HIGH-RESOLUTION SEISMIC ARRAYS IN AMATRICE VILLAGE FOR A BETTER ESTIMATION OF SITE EFFECTS

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ABSTRACT

The August 24th, 2016 M 6.0 Amatrice earthquake is the beginning of the 2016-2018 central Italy seismic sequence. One of the first places to be highly damaged is the wide territory of Amatrice municipality. Seismic Microzonation studies (SM) started during the early stages of emergency with the installation of the 3A temporary seismic network (Cara et al. 2019) and continued with an intense campaign of multidisciplinary studies (Priolo et al. 2020). On the light of the information retrieved, this work shows the results of additional geophysical investigations carried out in specific sites of Amatrice village including the historical center, the most damaged area. We applied f-k and MSPAC analysis to data collected at 5 sites to obtain dispersion curves and invert them to retrieve the subsoil Vs profile. All results were therefore integrated with the already available geological and geophysical information to better detail the subsoil model.

Keywords: Seismic motion, site effect, earthquake engineering, seismic array

INTRODUCTION

After five years from the August 24th, 2016 earthquake which severely stroke Amatrice village (central Italy), many studies have been published about the effects of the shaking produced in Amatrice terrace during all the seismic sequence. Many are the aspects considered from different authors: the damages especially produced in the historical center of Amatrice, coseismic effects (fractures, superficial faulting, slope instabilities), the study of the seismological sources involved in the sequence and the propagation process and the ground motion distribution of the major events of the sequence, the geological reconstruction of the area and the connections with possible site effects (a review is available by Cultrera et al., 2021 this conference). This last topic is of special interest for microzonation studies (SM working group, 2015) which have been realized, as prescribed the Italian Civil Protection, for the entire area affected by the damages of the 2016-2018 central Italy seismic sequence. These activities started almost from the beginning of the sequence with the installation of temporary networks and geological and geophysical surveys during the early stages of the emergency. Amatrice village in particular, has been widely investigated by public research institutions and private practitioners with tens of boreholes, downhole and geophysical measurements as single-station microtremor recordings and active and passive arrays and vertical electrical tomography surveys along the whole terrace. All these investigations, together with a vast geological survey, contributed for the realization of microzonation studies of Amatrice municipality and supporting the activities connected to the post-seismic re-building pointing out complexities in the structure of the subsoil within the first hundred meters. In this framework, the present work gives a contribution to the imaging of the geological-geotechnical characteristics of the subsoil by means of a campaign of geophysical measurements consisted in the realization of many 2D seismic arrays in specific sites inside the historical center of Amatrice and in its surroundings.

OVERVIEW OF THE AREA

Damage Scenario

Amatrice area is located in the north-eastern edge of Lazio region (central Italy), 100 km away from the city of Rome. Built in a basin and bordered by the high tops of Laga mountains to the East, life in this village is mainly characterized by rural and traditional activities. According to Fiorentino et al. (2018), who made a detailed analysis of the damage patterns in the village after August 24th, 2016 earthquake, the urban composition of its historical center derived from the medieval structure of the city, within the former city walls and the majority of the structures in the historical center of Amatrice were constituted by masonry building aggregates mainly made with cobblestones. The elevated level of destruction, continues Fiorentino et al. (2018), was mainly caused by the high vulnerability of the masonry buildings, mostly due to specific vulnerability factors such as the poor quality of masonry, the lack of connections between walls and the poor connection between external walls and floors. Furthermore, it is worth to notice that the heavy concrete-roofs added diffusely in the second half of last century contributed to worsen the destructive scenario. The macroseismic survey promptly carried out after the August 24th, 2016 earthquake reported that most of the buildings suffered severe damages or entirely collapsed, reaching a value of X in the seismic intensity scale of Mercalli-Cancani-Sieberg (Galli et al., 2016). The other following strong earthquakes were less destructive for Amatrice village mainly because the epicenters of the seismic sequence moved progressively towards north.

