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Deliverable # 11

Seismic characterization of stiff soil/ rock accelerometric sites from ambient vibrations monitoring

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1. Introduction

Identification of reference sites, i.e., sites where no seismic amplification affects may occur as the results of local morphologic/stratigraphic configuration, is of paramount importance in the seismic engineering practice. In general, it is assumed that sites where rocks or stiff soil outcrop, represent an example of reference site. However, it is well known that alteration or intensive fracturing of rock bodies may significantly alter their mechanical behaviour and in particular may be responsible of energy trapping phenomena that can significantly modify the amplitude of impinging waves. Thus, the simple geological identification of rock/stiff soil outcrop, does not warrant, by alone, the absence of site effects. Thus, it becomes mandatory providing some direct estimate of the seismic properties of the site of interest, to directly evaluate the actual absence of site effects.

To this purpose, the estimate of the local V_S profile is of primary importance. This can be achieved with invasive borehole techniques (down-hole, cross-hole) that are presumed to allow a direct estimate of the local V_S profile. Costs of these prospecting techniques are generally high and this prevents their widespread application. Furthermore, they are not actual " direct" techniques and require interpretation tools and practice that do not provide in many cases "unequivocal" V_S estimates. This implies that, in front of relatively high costs, no warrant exists of a correct definition of the local V_S profile. On the end, one has to take into account logistic difficulties in the application of these techniques at sites characterised by a rugged morphology, typical of rock/stiff soil outcrops, whose mechanical properties reduce the smoothing effect of erosive processes.

An interesting alternative to these techniques is represented by surface seismic prospecting both in the active and passive configurations. In this case, drilling is not requires and this dramatically reduces costs and survey duration. Furthermore, since relatively large volumes of the subsoil are explored with these techniques, retrieved information is more representative of the average configuration of the explored subsoil.

Active configurations require controlled energization of seismic wave field that is monitored at a number of geophones (seismic array) located at the surface of the ground around the source. In this configuration, both body waves and surface waves phases are considered to provide information about the subsoil seismic structure. Geometric configuration of the subsoil is better explored by body waves studies, that , however, present severe limitation in the exploration depth, at least when common exploration tools are considered. This depth is generally limited by the extension of the array (about 1/8 of array maximum length) and the energy of the source.

Surface waves (see, Deliverable 6 for details) provide less precise geometrical information about subsoil seismic configuration (flat layered Earth is the reference model) and require complex inversion procedures to deduce seismic structure of the subsoil from observations. Furthermore, due to the strong nonlinearity of relationships connecting surface observation and seismic structure of the subsoil, inversion is not able to provide unequivocal results. In front of these problems, however, these techniques allows reaching depths larger than those provided by body waves studies when the same array dimension are considered. Furthermore, phase velocity of surface waves is strongly sensitive to local V_S profile and this implies that this information (of major concern in seismic engineering application) can be retrieved from surface waves analyses.

In general, exploration depths of these techniques depend on the wavelength of surface waves measured in the field (exploration depth is of the same order of magnitude of the wavelength of concern). Thus, this depth is mainly limited by the range of frequencies excited by the source and by the dimension of the array: low frequency sensors and energy generators accompanied by large array dimension may provide relatively large exploration depths (of the order of hundreds of meter or more). These features makes these prospecting techniques appealing for a number of applications. However, common sources (hammers, etc.) appear unable to provide sufficient energization of low frequency components and this limits the exploration depths of these techniques.

In passive configuration, ambient vibrations randomly generated by a number of uncontrolled natural and artificial sources are monitored at single station or seismic array. In this case, energization of the wave field is not of concern and this implies that passive exploration is cheaper than the active ones. Furthermore, being surface waves the most energetic component of ambient vibration wave field, exploration depths that can be reached with these procedures only depend on the sensitivity of geophones and on the dimension of the array, since a number of effective low frequency sources actually exist (wind, sea waves, etc.). Thus, passive techniques present the same advantages (and drawbacks) of active seismic prospecting based on surface waves (see Deliverable 6 for details).

An application of passive seismic prospecting to the characterization of RAN sites is described here. In particular, the use of these techniques to identify reference accelerometric sites was tested. The appeal of these techniques mainly depend on their low costs (for explored volume) that make them feasible for extensive applications, such those required to characterize the large number of RAN accelerometric sites. On the other hand, the application of these techniques where rock/stiff soil situations are of concern, poses specific problems that require the development of on purpose procedures.

These problems depend on three aspects. The first one is related to the rugged morphology that in many cases characterizes this kind of sites (see above). This makes it difficult deploying lomg seismic arrays necessary to retrieve subsoil velocity profiles at significant depths. Furthermore, complex morphologies undermine the safe application of interpretative models, that, as stated above, are mainly based on the hypothesis of a flat layered Earth.

The second problem is related to the relatively high surface waves phase velocities expected when a rigid subsoil is of concern. In this case, surface waves, that constitutes a major component of ambient vibration wave field, will be characterised by relatively large wave lengths at a fixed frequency. This implies that larger exploration depths are generally available also when relatively high frequency sensors (4-5 Hz) are used. But it also implies that relatively large arrays are necessary for a reliable determination of phase velocities of these waves. However, due to the topographic complexity expected in correspondence of rigid subsoil configurations, such large arrays cannot be easily laid out.

A third important problem concerns the peculiar structure of the ambient vibration wave field in the presence of a rigid subsoil or when very thin soft sedimentary cover is present. This aspect will be discussed in some detail in the next section. In the following, the experimental procedure tested in the frame of the project is described in some detail, along with a couple of application examples. The whole set of applications and relevant results are reported elsewhere (Deliverable 7 for details).

2. Hints from theoretical models

Characterization of the ambient vibration wave field form the experimental point of view presents several problems. In fact, so far, inconclusive and in some cases contradictory results are provided by these investigations (e.g., Bonnefoy-Claudet *et al.* 2006a ; Koper *et al.* , 2010). This could be the effect of the strong sensitivity of ambient vibration spectral structure on the configuration of sources and the structure of the subsoil that can vary significantly from one site to the other (Albarello and Lunedei, 2010).

In this context, theoretical modelling can supply useful indication to overcome this stalled condition. In general, these models face the problem of the inherently stochastic nature ambient vibrations, whose sources cannot be identified individually and are generally characterised by high time/space variability (Okada 2003). Thus, modelling requires an approach nearer to the Statistical Physics than to standard Seismology and its strictly deterministic approach. In particular, average spectral properties (magnitude and phase relationships) of the observed wave field are of major concern, since, in general, they result much more sensitive to the underground structure than to the sources responsible for the observed wave field.

Recently, two general physical models of ambient vibrations wave field were presented: the first one (Tanimoto 2008) deals with the low frequency band (<0.5 Hz) while the second one (Albarello and Lunedei 2010; Lunedei and Albarello 2010) aims at representing ambient vibrations in the frequency range of engineering interest (>0.5 Hz, <20 Hz). Both these model are general in that no *ex-ante* assumption is made about the seismic phases present in the wave field. Both these models generalize the application of full wave field generated by harmonic point sources (e.g. Harkrider 1964; Aki and Richards 1980; Hisada 1994; Ben-Menahem and Singh 2000) previously adopted to simulate the wave field generated by finite number of independent random-like point sources (Bonnefoy-Claudet *et al.* 2006b, 2008) to the case of a continuous distribution of sources.

