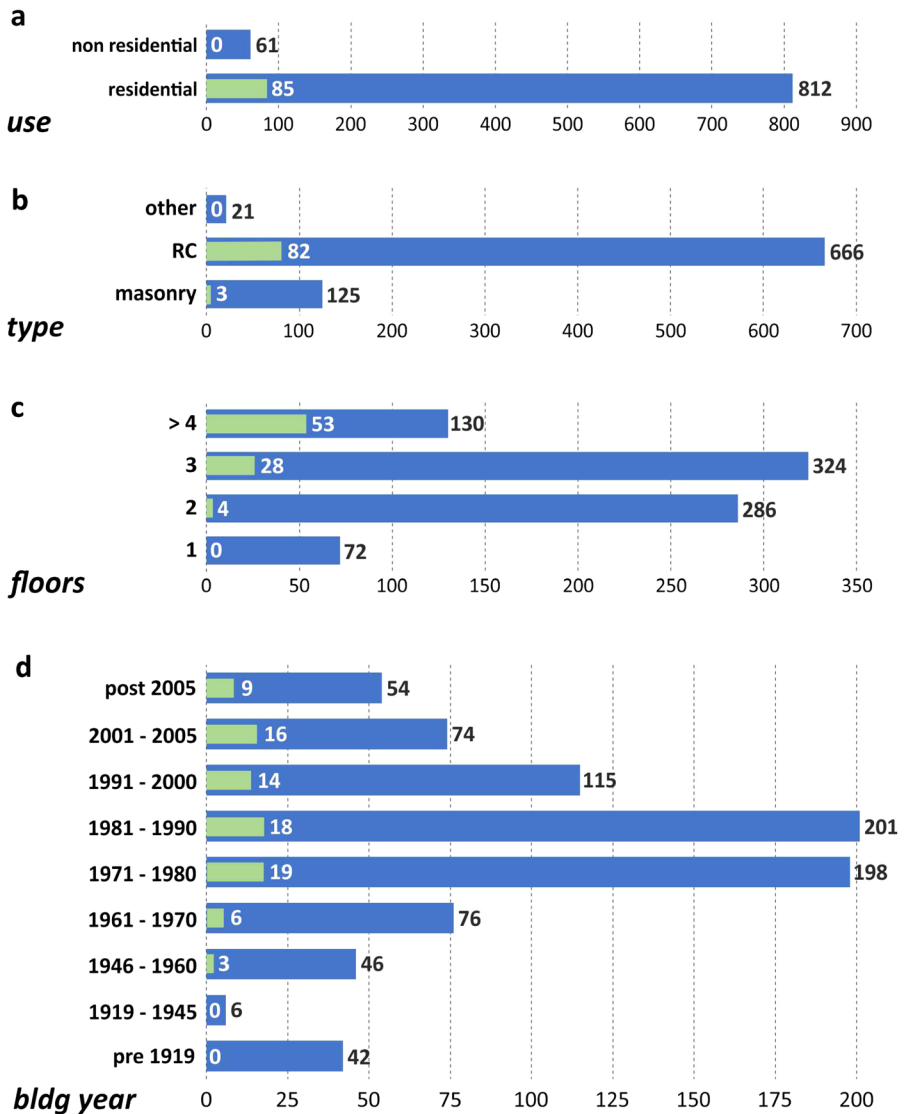
climatic oscillations and the activity of the Armento Thrust and its associated anticline with the consequent damming effect on the drainage. Accordingly, depositional phases of lake infilling were alternating to entrenching ones.

Relative to the Villa d'Agri area, the Mesozoic carbonate bedrock (Monte Viggiano Limestone; Fig. 1) consists of limestone, marly limestone and layered oolitic limestone. This formation mainly crops out on top of the northern reliefs and the higher portions of the slopes. These rocks commonly appear densely fractured and are often reduced to real fault breccias. The Cretaceous limestones are mainly covered by Quaternary units. In the higher part of the reliefs, these deposits are represented by some remnants of Lower-Middle Pleistocene well cemented slope breccias (Marsicovetere Breccia, Fig. 1), which clearly document an older largely eroded palaeosurface. On the other hand, especially on the foot of the slopes, poorly consolidated Upper Pleistocene sedimentary breccias occur characterized by 5 to 20 m of thickness. Only locally these deposits are covered by Holocene scree material up to 20 m-thick. As above mentioned, a large part of the urban area stands on an almost flat surface lithologically corresponding to the top of the terraced Upper Pleistocene alluvial deposits of the high Agri Valley, belonging to the fluvial terrace III-a of Bianca and Caputo (2003). Within the investigated area, their thickness varies from 0 up to 90 m moving away from the reliefs towards the present-day alluvial plain (Fig. 1).

Based on several geognostic surveys (cores, penetrometric tests, seismic refraction profiles, Multichannel Analysis of Surface Waves, seismic downholes and Horizontal-to-Vertical Noise Spectral Ratios surveys carried out in microzonation study of Villa d'Agri), it was possible to characterize the shallow subsoil from a geotechnical point of view (Tamburriello and Lizza 2012). In particular, the Mesozoic bedrock is characterized by seismic velocities,  $V_{s30}$ , ranging between 500 and 700 m/s depending on the local degree of fracturing. Similar values have been also obtained for Breccie di Marsicovetere (650 m/s). In contrast and as a consequence of the lower degree of cohesion and cementation, the shear wave velocity of the Upper Pleistocene slope deposits is around 450 m/s, while in the alluvial deposits it ranges between 250 and 400 m/s (Figure 6).

## 2.2 The built environment

The General Population and Housing Census (Italian National Institute of Statistics, ISTAT 2011) reports a number of 873 buildings for Villa d'Agri town (Fig. 2, blue bars). Most of them (812) are residential, the others (61) are strategic buildings susceptible to crowding such as the hospital, schools, fire and law enforcement barracks, social centers and commercial buildings. For the 812 residential buildings, ISTAT provides other types of information such as: built typology, number of floors and year of construction (Fig. 2b–d). Relative to the masonry buildings most of them were built before the 1960s and are mainly distributed in the northern sector and along the main road that crosses the valley and climbs towards the historic center of Marsicovetere. Conversely, the buildings made in reinforced concrete moment-resistant frame (666) with two or more floors are distributed in a homogeneous way in the residential area. Most of the buildings with three floors (40%), as well as the buildings with a lower number of floors, are distributed heterogeneously throughout the urban area; meanwhile, buildings with four or more floors (about 16%) are mainly located in the western part of the town. Most of Villa d'Agri's buildings were constructed between 1971 and 2000 (Fig. 2d). In Fig. 2, the green bars indicate the buildings selected for this study wherein seismic noise measurements have been performed.



