



Site characterization report at the seismic station IT.PVF – Pavullo nel Frignano (MO)

Report di caratterizzazione di sito presso la stazione sismica IT.PVF – Pavullo nel Frignano (MO)

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Subject: Final report illustrating the site characterization for seismic station IT.PVF	



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INTRODUCTION

In this report we present the geological setting and the geophysical measurements and results obtained in the framework of the 2019-2021 agreement between INGV and DPC, called *Allegato B2: Obiettivo 1 - TASK 2: Caratterizzazione siti accelerometrici* (Responsabili: G. Cultrera, F. Pacor) for the site characterization of station IT.PVF (Pavullo nel Frignano).

Location and coordinates are reported in Table 1.

Table 1

CODE	NAME	LAT [°]	LON [°]	ELEVATION [m]
IT.PVF	Pavullo nel Frignano	44.33310 *	10.82523 *	699 **
ADDRESS	Via Enzo Ferrari, 2, 41026 Pavullo nel Frignano (MO), Italy			

* Coordinates from ITACA (Nov. 2021) ** Elevation from CTR 5k Regione Emilia-Romagna



A. Geological setting

A1. TOPOGRAPHIC AND GEOLOGICAL INFORMATION

Topographic information related to the site are reported in Table 2. Table 3 summarizes all available geological maps from literature for geological analyses.

Table 2

Topography	Description	Topography Class	Morphology Class
	Flat surfaces, isolated slopes and reliefs with slope $i \leq 15^\circ$	T1	Valley edge (VE)

Table 3

Geological map	Source	Scale
IT.PVF	Geological Map of Italy, CARG Project – sheet 236 (Pavullo nel Frignano)	1:50.000
IT.PVF	Geological Map of Emilia-Romagna Region	1:10.000
IT.PVF	Geologic Technical Map of Pavullo nel Frignano Municipality (4) – Seismic Microzonation	1:10.000

In Table 4 Geological, Lithological and Lithotechnical Units (according to Seismic Microzonation classification; Technical Commission SM, 2015) are described and are concerned to maps of following chapters. The term “original” means the result comes from a preexisting cartography (Table 3); the term “deduced” means the result comes from an interpretation of a preexisting cartography according to the nomenclature of corresponding cartography.



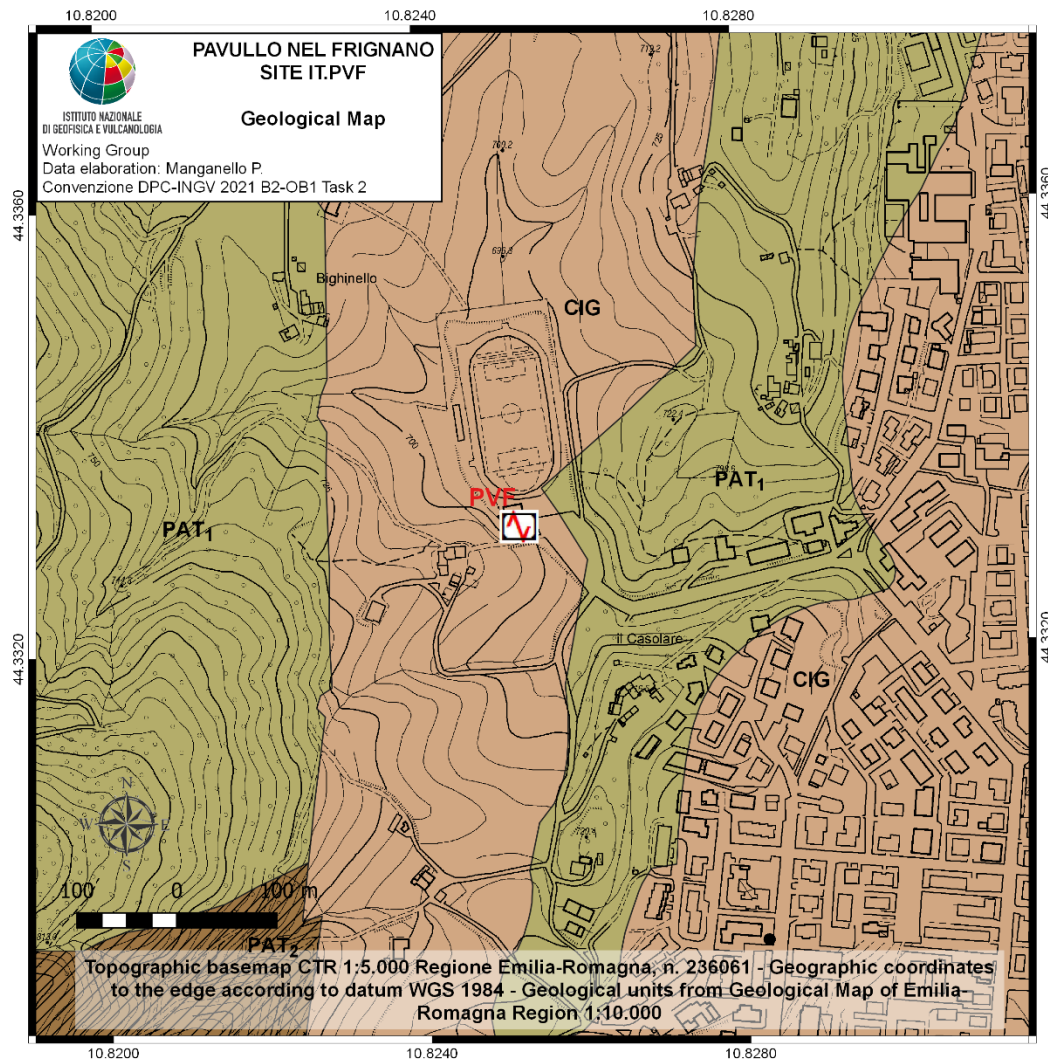
Table 4

GEOLOGICAL UNITS		LITHOLOGICAL UNITS		LITHOTECHNICAL UNITS	
Geological Map of Emilia-Romagna Region 1:10.000 <i>original</i>		Amanti <i>et al.</i> (2008) <i>deduced</i>		(MZS) <i>deduced</i>	
code	description	code	description	code	description
CIG	Cigarell Formation	A7	Silty-sandy marls	SFCOS	Fractured layered overconsolidated cohesive
PAT ₁	Sassoguidano Member (Pantano Formation)	A9	Hybrid arenites	LPS / SFLPS	Layered rock / Fractured layered rock
PAT ₂	Montecuccolo Member (Pantano Formation)	A11	Limestone- sandstone alternance	SFLPS	Fractured layered rock




A2. GEOLOGICAL MAP


In Figure 1 Geological Map is reported in a 1 km × 1 km square around the station.




Legend

 Seismic station
Stazione sismica

EPILIGURIAN SUCCESSION -
BISMANTOVA GROUP
SUCCESIONE EPILIGURE -
GRUPPO DI BISMANTOVA

 CIG - Cigarellò Formation
(Lower Langhian - Upper Serravallian)
CIG - Formazione di Cigarellò
(Langhiano Inferiore - Serravalliano Superiore)

 PAT1 - Sassoguidano Member
(Upper Burdigalian ? - Lower Langhian ?)
PAT1 - Membro di Sassoguidano
(Burdigaliano Superiore ? - Langhiano Inferiore ?)


