INTEGRATED PASSIVE AND ACTIVE GEOPHYSICAL PROSPECTIONS FOR SEISMIC SITES CHARACTERIZATION

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Introduction. The seismic monitoring of the territory is extremely important in a seismic area as Italy, in order to determine the strong ground motion parameters, as peak ground acceleration and velocity, and develop risk management strategies for earthquake hazards. For a correct definition of strong ground motion parameter, the knowledge of site effects is determinant.

In fact, the seismic motion is strongly affected by the materials through which seismic waves travel especially within the shallowest part of the subsurface. Local geological (lithology) and geomorphological conditions may produce strong modifications in the amplitude level, spectral content and time duration of earthquake ground motion. Furthermore, the knowledge of local site conditions (geology, topography, shear wave velocity, soil deposit thickness and resonant frequency) is fundamental for the definition of the EC8 site class (CEN, 2003) for each seismic station. Geological surveys are not enough for a detailed seismic site characterization and must be integrated by other investigation such as dedicated geophysical surveys. Among these, the most commons are the passive and active seismic investigations: seismic refraction and reflection, multichannel analysis of surface waves, H/V spectral ratio, spatially averaged coherency spectrum and frequency-wavenumber methods.

This contribution shows the results obtained from the integration of some geophysical methods for the characterization of some RAF sites in Friuli Venezia Giulia (Maselli, 2007): two are seismic noise techniques [H/V spectral ratio and frequency–wavenumber (F-K) methods] while the other is an active seismic method (seismic refraction) including both P and S waves analysis.

H/V spectral ratio (Nakamura, 1989) is a single-station method used to evaluate the resonance frequency of soft sediment over hard bedrock. This method calculates the ratio between the horizontal and the vertical Fourier spectra of ambient noise recorded at a single site by a three-component sensor. F-K method (Lacoss *et al.,* 1969; Horike, 1985) is an array-based method used to evaluate Vs profiles of soft, low velocity, sedimentary layers overlying hard bedrock. It extracts surface wave dispersion curves from ambient noise recordings. Vs profiles are estimated inverting the dispersion curves. Seismic refraction method measures the travel time of the seismic wave between the seismic source and the receivers to measure the velocity and the depth of the refracting surface. Four sites were investigated through these methods, one in correspondence with a borehole in Gemona del Friuli (GEMO) and the other three in correspondence with three RAF seismic stations: Gemona del Friuli (GESC), Polcenigo (POLC) and Monte Pala (PALA). Due to the presence pf a 120 meters long borehole reaching the basement, GEMO was selected as a reference site to compare the results obtained with the other methods and also to have a calibration site for the analysis.

Gemona del Friuli is located above an alluvial fan of exceptional dimension: 2.0 km of ray with frontal arc of 3.6 km and a total volume of sediments of about 3.0×10^9 m^3. The thickness of quaternary deposits is variable form 100 to 150 m, the elevation is about 560 m at the top of the alluvial fan and close to 195 m at the edge of the alluvial fan. Gemona del Friuli, located in a high seismic area, is interested by the presence of an important regional thrust: the Barcis-Starasella tectonic line. In the past, several events of medium-high intensity occurred in the area. The most recent destructive events were the Friuli earthquakes in May and September 1976. GEMO, located near the borehole, lied at the alluvial fan border. The stratigraphy of the borehole, drilled in 1981 by Friuli Venezia Giulia Region, shows a sequence of gravel, sand and clay until the carbonate rock is reached at a depth of about 115 m. GESC seismic station is installed in the middle of the alluvial fan. This area presents strong amplification effects, as testified by the damages caused by 1976 earthquakes.

Polcenigo is located at the border between Carnic Prealps and High Friulan Plain. At E-SE of Polcenigo there are some hills that are the result of the recent evolution of Carnic Prealps and are made of Pre-Quaternary rocks, as a result of the Quaternary activity of Aviano thrust (Carulli *et al*., 1982). POLC seismic station is installed on one of these hills, inside San Floriano rural park. The area is characterized by an alternation of marl, sandstone and siltstone, and conglomerate as end-member of the molasse sequence. This area, as demonstrated by the analysis of seismic recording at POLC station, highlights significant amplification effects.

Monte Pala, located at east from Pradis village, belongs to Carnic Prealps and reaches an altitude of 1231 m. The mountain is made by a narrow anticline tilted down toward the south, and is completely composed by limestone and dolomite. PALA seismic station is installed on a rock outcrop.