**Fig. 2** Numerical distribution of the 812 investigated buildings (blue bars) in terms of use (a), built typology (b), number of floors (c) and year of construction of the building (ISTAT 2011) (d). The green bars indicate the number of selected buildings where measurements were taken

To reconstruct the main characteristics of the Villa d'Agri's built environment two databases were used: the geotopographic database of the Basilicata Region (regional spatial data infrastructure of the Basilicata Region, <http://rsdi.regione.basilicata.it/>, last visited May 25, 2022) and the General Population and Housing Census (Istat 2011). The former provides information about the height and use of the buildings, while the latter on the age and built typology. The Istat database reports 873 buildings while the regional geotopographic database reports 1388 'polygonal geometries'. This difference is due to the fact

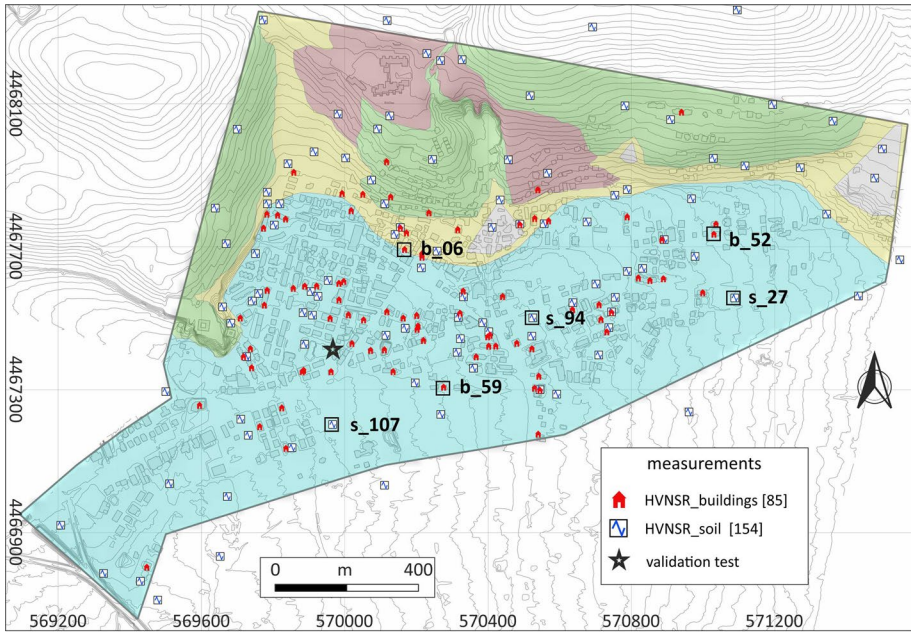


that in most cases buildings consist of several volumetric elements (such as balconies, turrets, emergency stairs, towers, etc. related to a single geometry). To assign all ‘polygonal geometries’ relevant to each building, two operations were carried out: (1) the geometries pertaining to the same building have been incorporated into a single one; (2) the height of the tallest element of the building was assigned to the new geometry. These operations have been performed by overlapping and carefully inspecting the available orthophotos in a GIS platform. In summary, the analysis carried out for this study concerns 659 geometries (out of 873), corresponding to 659 buildings for which the geology of the foundation soil is known.

### 2.3 Single-station seismic ambient noise measurements on soils and buildings

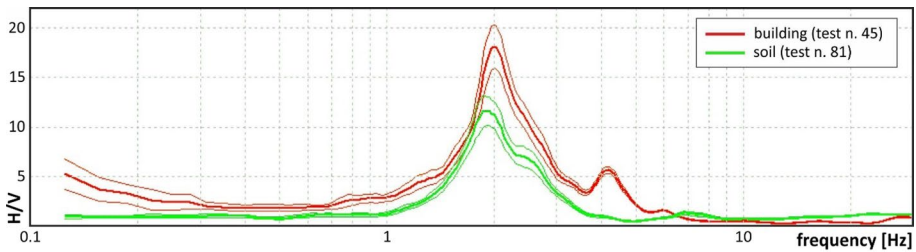
A total of 239 single-station seismic ambient noise measurements were carried out, 154 on urban soils and 85 inside the selected building typologies. Figure 3 shows the distribution of the measurements, including the location of the validation test site, and some pictures during the measurements on both soils and buildings. Each measurement was performed using a digital tromograph “Tromino” (MoHo s.r.l.) for at least 14 min and with a sampling frequency of 128 Hz. The performed measurements were analysed using Horizontal-to-Vertical Noise Spectral Ratio technique (HVNSR; Chàvez-Garcla et al. 1990; Field and Jacob 1995; Mucciarelli 1998; Parolai et al. 2004; Castro et al. 2004) following the SESAME Project (2004) criteria and the standard procedures proposed by Albarello et al. (2011). This technique is now considered the most robust for estimating the fundamental frequencies of soils (SESAME Project 2004; Molnar et al. 2022) and buildings (Gallipoli et al. 2009, 2010; Mucciarelli et al. 2011; Pan et al. 2014; Castellaro 2016; Salameh et al. 2016). The HVNSRs have been estimated performing the following procedure: each component was divided into non-overlapping windows of 20 s; each window was detrended, tapered, padded, Fast Fourier Transformed and smoothed with triangular windows with a width equal to 5% of the central frequency. In order to estimate the main vibrational frequencies in the two horizontal components, for each of the 20 s windows, the spectra for longitudinal, transverse and vertical components were computed, therefore reconstructing the two HVNSR curves (longitudinal spectrum and transverse spectrum over vertical one). Finally, the average HVNSR spectrum was obtained, providing also the relative  $\pm 2\sigma$  confidence interval. Some authors (Bonneyfoy-Claudet et al. 2006; SESAME Project 2004) suggested that strong transients in the signals may affect the estimation of the soils fundamental frequency. However, other authors (Parolai and Galiana-Merino 2006; Mucciarelli 2007) argued that a simple amplitude variation never caused such a problem.

In order to guarantee free-field conditions, the sensor was always posed at a distance equal to at least the height of the nearest buildings or trees (pictures in Fig. 3). In urban areas the “pure” free-field condition does not exist because the ground motion is strongly affected by the presence of buildings and vice versa (Mucciarelli et al. 2003; Gallipoli et al. 2006; Ditommaso et al. 2010). The wavefield in urban areas is characterised by the contribution of different sources and it is impossible to separate/eliminate the contribution of the free-field waves due to geological condition from those of buildings. In the present study, the measurements performed on urban soil quantify and characterise the frequency response of soils and overlying buildings as a whole. This is exactly what happens during earthquakes, that is soils and buildings respond according to the real ‘cumulative’ conditions, i.e. the soils according to the real urban conditions and buildings according to their interaction with foundation soil (Laurenzano et al.