 PAT2 - Montecuccolo Member
(Upper Burdigalian ? - Lower Langhian ?)
PAT2 - Membro di Montecuccolo
(Burdigaliano Superiore ? - Langhiano Inferiore ?)

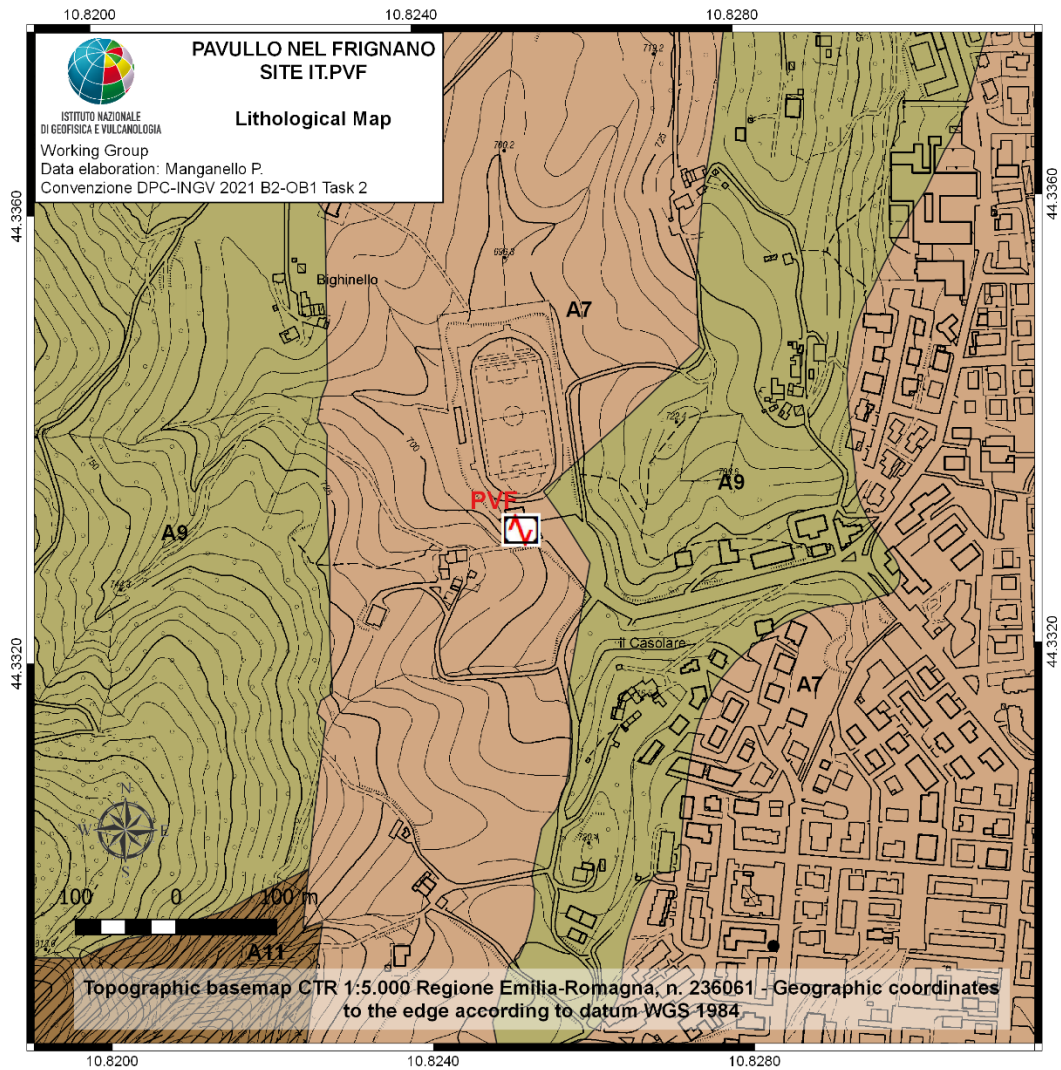
Figure 1: Geological map of seismic station IT.PVF. Scale 1:5.000. Geological units come from Geological Map of Emilia-Romagna 1:10.000.

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Cite as: Working group INGV "Agreement DPC-INGV 2019-21, All. B2- WP1, Task 2" (2021). Site characterization report at the seismic station IT.PVF - Pavullo nel Frignano (MO). <http://hdl.handle.net/2122/15038>



A3. LITHOLOGICAL MAP

In Figure 2 Lithological Map is reported in a $1\text{ km} \times 1\text{ km}$ square around the station.



Legend

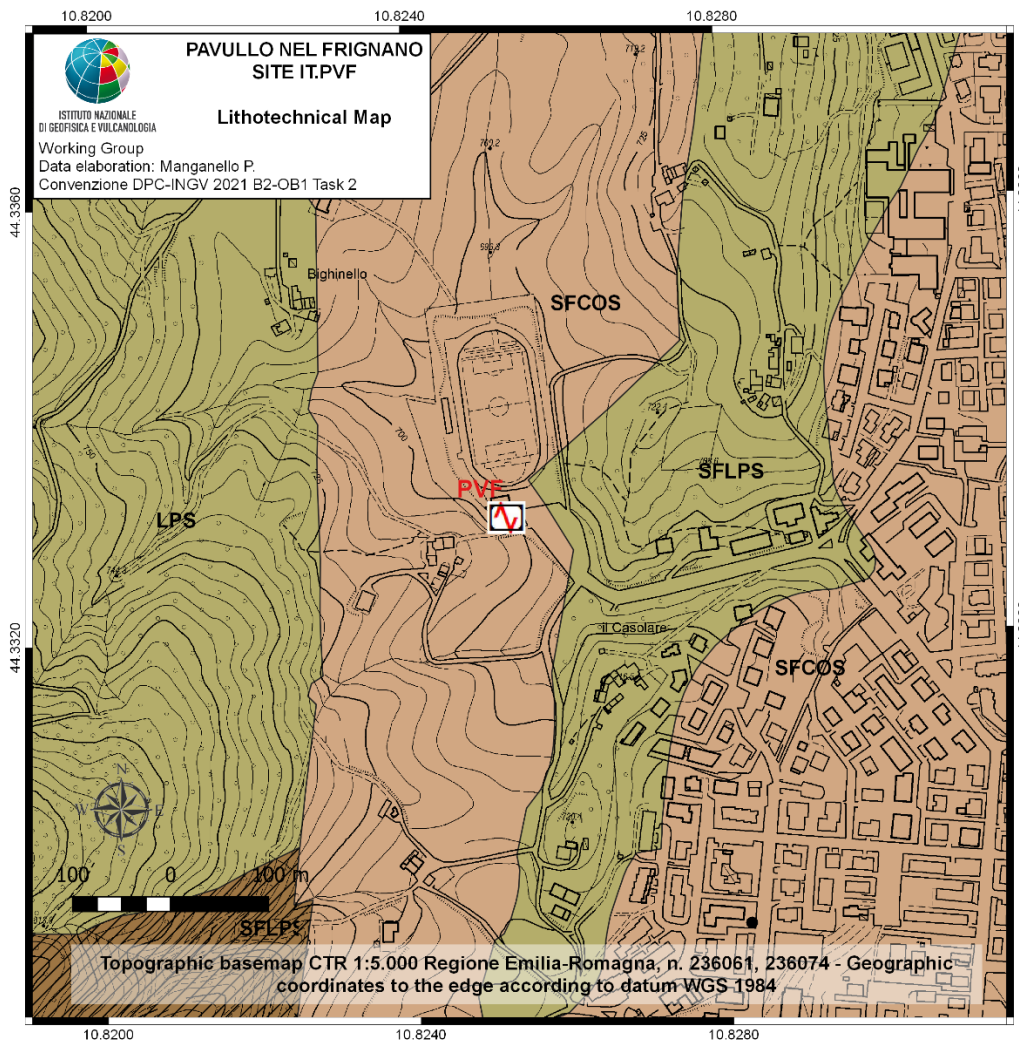
- | | |
|---|---|
| Seismic station
Stazione sismica | A9 - Hybrid arenites
A9 - Areniti ibride |
| Lithological units
Unità litologiche | A11 - Limestone-sandstone alternance
A11 - Complesso calcareo-arenaceo |
| A7 - Silty-sandy marls
A7 - Marne siltoso-sabbiose | |

Figure 2: Lithological map of the seismic station IT.PVF. Scale 1:5.000. The codes of the lithological units are assigned according to the nomenclature of the Lithological map of Italy ISPRA 1:100.000 (Amanti *et al.*, 2008).




