Velocity profile report at the seismic station IV.MILN–Milano (MI)

Report sul profilo di velocità sismica per il sito della stazione sismica IV.MILN – Milano (MI)

<table>
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<th>Working Group:</th>
<th>Date: Dicembre 2019</th>
</tr>
</thead>
<tbody>
<tr>
<td>Claudia MASCANDOLA</td>
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<td>Sara LOVATI</td>
<td></td>
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<tr>
<td>Marco MASSA</td>
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Subject: Final report illustrating measurements, analysis and results for Vs profile at station IV.MILN
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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, Allegato B2, WP1 - TASK 2: “Caratterizzazione siti accelerometrici” (Coord.: G. Cultrera, F. Pacor). In this report, the results for station IV.MILN, belonging to the Italian National Seismic Network (RSN-INGV), are presented. The recording station is located in the metropolitan city of Milan, in the Po Plain area (Northern Italy).

Geophysical measurements consist in two ambient vibration array in 2D configuration 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 (Vs) profile that is suitable for assigning the soil class according to the current Italian seismic code (NTC 2018) and the current Eurocode (EC8).
2. GEOPHYSICAL INVESTIGATIONS

Figure 1a shows the location of the IV.MILN seismic station (yellow triangle) and the location of the two microtremor arrays performed (yellow and red points). Figure 1b is a zoom on the array measurements. The smaller array (Array 1) has a radius of 12.5 m and it is reported with red points, whereas the bigger array (Array 2) has a radius of 50 m and it is reported with yellow points. The seismic sensors were positioned in a circular geometry in order to have a homogeneous azimuthal coverage that allows a better performance of the array techniques. The geographic coordinates of the array stations are reported in Table 1 for Array 1 and in Table 2 for Array2. The IV.MILN seismic station is 356 m far away from the center of the smaller array (Array 1 – MI06) and 270 m far away from the center of the bigger array (Array 2 – MI12).

Figure 1: a) location of the IV.MILN seismic station (yellow triangle) and of the 2D array performed at the site. b) Zoom on the array measurements. The red points indicate the stations of the smaller array, with a radius of 12.5 m. The yellow points indicate the stations of the bigger array, with a radius of 50 m.
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Table 1: geographic coordinates of the Array 1 stations (WGS84).

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Table 2: geographic coordinates of the Array 2 stations (WGS84).

All stations of the array are equipped with Reftek-130 digitizer and Lennartz 3D-5s velocimetric sensors. The measurements were recorded in July and lasted more than two hours. A view of the fieldwork is shown in Figure 2a and 2b for Array1 and Array2 respectively.
a)
Figure 2: fieldwork at the IV.MILN seismic station for Array1 (a) and Array2 (b).
2.1 ARRAY 1

The geometry of the Array 1 controls the response in terms of theoretical transfer function as described in Figure 3. On the left, the array transfer function is shown. On the right, the limits for the aliasing conditions are reported both in slowness and in velocity domains.

Figure 3: on the left, the theoretical array transfer function is reported for Array1. On the right, the aliasing conditions are reported in the slowness and velocity domains.
The H/V curves of the 9 stations are superimposed on each other in Figure 4, where the average H/V is reported in a solid black line and the corresponding standard deviation in dashed black lines. There is a general agreement of the H/V shapes showing a good overlapping in the frequency range 0.1-15 Hz. The H/V peak at 0.18 Hz (σ = 0.03 Hz) can be observed on all the H/V curves and it is probably due to a deep impedance contrast. However, Figure 4 shows a further amplification in the frequency range 0.4-0.6 Hz that can approach or exceed an amplitude of 2, one of the conditions for a clear H/V peak (SESAME Guidelines, 2004). The directional H/Vs from the 9 stations of Array 1 (Figure 5) do not show any polarization effect.

![Figure 4: H/V curves of the 9 stations of Array 1. The average is reported with a solid black line, whereas the corresponding standard deviation is reported with dashed black lines.](image-url)
Figure 5: directional H/V for the 9 stations of Array 1.
Data from the 2D array have been analyzed with the GEOPSY code (http://www.geopsy.org) in terms of high-resolution FK analysis on all the three components (NS, EW, Z). The dispersion curves obtained from the Array 1 are shown in Figure 6a for the vertical components, 6b for the radial components and 6c for the transverse components. The vertical and radial components allow picking the Rayleigh wave dispersion curves, whereas the transverse components allow picking the Love wave dispersion curves. The aliasing conditions (black lines) constrain the validity range of the picked dispersion curves in the frequency range 8-20 Hz.