**Fig. 3** Geological map of the investigated area with the distribution of the single-station seismic ambient noise measurements performed on soil (free field) and inside the buildings. The black star indicates the validation site. The small black boxes and corresponding labels indicate the sites shown in the photographs below





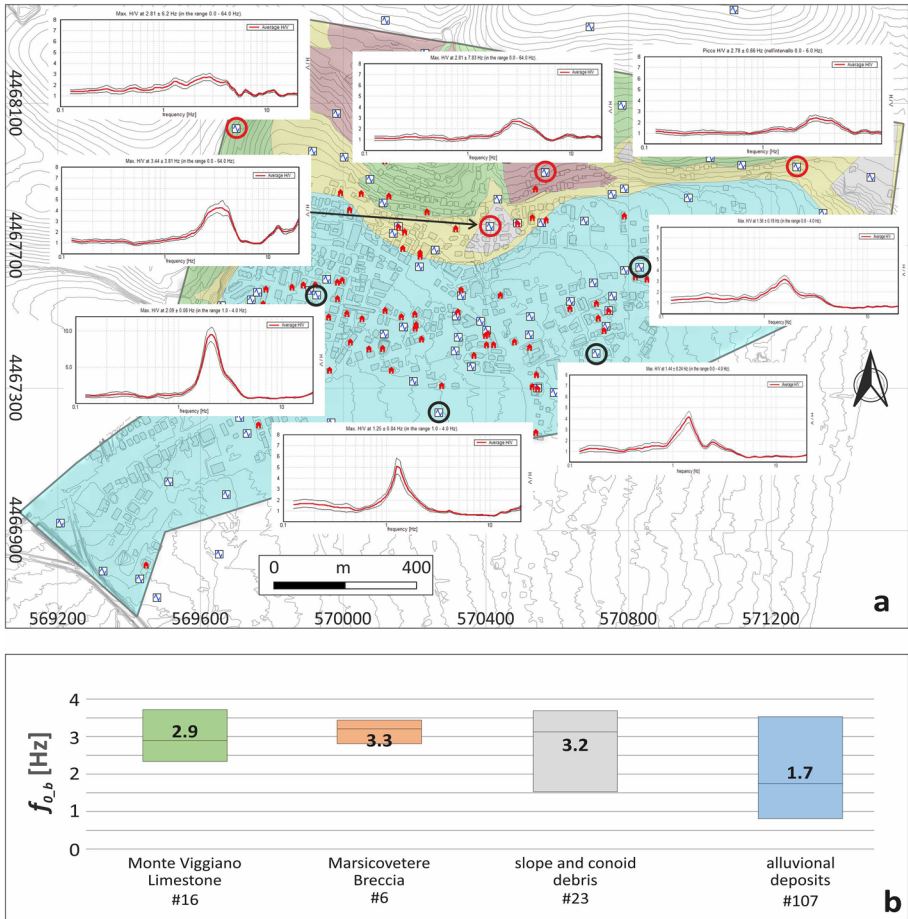
**Fig. 4** Example of two HVNSR functions obtained inside the building (red) and on the relative foundation soil (green)

2010). Anyway, the litho-stratigraphic conditions and mechanical characteristics of the urban soil of the Villa d’Agri town induce a strong impedance contrast, so that the frequency characteristics of soils are well constrained and could be not confused with the frequency contribution of the buildings. Figure 4 shows the overlapping of the HVNSR function of a building and its foundation soil: the fundamental frequency of the soil is about 1.9 Hz and that of the building is 3.1 Hz, the frequency contribution of the soil is so high that it is visible in the HVNSR of the building.

Soil measurements were performed with the aim to sample the principal types of shallow soils with different outcropping lithology, thickness of the deposits, local stratigraphy and geotechnical characteristics. Figure 5 shows some HVNSRs estimated on different outcropping geology and stratigraphic conditions highlighting the large variability among them. Most of the soil measurements were carried out, where possible, with an average inter-distance of 200 m and many others close to previous geological and geotechnical tests for further comparison and validation. On average, each measurement was made every two hectares except on the Monte Viggiano Limestone, where the steep morphology prevented to perform them in the same regular way. The total number of the performed measurements and their distribution were sufficient for the mechanical and stratigraphic characterization of the whole Villa d’Agri’s urban area. Particular attention was paid to the influence of human activities on the acquired data. The main sources of anthropogenic noise are emitted by the activities of a mining quarry located in North-West direction with respect to the town and by the extraction of oil from wells in the North-East. Even outside the urban context, their relative proximity has influenced in some cases the estimation of the HVNSR curve, generating spurious peaks and forcing us to repeat the test at different times of the day.

In order to visualize sparse soil frequencies as continuous fields in the spatial domain (Cadet et al. 2011; Brax et al. 2018; Pinzón et al. 2019; Gallipoli et al. 2020), the inverse distance weighting or inverse distance weighted (IDW) method has been applied (Li and Heap 2008). This method allows to estimate the  $f_{0,s}$  and  $A_{0,s}$  values at unsampled points using a linear combination of values at sampled points weighted by an inverse function of the distance from the point of interest to the sampled points. The assumption is that sampled points closer to the unsampled point are more similar to it than those further away in their values. The weights can be expressed as:

$$\lambda_i = \frac{1/d_i^p}{\sum_{i=1}^n 1/d_i^p}$$



**Fig. 5** **a** Some HVNSR curves estimated at sites along the slope (red circles) and on top of the terraced alluvial deposits (black circles). **b** Distribution of the fundamental resonance frequencies of urban soils distinguished by outcropping lithology. Boxplot width is proportional to the square-root of the number of measurements for each group (reported below in white). The lower and upper hinges of the box correspond to the first and third quartiles (the 25th and 75th percentiles); the central line in the box is the median (50th percentile)

as proposed by Bivand et al. (2013), where  $d_i$  is the distance between  $x_0$  and  $x_i$ ,  $p$  is a power parameter, and  $n$  represents the number of sampled points used for the estimation. The main factor affecting the accuracy of IDW is the value of the power parameter (Isaaks and Srivastava 1989). Weights diminish as the distance increases, especially when the value of the power parameter increases, so nearby samples have a heavier weight and have more influence on the estimation, and the resultant spatial interpolation is local (Isaaks and Srivastava 1989). The most popular choice of  $p$  is 2 and the resulting method is often called inverse square distance or inverse distance squared (IDS). This method allows the estimation of the isofrequency and isoamplitude maps for the Villa d’Agri’s urban soil (Fig. 7).