H/V spectral ratio. Seismic noise was recorded in the four sites: GEMO, GESC, POLC and PALA. The acquisition was performed with a Lennartz LE-3D/5s seismometer for about one hour. The analysis was performed with Geopsy software, developed during Site EffectS assessment using Ambient Excitations (SESAME) European Project, for ambient vibrations processing and site characterizations (Bard *et al.*, 2004). For each site, the resonance frequency and the polarization of seismic energy were determined. Furthermore, the application of a relation that links the resonant frequency to sediment thickness (Haskell, 1960) allowed estimating the bedrock depth. The fundamental frequency, f_0, of a layer over a half-space is given by $f_0=Vs/4H$, where Vs is the shear wave velocity of the sediments and H is the total thickness of sediments.

At GEMO site, located close to the borehole, at the border of the alluvial fan, a resonant frequency of 1.0 Hz was determined, with a significant local amplification. Knowing the bedrock depth from the borehole and applying Haskell relation to the resonant frequency, it was possible to determine the mean shear wave velocity of the sediments above the bedrock. The resulting velocity is 445 m/s, value compatible with the materials of the area.

For GESC site, located at the middle of the alluvial fan, the determined resonant frequency is 0.8 Hz. The amplification of that frequency is significant. Since GEMO and GESC sites present similar geological conditions, the shear wave velocity used for the determination of the bedrock depth was the same found in GEMO. The depth of the bedrock evaluated with Haskell low is about 140 m. This depth is in agreement with the value found by a gravimetric survey (Furlanetto, 2004).

In POLC site, located on San Floriano hill, the determined resonant frequency is about 1.1 Hz. Also for this site, the relative amplification is very high. For the bedrock depth estimation, it was supposed that the shear waves velocity is similar to those evaluated in GEMO site. The obtained bedrock depth is 102 m.

For PALA site, located directly on the carbonate bedrock, the seismic response do not present any resonant frequency, as expected.

F-K. Four seismic arrays were performed in GEMO, GESC, POLC and PALA sites in order to characterize the surface layers. The geometry of the array used in each site was triangular. Each array was made by two set of three sensors arranged in two circles, with respectively 25 and 50 m of ray, having an angular distance equal to 120°, and one sensor in the center (Fig. 1). In each case, seismic noise was recorded for, at least, thirty minutes. The acquisition was performed with a Reftek acquisitor, model 130-01, and 7 Lennarts LE-3Dlite. The analysis was performed using Geopsy software. In particular, were used the tools for F-K analysis (Asten and Henstridge, 1984; Horike, 1985; Yamanaka *et al.*, 1994) and for the dispersion curve inversion (Sambridge, 1999a, 1999b). For each site, the theoretical array response was evaluated in order to determine the array resolution (Kmin/2) and aliasing (Kmax) limits (Fig. 2). The performance of an array with respect to the determination of phase velocity depends on its geometry and on the wavefield characteristics. In this paper, the results obtained for the two sites located in Gemona del Friuli (GEMO and GESC) will be described.

For GEMO site, the velocity spectrum obtained with F-K method is reported in Fig. 2. The dispersion curve of the fundamental mode is apparent in the figure. The portion of curve used for the inversion, highlighted in black, has a limited frequency range. At low frequency, it is limited by the energy loss, the array resolution and the corner frequency of the geophones used, while at high frequency by aliasing. The velocity profiles obtained from the inversion and the respective dispersion curve are shown in Fig. 2. The velocity profiles of P and S waves reveal, for both cases, a sharp increase in the velocity at a depth of about 115-120 m. The P waves velocity increases from about 1200 m/s to 2200 m/s while the S waves from about 850 m/s to 1300 m/s. The depth of discontinuity is in agreement with the depth of the bedrock in the borehole: 115 m.

