Velocity profile report at the seismic stations IT.TER – Teramo (TE)

Report sul profilo di velocità sismica per il sito della stazione sismica IT.TER – Teramo (TE)

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Subject: Final report illustrating measurements, analysis and results for Vs profile at seismic station IT.TER
Summary

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1. Introduction

In this report, we present the geophysical measurements and the results obtained in the framework of the 2019-2021 agreement between INGV and DPC, called Allegato B2: Obiettivo 1 – Task B: Caratterizzazione siti accelerometrici (Coord.: G. Cultrera, F. Pacor) for the characterization of sites of the Italian National Seismic Network (RSN) with accelerometers. Here the results for IT.TER station are presented.

We performed a MASW survey with active source and 72 vertical geophones installed at margin of the road close to the seismic station IT.TER. In combination with the MASW survey, we also installed 8 seismic stations for ambient seismic noise measurements. Using surface-wave frequency-wavenumber analysis, we provide results in terms of resonant peaks and dispersion curves inverted to obtain shear-wave velocity ($V_s$) profiles for the studied area. The inverted models are suitable for determination of the average $V_s$ velocity in the uppermost 30 m ($V_{s30}$) and assigning then the soil class category as prescribed by building codes (EC8, NC8 or NC18).
2. Geophysical investigation

IT.TER seismic station is located in the city of Teramo, in the southern part of Piano Solare neighbourhood, in the garden of “La Coccinella” nursery school, at the border of Felice Barnabei road. Figure 1 shows the location of IT.TER station (blue marker), the position of the geophones line used for MASW survey (orange line in Fig. 1) and the locations of temporary seismic stations deployed in the target area (yellow markers in Fig. 1). The linear array was performed using 72 vertical geophones equipped with vertical sensors (4.5 Hz natural frequency). Noise measurements were performed by 7 stations equipped with triaxial geophones (4.5 Hz natural frequency, Terrabot stations by Sara Electronics; the TB stations in Fig. 1) and 1 station composed of a reftek130 digitizer with Lennartz-5s sensor (Le5s+ref station in Fig. 1). All the geophysical measurements were recorded the 20th September of 2019.

Figure 1: Plan view of the geophysical surveys in Teramo city, near the IT.TER station (blue triangle). The orange line shows the linear MASW array using the 72 vertical geophones, the yellow marks indicate the positions of the 8 temporary seismic stations deployed for seismic noise acquisition.
2.1 H/V spectral ratio from temporary seismic noise measurements

Figures 2 and 3 show the actual H/V curves for the 8 temporary seismic stations. For all stations and in the frequency range 0.5-6 Hz, there is a good agreement of the H/V shapes without pronounced spectral peaks and with amplitudes lower than 2. At higher frequencies, between 8-15 Hz, there are spectral H/V peaks higher than 2 for the stations installed along the Barnabei road (TB00, TB05 and TB06). Such peaks are not observed at the other stations, including those installed a few meters from the IT.TER station. These high frequency peaks observed at the three stations could be related to the proximity of the road or to the presence of very thin layers near the slope that skirts the southern edge of road.

Figure 2: Plan view of the seismic noise measurements with the corresponding H/V noise spectral ratios. The seismic stations recorded ambient vibrations for about two hours.
Figure 3: Comparison of H/V spectral ratios (mean curves) computed for the different temporary seismic stations installed in the target area.

Please note that a microzonation study (MZS Teramo) of level 3 (http://www.sisma2016abruzzo.it/index.php/11-informazioni-di-servizio/98-microzonazione-sismica-di-iii-livello) was available for Teramo from March 2019. The closest noise record provided by MZS is named P342 and is located about 150 m north from our measurements (intersection between Via Cona and Via Barnabei), with \( f_0 \) assigned equal to 3.72 Hz. A weak H/V peak at this frequency is also visible in our measurements in Fig. 3.