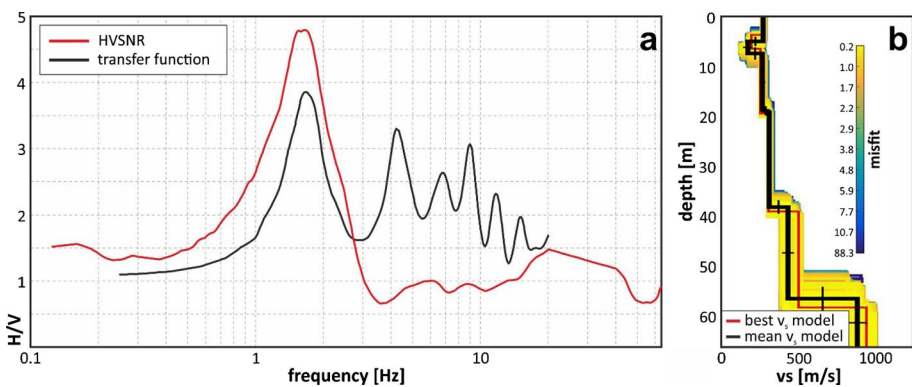
To estimate the main vibrational frequency of the selected 85 buildings, as suggested by other authors (Gallipoli et al. 2010; Castellaro 2016), 14-min recording (128 Hz sampling

rate) for each building was carried out by posing the sensor on the top floor near the column-beam junction for the reinforced concrete building and close to the load-bearing wall for the masonry ones. The sensor has been always aligned towards the direction of maximum development of the building (North–South direction along building longitudinal elongation; pictures in Fig. 3). The studied buildings have residential use (85), most of which (95%) are made of moment-resistant reinforced concrete frame, while only 3 are masonry (Fig. 2a, b, green bars). The buildings have been selected considering the year of construction so as to have an indication on the structural and built characteristics in accordance with the seismic code in force at that time. Most buildings (70%) consist of at least 4 floors above ground, 17% of 3 floors and the remaining 13% of only two floors (Fig. 2c). The lowest measured building has a height of about 6.5 m and the highest one of 19.5 m, the latter being the tallest in the area. On average, approximately 12 buildings have been measured for each decade since 1981, while the remaining 28% were built between 1951 and 1980 (Fig. 2d). The 66% of the measured buildings are built on alluvial deposits (Fig. 5b), while the remaining ones are distributed on limestone (18%) and on breccias and debris (16%).

### 3 Results and discussion

#### 3.1 Main frequencies of urban soils

First, to validate the HVNSR functions, we compared the one estimated at one site located on alluvial deposits with the transfer function obtained by using the 1-D numerical simulation (STRATA program; Kottke and Rathje 2008) according with the  $V_s$  layered profile evaluated by joint inversion of Extended Spatial Auto Correlation (ESAC) and HVNSR (Fig. 6). To account for measurement-related uncertainty, both velocity and strata thickness values were varied by 10%. The seismic input is represented by 5 real accelerograms recorded on rock and compatible with the NTC-2008 spectra provided for the Villa d’Agri site at 475-year return period, soil class C and topographic class T1 (flat surface). Most of



**Fig. 6** **a** Comparison between the HVNSR and the transfer function evaluated in the validation site (black star in Fig. 3); **b**  $V_s$  profile evaluated by joint inversion of Extended Spatial Auto Correlation (ESAC) and HVNSR techniques

the HVNSRs estimated on the alluvial deposits show clear resonance peaks, whereas the amplification functions evaluated along the slopes have lower amplitude values spread over a wider range of frequencies (Fig. 5a). In particular, the HVNSRs estimated in the northern part of the urban area show peaks with lower amplitude at higher resonance frequency ( $f_{0,s} \approx 3$  Hz), while moving towards the valley the HVNSR peak exhibits much higher amplitude values and lower fundamental resonance frequency (about 1–2 Hz) probably due to the increase of the alluvial deposits thickness (Fig. 5a).

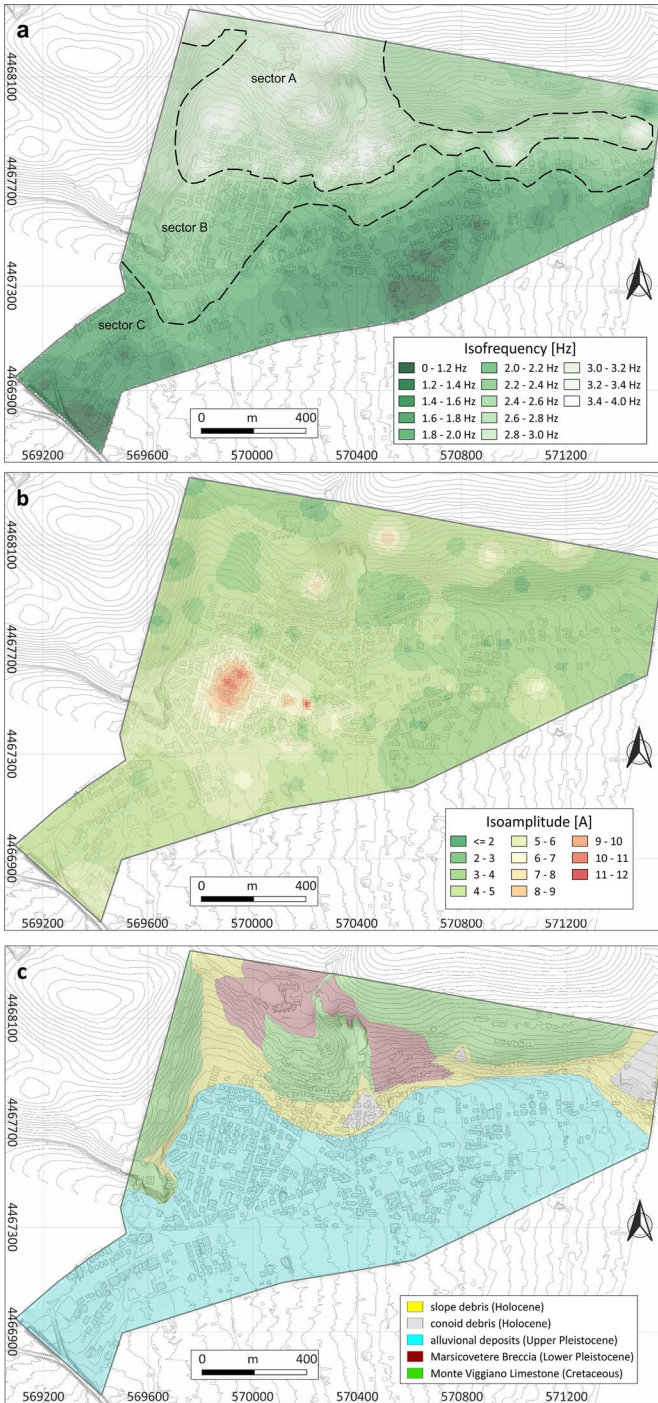
The iso-frequency and iso-amplitude maps provide spatial distribution of the fundamental frequencies ( $f_{0,s}$ ; Fig. 7a) and relative amplitude value ( $A_{0,s}$ ; Fig. 7b) of soil resonance peaks at each point of the urban context. The frequency of the fundamental soil resonance peak ( $f_{0,s}$ ) varies mainly between 0.8 and 3.7 Hz, with a median value of 2.1 Hz (Fig. 7a), the main peak amplitude value between about 2 and 12 with a median value of 4.5 (Fig. 7b; see Supplementary Material). Looking at the distribution of the fundamental frequencies as a function of the outcropping lithology, the  $f_{0,s}$  is higher (about 3.2 Hz as median value, Fig. 5b) for the sites located on the slope (Marsicovetere breccia, Monte Viggiano limestone, conoid and slope debris) with respect to those located on the thicker alluvial deposits (1.7 Hz as median value; Figs. 5b).