This model has been applied here to explore major features of ambient vibration wave field when a rigid subsoil is of concern. To this purpose a simple reference configuration was considered that includes two layers only (Table 1). The profile presents a very sharp impendence contrast (about 6.58 for shear waves) at a depth of 25 m, which results in an expected S-wave resonance frequency f_S=2 Hz, with a corresponding P-wave resonance frequency f_P=4 Hz.

***Table 1**. Reference subsoil configuration considered for computations. H is the layer thickness, V_P and V_S represent the body-wave velocities, ρ is the density, Q_P and Q_S are the seismic quality factors for body waves and ν is the Poisson's ratio (modified from Bonnefoy-Claudet et al., 2006a).*

Layer	*H* (m)	V_P (m/s)	V_S (m/s)	ρ (kg/m^3)	Q_P	Q_S	ν
1	25	400	200	1900	50	25	$0.\bar{3}$
2	5000	2000	1000	2500	100	50	$0.\bar{3}$
3	∞	3500	2000	2500	100	50	$0.2\overline{57}$

The expected spectral structure of ambient vibrations in this case is illustrated in Figure 1. One can see a dramatic lowering of spectral power below the resonance frequency. The most energetic part of the signal is in range between the S waves and P waves resonance frequencies. Above f_P , a slight lowering of the signal is expected, that is less pronounced than that below f_S. A closer insight (Albarello and Lunedei, 2010) reveals that that above f_P , ambient vibrations are mainly constituted by surface waves while below f_S their contribution results almost negligible. In between, a variable percentage of surface waves is present in the vertical and horizontal ground motion spectral components. One can see that maximum amplitude of the Horizontal to Vertical Spectral Ratios (HVSR) curve is reached in correspondence of the f_S resonance frequency (SESAME, 2004).

This model allows exploring spectral structure of ambient vibrations on rigid subsoil. This effect was modelised by considering a variable thickness of the soft sedimentary cover. As expected, maxima of the HVSR curve displaces towards higher frequencies with the thinning of the soft coverage, by following the displacement of the f_S resonance frequency (panel *c* of Figure 1). At the same time, in the frequency range of interest (0.5-20 Hz to say) power of ambient vibration dramatically decreases (see panels a and b in Figure 1). This patterns suggests that most powerful components of ambient vibrations are due to energy trapping of seismic phases within the soft layer.

By extrapolating this pattern, one could expect that when this layer is completely absent or negligible, ambient vibrations are characterized by very small ground motion amplitudes with small contribution of surface waves.

This has very important consequences for passive prospecting on rigid soil or outcropping rocks. In fact, in these situations, one could expect very a small signal with a vanishingly small presence of surface waves in most part of the spectrum. This also implies that, due the very low level of the signal, small local sources of seismic noise may play a major role by significantly perturbing measurements.

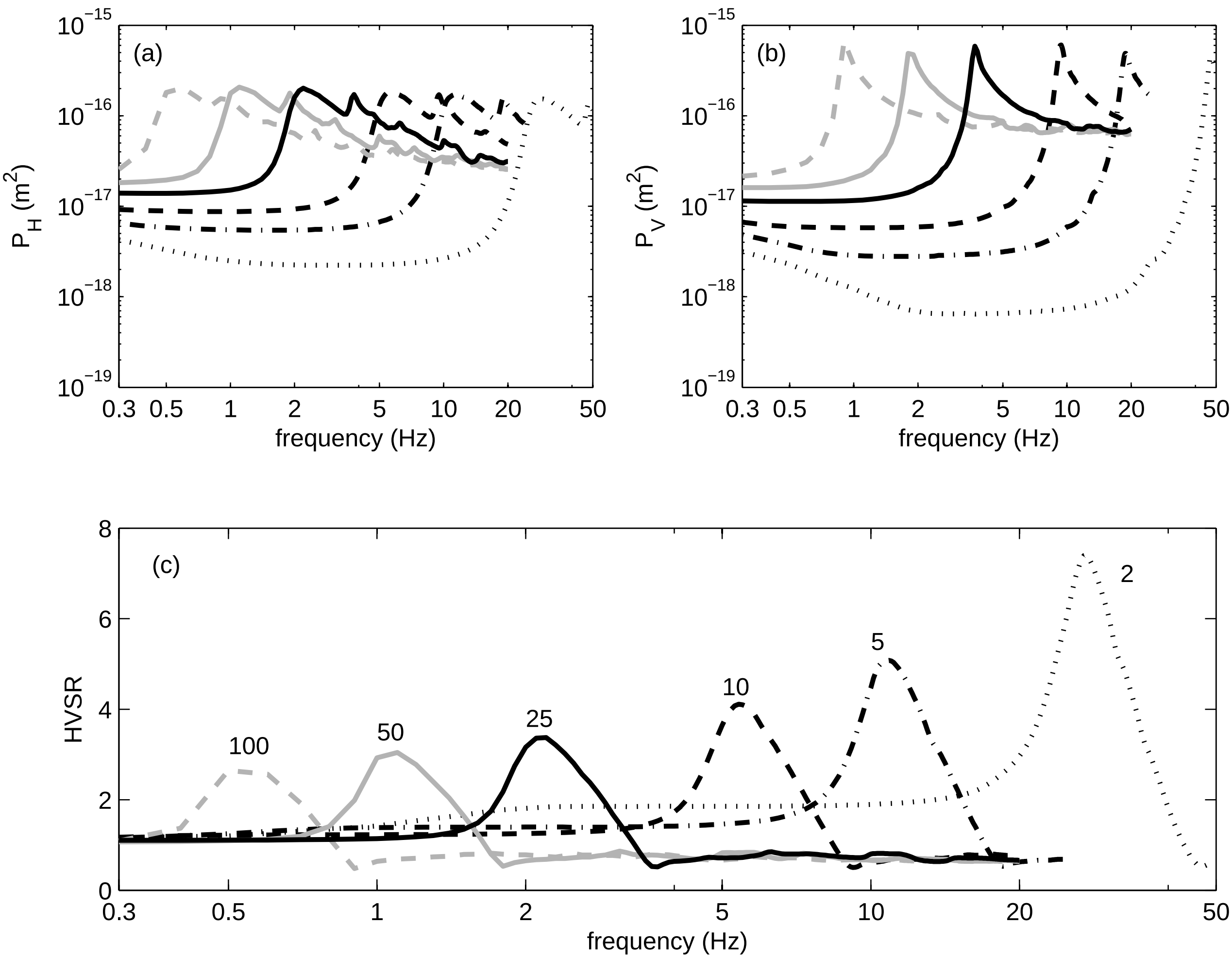

Figure 1. *Effect of the soft layer thickness variation on the expected ambient vibrations full wave field, computed by using the full wave field model described in Lunedei and Albarello (2010). In panel c the thicknesses (in meters) are reported in the plot: each one is coupled to a line type corresponding to those used in the other panels. Solid black lines refer to profile in Tab. 1 (H=25 m). Panels a and b respectively report expected values of the average spectral power relative to the horizontal (P_H) and vertical (P_V) ground motion components. Panel c reports the shape of the horizontal to vertical ratios spectral ratios (HVSR).*