A4. LITHOTECHNICAL MAP


In Figure 3 Lithotechnical Map is reported in a $1\text{ km} \times 1\text{ km}$ square around the station.




Legend

 Seismic station
Stazione sismica

GEOLOGICAL SUBSTRATE SUBSTRATO GEOLOGICO

 SFCOS - Fractured layered overconsolidated cohesive
SFCOS - Coesivo sovraconsolidato stratificato fratturato

 LPS - Layered rock
LPS - Lapideo stratificato

 SFLPS - Fractured layered rock
SFLPS - Lapideo stratificato fratturato


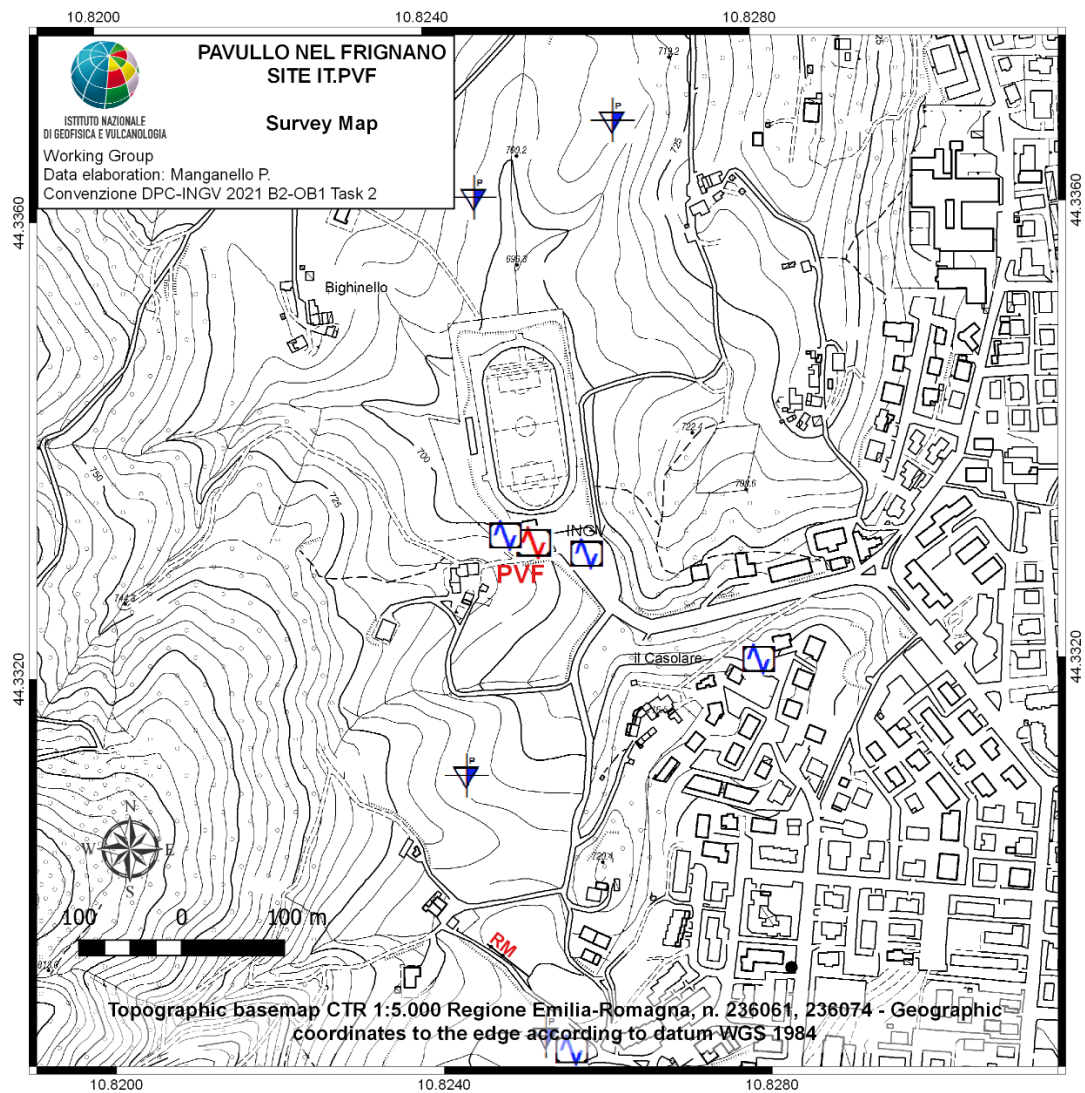
 SFLPS - Fractured layered rock
SFLPS - Lapideo stratificato fratturato

Figure 3: Lithotechnical map of the seismic station IT.PVF. Scale 1:5.000. The lithotechnical units are assigned according to the nomenclature of Seismic Microzonation (Technical Commission SM, 2015).



A5. SURVEY MAP

Figure 4 shows the Survey Map reporting both previous investigations and geophysical surveys conducted by INGV Working Group.



Legend

- | | |
|-------------------------------------|--|
| Seismic station
Stazione sismica | Heavy dynamic penetrometer test
Prova penetrometrica dinamica pesante |
| | HVSr |
| | Refraction Microtremor |
| | INGV 8-stations array
INGV array 8-stazioni |

Figure 4: Map of the surveys in the surroundings of the station IT.PVF. Scale 1:5.000.

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Cite as: Working group INGV "Agreement DPC-INGV 2019-21, All. B2- WP1, Task 2" (2021). Site characterization report at the seismic station *IT.PVF - Pavullo nel Frignano (MO)*. <http://hdl.handle.net/2122/15038>



A6. GEOLOGICAL MODEL

6.1 General description

The seismic station IT.PVF is installed in the territory of Pavullo nel Frignano Municipality (Modena Province).

From a geological point of view the study area is related to the evolution of the Emilian slope of Northern Apennines, which are an active NW-SE trending thrust and fold belt originated in the Tertiary age as a consequence of the collision between two continental blocks, European plate and the Adria microplate, connected at the beginning with the African plate. The main orogenic phases and the piling of nappes started in the Oligocene – Miocene limit. In the Northern Apennines are present different paleogeographic domains: Ligurian Domain (magmatic-sedimentary successions consisting in the remnants of the Piedmont-Ligurian ocean), Subligurian Domain (Paleocene – lowermost Miocene), Umbro-Tuscan Domain (successions of the continental margin of Adria plate), Epiligurian Domain (wedge-top sediments deposited from Middle Eocene). The Epiligurian units lie on top of the Ligurian Succession through a regional angular unconformity and are not importantly deformed by the Ligurian tectonic phases (Abbate *et al.*, 1970; Elter *et al.*, 2012; Comune di Pavullo, 2013; Conti *et al.*, 2020).