The comparison between the isofrequency map (Fig. 7a) and the detailed geological map (Fig. 7c) shows that the variation of fundamental frequency follows the outcropping lithology; indeed, the isofrequency map seems to be correlated with the thickness of the Quaternary sediments. This trend allows to divide the urban context into three sectors:

- Sector A extends along the northern part and is mainly characterized by breccias and limestones showing a frequency range of about 3–4 Hz and a sedimentary thickness that could reach about 30 m (Lizza and Tamburiello 2012).
- Sector B covers to the central urban area from the slope towards the valley bottom. It mainly consists of slope debris deposits showing a frequency range of 2–3 Hz and a sediment thickness varying between 5 and 10 m (Lizza and Tamburiello 2012). The distribution of the isofrequency curves mimics the slope as well as the lithological boundaries in the geological map (Fig. 7a–c).
- Sector C: it develops in the southern sector of the investigated area, more specifically along the terraced alluvial plain. It is characterised by fundamental frequencies of about 2 Hz that decrease closer to the sedimentary ipocentre of the valley; this is due to the increase in thickness of silty/sandy and sandy/silty clays overlying the Monte Viggiano Limestone (here representing the seismic bedrock) which reaches a depth of 90–100 m (Lizza and Tamburiello 2012).

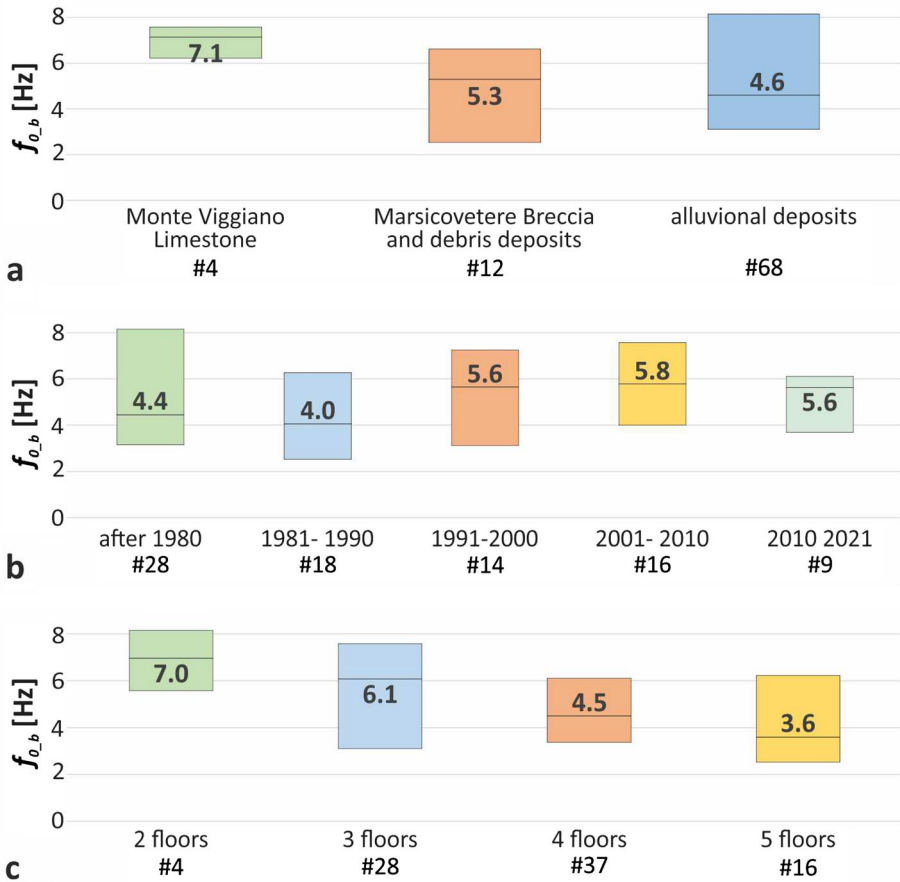
### 3.2 Fundamental vibrational frequencies of buildings

The height of the 85 investigated buildings ranges between 6.6 and 19.8 m and their fundamental vibrational frequencies ( $f_{0,b}$ ) varies between 2.5 and 8.2 Hz with a median value equal to 4.8 Hz (Fig. 8). As already pointed out by Veletsos and Meek (1974), Luco (1988) and Brunelli et al. (2021) the interaction between structures and the foundation soil may have significant effects on the building response: indeed, the Villa d'Agri buildings founded on stiffer lithotypes are characterised, on average, by relatively higher frequency values (about 7.1 Hz for buildings founded on Monte Viggiano Limestone and 5.3 Hz on breccias and debris, Fig. 8a) compared to the buildings on alluvial deposits (about 4.6 Hz). For a more in-depth discussion about the variation of building frequency as a function of



**Fig. 7** Iso-frequency (a) and isoamplitude (b) maps of the investigated area as obtained; c Detailed geological map. The dotted lines indicate the sectors characterised by the same frequency ranges