Geological Setting

Geological studies already available for the area before the Amatrice earthquake (among all Centamore et al., 1991a; Cacciuni et al., 1995) were all aimed at reconstructing the stratigraphic, structural and morphological setting at a regional scale. The Amatrice basin is an intramountain depression filled with the turbiditic deposits of the Miocenic pre-evaporitic member of Laga Formation, occasionally covered by Pleistocene-Holocene continental deposits (Amatrice-Sommati Unit - UAS) arranged as fluvial fans or fluvial terraces (Vignaroli et al., 2019). The basin is bounded to the east by the west-dipping Gorzano-Laga normal fault which was active during Quaternary and also during the 2016-2018 central Italy seismic sequence, and to the west by the Sibillini thrust front. Within the Laga Formation deposits which outcrop in Amatrice terrace area, two lithofacies are present: the siltstones and the sandstone dominated lithofacies; the maximum estimated thickness of this Formation, which is considered as the seismic bedrock of the area, is around 1200 m (Bigi et al., 2011). The UAS consists of up to 60m-thick alluvial gravel and sands deposits of active channel. In the framework of microzonation studies one of the main tasks was the detailed geological reconstruction of the entire area affected by the seismic sequence. Vignaroli et al. (2019) produced a detailed geological map (scale 1:5,000 – a subset in Fig. 1) and several geological sections (see Fig. 2) for the Amatrice area which clearly picture subsoil variabilities both in the shallow sedimentary deposits and in the bedrock (Laga Formation - LAG). Those variabilities are due to erosional/depositional phenomena and to the presence of tectonic elements in the area. In particular, Amatrice downtown is also intersected by a NW-SE-oriented hidden normal fault (Amatrice fault system) which affects the Miocenic substratum of the historical center, cutting and slipping the turbiditic (LAG) succession of the area and causing lateral geological discontinuities which can be relevant for the seismic response of the area (see Fig. 2).

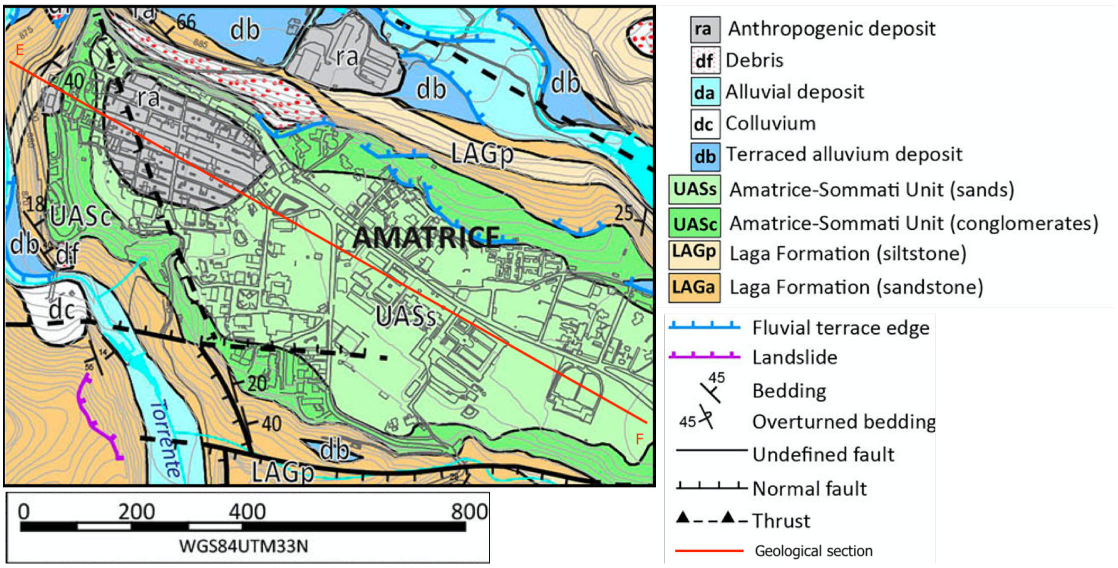

Figure 1 - Geological map of Amatrice terrace (modified from Vignaroli et al., 2019)