### 2.2 Linear Array measurements results

The vertical geophones used during the survey were lined up in a straight line (parallel to the Felice Barnabei road; see Fig. 1) and were equally spaced of 1 m. For the MASW analysis, we acquired the seismic signals produced by the impact of a 5 kg hammer on the ground. The shots were made along the line at distances of -5 m, -1m, 36.5 m, 71 m and 76 m from the first geophone (considered at 0m). In each shot point, the measurements were repeated three times in order to increase the signal-to-noise ratio. The seismic data were acquired using...
three multichannels systems (Geode manufactured by Geometrics) with a sampling rate of 0.125 ms for a duration of 2 s. Figure 4 illustrates the measurements performed along via Felice Barnabei.

Figure 4: Photos showing the linear array of geophones deployed in the margin of Via F. Barnabei (Teramo). IT.TER station is housed inside the gray box visible in the photos (indicated by the red arrow). Terrabot equipment (in red) is visible in the center and right photos. The reftek connected to Le3d-5s (in blue) is visible in the right photo.

The acquired data were processed using the GEOPY software tools (www.geopsy.org) in order to extract the surface-wave dispersion properties of subsoil by applying frequency-wavenumber (FK) transform to the seismic signals. Figure 5 shows the results obtained with the linear active survey (MASW). A fairly clear dispersion curve (from 20 Hz up to 80-100 Hz) is obtained for shots with offset -5 m, -1m and 36.5 m from the first geophone, although the middle shots (offset 36.5) provide lower apparent velocities. For the shots at the end of acquisition line (offset at 72 m and 76 m), FK analysis do not highlight a clear dispersion curve appearing more noisy and disturbed with respect to the other shots.
Figure 5: FK analysis. The results obtained by linear MASW array for each single shot are shown; from top to down the offset is -5 m, -1 m, 36.5 m, 36.5 m, 72 m and 76 m. Plots in the same horizontal panel refer to the same shot location. The plots in the last column represent the stack image obtained for the same offset. For the central offset (36.5 m), there are 6 different results because the data are processed in forward (geophones from #1 to #36) and reverse (geophones from #37 to #72) mode, respectively.
2.3 Results from 2D Array measurements

We acquired also passive data at the linear array (with the same equipment used in the MASW active survey). Passive data (or noise) were acquired in 15 time windows of 240 s length (4 minutes) at a sampling rate of 4 ms. Merging the data of selected geophones (along linear array) in seismic noise acquisition with the temporary seismic stations, we constructed a dataset from a 2D array with a L-shaped geometrical configuration (Fig. 6). The time synchronization between geophones and seismic stations was provided through a cross-correlation analysis in the frequency band 5-7 Hz, based on the time windows acquired at geophone #61 and TB00, about 2 m away from each other. The final 2D array with L-shaped geometry (Fig. 6) was composed of 19 stations (7 Terrabot, 1 reftek connect to Le3d5s, and 11 vertical 4.5 geophones).

The resulting synchronized data of the 2D array have been analysed in terms of conventional frequency-wavenumber (FK) analysis to the vertical component of the noise. The results were interpreted in terms of Rayleigh surface-waves (http://www.geopsy.org). Figure 6 shows the dispersion results; the apparent velocity values are ranging from about 900 m/s (at 15 Hz) up to about 700 m/s at 20 Hz. The dispersion curve in Fig. 6 derived from 2D passive array was integrated to the one obtained from MASW analysis.
Figure 6: Left) Geometry of the 2D array. Stations within the array are represented by a red triangle. Right) FK analysis performed on data acquired by 2D array. Results are shown in the velocity-frequency plan; the theoretical resolution ($K_{\text{min}}/2$, $K_{\text{min}}$) and alias limits ($K_{\text{max}}/2$, $K_{\text{max}}$) are also overlaid as black (solid and dashed) curves.
3. 1D seismic velocity model

We extract a combined dispersion curve integrating the results of both linear and 2D arrays, aimed at reconstructing the 1D velocity model. For the linear MASW survey, we selected the dispersion curves at offset -5 m and at -1 m that show a more continuous feature than the others, and are better connected with results of 2D array around 20-25 Hz. Figure 7 shows the dispersion curve picked from the 2D array (black curve with error bars) and the curves from MASW analysis. The two curves at offset -5m and -1m were cut at 40 Hz, and resampled with 30 points; the error bars was also introduced following the uncertainties shown in Fig. 5. The final dispersion curve used as target in the inversion procedure is shown in Fig. 8.