In particular the study area is characterized by the presence of two formations of the Bismantova Group of Epiligurian succession: Pantano Formation (Sassoguidano Member and Montecuccolo Member) and Cigarellino Formation.

6.2 Geological section

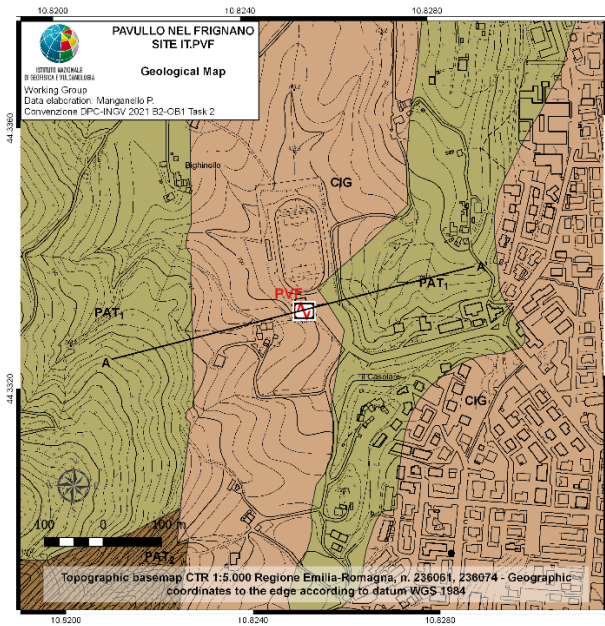
In the surroundings of the IT.PVF seismic station there are not boreholes, and the executed surveys are represented by Heavy Dynamic Penetrometer Tests, Refraction Microtremor survey and single station ambient vibration measurements (HVSr).



The WSW-ENE oriented geological section highlights the geological and structural setting of the IT.PVF site. The trace with the location of the section is reported as a black line in the geological map (Fig. 5 upper left).

6.3 Subsoil model

The geological description reported from the surface to the bottom is described in the following part. A subsoil model is built up to a depth of 35 *m* on the basis of geological and stratigraphic information (Figure 5 bottom). The stratigraphic succession shows the presence of the Cigarellino Formation (Lower Langhian - Upper Serravallian), which belongs to the Bismantova Group of Epiligurian Succession. Two inactive normal faults mark the contact between the Cigarellino Formation (CIG) and the Sassoguidano Member of the Pantano Formation (PAT₁).



Legend

Seismic station
Stazione sismica

EPILIGURIAN SUCCESION -
BISMANTOVA GROUP

SUCCESSIONE EPIILIGURE -
GRUPPO DI BISMANTOVA

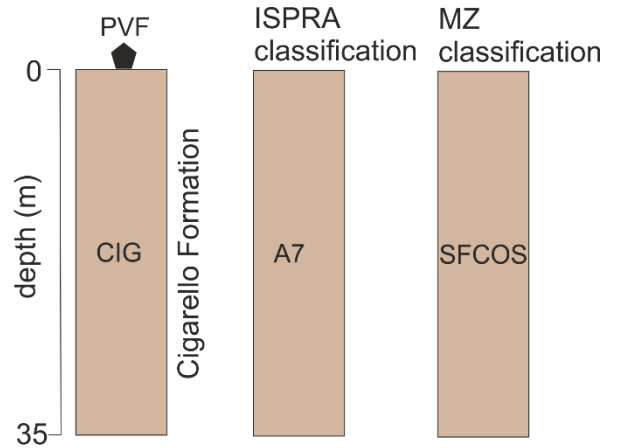
CIG - Cigarello Formation
(Lower Langhian - Upper Serravallian)

CIG - Formazione di Cigarello
(Langhiano Inferiore - Serravalliano Superiore)

PAT1 - Sassoguidano Member
(Upper Burdigalian ? - Lower Langhian ?)
PAT1 - Membro di Sassoguidano
(Burdigaliano Superiore ? - Langhiano Inferiore ?)

PAT2 - Montecuccolo Member
(Upper Burdigalian ? - Lower Langhian ?)
PAT2 - Membro di Montecuccolo
(Burdigaliano Superiore ? - Langhiano Inferiore ?)

Trace of geological section
Sezione geologica



m a.s.l.

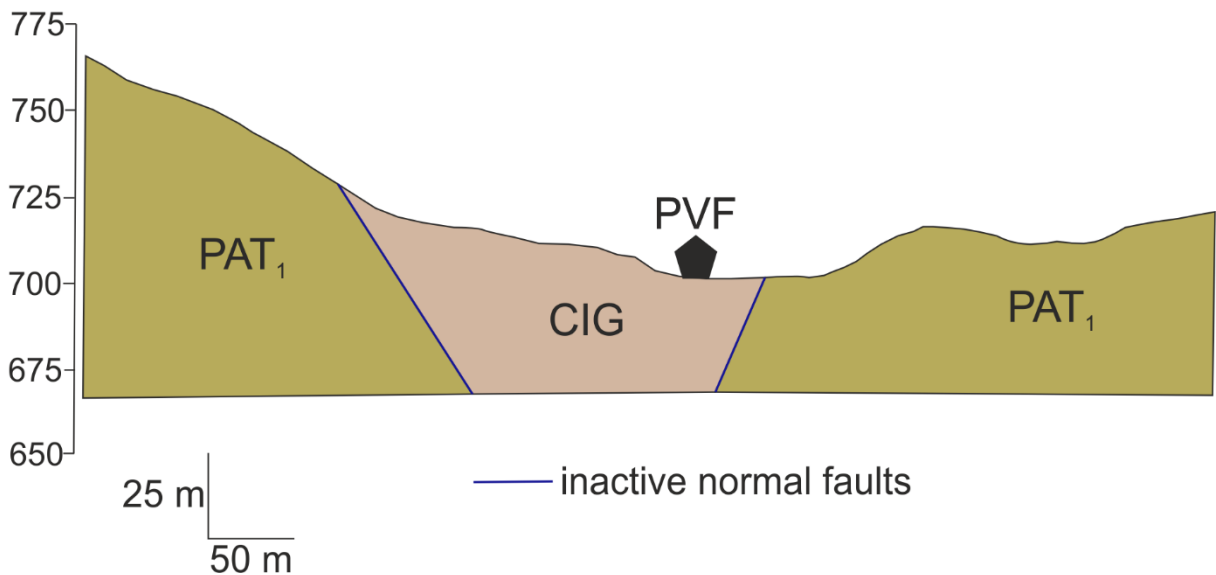


Figure 5: Upper left: Geological map of the study area where is installed IT.PVF seismic station. Upper right: Geological section. Bottom: Subsoil model for the site.



B. V_s profile

B1. GEOPHYSICAL INVESTIGATIONS

Geophysical measurements executed nearby the station PVF of the network IT (PCM-DPC, 1972) consist in ambient-vibration measurements in both single-station and 2D array configuration (Figure 6) that provide results in terms of resonance frequency of the soil deposits and in terms of dispersion curves of surface waves. These curves are inverted to obtain a shear-wave velocity (V_s) profile that, together with the geological study at section A, is suitable for assigning the soil class according to the current Italian seismic code (NTC18) and Eurocode (EC8). Figure 7 shows the location of the station IT.PVF (Latitude 44.33310, Longitude 10.82523 WGS84) installed in Pavullo nel Frignano (MO).