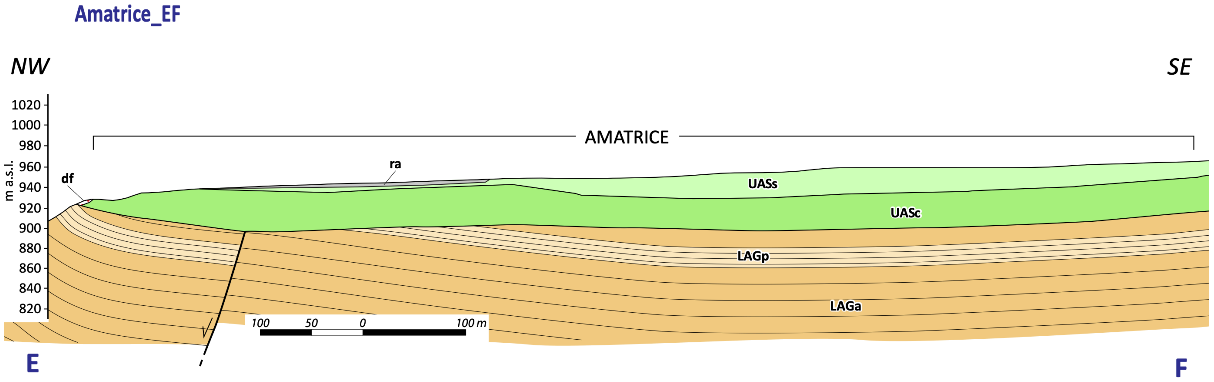

Figure 2 – NW-SE geological section of Amatrice terrace (see location in Fig. 1) (modified from Vignaroli et al. 2019).

3A Temporary Seismic Network and Seismological Data

In occurrence of the seismic emergency, many institutions contributed for the installation of temporary networks (e.g., Cultrera et al., 2016, Cara et al., 2019, Priolo et al., 2020) in sites of all the villages of Amatrice municipality which suffered damages >=7 MCS after the August 24th, 2016 earthquake and first aftershocks, as reported by the macroseismic survey carried out by Galli et al. (2016). These 50 stations recorded in continuous mode velocimetric and accelerometric signals for the first 2 months of the seismic sequence, collecting a huge number of earthquakes and microtremor useful for all the scientific community to study the different aspects of the seismic sequence (Milana et al., 2020, Priolo et al., 2020, Luzi et al., 2020, Pagliaroli et al., 2020, Felicetta et al., 2021 among many). Amatrice terrace, in particular, hosted in less than 1 km^2 seven temporary seismic stations, with one of the aims to collect data (an example in Fig. 3) to evaluate the empirical amplification function of specific sites and the possible variation in their site responses to connect with the subsoil geological heterogeneities.