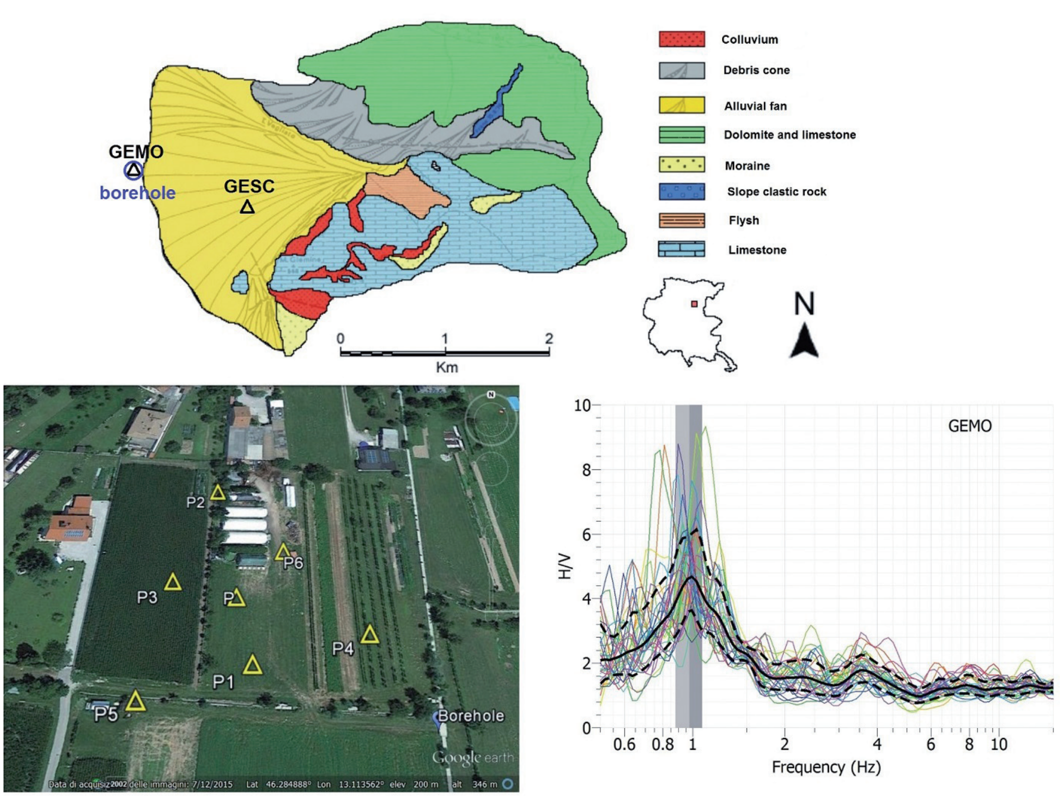

Fig. 1 – On the top, a schematic representation of Gemona del Friuli alluvial fan form a geological and geomorfological point of view (Maselli, 2007). The location of the two investigated sites (GEMO and GESC) is also reported. On the bottom, the picture on the left displays the geometry of the seismic array applied in GEMO site. The location of the borehole is shown. The picture on the right represents the result of H/V spectral ratio. Each colored curve corresponds to the H/V spectral ratio determined for each window analyzed, the black line to the average H/V spectra and the dotted lines to the standard deviations. The resonant frequency is 1.0 Hz.

In GESC site, the velocity spectrum obtained was more difficult to interpret and the identification of the dispersion curve was not easy. However, from the inversion of the dispersion curve, the P and S velocity profiles show an important increment in the velocity at a depth of about 130 m. This discontinuity is probably related to the sediment-bedrock contact. Such result is in agreement with the H/V spectral ratio analysis and previous studies made in Gemona del Friuli: gravimetric survey (Furlanetto, 2004) and seismic noise investigation (Pavan, 2007).

Active seismic. An active seismic investigation was performed in GESC site in order to determine the propagation velocity of compression and shear waves. Two NNO-SSE seismic profiles were acquired: one with vertical geophones and the other with horizontal ones. The P waves profile is made of 23 vertical geophones for a total length of 44 m, being the geophone interval equal to 2 m (Fig. 3). The S waves profile is made of 18 horizontal geophones, having a constant separation equal to 2 m, for a total length of 34 m. Several shots were executed on both sides of the profile in order to obtain conjugate profiles. For the P waves profile, eight off-end shots were executed at respectively 2, 4, 10 and 20 m from the external geophones, while, for the S waves profile, only six shots located at respectively 2, 4 and 10 m. The data was analyzed with Plus-Minus (Hagedoorn, 1959) and General Reciprocal (Palmer, 1980) methods. A three layers model was used for the interpretation of the P and S waves travel times. The reflector depth under each geophone and the velocity fields along the seismic profiles were estimated.