3. An experimental protocol for ambient vibration prospecting on stiff soil/rock sites

Major difficulties one can expect when ambient vibration monitoring is applied at stiff soil/rock sites can be summarized as follows:

1. *rugged morphology that prevents laying out of large seismic array configurations*
2. *long expected wavelength for surface waves present in the ambient vibration wave field that requires laying out of large arrays to be characterized*

3. *low spectral powers of the expected ambient vibration wave field and strong sensitivity to small local erratic sources*

The first problem can be faced by fully exploiting single station ambient vibration measurements (HVSR technique) that are characterised by negligible soil occupancy. In principle, these measurements are able to provide important constraints to the subsoil structure. As an example, presence of sharp variations in the V_S profile below the surface can be easily detected with this technique from the presence of maxima in the measured HVSR curve. Furthermore, since the amplitude of HVSR maxima are conditioned by the impedance contrast at this variation (see, e.g., Deliverable 6), the shape of the experimental HVSR curve provides important constraints to the V_S profile in the subsoil. However, the constraining power of this technique is greatly enhanced when HVSR measurements are jointly inverted by also considering relevant dispersion curves provided by array measurements (see, e.g., Picozzi and Albarello, 2004 and references therein).

This last piece of information can be deduced from array measurements only (see Okada, 2003) and thus, this kind of measurements have to be provided in some way also in the cases where local topography does not allow an easy lay out of the experimental tool. In these cases, however, a detailed geological survey could allow detection of nearby sites characterized less complex topography and representative of the same (or of nearly the same) subsoil configuration. In these cases, array measurements can be carried on at a site different form the one of concern by allowing the estimate of the V_S profile of the geologic body present both under the array and the site of concern.

Due to the relatively small dimension of the array that in these cases can be deployed, one can expect that the range of wavelengths that can be actually explored is severely limited. Furthermore, due to the expected low amplitudes of ambient vibrations in general and of surface waves component in particular, robust experimental approaches should be preferred.

A key aspect of this procedure is the evaluation of reliability of V_S profile deduced at sites different from the ones of concern as representative of the subsoil configuration at this last site. Beyond geological considerations and observations, this can be checked by evaluating the capability of the V_S profile to reproduce single station measurements at the site of concern.

On the basis of these consideration, an intense experimental activity was carried on in the frame of the project to set up an experimental protocol effective in the case rock/stiff soil sites. In the following, such an experimental protocol based on both single station and array measurements of ambient vibrations under the strict geological control will be described in some details.

3.1 Outline of the protocol

It involves four major elements:

- *Detailed Geological survey of the study area resulting in a geo/lithologic map at the scale 1:5000 of the area surrounding the relevant RAN station. This also aimed at the evaluation of the degree of lateral heterogeneity present in the lithological structure paying major attention to faults and their relevant damage area (that can result in energy trapping phenomena)*
- *Extensive single station ambient vibration survey at the station and in the surrounding area to detect possible lateral variations potentially responsible for site effects*
- *Ambient vibration measurements carried on with a seismic array at the RAN site or at a site representative of the subsoil configuration at the RAN site. In this last case, suitable inversion procedures and test were carried on to warrant the representativeness of ambient vibration measurements*

- *Global interpretation of measurements to determine the V_S profile and of the resonance frequency at the RAN site by considering the whole set of collected data*

Details concerning experimental tools and processing techniques are given in the following sections.

3.2 Single station measurements

The goal of this kind of measurements is the retrieval of the HVSR curve that represents for each frequency, the average ratio between Horizontal (H) to vertical (V) ground motion components of ambient vibrations (SESAME, 2004). Each single-station measurement was executed with a three-directional digital tromograph Tromino Micromed (see www.tromino.it) with a sampling frequency of 128 Hz and an acquisition time length of 20 minutes. This value represents a good compromise between the celerity of the measurement execution (which is one of the main merits of this technique) and its accuracy, according to the SESAME guidelines and other studies (see, e.g., Picozzi et al., 2005). To provide HVSR curves, the time series relative to each ground motion component was subdivided in non-overlapping time windows of 20 s. For each of these, the signal was corrected for the base line, padded with zeros, and tapered with a Bartlett window; the relevant spectrogram was smoothed through a triangular window with frequency dependent half-width (5% of central frequency) and the H/V ratio (HVSR) of the spectral components (the former being the geometric mean of North-South and East-West components) was computed for each frequency. Spectral ratios relative to all the time windows considered were then averaged, and a mean HVSR curve was computed along with the relevant 95% confidence interval.

Before interpreting HVSR curve in terms of subsoil dynamical properties, we checked the possible occurrence of spurious HVSR peaks (e.g., due to impulsive or strongly localized anthropic sources). To this purpose, we investigated both the time stability of spectral ratios over the recording length and their directionality. The latter was analyzed by estimating the HVSR curves derived by projecting the ground motion along different horizontal directions. If transient directional effects were identified in the directional HVSR curves, the relevant portions of the record were discarded.

This check was formalized into a classification procedure previously adopted in the ambient vibration surveys in the area damaged by the L'Aquila earthquake, whose criteria were shared by the research units participating in the project and are summarized in the Appendix of Deliverable 7.

3.3 Array Measurements

This technique consists in recording ambient vibration ground motion by means of an array of sensors (vertical geophones) distributed at the surface of the subsoil to be explored (see, e.g., Okada, 2003). Relevant information concerning phase velocities of waves propagating across the array are obtained from average cross-spectral matrixes relative to sensor pairs. In the present analysis, plane waves propagating across the array were considered only. Since vertical sensors were used only, these waves are interpreted as plane Rayleigh waves in their fundamental and higher propagation modes. Determination of Rayleigh wave phase velocities V_R as a function of frequency (dispersion curve) from cross-spectral matrixes can be carried on in several ways. In the present analysis, the Extended Spatial Auto Correlation (ESAC) technique (Ohori et al. , 2002; Okada, 2003) was applied. The basic element of this analysis is the cross-correlation spectrum deduced by the analysis of ambient vibrations measured at a couple of sensors $\phi(f,r)$ where f is frequency and r is the distance between the relevant sensors .

To this purpose, registrations relative to each sensor are partitioned in a number of non overlapping time windows of fixed duration (20 sec). Time windows characterised by energy bursts were removed from the analysis. To this purpose, a time segment is considered in the analysis if standard deviation of all the traces of that time window do not exceed the threshold fixed in advance for each trace. In general, this threshold was fixed to be 2 times the standard deviation computed over the whole registration for the relevant trace. In each accepted time window, linear trend was removed and the resulting time series was padded and tapered (5% cosine windows). For each time window and couple of sensors, the cross spectrum was computed. The average cross spectrum was then computed for each couple of sensors by considering all the relevant time series. The resulting average cross-spectrum was thus smoothed in the frequency domain by a moving triangular window having an half-width proportional to the central value (usually 10%) and normalized to the relevant auto spectra.