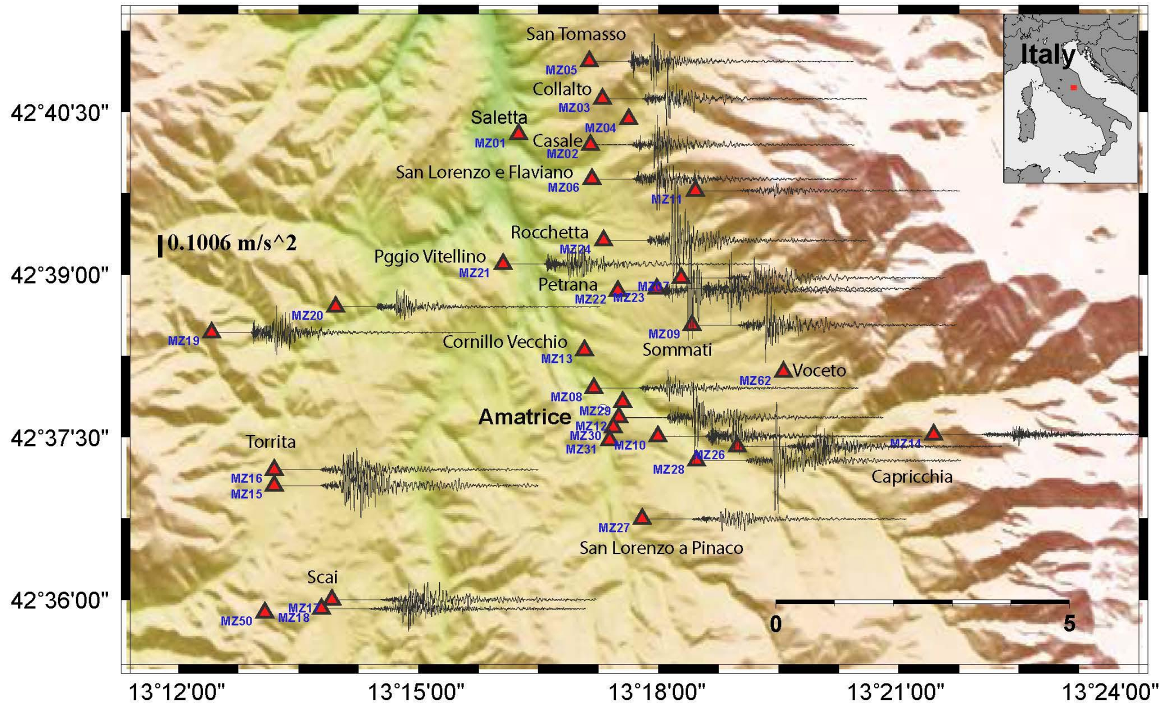

Figure 3 – Mw 4.0 recorded on October 16th, 2016 from 3A network stations in Amatrice area. Epicentral distance is about 16 km (from Cara et al. 2019).

The spectral ratios analysis of earthquakes (Priolo et al., 2020, Milana et al., 2020, Felicetta et al., 2021) by using single station and reference station methods allowed to retrieve the HVSR curves and the empirical amplification functions for each station. Milana et al. (2020) also deployed a wide campaign of microtremor in Amatrice terrace (see SM microtremor location in Fig. 4) revealing spatial variability of the microtremor spectral ratios (hereinafter HVNSR) of the area, also within a range of few tens of meters as well as interesting polarization effects in the historical center.

THE EXPERIMENT AND ARRAY ANALYSIS

The geophysical campaign was deployed between October 2nd and 4th 2017, when the debris removal activities in Amatrice area were still in progress. The logistic organization has been a key point for the realization of almost all the surveys, especially the ones in the historical center which were deployed along the only road open to the vehicular traffic. The surveys consisted in circular arrays with 10, 60 and 150-200 m aperture (small, medium and big in Fig. 3) for 2 sites, one star-shaped array and 2 L-shaped arrays for the historical center. The seismic stations were equipped with WARAN digitizer, Lennartz 3D-5s sensors, data synchronization with internal GPS and central field processing and control unit thanks to wireless communication for real-time data transmission. Velocity profiles of sites investigated with 3 concentric circular arrays have the advantage of being reconstructed by inverting the