Seismic noise is acquired using 8 Reftek-130 24-bits recording systems equipped with short-period Lennartz LE-3D/5s sensors and GPS timing (Figure 7). The sampling rate is fixed to 200 Hz, while the gain is set as “high”. Ambient noise recordings have a minimum duration of 1 hour. The array geometry (Figure 8) is chosen in order to have a good coverage of both azimuths and inter-station distances, the latter between the minimum (about 10 m) and the maximum (about 30 m). These ranges allow the analysis of a range of wavelengths that guarantee sufficient shallow resolution (Okada, 2003) in order to estimate the $V_{s,30}$ and the site-class according to current building codes (i.e. NTC18 and EC8).



Figure 6: Map of the geophysical measurements performed at the IT.PVF site. The yellow place-markers indicate the geometry used for 2D array in passive configuration. The red triangle indicates the IT.PVF accelerometric station (image from Google Earth <http://www.earth.google.com>).



Figure 7: Left: IT.PVF accelerometric station installed in Pavullo nel Frignano (MO). Upper right: Single station ambient noise measurement. Bottom right: 2D passive ambient noise array installed close to the IT.PVF station.

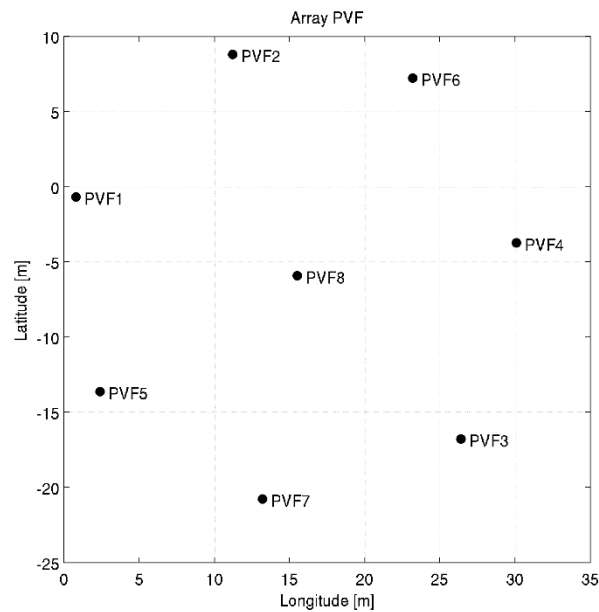
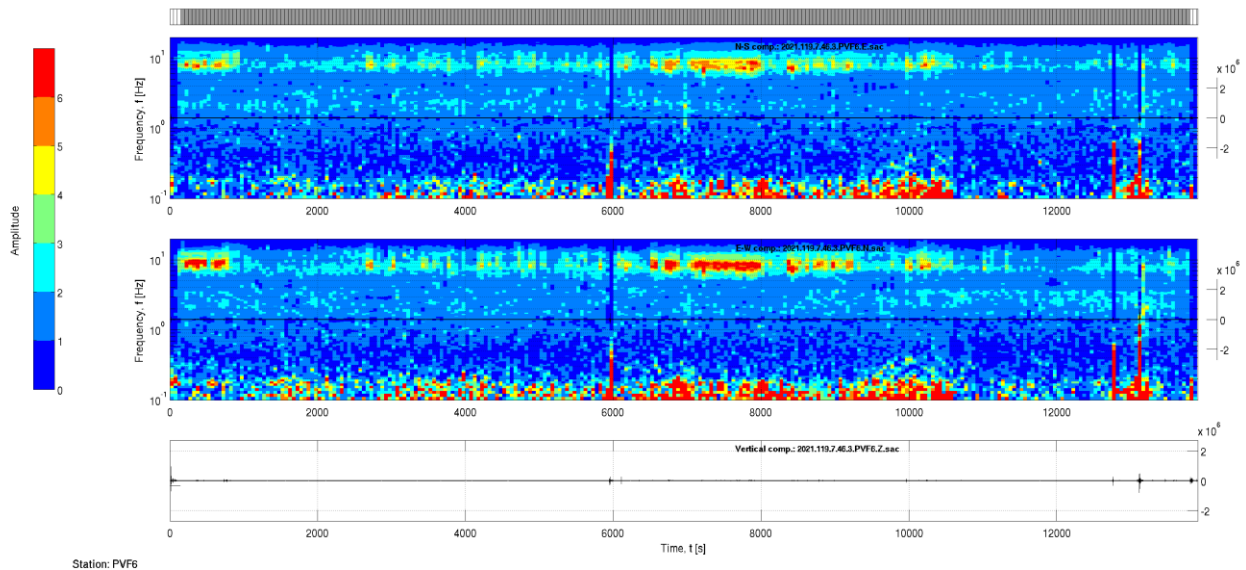


Figure 8: Array geometry.

The first step of the analysis consists in a visual inspection of the recordings at each station of the array. In particular, in order to identify malfunctioning and to select signal windows suitable for the surface wave analysis, the quality of the recording is evaluated analyzing the signal stationarity in the time domain, the relevant unfiltered Fourier spectra, and the H/V variation over time. Figures 9 and 10 provide graphical results about station PVF6.

It is common practice during surface wave investigation to verify the reliability of the one-dimensional site structure assumption (Aki, 1957; Okada, 2003). For this reason, we estimated the HVSR at each station of the array and the stability of HVSR among the array stations has been verified. Figure 11 depicts the HVSR assumed as representative for the array.



Station: PVF6

Figure 9: HVSR versus time (top and central panel for the NS and EW component, respectively) and corresponding time-histories.

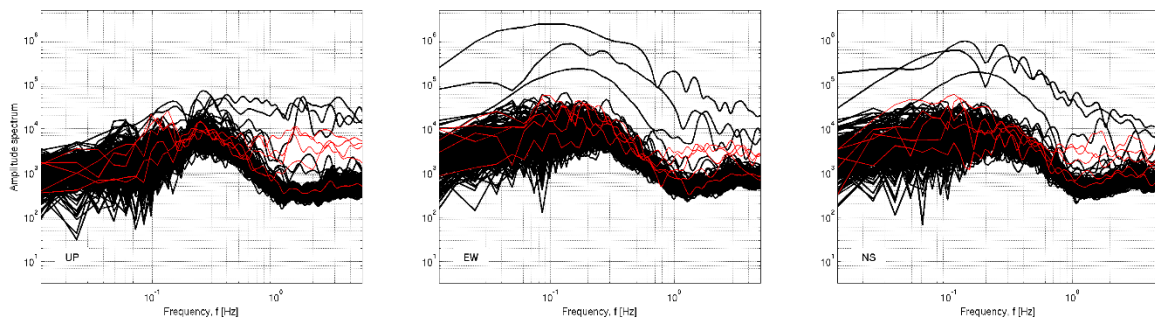


Figure 10: Fourier spectra for each noise window (left: Vertical, center: EW, right: NS). Red spectra are excluded from HVSR analysis.