In the assumption that ambient vibration wave field can be represented as a linear combination of statistically independent plane waves propagating with negligible attenuation in a horizontal plane in different directions with different powers, but with the same phase velocity for a given frequency, the normalized cross-spectrum $\phi_{ij}(f,r)$ relative to sensors located at a distance r, can be written in the form

$$\phi(f,r) = J_0\left(\frac{2\pi fr}{V_R(f)}\right)$$

where J_0 is the Bessel function of *0-th* order. In the ESAC approach, the value of V_R relative to each frequency f is retrieved by a grid search algorithm to optimized (in a RMS sense) the fit of the above function of r for the relevant frequency f (Ohori et al. , 2002; Okada, 2003). Robustness of this fitting procedure was enhanced by adopting the iterative procedure proposed by Parolai et al., 2006). By following these last Authors, uncertainty on "apparent" velocities was computed by means the second derivative of the misfit function relative to grid search procedure (see, Menke, 1989). However, since these estimate tend to be under-conservative in some cases, the lower bound of the confidence interval for experimental V_R values was fixed by using the relationship proposed by Zhang et al. (2004) as a function of the adopted sampling rate and array dimension.

The $V_R(f)$ value obtained in this way, is the "apparent" or "effective" Rayleigh waves phase velocity that coincides with the actual phase velocity only in the case that higher modes play a negligible role. In the other cases, a relationship can be established between actual phase velocities and the apparent one (Tokimatsu, 1997). The fact that the ESAC approach allows the determination of the apparent dispersion curve instead of the modal ones could represent an important limitation of this procedure with respect to other approaches (e.g., f-k techniques). On the other hand, this makes the approach here considered more robust with respect to the alternative procedures, since it does not require troublesome picking of existing propagation modes.

In the present study, ambient vibrations were recorded for 20 minutes at a 256 Hz sampling rate by using 16 vertical geophones (4.5 Hz) and a digital acquisition system produced by Micromed (http://micromed.com/brainspy1.htm). Geophones were placed along two crossing perpendicular branches (with maximum dimensions lower than 100 m) and irregularly spaced (in the range 0.5-30 m).

3.4. Inversion procedures

HVSR and apparent V_R curves have been jointly inverted to constrain to the local V_S profile. To this purpose, a genetic algorithm procedure was considered. This is an iterative procedure, consisting in sequence of steps miming the evolutionary selection of living being (see Picozzi and

Albarello, 2007 and references therein). The formalization proposed by Lunedei and Albarello (2009) was used as the forward modelling modelling implemented in the procedure. This procedure assumes the subsoil as a flat stratified viscoelastic medium where surface waves (Rayleigh and Love with relevant higher modes) propagate only. From this model, both theoretical HVSR and effective dispersion curves can be computed from a set of parameters representative of the hypothetical subsoil (V_S, V_P, density, Q_P and Q_S profiles). The discrepancy between theoretical and observed HVSR and dispersion curves were then evaluated in terms of a suitable misfit function, strictly linked to the well-known χ^2 function, that allowed different choices about the combination of the discrepancies of V_R and HVSR curves, with different weights as well. The confidence interval around preferred *Vs* values and layer thickness were evaluated by following Picozzi and Albarello (2007).

4.Examples

4.1 The Montecassino Ran site (MTC)

A first step, a detailed geologic survey of the area surrounding the RAN site was carried on (Figure 2).

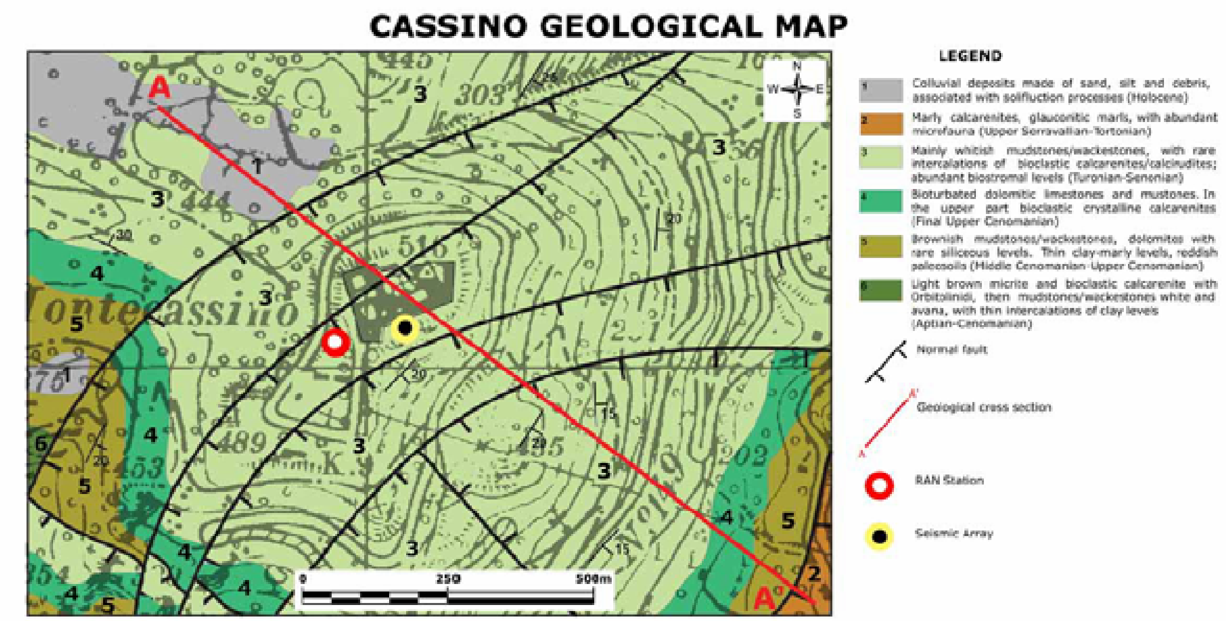

Figure 2*: Geologic map of the Montecassino RAN site*

The Montecassino RAN station is located in the South-Eastern sector of Monte Cairo (Southern Latium). From a topographic point of view the M. Cassino RAN station belongs to the T4 topographic class.

The site is characterized by the cropping out of a thick Cretaceous inner platform succession belonging to the Laziale-abruzzse domain. The sedimentary succession is characterized by bioclastic limestones, brownish limestones, marls, bio-clastic calcarenites dolomitic limestones and dolomites. Field analyses carried out in the site allow us to identify up to 6 different formations as listed below: 6) Downward light brown micrite and bioclastic calcarenite with Orbitoidi, then mudstones/wackestones white and avana, with thin intercalations of clay and sporadic levels of flint. Middle portion is characterized by laminated dolomicrite and light brown mudstones/wackestones and marly-conglomeratic levels with large quantity of quartz. Upward dolomite with laminations and saccaroid dolomites. 5) Brownish mudstones/wackestones, dolomitic limestones, dolomites with rare siliceous levels. Thin clay-marly levels, reddish paleosoils. Conglomerates, reddish calcareous hard-ground and dark dolomites. 4)Bioturbated dolomitic limestones and mudstones/wackestones. In the upper part bioclastic crystalline calcarenites/calcurydites. 3) Mainly whitish mudstones/wackestones, with rare intercalations of bioclastic calcarenites/calcirudites; abundant bioclastic calcarenites/calcirudites; abundant biostromal levels and dissolution processes. 2) Calcareniti a Briozoa member has been distinguished. Whitish/gray calcarenites/calcirudites with Briozoa and fragments of Lithotamnium, interbedded with whitish saccaroids calcarenites laterally passing to gray-yellowish calcarenites with Briozoa and Pecten. 1) Continental deposits mainly characterized by alluvial/colluvial deposits.