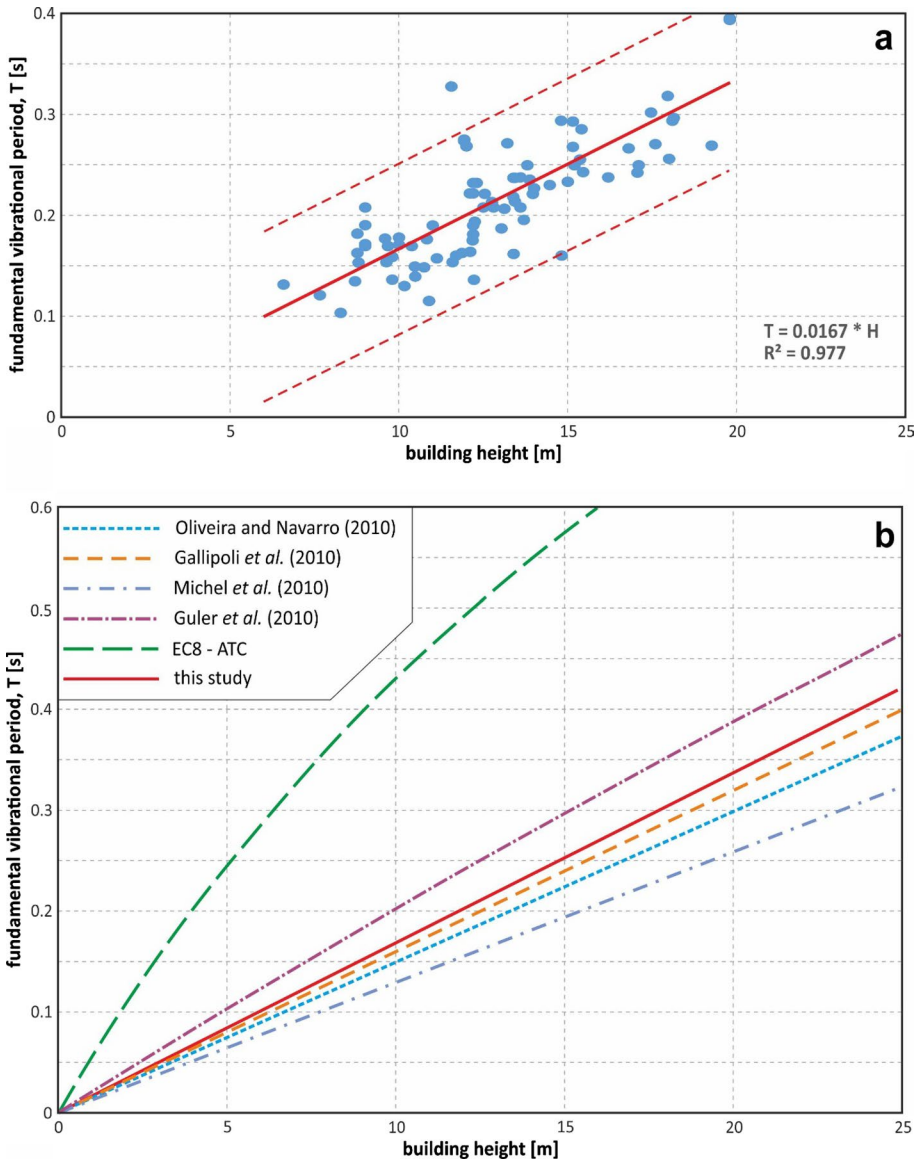




**Fig. 8** Distributions of the HVNSR first vibrational frequency of the 85 buildings vs (a) lithology of foundation soil; (b) year of construction and (c) number of floors

foundation soil characteristics, see Gallipoli et al. (2023). Regarding the year of construction (Fig. 8b), the first vibrational frequency ( $f_{0,b}$ ) shows a slightly higher increasing trend after the 1980 Irpinia earthquake, when the new regulations of the seismic design code entered in force. The major frequency variations occur with the increase of number of floors, the average first vibration frequency values decrease with the increase of the number of floors (Fig. 8c), although this is an expected relation it can be considered as a sign of good data quality.

This consideration allowed to obtain a relationship between the first vibrational period  $T$ (s) and the corresponding height ( $H$ ) through a simple linear regression with zero intercept in the form  $T = a * H$  (Fig. 9a); the angular coefficient,  $a=0.0167$ , has been estimated by means of an ordinary least squares approach and  $R^2=0.977$  shows the goodness of the fit. By evaluating the residual analysis and the errors for linear and power models, Gallipoli et al. (2023) suggest that power law does not improve the description of the experimental data, so they also have assumed that the simpler linear model is a sufficiently accurate approximation to describe the experimental data. Other authors have also proposed a linear model for describing period-height relationships: e.g., Guler et al. (2008) for 6 Turkish



**Fig. 9** Experimental relationship between building period T(s) and height for the 85 sampled buildings (a) and other published studies (b), the solid and dotted red lines represent the regression curve ( $T=0.0167 * H$ ) and the prediction interval, respectively

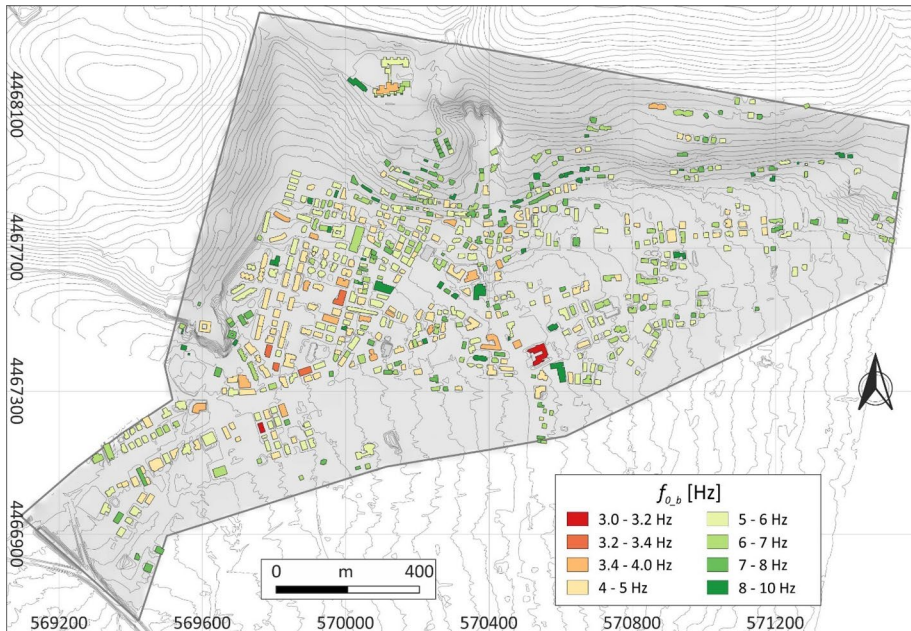
buildings; Michel et al. (2008) for 60 French buildings; Oliveira and Navarro (2010) for 39 Spanish buildings; Gallipoli et al. (2010) for 244 European buildings; Pan et al. (2014) for 116 Singaporean buildings; Salameh et al. (2016) for 330 Lebanon buildings; Gallipoli et al. (2023) for 327 RC buildings and 71 masonry buildings. As above mentioned, for the Villa d’Agri data the experimental relationship is  $T = 0.0167 * H$  and it is in good agreement with those suggested by other authors (Fig. 9b), while the relationship provided by

the seismic code for reinforced concrete buildings (EC8, 2003; CEN 2004) returns much higher frequencies. The code relationships are too simplistic to predict the fundamental period; in contrast, the vibrational periods estimated by performing experimental measurements on the building take into account the behavior of the structure as a whole, that is, the vibrational behavior of the frame including the infills and the interaction with the foundation soil. Recently Piro et al. (2019) and Brunelli et al. (2021) developed a simplified analytical method that takes into account the interaction effect between masonry buildings and foundation soil; in this case the agreement between experimental and numerical data is very good.