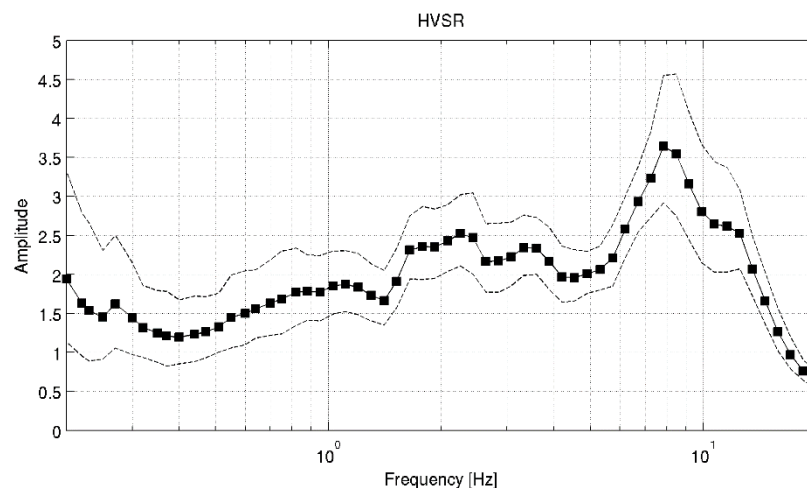


Figure 11: HVSR representative for the array. Dashed lines represent \pm one standard deviation.



The Rayleigh-wave dispersion curve is estimated by analyzing the vertical component of the recorded seismic noise. In particular, the Extended Spatial Auto-Correlation (ESAC; Ohori *et al.*, 2002; Okada, 2003) and the frequency-wavenumber (F-K; Lacoss *et al.*, 1969; Capon, 1969) methods are adopted. Further details about the combined use of ESAC and F-K approaches can be found in Parolai *et al.* (2006).

Both analyses use 80 synchronized signal windows of 60 s each, extracted from recordings within the UTC date-time interval 2021-04-29 07:55:00 – 2021-04-29 09:15:00, avoiding time periods affected by local disturbance (after this time-frame acquisition was affected by rainy conditions).

The ESAC Rayleigh-wave dispersion curve is obtained by minimizing the root-mean-square (RMS) of the differences between experimental and theoretical Bessel functions (Figure 12). Values differing by more than two standard deviations from those estimated by the best fitting functions are automatically discarded (red circles in Figure 12) and the procedure is repeated iteratively. For this data set, data are also discarded whenever the inter-station distance is 2 times longer than the relevant wavelength. Figure 13 shows the Rayleigh-wave dispersion curve estimated using the ESAC approach.

The F-K analysis allows checking on the noise source distribution. One of the basic assumptions for the application of the ESAC method is indeed that the seismic noise wavefield is nearly isotropic. Figures 14 and 15 show results of the F-K analysis in terms of power density function for several frequencies using the Maximum Likelihood Method (MLM) and the Beam Forming (BF) respectively. Figure 16 shows the bad agreement between the Rayleigh wave dispersion curves estimated by both ESAC and F-K approaches, probably due to the low-quality of acquired data in the high-frequency range, caused by rainy conditions.

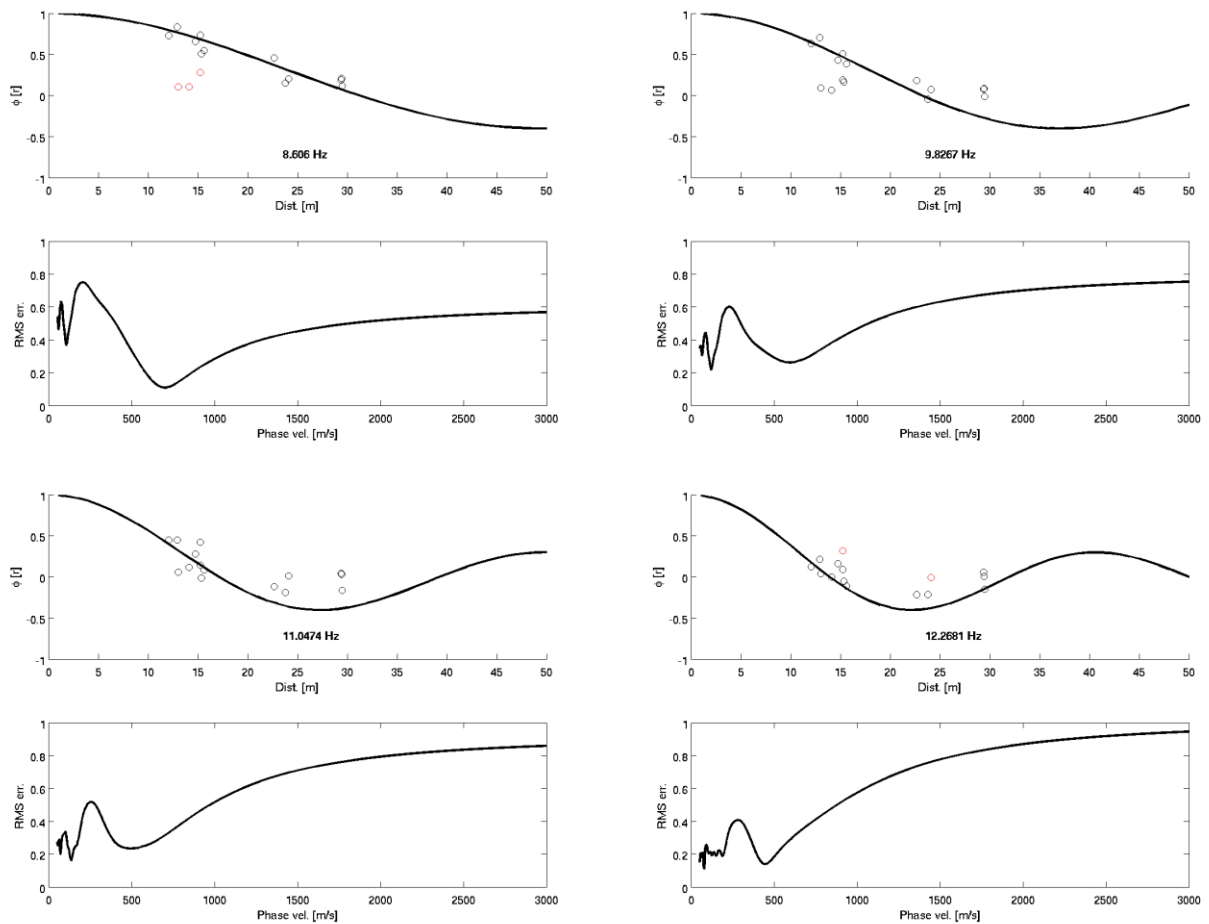


Figure 12: Experimental space-correlation function values versus distance (circles) for different frequencies. The red circles indicate values that are discarded. The black lines depict the estimated space-correlation function values for the phase velocity that furnishes the best fit to the data. The bottom panels show the relevant root-mean-square errors (RMS) versus phase velocity tested.