![ARRAY 1 - Vertical](image_url)
Figure 6: Picked dispersion curve in the slowness domain with the high-resolution FK analysis on the vertical components (a), the radial components (b) and the transverse components (c) of Array 1. The limits for the aliasing conditions are reported with black lines.


The modified spatial autocorrelation technique (MSPAC) has also been applied to the passive data to obtain the autocorrelation curves. Figure 7a shows the 6 rings adopted for the MSPAC analysis on Array 1 and Figure 7b shows the spatial autocorrelation curves computed for each ring.
Figure 7: a) rings selected for the MSPAC analysis on Array 1; b) autocorrelation curves of the 6 rings.
The auto-correlation curves in Figure 7b have been inverted to obtain the corresponding Rayleigh wave dispersion curve (Figure 8) in the frequency range 1.7-5 Hz. The black lines indicate the validity range of the picked dispersion curve.

Figure 8: picked dispersion curve in the slowness domain with the MSPAC method on Array 1. The black lines indicate the validity range of the picked dispersion curve.
2.2 ARRAY 2

The geometry of the Array 2 controls the response in terms of theoretical transfer function as described in Figure 9. On the left, the array transfer function is shown. On the right, the limits for the aliasing conditions are reported both in slowness and in velocity domains.

Figure 9: on the left, the theoretical array transfer function is reported for Array 2. On the right, the aliasing conditions are reported in the slowness and velocity domains.
The H/V curves of the 9 stations of Array 2 are superimposed on each other in Figure 10, where the average H/V is reported in a solid black line and the corresponding standard deviation in black dashed lines. As for the Array1, there is a general agreement of the H/V shapes showing a good overlapping in the frequency range 0.1-15 Hz. The H/V peak at 0.18 Hz (σ = 0.03 Hz), already observed from the H/V analyzes on Array 1, is still observed on all the H/V curves from Array2. The directional H/Vs from the 9 stations of Array 2 (Figure 11) do not show any polarization effect.

Figure 10: H/V curves of the 9 stations of Array 2. The average is reported in a solid black line, whereas the corresponding standard deviation is reported in dashed black lines.
Figure 11: directional H/V for the 9 stations of Array 2.
Data from the 2D array have been analyzed with the GEOPSY code (http://www.geopsy.org) in terms of high-resolution FK analysis on all the three components (NS, EW, Z). The dispersion curves obtained from the Array 2 are shown in Figure 12a for the vertical components, 12b for the radial components and 12c for the transverse components. The vertical and radial components allow picking the Rayleigh wave dispersion curves, whereas the transverse components allow picking the Love wave dispersion curves. The aliasing conditions (black lines) constrain the validity range of the picked dispersion curves in the frequency range 2-12 Hz.
Figure 12: Picked dispersion curve in the slowness domain with the high-resolution FK analysis on the vertical components (a), radial components (b) and transverse components (c) of Array 2. The limits for the aliasing conditions are reported with black lines.
The modified spatial autocorrelation technique (MSPAC) has also been applied to the passive data to obtain the autocorrelation curves. Figure 13a shows the 5 rings adopted for the MSPAC analysis on Array 2 and Figure 13b shows the spatial autocorrelation curves computed for each ring.
**Figure 13:** a) rings selected for the MSPAC analysis on Array 2; b) autocorrelation curves of the 5 rings.
The auto-correlation curves in Figure 13b have been inverted to obtain the corresponding dispersion curve in the frequency range 0.38-4 Hz (Figure 14). The black lines indicate the validity range of the picked dispersion curve.

Figure 14: picked dispersion curve in the slowness domain with the MSPAC method on Array 2. The black lines indicate the validity range of the picked dispersion curve.
3. SEISMIC VELOCITY MODEL

Figure 15 compares the dispersion curves obtained from both the FK and MSPAC analyzes on Array 1 and Array 2. Figure 15a shows all the Rayleigh wave dispersion curves, whereas Figure 15b shows all the Love wave dispersion curves. Even if we observe a good consistency between the different curves, they have to be interpreted in order to assign the relative mode (fundamental mode or higher modes). This interpretation is made by performing several inverse models with different initial assumptions on all the dispersion curves. The inverse model that could fit with the lowest misfit the highest number of curves is the one selected to define the Vs profile, with the corresponding initial assumptions on the different dispersion curves.