The site is characterized by the presence of several faults. These last has been kinematically caracterized as normal faults, mainly dip-slip, with an anti-Apenninic SW-NE trend. The average deep angle is 70-80° SE that gradually offset toward the South-Eastern sector the whole sedimentary succession. An important normal fault N-S trending offset to the E the upper portion of the succession as demonstrated by the cropping out of the Miocene formation at the base of the M. Cassino hill.

A representative geological section is reported in Figure 3.

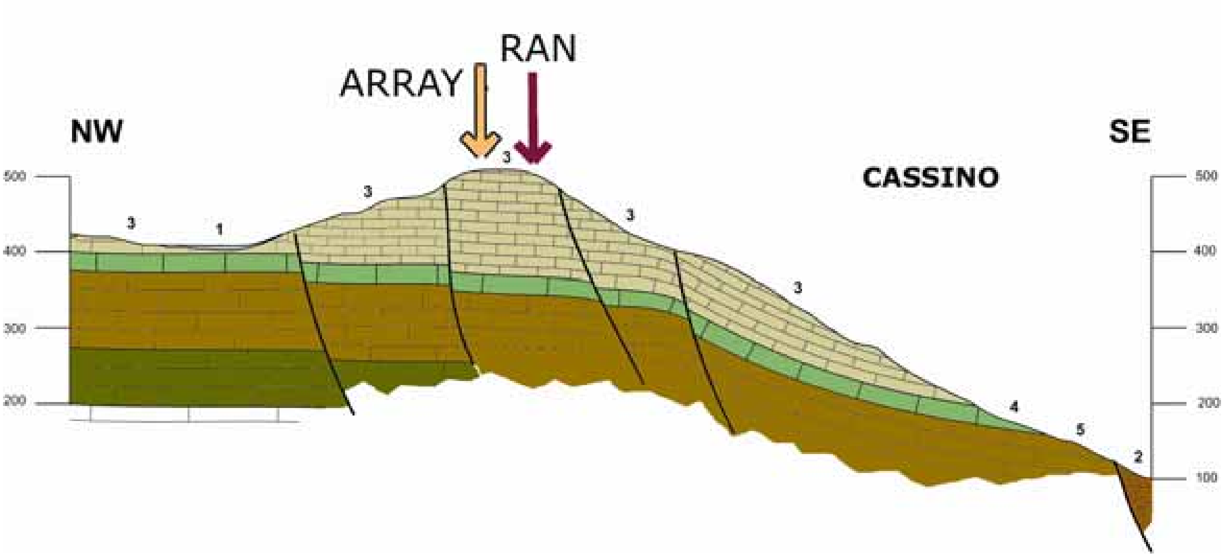

Figure 3 *Geological section across Montecassino area (see trace in Fig.2): RAN indicates location of the MTC accelerometric station. ARRAY indicates the position of the array*

A single station measurement was carried nearby the RAN station (Figure 4) on 15th of May 2009. The analysis of this measurement revealed the presence of strong electromagnetic noise affecting a significant range of frequencies.

Figure 4. *Location of the RAN station and of the corresponding single station ambient vibration measurement*

The resulting HVSR curve is reported in Figure 5. One can see that, if one discards the apparent peak around 1-2 Hz induced by electromagnetic noise, a sharp peak only emerges in the high frequency range (just above 18 Hz) that can be attributed to a very thin soft coverage of the rock that constitutes the bulk of the hill.

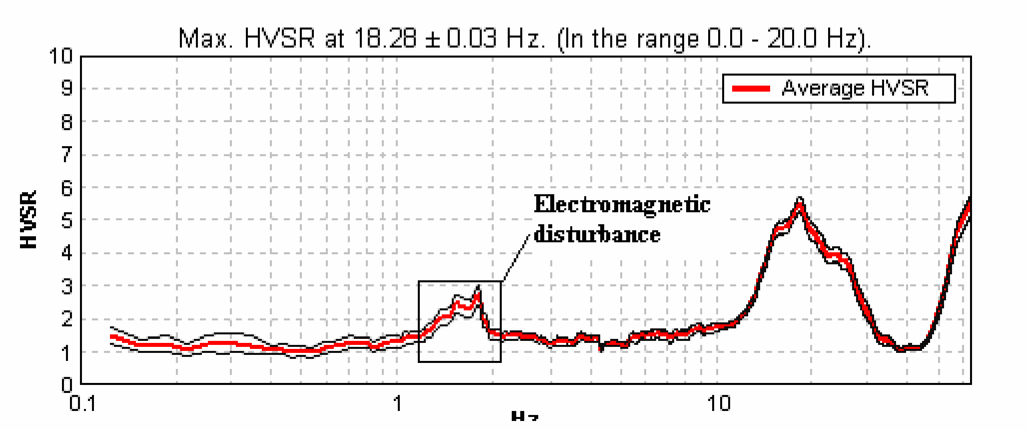

Figure 5. *HVSR curve obtained at the RAN station. The red line indicates the average HVSR values, while the black thin lines indicate the relevant 95% confidence interval*

Due to the very difficult topographic situation (the RAN station is located at the edge of the terrace where the Montecassino Abbey is located , Fig 6), array measurements were carried on at the foothill, few hundreds meters apart.

The apparent V_R pattern is shown in Figure 7. Geological analyses indicate that at the array, bedrock is nearly outcropping. In fact, the shape of apparent V_R values is compatible with a uniform rock formation characterised by a *Vs* value of the order of 1400 m/sec. At the site were array was located, a number of HVSR measurements were carried on to reveal possible lateral variations in the subsoil around the array. These allowed to exclude such variations: all the relevant HVSR curves resulted flat, confirming geological indications and suggesting that a uniform rock body constitutes the local subsoil.

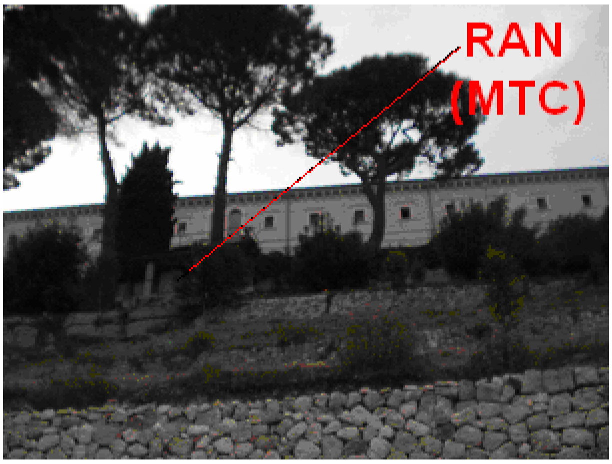

Figure 6. *Location of the RAN station, at the edge of the terrace where the Montecassino Abbey is located*

However, a uniform subsoil is incompatible with the HVSR curve at the RAN station, where a resonance frequency was detected by HVSR measurements, that is compatible with the presence of a sharp shallow transition between a soft coverage (possibly landfill of anthropic origin) and the underlying bedrock.