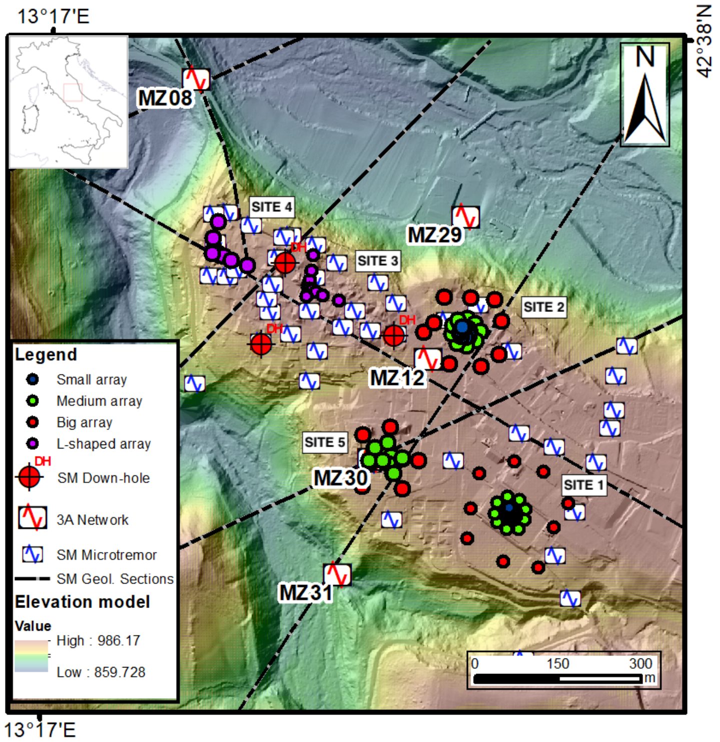

Figure 4 - General map of the investigations performed in Amatrice terrace after August 24th, 2016 earthquake

averaged curve obtained by merging the dispersion curves of each array, covering different wavelengths and therefore reaching different depths below the surface. Site 1 is shown as example of the analysis process of circular arrays. We first evaluated HVNSR at all the stations to check whether the 1D assumption is verified in the study area, to successfully apply the f-k analysis to data in array configuration. Conventional f-k and MSPAC processing (Geopsy modules) were applied to the vertical component of the signals and the dispersion curves for each array were retrieved by picking the maxima of the power in the frequency/slowness domain and associating a range of uncertainty to the curve. The array response function was evaluated to select a reliable range of the dispersion curve according to the resolution of the arrays and then a final dispersion curve was built averaging the curves of the single arrays. For the inversion process we applied an improved neighborhood algorithm (Wathelet et al. 2008) by using "dinver" module of the Geopsy package. The averaged dispersion curve together with part of the HVNSR curve were considered as targets, and the initial model is made by 4 layers over half-space with a very wide range of freedom both in the velocity and the thickness parameters to avoid constrains in the inversion process.