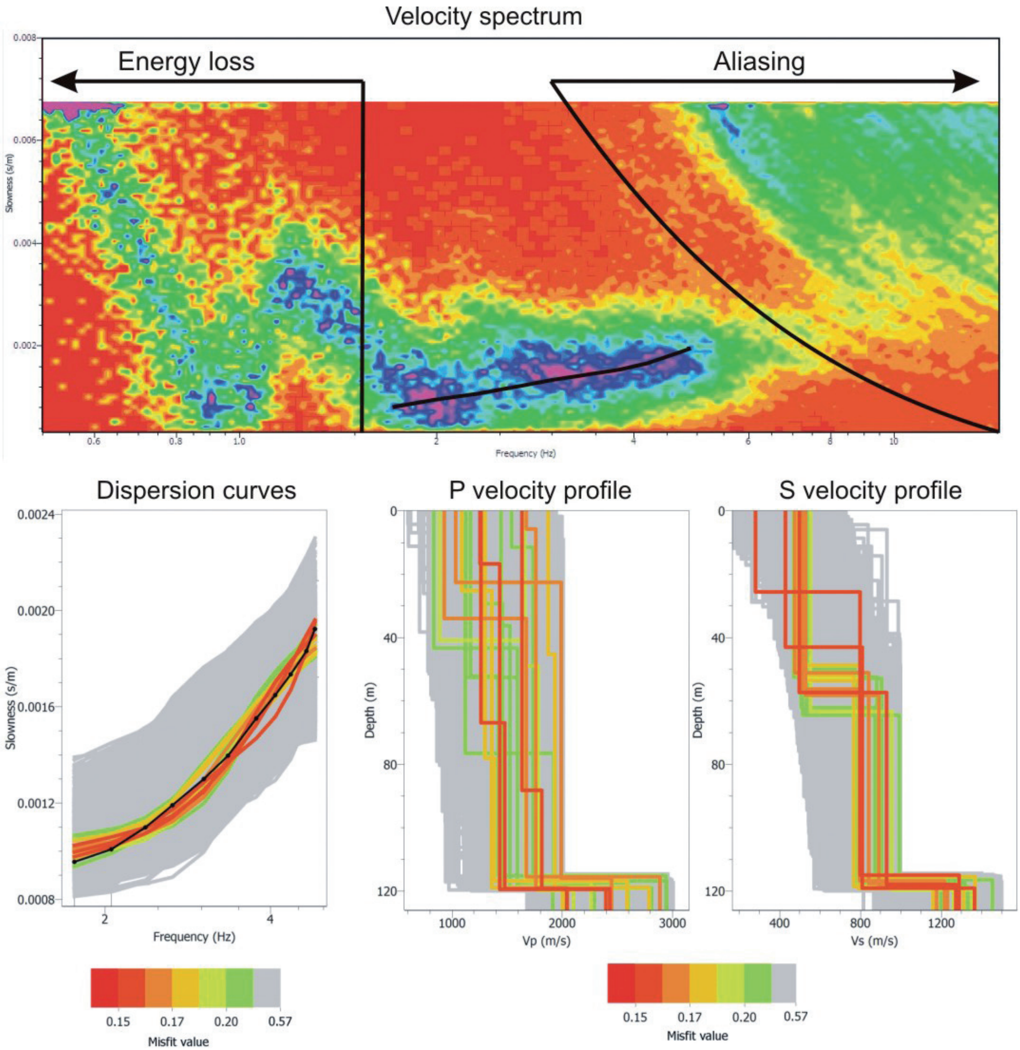

Fig. 1 – On the top, the velocity spectrum (slowness-frequency) obtained with F-K method for GEMO site. The dispersion curve of the fundamental mode is easily identifiable. Only the portion highlighted in black was used for the inversion, it is limited by the energy loss and the spatial aliasing. On the bottom, the P and S waves velocity profiles and the respective dispersion curves. The different colors refers to the misfit value. The grey band contains the whole space of parameters where the algorithm searches the solutions.

For the P waves, the first layer presents a regular trend, with a depth increasing in SSE direction, while the second one presents a more irregular trend. In Fig. 3 is represented the 2D velocity profiles, where it is possible to estimate the depth of different refractors. The obtained velocity model exhibits a velocity gradient both vertical and horizontal, with a velocity increase in south direction. The first layer has a velocity between 400 and 540 m/s, with a thickness of 4-6 m. The second layer shows a velocity increase from 600 to 700 m/s and a thickness variable from 3 to 7 m. The deepest layer presents a maximum velocity close to 1100 m/s and a depth of about 13 m. The obtained velocity values are compatible with alluvial fan materials and the lateral velocity variations are coherent with the geomorphological setting of the area. It is important to highlight that the model obtained using refracted waves is correct only if there are no low velocity channels (i.e. velocity inversions) in the surface.