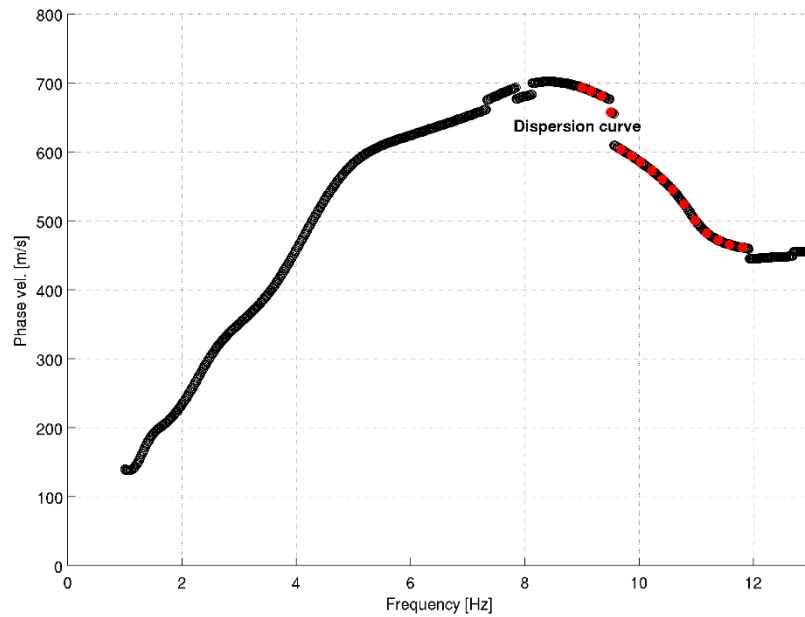


Figure 13: Rayleigh-wave dispersion curve from ESAC. Red-filled circles represent values potentially used for inversions.

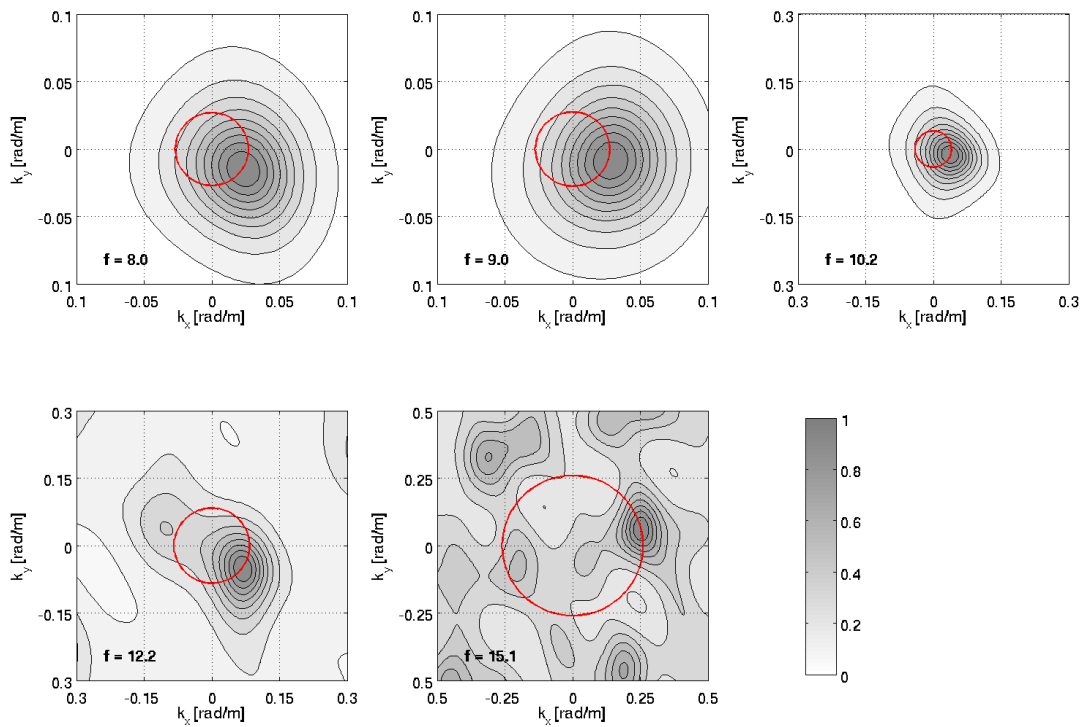


Figure 14: F-K power density function (Maximum-Likelihood Method) at selected frequencies.

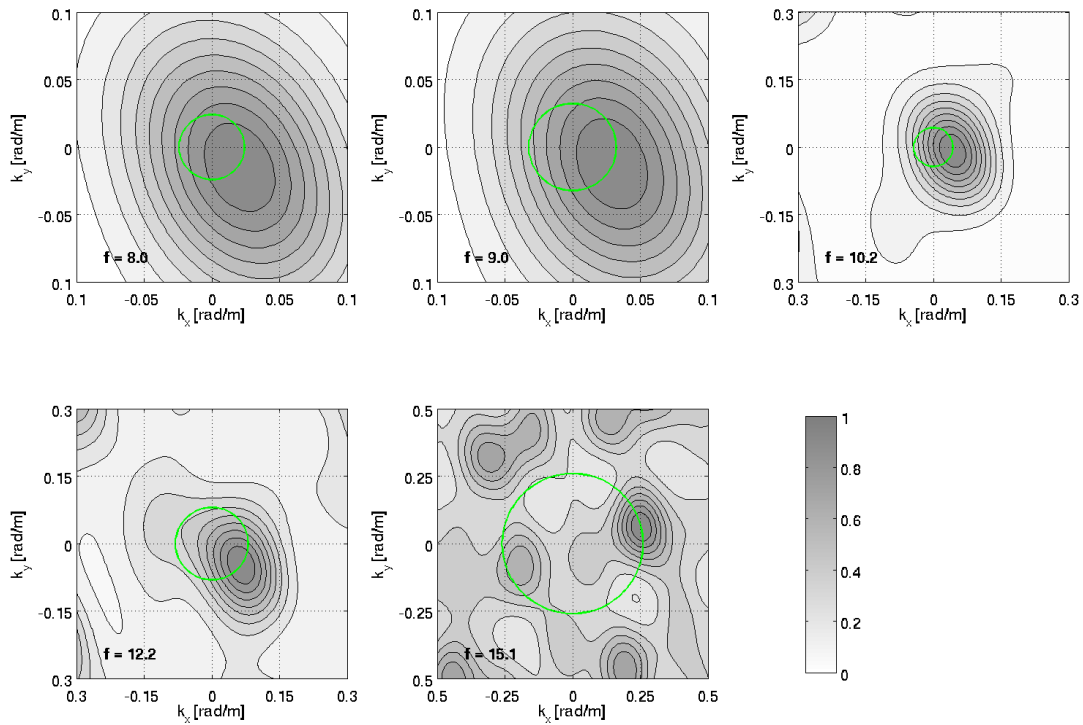


Figure 15: F-K power density function (Beam-Forming) at selected frequencies.