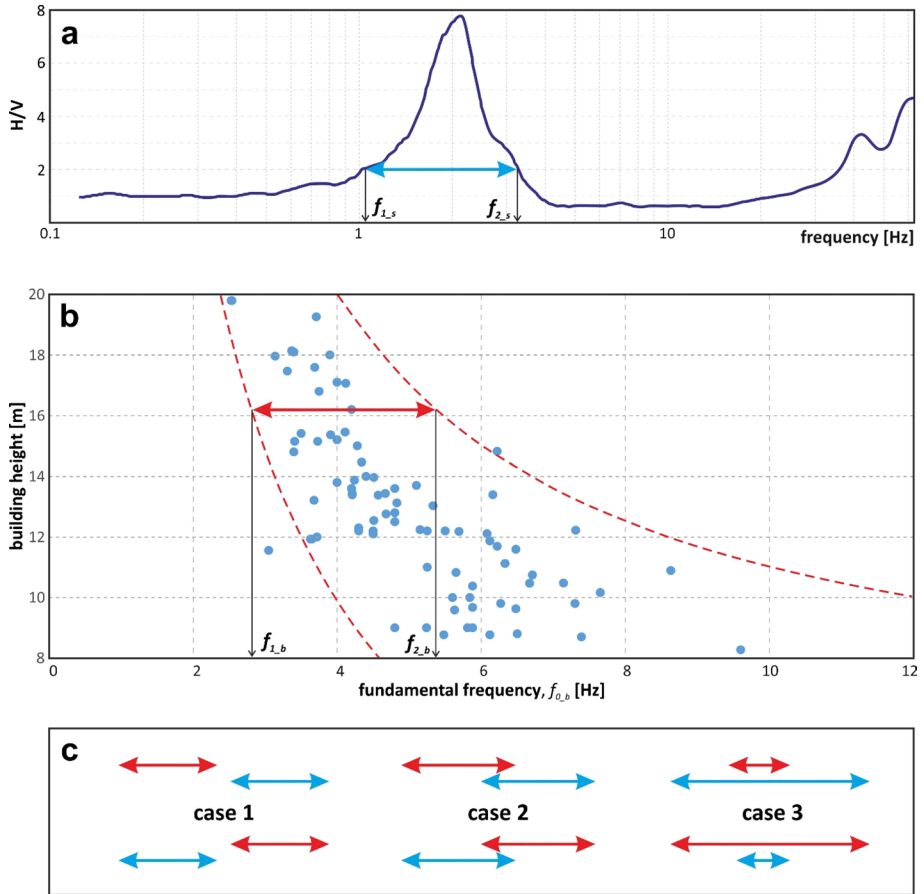
Thanks to the availability of the heights for all Villa d'Agri's building (regional spatial data infrastructure of the Basilicata Region, <http://rsdi.regione.basilicata.it/>, last visited May 25, 2022) and using the experimentally estimated period-height ( $T$ - $H$ ) relationship, it was possible to predict the main vibrational frequency for all the buildings (659) with height between 6.5 and 19.8 m. The estimated first vibrational frequencies ( $f_{0,b}$ ) approximately range between 2.5 and 9.8 Hz (Fig. 10) and most buildings (78%) have main vibrational frequency above ca. 4 Hz.

### 3.3 Soil-building resonance map

In order to evaluate where the soil-building interaction effect could potentially occur during future earthquakes, the first vibrational frequency of each building was compared with the first one of the corresponding foundation soil. Since most of the energy belongs to the first mode of vibration compared with that of the higher modes, it was decided to evaluate



**Fig. 10** The first vibrational frequency ( $f_{0,b}$ ) for 659 buildings of Villa d'Agri town



**Fig. 11** Example of identification of the two frequencies  $f_{1,s}$  and  $f_{2,s}$  of the soil HVNSR (a); example of identification of the two frequencies  $f_{1,b}$  and  $f_{2,b}$  of the building HVNSR (b); three different cases of overlapping between  $[f_{1,s}$  and  $f_{2,s}]$  and  $[f_{1,b}$  and  $f_{2,b}]$  (c)

the double resonance effect between the first vibrational frequency of each building and that of its foundation soils.

Soil-building resonance levels were evaluated and classified overlapping the soil amplified frequency range with that of the corresponding building. Accordingly, for each point the frequencies  $f_{1,s}$ ,  $f_{2,s}$ ,  $f_{1,b}$  and  $f_{2,b}$  were identified as shown in Fig. 11a, b. In particular, for each soil HVNSR function, the two frequencies ( $f_{1,s}$  and  $f_{2,s}$  with  $f_{1,s} < f_{2,s}$ ), at which the HVNSR curve intersects the amplitude threshold 2 (amplitude threshold above which amplification is considered to occur; Fig. 11a), define the considered range of frequencies for our purpose. Similarly, for each building,  $f_{1,b}$  and  $f_{2,b}$  are the two extreme frequencies encompassing the uncertainties of the experimental  $T-H$  relationship for a given height (Fig. 11b). It is worth noting that while uncertainty curves are linear in the period-height domain (Fig. 9a), they become curvilinear in the frequency-height domain (Fig. 11b); as a consequence, the frequency ranges are narrower for tall buildings and wider for low buildings.

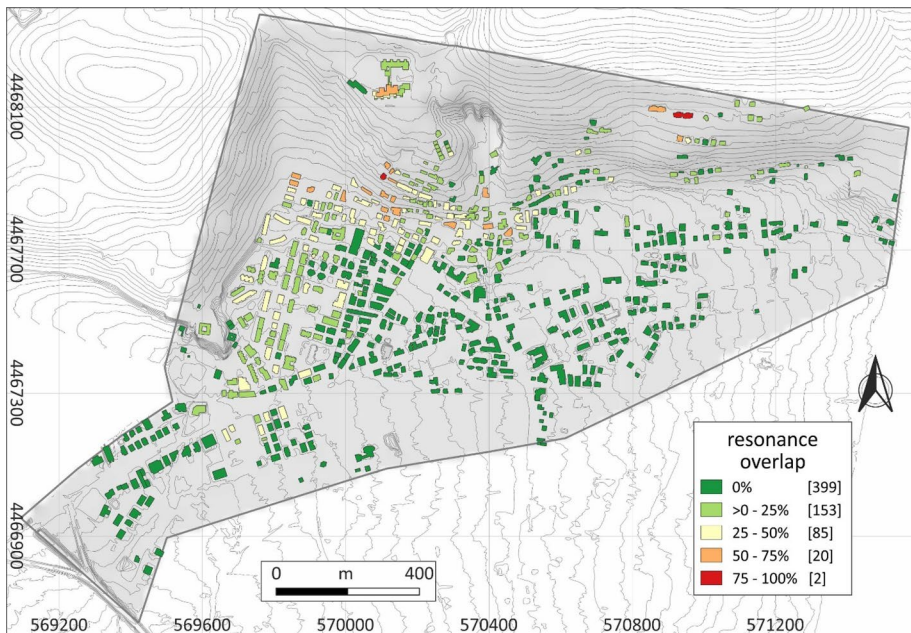
Based on the described approach, three major cases (Fig. 11c) schematically represent all possible intersection combinations between soil ( $f_{1_s} - f_{2_s}$ ) and building ( $f_{1_b} - f_{2_b}$ ) frequency ranges:

- **Case 1:** the interval of the amplified building frequencies is completely disjoint from that of the underlying foundation soil and consequently there is no resonance effect;
- **Case 2:** the amplification intervals of building and foundation soil only partially overlap and this induces some amount of double resonance effect;
- **Case 3:** the interval of the amplified building frequencies completely overlaps with that of the foundation soil or viceversa and hence a strong double resonance effect is expected.