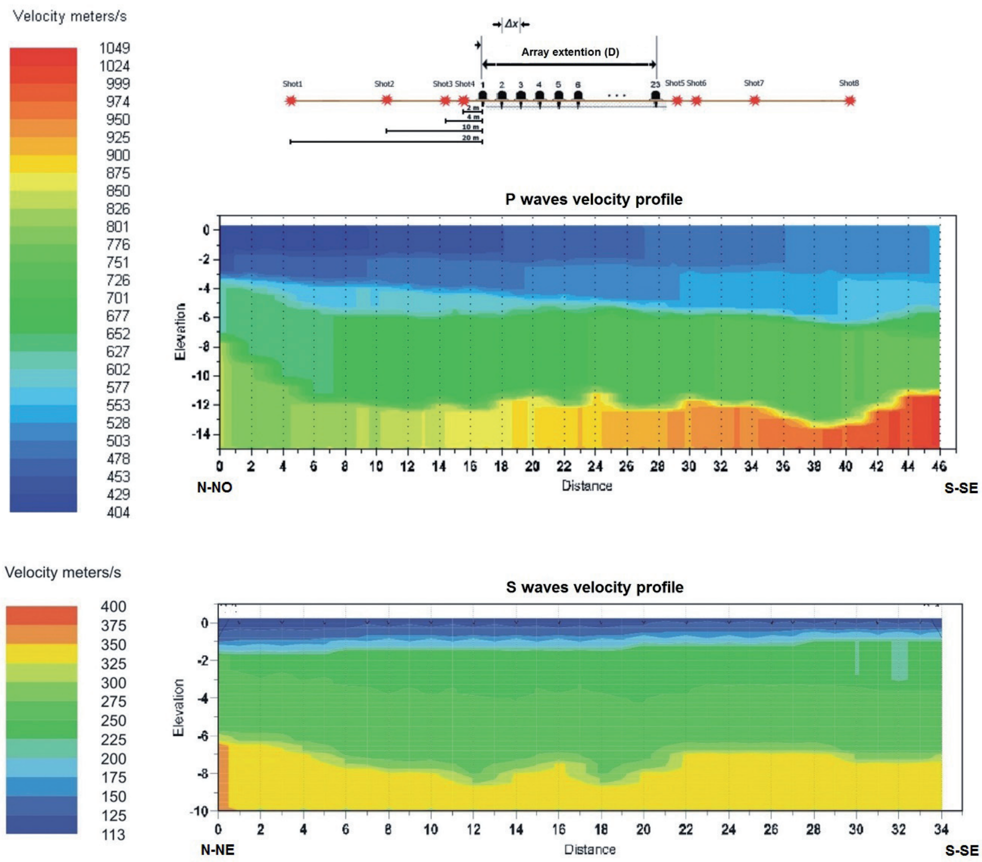

Fig. 3 – On the top, the geometry of the P waves seismic profile and the resulting velocity profile. On the bottom, the resulting S waves velocity profile. The velocity values are represented in a color scale; note that the colors scale for P and S waves is different.

For the S waves, the determined geometry is in agreement with the P waves obtained profile, even though with the limited length of the profile and the relative small number (18) of geophones used it is possible to image only two layers (Fig. 3). The S waves profile allows recognizing a surface layer characterized by a low velocity (about 150 m/s) and a small thickness (1-1.5 m), interpreted as the weathering.

Conclusions. The passive and active seismic investigations made at four sites in Friuli Venezia Giulia allow the determination of the seismic characteristics of these sites. The presence of a reference site, as GEMO in our case where the borehole stratigraphy was available, represents an important starting point for the integrated approach affordability. In fact, it allowed to verify the results obtained with the different techniques by a direct calibration. The depth of the discontinuity found with F-K array based method is in agreement with the borehole information, confirming the validity of the obtained results. The resonant frequency found with the H/V spectral ratio of seismic noise was used, according to Haskell low, in combination with the bedrock depth to determine the average shear wave velocity of the sediments. In GESC site, H/V spectral ratio and F-K methods allowed to identify the presence of a discontinuity at the same depth. Furthermore, these results are in agreement with a gravimetric survey made in Gemona del Friuli (Furlanetto, 2004). The seismic refraction allowed the definition of a 2D velocity profile, down to a depth of about 15 m for P waves and about 10 m for S waves. The geometry of P and S profiles are similar, even if on the S profile it was also possible to recognize a surface weathered layer. In POLC site, the resonant frequency found with H/V spectral ratio was used, according to Haskell low, to determinate the bedrock depth. It was supposed that the shear waves velocity is similar to those evaluated in GEMO site. This study demonstrates, in different sites, how the integration of different methods represents the better strategy for a complete and optimal site characterization. Given the good results obtained at the investigated sites and the importance of site characterization for a correct definition of the seismic stations site class (CEN, 2003), the illustrated active and passive geophysical prospections will be performed at the seismic stations managed by our university.

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