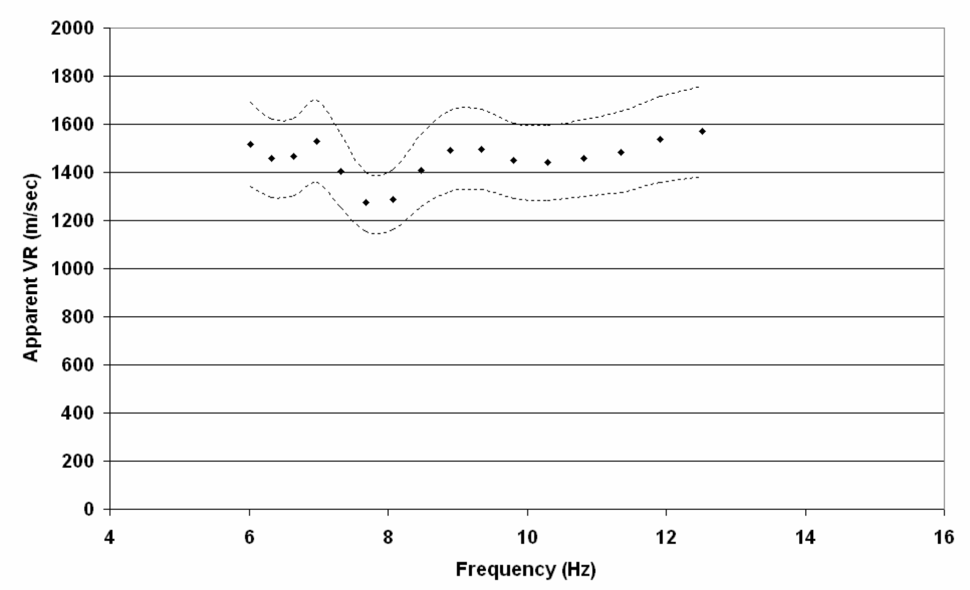

Figure 7. *Apparent VR curve deduced from array measurements. Dots indicate VR estimates while dashed lines bound the relevant 95% confidence interval*

In order to make these results compatible, an inversion of HVSR curve in Figure 4 (after that electromagnetic noise was discarded) was attempted by using Genetic Algorithms technique. In this inversion, V_S values of the bedrock was kept fixed to the value deduced from array measurements and a soft coverage configuration was searched for, that is compatible with HVSR measurements at the RAN station.

Outcomes of this inversion are reported in Figure 8 where the presence of thin soft layer (about 5 m thick possibly representative of onthropic landfill) is revealed above the seismic bedrock

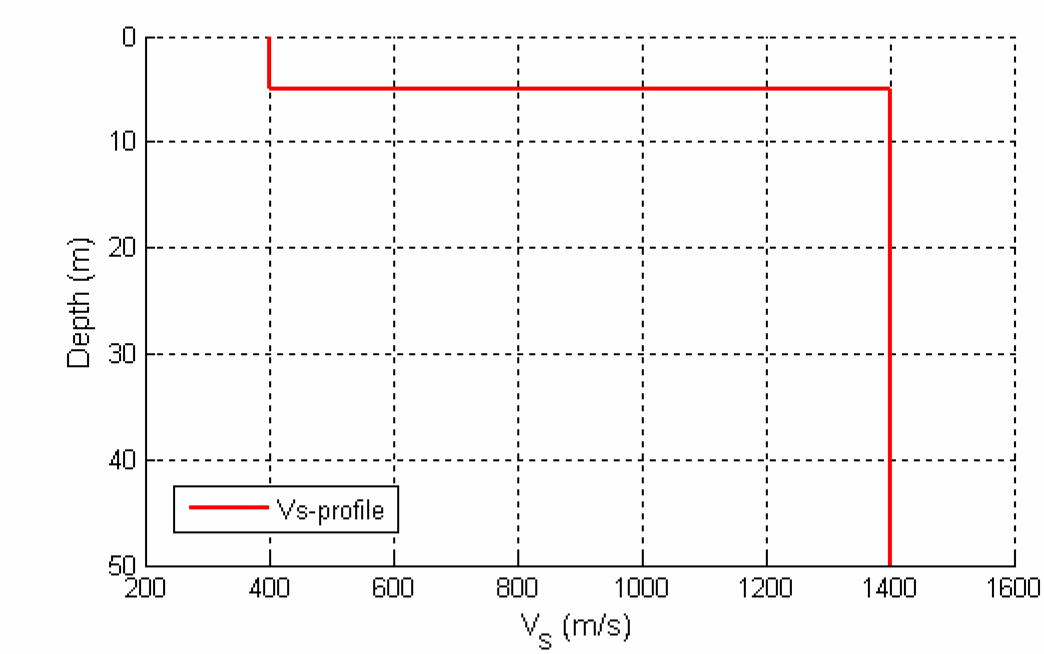

Figure 8. *Vs Velocity profile at the Montecassino RAN station*

4.2 The Capestrano Ran site (CPS)

The geologic setting around the CPS RAN site as deduced by a detailed geologic survey is reported in Figure 9.