Following the mentioned cases, each building has been classified and the spatial representation has been produced by adopting a traffic light colour scheme in which red indicates that the double resonance phenomenon has a high potential to occur, while dark green indicates that the possibility is practically zero. Consequently, the risk associated with this phenomenon is maximum in the former case and minimum (or zero) in the latter, with intermediate values for the other colors used in Fig. 12.

From a careful evaluation of the map (Fig. 12), some major findings could be outlined:

- for only 2 buildings (0.3%) there is a complete overlap between  $[f_{1_b} - f_{2_b}]$  and  $[f_{1_s} - f_{2_s}]$  (case 3); these buildings, coloured in red to assign them a potentially severe resonance level, are located in the northern part of the urban context and are located on limestone;



**Fig. 12** Map of soil-building resonance levels of the Villa d'Agri town



- about 3% of buildings (20) shows a large overlapping (between 50 and 75%—case 2) between  $[f_{1_b} - f_{2_b}]$  and  $[f_{1_s} - f_{2_s}]$ ; the great majority of these buildings, coloured in orange, is placed along the slope and they are mainly founded on the debris and limestone;
- 85 buildings (about 13%) exhibit a medium overlapping (between 25 and 50%) between  $[f_{1_b} - f_{2_b}]$  and  $[f_{1_s} - f_{2_s}]$ ; these buildings, coloured in light yellow, are mainly distributed in the western sector of the town, at the foot of the slope and close to the area with the terraced alluvial deposits;
- for about 153 buildings (23%) there is a limited overlapping (0–25%) between  $[f_{1_b} - f_{2_b}]$  and  $[f_{1_s} - f_{2_s}]$ ; these buildings are coloured in light green to indicate a low resonance level and are located at the foot of the slope;
- lastly, 399 buildings (representing about 60% of the buildings) show no overlap between soil and building frequency intervals; they are thus coloured in dark green and are mainly distributed along the terraced deposits.

## 4 Conclusion

The experimental evidence obtained by means of 154 HVNSR functions estimated on the urban soils of Villa d'Agri town, reveals important lateral variations in terms of local amplification. In particular, in the north-west topographically higher area, where the Monte Viggiano Limestone largely outcrops, the soil is generally characterized by a low amplification values in a broad frequency interval. Descending downward, progressively higher amplifications are observed, probably due to the strong impedance contrast between a thick layer of clay soil (20–90 m) and the underlying carbonate bedrock. The isofrequency map closely mirrors the geological map: (a) the northwestern sector of the town is characterised by frequencies in the range 3–4 Hz and sediment thickness between 5 and 10 m; (b) the slope area, where sediment thicknesses reach up to 20 m, shows a gradual decrease in main peak frequencies down to about 2 Hz; (c) the third sector more or less coincides with the terraced alluvial deposits, the estimated HVNSRs functions show a clear resonance peak at lower frequencies ( $f_{0_s} < 2$  Hz).

The first vibrational frequency has been measured for 85 selected buildings performing single-station ambient noise recordings on the top of the buildings and applying the HVNSR technique. The height of these 85 buildings ranges between 6.6 and 19.8 m and the frequency ( $f_{0_b}$ ) varies between 2.5 and 8.2 Hz. Based on these experimental values, the prediction equation between first vibrational period,  $T_{0_b}$ (s), and height  $H$ (m), has been estimated by applying a linear regression with zero intercept in the form  $T = 0.0167 * H$ . Using this  $T$ - $H$  relationship and the available information on the height of each building, the first vibrational frequency was deduced for all 659 buildings investigated.

By comparing the amplified frequency ranges of each building with those of the corresponding foundation soil, the soil-building resonance map has been reconstructed. A severe double resonance effect is predicted for only 2 buildings (0.3%), whose foundations are located directly on the Monte Viggiano Limestone; for about 16% (105) of the buildings, a high-to-moderate double resonance effect is likely; 153 buildings (23%), on the other hand, are instead characterized by a low level of resonance hazard. Most of these buildings are located on the northern relief and along the slope. For the remaining buildings (60%), the

hazard associated to the double resonance phenomenon between soil and building is practically zero. These are mainly distributed on top of terraced alluvial deposits.

This approach made it possible to assess the resonance effect of each building with respect to the corresponding foundation soil. Knowledge of this spatial information is extremely important for identifying the most dangerous areas of the city, that is, those areas where the effect of the soil-building resonance is most likely to cause increased damage during earthquakes.

It should be noted, however, that the soil-building resonance map proposed in this study represents a “snapshot” of the interaction effect in the linear-elastic domain, and this picture could change during long-duration shaking associated to moderate-to-severe earthquakes. In fact, shifting the fundamental vibrational frequency of the building due to damage could cause additional resonance intervals compared with the elastic-linear case. With this in mind, future developments of this investigation should be devoted, first, to the evaluation of resonance maps assuming different degrees of building damage and, second, to the evaluation of seismic risk maps, since vulnerability data are available for all buildings in Villa d’Agri. In addition, since soil-building interaction is an extremely important problem in urban areas during earthquakes, an effort should be made to implement soil-building resonance levels in microzonation studies, in this way such studies would be a more appropriate and comprehensive approach for a proper seismic territorial planning and more rational allocation of economical sources for retrofitting. Building fundamental vibrational period and building height are key parameters for earthquake engineering applications on existing buildings. Consequently, characterizing the entire built environment in terms of building fundamental periods, built typologies, structural and geometrical characteristics, vulnerability and foundations soil mechanical properties is a proactive action to better assess seismic risk in urban areas according to the new resilient approach for risk mitigation (Vona 2020). The FRIBAS open access database (<https://doi.org/10.5281/zenodo.6505442>) goes in this direction, i.e., it contains 37 main characteristics for 312 buildings (71 masonry, 237 reinforced concrete and 4 mixed types) and related foundation soil, thus providing the basis for studying the influence of each parameter on the building behavior and for assessing the dependence of period  $T$ (s) not only on height, but also on other appropriately weighted parameters.

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**Data availability** The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Conflict of interest** The authors have no relevant financial or non-financial interests to disclose.

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