**Introduction.** Most of the carbonate relief of the Campania Region (southern Italy) are mantled by pyroclastic deposits originated during eruptions of the Somma-Vesuvius and Phlegraean Fields volcanic centers. Such deposits, commonly characterized by an alternation of ashy and pumiceous layers, have been frequently involved in high velocity flow/avalanche instabilities causing important loss of life and extensive damages (e.g. Guadagno et al., 2005; Revellino et al., 2013) to properties and infrastructures.

Their physical and stratigraphic characteristic, their geometry and spatial continuity and the morphology of the affected slope have been recognized to control the location of the source zone and the triggering mechanisms (e.g. Guadagno et al., 2005; De Vita et al., 2013). Especially, the thickness of the deposit and its internal architecture seems to be a key predisposing factor for the development of these instabilities (De Vita et al., 2006, 2013) and their knowledge is essential for the analysis of landslide susceptibility.

On this basis, in this work, we experiment multiple geophysical methods to characterize the geometry and the stratigraphic characteristics of pyroclastic deposits covering the northern slope of Mount Vallatrone in Campania region (southern Italy). Especially, for our analysis we used HVSR measurement, MASW and GPR surveys. All of the surveys were completed along a section where a detailed stratigraphy, reconstructed using data from a hand excavated borehole, was available. This improve our experimentation allowing a comparison/integration of the results.

**Geologic setting.** The experimentation site is located along the northern slope of the Mt. Vallatrone (Fig. 1) a relief of the Avella-Partenio Mountains in southern Italy. Such mountains are formed of Jurassic-Cretaceous carbonate-dolomitic rocks (Sgrosso,1965; D’Argenio et al., 1970). Many fractures and NW-SE and NE-SW trending normal faults are present (Ippolito et al., 1973). Structural evolution, connected to Quaternary tectonic phases, as well as geomorphological degradation processes, generated internal depressed areas into carbonate ridges. Frequently, several meters of air-fall pyroclastic deposits, characterized by an alternation of ash and pumice layers, overlie the calcareous slopes.

The distribution of pyroclastic deposits is not homogeneous, but follows the original dispersion axes of the various volcanic eruptions (Rolandi et al., 1993). Stratigraphy of pyroclastic deposits is not frequently exposed and, for our investigation, was investigated hand-excavating a borehole (Fig. 1). Such borehole reveals the stratigraphy down to a depth of about 6 m (Fig. 1). It
is characterized by pyroclastic deposits enriched in yellow or grey pumices, interspersed with ashy levels, down to a depth of 5±1 m; carbonate deposits follow in the succession.

**Data acquisition and method.** We used three geophysical methods, which include passive method (microtremor HVSR) and active methods (Ground Penetrating Radar - GPR, and MASW analyses) to estimate the depth and reconstruct the internal architecture of pyroclastic deposit mantling the northern slope of the Vallatrone Mount in southern Italy.

Horizontal-to-Vertical Spectral Ratio (HVSR) method, applied to microtremor, provides an estimate of the resonance frequency of cover sediments, in the hypothesis of a 1D medium. In particular, a 1D medium, consisting of a sedimentary layer resting on bedrock, generates a peak in the HVSR curve. This peak, due to a site effect, is defined stratigraphic peak (Haghshenas et al., 2008; Castellaro and Mulargia, 2009).

GPR is an active prospecting method, which is based on the analysis of the reflections of electromagnetic waves transmitted into the ground. It allows the detection of electromagnetic discontinuities in the soil generated by layers or isolated bodies, having different dielectric properties (Davis et al., 1989). The instrumentation consists of a control unit, which generates an electromagnetic pulse of a few nanoseconds; this is sent to an antenna, which, in turn, transforms it into a higher-amplitude pulse, and radiates it into the ground. The frequency of the antenna can vary from a few MHz up to GHz and is chosen according to the depth of investigation to be reached and to the desired resolution. These two parameters are inversely proportional to each other (Annan, 1976; Coco e Corrao, 2009).

The acquisition technique used is that of the continuous profile, that is performed with the displacement of the pair of antennas moved in a continuous manner along the predetermined profile, with low and constant speed drag. We used a GPR antenna provided by IDS, with a frequency of 80 MHz; this means that the source of radiation has a frequency range between 80 and 120 MHz. The acquisition was carried out in monostatic mode.

The multichannel analysis of surface waves (MASW) method deals with high-frequency Rayleigh waves, to estimate the near-surface S-wave profile. The MASW technique provides the Rayleigh wave dispersive function from which one can derive the 1D Vs profile, with the assumption that the subsurface is a layered half-space in horizontal and parallel layers (Dal Moro, 2008). Instrumentation is generally composed of a multi-channel seismograph, vertical geophones with natural frequency of 4.5 to 10 Hz, and a seismic source. Using three different geophysical methods, as described above, we produced satisfying results that highlight the physical properties of the soil, useful to characterize the pyroclastic blanket. Finally, geophysical results were put in relation with the stratigraphic data.

**Data processing and results.** The HVSR microtremor technique has proved an effective tool for assessment of site resonance frequencies (Haghshenas et al., 2009). Seismic signals were recorded using a Tromino (Micromed) triassial station, 24 dB, 0.1-256 Hz. We collected the seismic signal for thirty minutes, at 128 Hz sample rate. Data analysis was performed using the Grilla software provided by Micromed. Signals relative to each component were subdivided in non-overlapping time windows of 16 s, and tapered with a 5% cosine function. Spectra were smoothed using the Konno & Ohmachi window (b=40). The resulting spectral ordinates relative to NS and EW components were geometrically averaged. HVSR curves over the 16-s-long time windows were then averaged to compute the final HVSR curve, as shown in Fig. 2. The HVSR curve shows a clear amplitude peak at 6.44 ±1,62 Hz. This peak corresponds to a local maximum in the horizontal components (green and blue lines in Fig. 2c) and to a local minimum in the vertical component (purple line), and this pattern proves the stratigraphic origin of this peak (Castellaro and Mulargia, 2009). Clearly, the pyroclastic layer resting on the carbonate bedrock generates this significant peak in the HVSR curve (stratigraphic peak).