![Dispersion curves comparison](image-url)
To proceed with the inversion, we estimate the ellipticity curve from the H/V curve, considering in particular the right flank of the H/V peak that carries the important information on the underground structure. To reduce the contribution of the other waves in the H/V flanks, a common practice consists in reducing the H/V amplitude for the square root of 2 (Foti et al., 2011). The estimated ellipticity curve is reported in Figure 16 (blue curves) together with the average H/V curve (black curve).
Finally, we jointly invert the following targets:

1) Rayleigh wave dispersion curves (fundamental and higher modes) in Figure 15a
2) Love wave dispersion curves in Figure 15b
3) ellipticity curve in Figure 16 (blue curves)

The fit between the experimental and theoretical curves is shown in Figure 17. The Rayleigh wave dispersion curves are interpreted and assumed to be relative to the fundamental mode, besides the first, second and third higher modes (Figure 17a). On the other hand, the Love wave dispersion curves are interpreted and assumed to be relative to the first higher mode.

Figure 17: Joint inversion of the Rayleigh wave dispersion curves (a) and Love wave dispersion curves (b) obtained from the array measurements (Array 1 and Array 2) with the additional constrain of the estimated ellipticity curve (c). The field data are reported with black curves.

A fairly good fit is obtained between experimental and theoretical curves using a model parameterization composed of four layers over halfspace. The $V_s$ profile obtained from the inversion process is reported in Figure 18a, with a zoom on the shallow structure in Figure 18b. The results indicate shallow soft layers with thickness <40 m and $V_s$ around 230 m/s. A deeper layer shows $V_s$ of 457 m/s down to 190 m in depth, where a another layer is characterized by $V_s$ values around 800 m/s. The halfspace is found at 1110 m in depth with $V_s$ of 1824 m/s.

![Figure 17](image.png)
The best Vp and Vs models (i.e. lowest misfit) resulting from the inversion process are proposed in Figure 19. The corresponding values are reported in Table 3.
Figure 19: Best-fit models of $V_p$ (left panel) and $V_s$ (right panel) values.

<table>
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Table 3: Best-fit models
4. CONCLUSIONS

Geophysical measurements executed at the IV.MILN seismic station consist in two ambient-vibration arrays in 2D configuration. The H/V analyzes executed on the array measurements indicate one main resonant peak at 0.18 Hz, in agreement with the H/V analysis at the IV.MILN seismic station (INGV-CRISP project, 2015-2016). A further mild amplification in the frequency range 0.4-0.6 Hz is observed on the H/V curves from Array 1. The directional HV from both Array1 and Array2 do not show any significant polarization effect in the analyzed frequency range 0.1-15 Hz.

To assess the Vs profile at the site, a joint inversion of the Rayleigh wave and Love wave dispersion curves was performed, with the additional constrain of the estimated ellipticity curve. The Vs profile was subsequently correlated to the stratigraphic model provided in the geological report at IV.MILN (Working group INGV (2019). Geological report at the seismic station IV.MILN), showing a good correlation in the first 90 m of the subsoil (Figure 20). A first layer with thickness <40 m and Vs around 230 m/s correlates with the gravel and sand layer belonging to the Guanzate Unit (Working group INGV (2019). Geological report at the seismic station IV.MILN), whereas a further layer with Vs of 457 m/s correlates with a subsequent predominant sand layer (Figure 20).

The Vs profile obtained in this study also indicates a further velocity discontinuity at around 190 m in depth, in correspondence to the base of the Quaternary continental sediments (i.e., R-Surface, Working group INGV (2019). Geological report at the seismic station IV.MILN), where the shear-wave velocity moves from 457 m/s to 779 m/s (referring to the best-fit model of Figure 19). This discontinuity is constrained with the mild H/V peak at 0.6 Hz. Moreover, a deeper velocity discontinuity is observed at 1110 m in depth, in correspondence to the base of the Quaternary marine sedimentation (Working group INGV (2019). Geological report at the seismic station IV.MILN), where the shear-wave velocity reach around 1800 m/s. This deeper discontinuity is constrained with the H/V peak at 0.18 Hz.
According to the current Italian seismic code (NTC 2018), if the bedrock ($V_s > 800\, \text{m/s}$) is more than 30 m in depth, the equivalent velocity ($V_{s,eq}$) is equal to the $V_{s,30}$. This is the case of the IV.MILN site, where the $V_{s,30}$ computed from the available $V_s$ profile is 236 m/s, and the site is classified in the soil category C for both the NTC18 and EC8 seismic classifications (Table 4).

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Table 4: Soil Class

Figure 20: correlation between geological and geophysical information at the IV.MILN site (geological section from Working group INGV (2019). Geological report at the seismic station IV.MILN – Milano).
REFERENCES


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