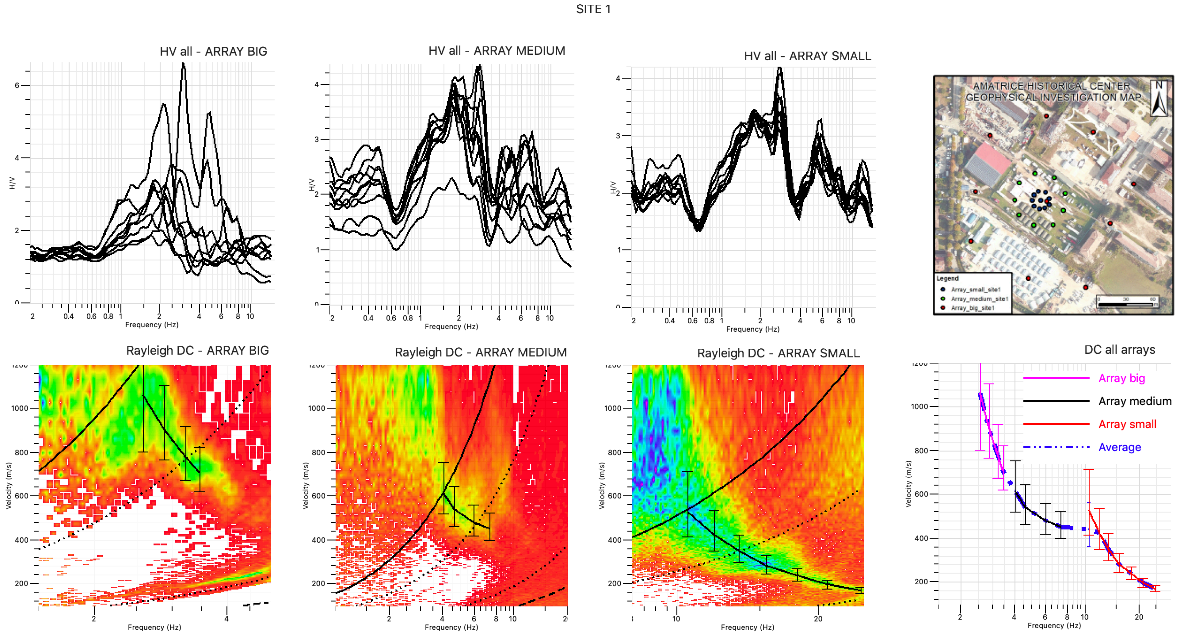

Figure 5 – Site 1 arrays: HVNSR (top) and f-k results with picked dispersion curves (bottom) for the circular arrays with 10, 60 and 150 m aperture. Picked dispersion curves and average curve considered in the inversion process (bottom-right). Map of Site 1 arrays (top-right).

More than 100,000 valid models have been produced and the best model has a minimum misfit of 0.444. The Vs best model was then used to simulate the ellipticity curve (using "gpell" module of Geopsy packet) for the site and compare it with the HVNSR curves of the smaller and most central array. The match is very satisfactory, reflecting that the 1D structure of the subsoil of the site is well depicted by the resonance peaks of microtremor spectral ratios.

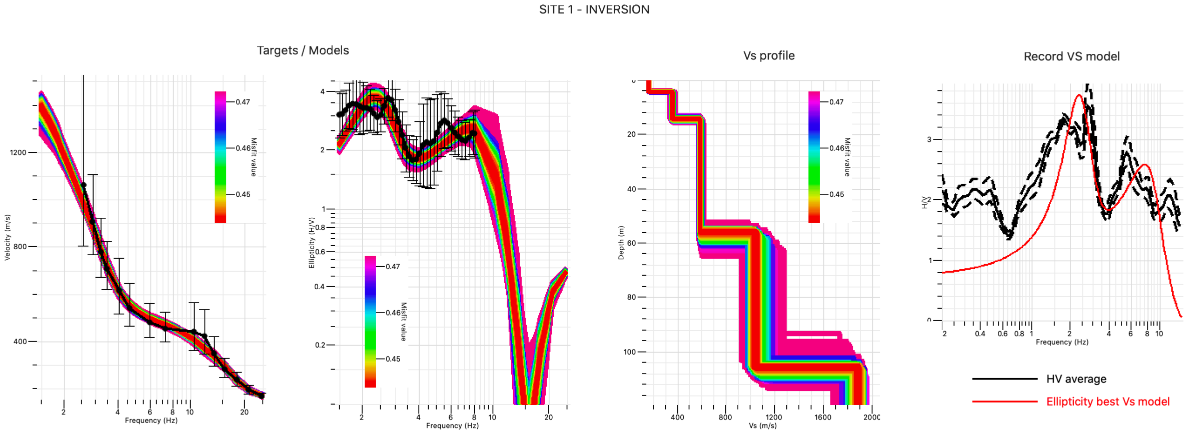

Figure 6 - Inversion results of SITE 1: From left to right, comparison of input targets and models produced, Vs profile and comparison between average HVNSR of small array and ellipticity curve modeled considering the best velocity profile.

Site 4 is reported as example of L-shaped array (Fig. 7). The analysis procedure is similar to the one previously described for Site 1. From the F0 map and the HVNSR plot (Fig. 7 top) is possible to observe, despite the location of the site at the northern edge of the terrace, that the resonance frequency is quite similar for almost all the stations of the array which has the longer branch of about 60 meters of length. For this kind of geometry, we noticed that MSPAC analysis gives inconsistent results therefore we applied the conventional f-k analysis and jointly inverted with the HVNSR peak. The synthetic ellipticity curve obtained considering the best velocity model reflects the average HVNSR curve of the site both in terms of frequency peak and amplitude. The velocity profile retrieved is in good agreement with the geological model (see Fig. 2) of the site.