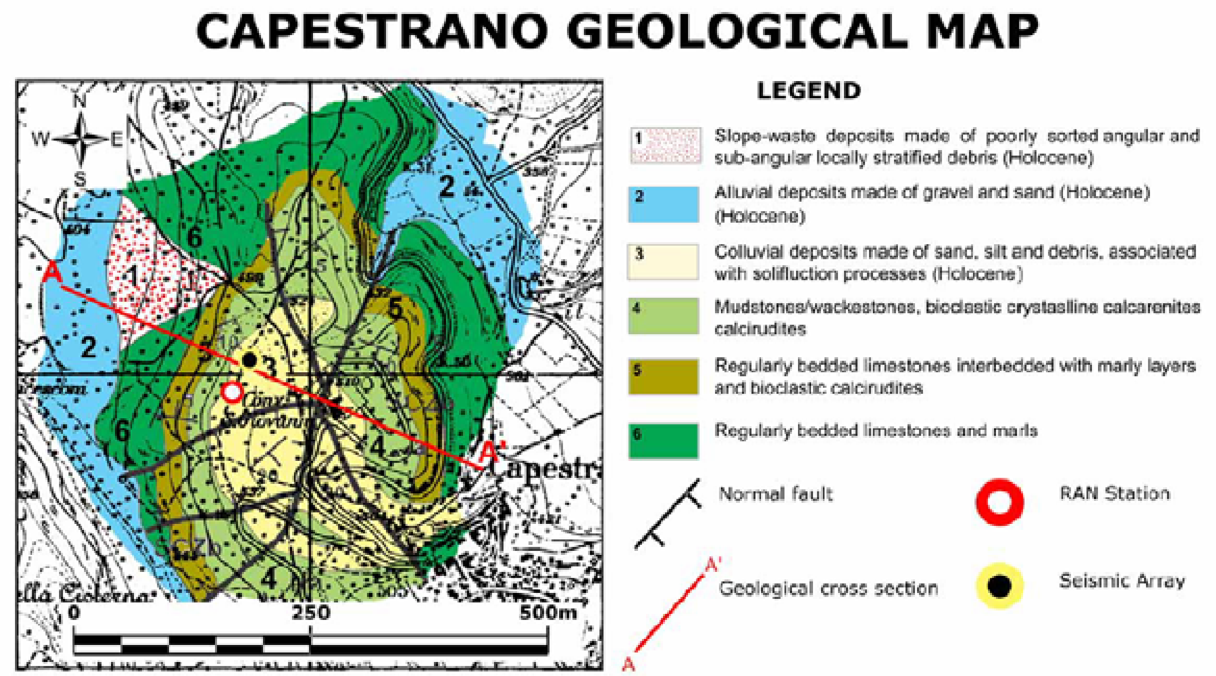

***Figure 9**: Geologic map of the Capestrano RAN site*

The Capestrano RAN station was realized on the top of a small hill at 537 m over the sea level. The station is located above a tin colluvial deposits just over the top of a cretaceous sedimentary succession belonging the laziale abruzzese domain. From a geometrically point of view the sedimentary succession is folded by a wide syncline with a sub-vertical fold plane. The average strata dip angle is always comprised between 5° to 10°. From the bottom of the cropping out formations it is possible to identify the following rocks: 6-5) regularly bedded limestones with nodules and flinstone bands, light brown micrite and bioclastic calcarenite, then wackestones with thin intercalations of clay and sporadic levels of flint. The base of the formation is characterized by a tick calcirudites horizon; 4) Mudstones and wackestones regularly bedded with intercalation of bioclastic crystalline calcarenites and calcirudites; 3) Colluvial deposits mainly composed of sand, silt and debris associated with solifluction processes; 2) Alluvial deposits made of gravel and sand with various thickness; 1) Slope-waste deposits made of poorly sorted angular and sub-angular. Locally the deposits present a well organized stratification.

The site is characterized by the presence of several normal faults offsetting the whole sedimentary succession. Despite the small offset (up to 40m) the fault planes recognized cross-cutting the whole zone with a main strike direction of N170°-20°. The main fault plane is characterized by a N20° trending, dip-slip W-dipping normal fault offsetting both the sedimentary succession and the other fault planes. Field analyses carried out allow us to identify and kinematically characterize up to 10 normal faults, but only 4 were mapped. Most of the un-mapped faults planes was characterized by centimetric offset and very poor planimetric extension. Fracture sets were observed across the limbs and the hinge of the fold (limb dips range from 5° to 10°). The fracture sets recognized was identify as dissolution cleavage showing a sub-vertical planes sub-parallel to the fold hinge. A second sets of fracture were identified and linked to the faults mechanisms. Both the ARRAY and the RAN (very close each other) lie over the same tin cover deposits just above an intense fractured sedimentary succession.

A representative geological section at the RAN station is reported in Figure 10. From a topographic point of view the Capestrano RAN station belongs to the T3 topographic class.

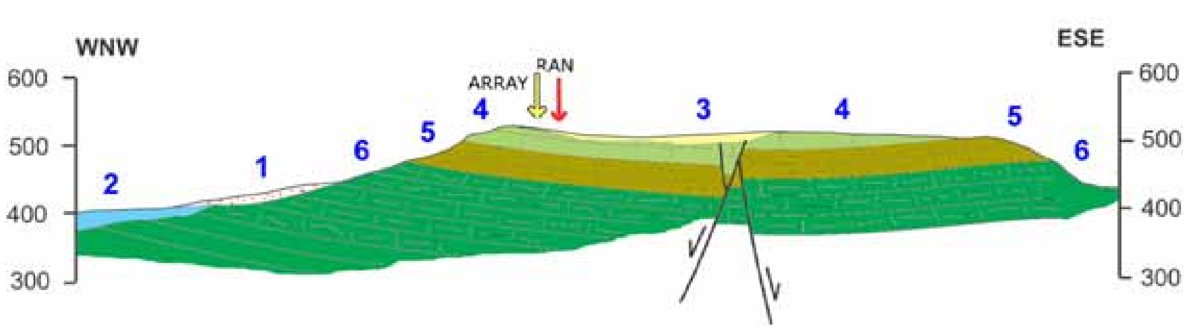

Figure 10 *Geological section across Capestrano area (see trace in Fig.9): RAN indicates location of the CPS accelerometric station. ARRAY indicates the position of the array*

In the case of the Capestrano site, both single station and array measurements were carried on nearby the RAN station (Figure 11). Resulting HVSR curve is reported in figure 12 and reveals the presence of a broad resonance peak with a maximum at the frequency of about 2.7 Hz in the presence of electromagnetic disturbances around 5 Hz.

Figure 11. *HAVSR measurements at the CPS RAN station. The silver small object at the bottom of the picture in the tromograph Tromino used for single station ambient vibration measurements.*

Due to the relatively flat morphology around the RAN station, the deployment of the array did not present any particular problem. These measurements provided the dispersion curve in Figure 13, that seems compatible V_S velocities relatively high and increasing with depth.

The curve in figures 12 and 13 were jointly inverted by providing the V_S profile in Figure 14. This indicates the presence, below a very thin soft coverage (1 m) of two rigid layers. The shallower one (10 thick with a V_S of about 700 m/sec) nearly correspond to the unit 4 (see section in figure 10). This overlies a deeper more rigid layer (with V_S values of the order of 1000 m/sec) having a larger thickness (about 50 m that nearly corresponds to unit 5 in the section of Figure 10) overlaying a more rigid structure (unit 6 in figure 10).

In this case, an almost perfect convergence of outcomes provide by geophysical and geological was achieved.