We also acquired two 2D GPR profiles: Profilo01 for a total length of 23 m, and Profile02 for a length of 21 m. GPR data displayed directly after the acquisition, generally also contain "noise", making interpretation difficult. The identification of the optimal processing sequence depends
Fig. 2 – a) GPR distance-depth section (radargram) as derived along the Profile 01. The radargram shows a main refractor at a depth of 5.5 meters. b) Mean HVSR curve (red line) +/- 1 standard deviation (black lines). A clear amplitude peak is present at 6.44 Hz. c) Amplitude spectra of the NS, EW, and vertical component of ground motion. Vertical units are in mm/s.
on the quality and characteristics of recorded data. GPR processing was performed through commercial software GRED HD. The first processing step was to estimate the propagation velocity through the clearest hyperbola in the radargram. In this way we estimated a propagation velocity of 5.40 cm/ns. Then a band-pass filter, 20-200 MHz, and a SOIL SAMPLE effect were activated to eliminate the initial part of the profile corresponding to the air propagation, and to define the start time. Processing continued by applying the Smoothed Gain, to improve the signal sharpness. Finally, with the purpose of correctly converting from time-distance to depth-distance section, the migration process was applied in the domain of MIGRATION_TD time.

The Profile01 shows a very shallow reflector with high amplitude reflected phases at an average depth of 5.5 m (Fig. 2). The sharp amplitudes and the comparison with stratigraphic data suggest that these phases are generated by the reflection from the top of carbonate rocks. The profile also shows five horizontal sub-layers within the pyroclastic layer, which can be interpreted through the core drilling stratigraphy. The Profile02, arranged parallel to the first one and spread to a distance of 10 m shows the same situation of the first profile, clearly marking the passage from pyroclastic sediments to carbonate deposits, at an average depth of 5.5 m. This interpretation is also supported by a sharp seismic velocity change, as shown in the following MASW analysis.

MASW profiles were positioned at the same location of GPR acquisition, crossing the drilling location and the HVSR measurement station (Fig. 1). We used a RAS-24 seismograph, 24 bit, 117db @ 2 ms, equipped with vertical geophones of 4.5 Hz and 10Hz. The source consisted of an 8 kg hammer. We acquired 13 recordings (shots), along the same line, obtaining profiles with a length of 22 m, spacing of 2 m. Recordings were obtained with different offsets, and, for the same offset, geophones of 4.5 Hz and 10 Hz were used. The chosen profile has an offset of 4 m from the first geophone, and 10 Hz geophones. Processing was performed with the Geopsy software (http://www.geopsy.org/), a powerful open source software for processing of a wide variety of geophysical data. The first step was to import the files containing the field data, typically in SEG2 format, ensuring the acquisition parameters used for the imported files. The result of processing is the conversion of the MASW time-distance sections into a frequency-wave number spectrum. The assumption is that the most energetic part in the signals is composed by Rayleigh waves. So, the manual picking of the maxima in the spectrum allows to define the Rayleigh wave dispersion function. The obtained dispersion curve was then inverted to obtain the subsoil velocity 1D model, though the Dinver software (http://www.geopsy.org/). This inversion algorithm is based on a stochastic direct search method for finding models of acceptable data fit inside a multidimensional parameter space. The operator has the task of acting in order to reach the solution closest to the true subsoil structure. In doing this, constrains from geophysical, other than stratigraphic data methods, are advantageous. In our study case, data obtained from direct survey, HVSR and GPR data were crucial, in order to define a suitable initial parameter space (Fig. 3a).

We started from a two layers initial model, formed by: a first layer with a linear increment of P-wave velocity (100-400 m/s), S wave velocity (80-300 m/s), Poisson’s ratio (0.3-0.4), and density (1500-2000 kg/m³); a second layer with uniform parameters, which are left varying among models in the ranges: (400-1500 m/s) for the $V_p$, (200-700 m/s) for the $V_s$, (0.2-0.4) for the Poisson ratio, (1800-220 kg/m³) for the density. The obtained best-fit solution is very close to the subsoil structure estimated by the GPR method and by the direct survey (Fig. 3b): a pyroclastic cover layer subdivided into 5 sub-layer overlying the carbonate basement.

This paper reports results from measures carried out by using different geophysical methodologies in order to assess their applicability in estimating the near-surface Earth structure. The MASW method is the most popular techniques to derive the S-wave profile of the subsoil, in the hypothesis of a 1D layer structure. HVSR is definitely the cheapest and the most practical method. It allows a punctual inspection of the subsoil structure, in the hypothesis of a 1D medium with a strong impedance contrast at depth. It has identified the site’s fundamental resonance
frequency, equal to 6.44±1.6 Hz, generated by the impedance contrast between pyroclastic sediments and carbonate basement. Considering the simple quarter-wavelength fundamental frequency relationships, this estimate may also furnish a constrain on the estimates of Vs and/or thickness obtained by the MASW survey. GPR method offered a 2D definition of the target and the advantage of a versatility and speed of use, as well as high sensitivity in detecting changes in the dielectric properties of deposits, related to the presence of water in the middle.

Results have demonstrated the validity of all the applied geophysical methods in describing changes in the physical properties of the target in question (pyroclastic deposit). Integrate prospecting methodologies guarantee useful constrains to define the physical and geometrical features of the pyroclastic cover deposits.

References