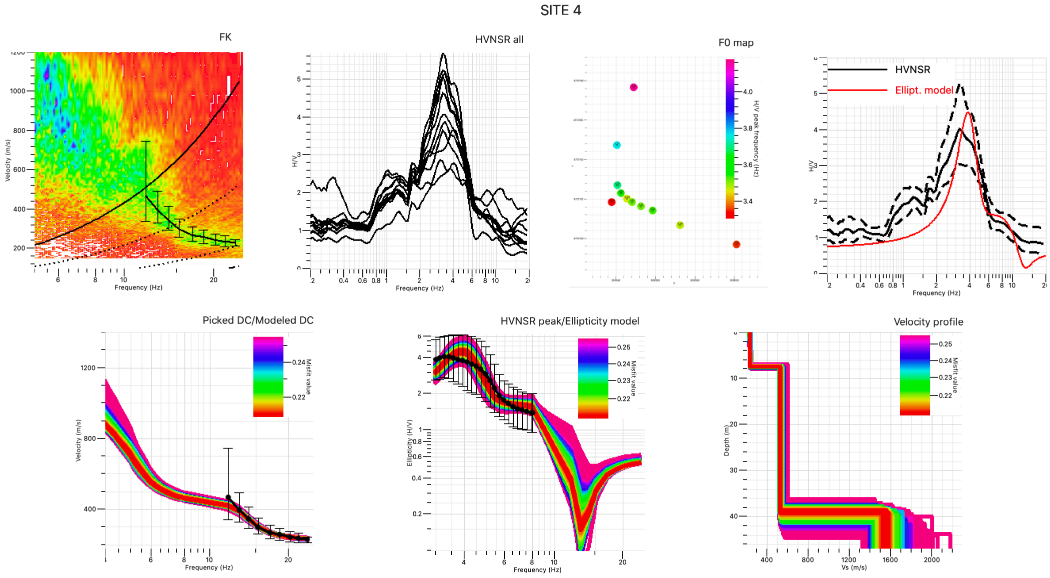

Figure 7 - Results for Site 4: Top from left to right, f-k analysis and picked dispersion curve, HVNSR of all the stations, F0 map of the array and HVNSR average compared to ellipticity simulated from the best velocity model. Bottom from left to right, results of the inversion.

VELOCITY PROFILES AND CONCLUSIONS

With the aim to help the post-emergency studies useful for the new urban planning of Amatrice area after the 2016-2018 central Italy seismic sequence, a 3 days-geophysical campaign of seismic arrays has been deployed downtown.
The geometrical configuration of the arrays allowed to retrieve satisfactory dispersion curves, especially for the circular arrays, while L-shape arrays provided good results only for shallow depths. A synthesis of results is reported in terms of Vs profiles (Fig. 8) together with some conclusions.