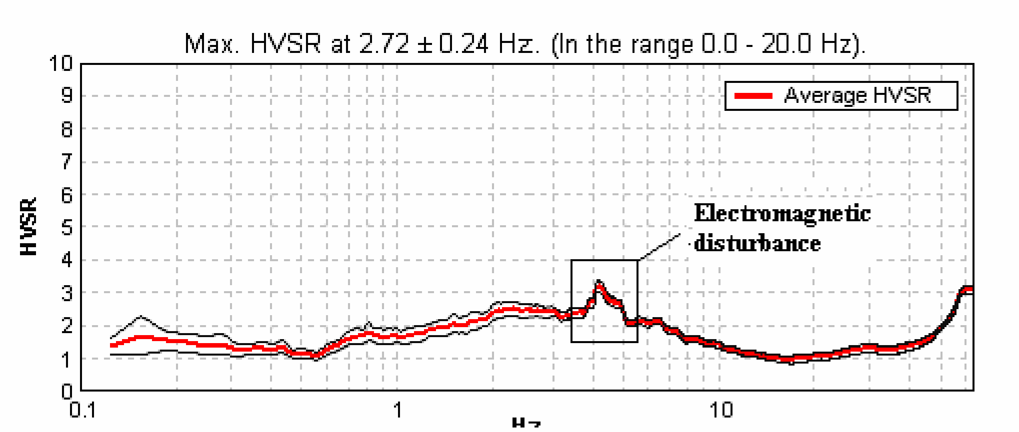

Figure 12. *HVSR curve obtained at the RAN station CPS. The red line indicates the average HVSR values, while the black thin lines indicate the relevant 95% confidence interval*

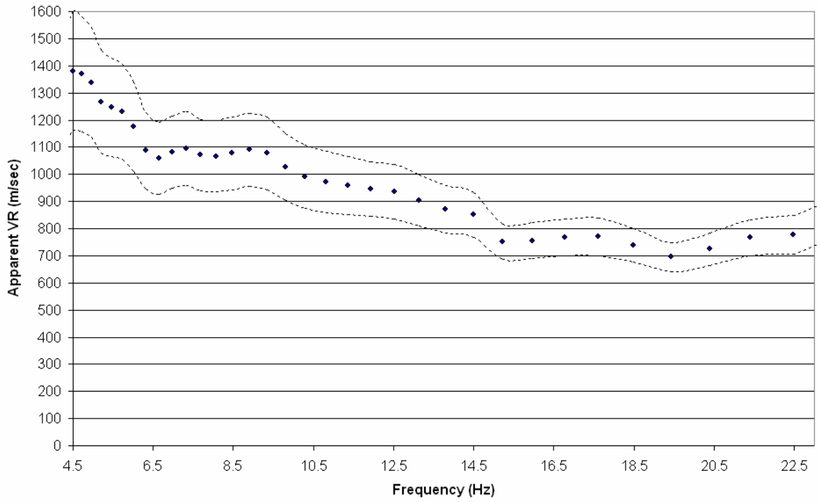

Figure 13. *Apparent VR curve deduced at the Cepestrano RAN site from array measurements. Dots indicate VR estimates while dashed lines bound the relevant 95% confidence interval*

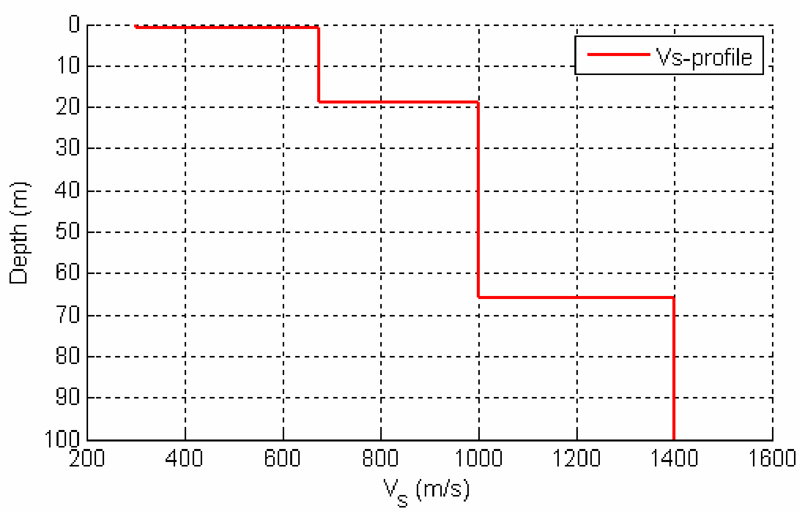

Figure 14. *Vs Velocity profile at the Capestrano RAN station*

5. Conclusions

The application of cheap prospecting techniques to the seismic characterization of stiff soil/ rock sites was tested. In particular, a survey protocol based on the joint application of single station and array ambient vibration monitoring under a strict geological control was applied to estimate the V_S profile in correspondence of RAN accelerometric sites. Single station measurements can be applied everywhere, irrespective to the local morphology and when analysed by using the HVSR technique allows the detection of resonance phenomena and provide a direct measure of the resonance frequency at the site of interest. Repeating these measurements all around the site of interest, also allows detection of lateral variations of rock mass lateral variations potentially responsible for energy trapping phenomena or other site effects. Furthermore, the shape of the HVSR curve contributes constraining the local V_S profile. ESAC analysis of array ambient vibration measurements, supplies robust estimates of the effective dispersion curve of Rayleigh waves. This curve, jointly inverted with HVSR data constrained by geological information allows the determination of the local V_S profile up depths of several tens to hundreds of meters. When local topography does not allow deployment of array, a detailed geological survey allows detection of alternative sites where measures can be carried on that can be considered as representative of the subsoil configuration at the site of primary interest. Operating HVSR estimates at both the sites, allows evaluating reliability of this assumption and, eventually, to modify the profile deduced at the alternative site to reproduce the curve at the site of interest.

In the frame of the research project, the above procedure was successfully applied to ten sites by providing the results summarized in Table 2. It is worth noting the presence of resonance phenomena, also in the cases of outcropping rock formations. To this respect the case of Mormanno (MRM) represents the only exception.

Table 2. *Synthesis of results obtained by the application of the experimental protocol described in the text at a number of accelerometric RAN stations. Columns respectively report: the name and the acronym of the station, the average V_S value up to a depth of 30 m from the surface, the depth of the bedrock (e.g., where V_S >800 m/sec), the average V_S value up to this bedrock and the fundamental V_S resonance frequency measured at the site.*

Site	Station	VS_{30} (m/s)	Bedrock (m)	VS_h (m/s)	f_0 (exp.) (Hz)
CAPESTRANO	CPS	730	19	630	2.7
AQUILA COLLE DEI GRILLI	AQG	1150	0	0	6.3
PESCASSEROLI	PSC	1000	0	0	4.3
AQUILA PETTINO	AQP	830	7	500	1.9
SCANNO	SCN	840	20	750	3.6
MORMANNO	MRM	1400	0	0	No
SPEZZANO SILA	SPS	320	29	310	3.4
VIBO MARINA	VBM	450	34	460	5.2
VIBO VALENTIA	VBV	510	24	450	13.5
MONTECASSINO	MTC	1000	5	400	18.3

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1. Scope and Description of the Deliverable

This deliverable mainly describes an experimental protocol on purpose developed for the seismic characterization of rock/stiff soil sites from passive seismic surveys. Two application examples are discussed in some detail, in order to show actual feasibility of the proposed approach

2. Availability/Restrictions and contact person

3. Relevance for DPC and/or for the scientific community

4. Changes with respect to the original plans and reasons for it

At the beginning of the project, in order to better constrain the classification of rock/stiff soil sites, a geomechanical characterization of the soil mass was planned also. However, the local geology, rugged topography and presence of sedimentary or alteration layers at the various outcropping rock sites investigated within Project S4, prevented an exhaustive geomechanical characterization and was abandoned. Therefore, the scope of the work was modified and attention was mainly focused on evaluating feasibility of low cost passive seismic investigations at rock sites. The investigations carried on in the frame of the project confirmed the feasibility of these techniques when accompanied by a detailed geologic survey of the area under investigation.