To proceed with the inversion step, the dispersion curve derived from the vertical component of motion has been associated with the fundamental mode of Rayleigh surface-waves. Then, we inverted the apparent surface-wave dispersion curve of Fig. 8 aimed at recovering the shear-wave velocity (Vs) model. Because the HV curves were almost flat at least up to 6 Hz (see Fig. 3), they were not considered during the inversion step.

The resulting models after the inversion of the dispersion curve are shown in Fig. 9. We tested several model parameterization composed of one or two main layers over halfspace, where in the first layer a Vs increasing with depth was also allowed (following a linear-law or a power-law). Vs models (Figs. 9 and 10) show velocity values increasing from 100 m/s up to 280 m/s in the uppermost layer (about 2 m thick). A layer with Vs of about 520 m/s is found from depth to 2 m up to 12 m deep. The reference layer is therefore found by the inversion at 12 m deep. The best Vp and Vs models (i.e. lowest misfit) resulting from the inversion are proposed in Fig. 10 and Table 1. For comparison, we show also the closest MASW (Fig. 11) and well (Fig. 12) provided by the MZS III level (called L62 and P281 in MZS Teramo level III, respectively), both carried out about 150 m north our survey. Our model shows on the average larger velocity of the bottom layer with respect to the MZS one, and a good match with the stratigraphy (Fig. 12) in terms of depth of the marls substratum (found at about 12 m).
Figure 7: Comparison between dispersion curves by 2D passive array and 1D active array (curves with offset equal to -5m, -1m, 36.5 m and 72 m are shown). The final dispersion curve selected for the inversion step was provided by the 2D array (black curve with vertical bars within 16-20 Hz) and the curves at offset -5 and -1 m. The curves at offset 36.5 and 72 m were not considered.
Figure 8: The final dispersion curve selected for the inversion step was provided by the 2D array (black curve with vertical bars within 16-20 Hz) and the red curve (within 22-38 Hz which was obtained as an average between the masw curves with offset -5 and -1 m).

Figure 9: Resulting models after the inversion of the dispersion curves (the field dispersion is shown in black colour). The best Vs model is presented in Fig. 10.


Figure 10: Best Vp and Vs models after the inversion of the dispersion curve.

Figure 11: MASW named L62 from MZS III level of Teramo.
Figure 12: Stratigraphy from well named P281 found in MZS III level of Teramo.

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Table 1: Best-fit model.
4. CONCLUSIONS

Surface-wave analysis at IT.TER station indicates a site of soil class B (Table 2). The best Vp and Vs models (i.e. lowest misfit) resulting from the inversion are proposed in Fig. 10 and Table 1. HV noise spectral ratios are almost flat up to 6 Hz, although we found a weak-frequency peak at about 3.5 Hz. A 2D passive circular array (with L-shaped geometry) provides a dispersion curve in the frequency range 16-20 Hz; the 1D active linear array of geophones provides a dispersion curve from 20 to 40 Hz (see Fig. 8). The inversion of a combined dispersion curve provides the Vs models of Fig.s 9 and 10 where the bottom layer is found at a depth of 12 m (Fig.s 16, 17 and Table 1).

The $V_{s30}$ retrieved from the best inverted model is 647 m/s (Table 2), therefore IT.TER is classified following EC8 or NTC08 as soil class B also taking into account the geological information (see the Geological Report associated to this station [http://hdl.handle.net/2122/12958]). Following the definition of $V_{S,eq}$ within NTC18 and because the value of 800 m/s is reached at a depth of 12.4 m, the $V_{S,eq}$ is equal to 398 m/s and the soil class remains B (with the substratum considered as the marls formation found at 12 m of depth).

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<table>
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Table 2: Soil class following NTC08 and NTC18.
5. REFERENCES


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