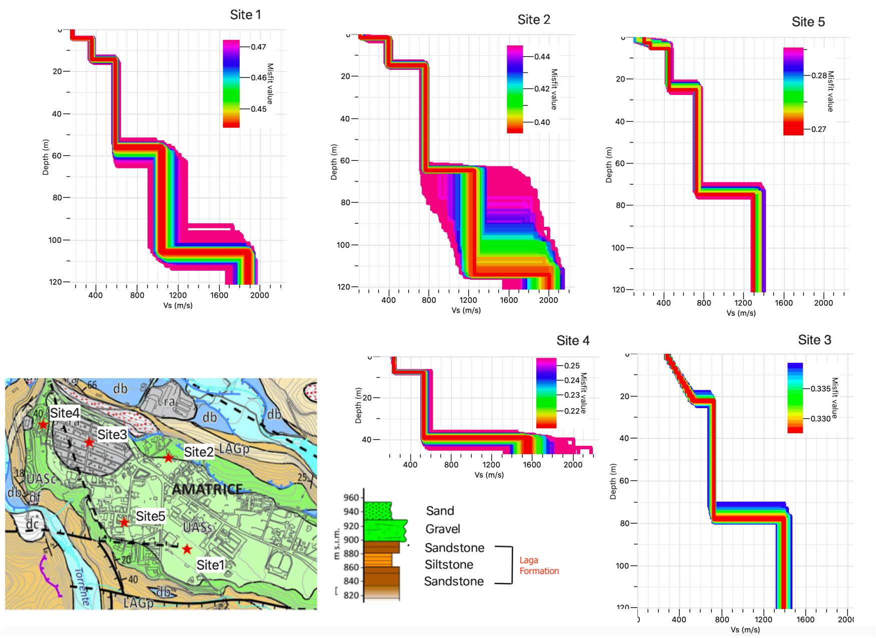

Figure 8 - Vs profiles of the 5 sites investigated and location map with a general stratigraphic log of Amatrice terrace.

All the velocity profiles are obtained by joint inversion of dispersion curve and the part of the HVNSR curve which contains the fundamental resonance peak (occasionally including the autocorrelation curves derived from MSPAC analysis, in case of good results). Site 1, 2 and 5 show similar velocity profiles in terms of depth of the velocity contrasts except Site 5 which does not show the deeper interface expected at around 100 meters. This could be due to the lower resolution of the big array at larger wavelengths compared to the two circular arrays or to a possible difference in the deep geological structure between the three sites (see geological map and section in Fig.1 and Fig. 2).
The velocity profile can be described in terms of geological interpretation as follows from top to bottom:

- a first few-meters thick layer compatible with colluvium;
- a layer with bottom interface that reaches between 15 and 20 meters of depth with average Vs velocity (400 m/s) compatible with a sandy layer;
- a layer with velocity between 600 and 750 m/s which can be interpreted as the gravelly layer with variable percentage of silty-sandy matrix;
- a layer with thickness of around 50 m and average Vs between 1050 and 1250 m/s compatible with the turbiditic Laga Formation;
- a deeper layer for Sites 1 and 2 which was also present in the velocity profile of San Cipriano site in Milana et al. (2020), is still not identified as a main geological feature because there is no evidence from geological investigations at those depths.

Sites 3 and 4 are located in the historical center and the L-shaped configuration of the two arrays was constrained by the logistic of the area. Site 3 gives good results from f-k analysis between 20 and 30 Hz constraining the velocity of the shallower layer. To reconstruct the velocity profile for the deeper part we added the dispersion curve of Milana et al. (2020) obtaining similar results. It is worth to notice that the geological profile from Vignaroli et al. (2019) for the area highlights a deep lateral heterogeneity which can affect the reliability of the result for this site because of the intrinsic limitations of the geophysical technique applied in this study. Conversely, Site 4 velocity profile fits quite well with the geological reconstruction of the site.

We can conclude that these new investigations can contribute to better reconstruct the subsoil of Amatrice in some specific areas but some points are still debatable: the identity of the resonance peak for the Amatrice terrace and the influence of lateral heterogeneities and topographic effects of the historical center in the quantification of the site response of the area. These points can be connected to the wide variability of the geotechnical characteristics of both the UAS continental deposits and the turbiditic Laga formation that can affect HVNSR curves both with a shift in the fundamental resonance frequency or with a lower amplitude of the peak (in case of local smaller impedance contrasts). This variability could be also due to the presence of geological features as the hidden pre-quaternary faults which displays the Laga Formation and suddenly break the lateral continuity of its strata succession. To answer to these open questions, further studies are needed as numerical simulations and other ad-hoc investigations for areas where the subsoil reconstruction is still affected by uncertainties.

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