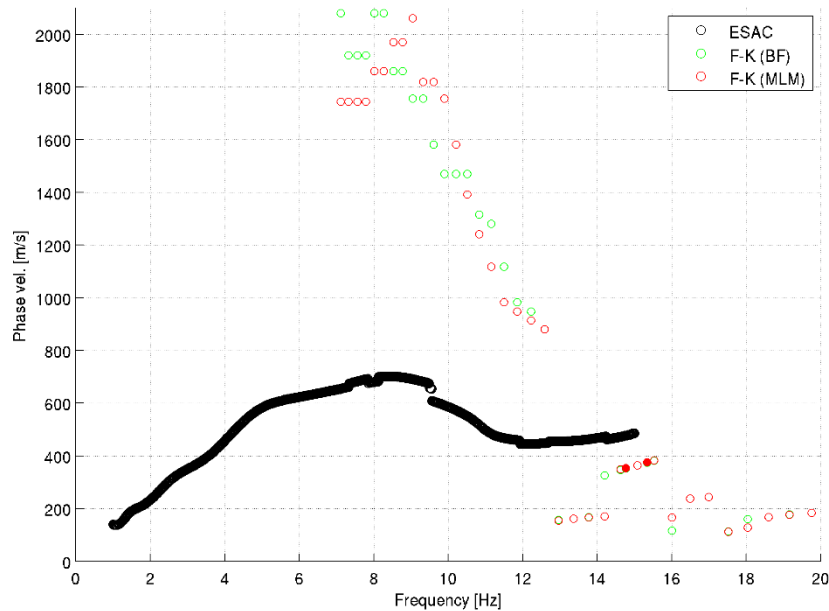


Figure 16: Comparison of experimental phase velocity estimated by the ESAC and the F-K (for both Beam-Forming and Maximum-Likelihood Method) methods. Filled circles represent values potentially used for inversions.



B2. SEISMIC VELOCITY MODEL

The non-linear inversions are performed using the software *joinv6* (Parolai *et al.*, 2005; Giustiniani *et al.*, 2020), which adopt a genetic algorithm (Yamanaka and Ishida, 1996). The forward modelling of Rayleigh wave phase velocities and HVSR curves is performed under the assumption of a vertically heterogeneous 1D Earth model using the modified Thomson-Haskell method proposed by Wang (1999) and following the suggestions of Arai and Tokimatsu (2004) and Tokimatsu *et al.* (1992). The modelling is not restricted to the fundamental mode, preserving the possibility that higher modes participate in simulating the observed dispersion and HVSR curves.

The experimental dispersion curve used as input for inversions is the one estimated from the ESAC analysis in the frequency interval 9-12 Hz. The experimental HVSR is used between about 5 and 15 Hz. In the left panel of Figure 17 tested models are shown in different colors according to their cost value: the more reliable model (minimum cost) is in white, the models lying inside the 10% range of the minimum cost are in black and the other tested models are shown in grey. In the right-central and right-bottom panels of Figure 17 agreement between experimental and theoretical (grey and open circles, respectively) Rayleigh-wave dispersion curves and HVSR are shown. The agreement is good and, considering the wavelengths related to the dispersion curve frequency range, the V_s profile between about 5-35 m is quite-well constrained. Table 5 reports the minimum-cost shear-wave velocity model.

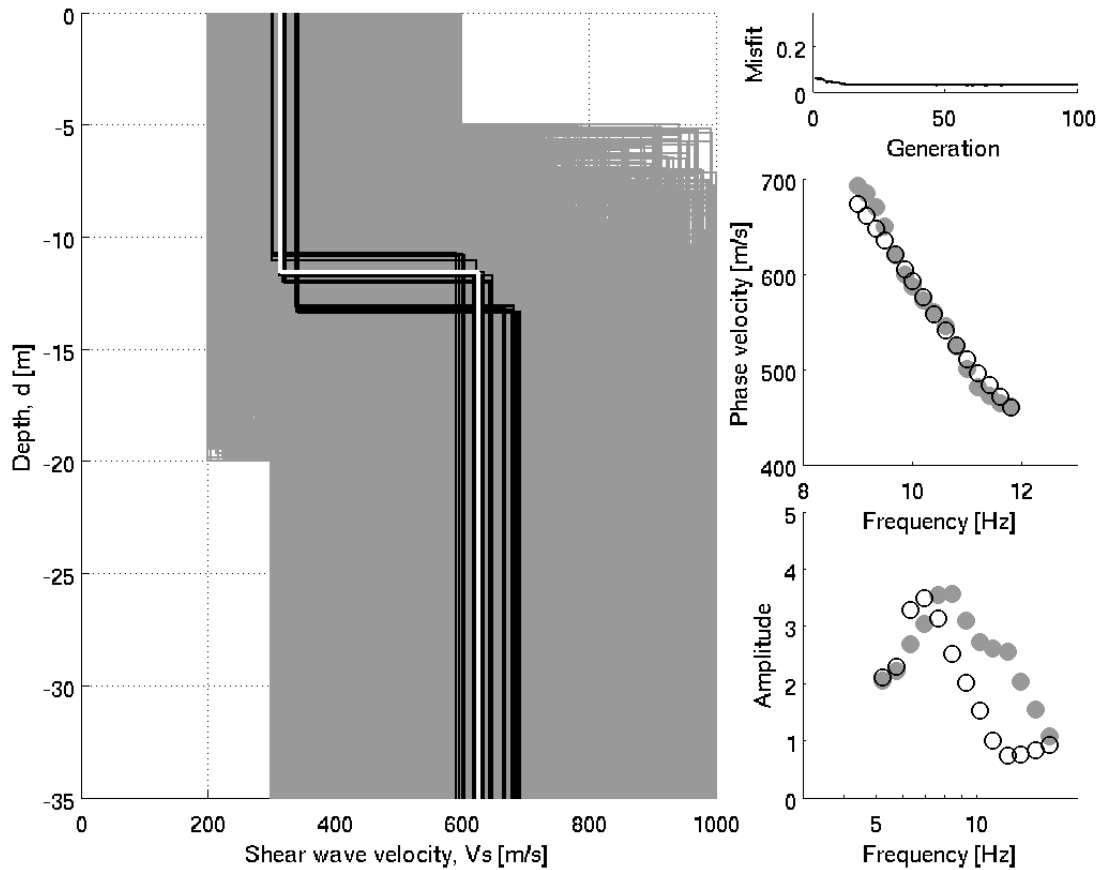


Figure 17: Shear-wave velocity models modeled during the inversion procedure (left panel): tested models (grey lines), the minimum cost model (white line) and models lying inside the minimum cost + 10% range (black lines); the generation values versus misfit (right-upper panel); the fitting of experimental data (grey circles) and empirical values relative to the minimum cost model (white circles) relevant to the dispersion curve (right-central panel) and to HVSR (right-bottom panel).

Table 5: Best-fit shear-wave velocity model

From [m]	To [m]	Thickness [m]	V_s [m/s]
0	11.6	11.6	314
11.6	-	-	627



B3. CONCLUSIONS

As evinced from results of geophysical investigations carried out by INGV Working Group, we can attribute to the Cigarello Formation V_s values between 314 and 627 m/s , compatible with EC8 class assigned at the site according to geological evidences.

According to the current Italian seismic code (NTC18), if the bedrock ($V_s > 800 m/s$) is more than 30 m in depth, the equivalent velocity ($V_{s,eq}$) is equal to the $V_{s,30}$. From Figure 17, the velocity of 800 m/s is reached for an unknown depth, well below the depth of 30 m .

Therefore, in this case, both $V_{s,eq}$ and $V_{s,30}$ are equal to 453 m/s . Of consequence, IT.PVF site is classified in the soil category B, for both the NTC18 and EC8 seismic codes (Table 6).

Table 6: $V_{s,eq}$, $V_{s,30}$ and soil classes

$V_{s,eq} = V_{s,30}$ [m/s]	Soil class (NTC18)	Soil class (EC8)
453	B	B

ACKNOWLEDGEMENTS

Authors wish to thank Stefano Parolai, Paolo Bernardi and Ilaria Dreossi (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale – OGS), for providing us the software “joinv6”, which has been adopted as inversion procedure to estimate the shear-wave velocity model, and for the precious guide in its usage.



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