APPLICATION OF SURFACE WAVE METHODS FOR SEISMIC SITE CHARACTERIZATION

CATANIA (PIANA) (CAT)

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1 Introduction

In this report a summary of the results obtained for the characterization of the accelerometric station of Catania (Piana) of the RAN within Project S4 is presented. The analysis was performed using active and passive surface wave method .

Catania (Piana) RAN station lies on the alluvial plane of Catania, approximately 3.5 km from the sea. No shallow bedrock is expected, but a sequence of soft layers made up of alluvial deposits with a S-wave velocity increasing with depth.

The map, site location and measurements arrays are shown in Figure1, Figure 2 and Figure 3.

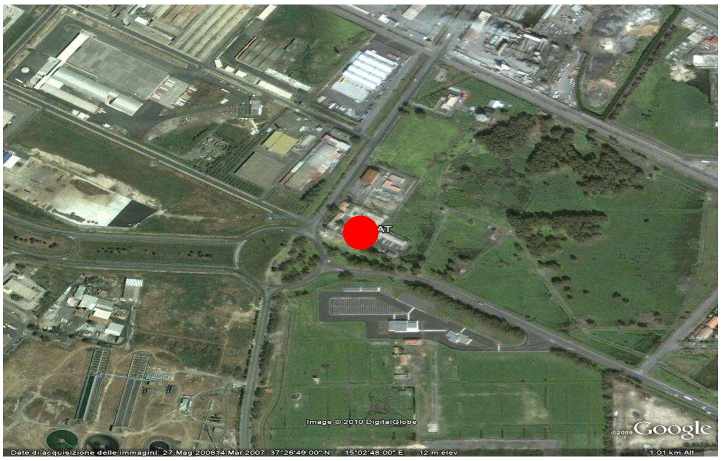

Figure 1 Catania (Piana): site map

Figure 2 Catania (Piana): array map. The red line represents the active measurements array; the black circle and the red circle represent the two circles along which receivers for passive measurements were arranged.

Figure 3 Catania (Piana): site location and active measurement array.

Goal of the seismic tests is the estimation of the S-wave velocity profile of the subsoil. Both passive and active surface wave tests were performed in order to increase the investigation depth, as no shallow bedrock is expected.

The primary use of surface wave testing is related to site characterization in terms of shear wave velocity profile. The V_S profile is of primary interest for seismic site response studies and for studies of vibration of foundations and vibration transmission in soils. Other applications are related to the prediction of settlements and to soil-structure interaction.

With respect to the evaluation of seismic site response, it is worth noting the affinity between the model used for the interpretation of surface wave tests and the model adopted for most site responses study. Indeed the application of equivalent linear elastic methods is often associated with layered models (e.g. the code SHAKE and all similar approaches). This affinity is also particularly important in the light of equivalence problems, which arise because of non-uniqueness of the solution in inverse problems. Indeed profiles which are equivalent in terms of Rayleigh wave propagation are also equivalent in term of seismic amplification (Foti et al., 2009).

Many seismic building codes introduce the weighted average of the shear wave velocity profile in the shallowest 30m as to discriminate class of soils to which a similar site amplification effect can be associated. The so-called $V_{S,30}$ can be evaluated very efficiently with surface wave method also because its average nature does not require the high level of accuracy that can be obtained with seismic borehole methods.

In the following a methodological summary of techniques and the description of the results is presented.

For Further explanation of surface wave methodologies, see document: Project S4: ITALIAN STRONG MOTION DATA BASE, Deliverable # 6, Application of Surface wave methods for seismic site characterization, May 2009.

2 Surface wave method

Surface wave method (S.W.M.) is based on the geometrical dispersion, which makes Rayleigh wave velocity frequency dependent in vertically heterogeneous media. High frequency (short wavelength) Rayleigh waves propagate in shallow zones close to the free surface and are informative about their mechanical properties, whereas low frequency (long wavelength) components involve deeper layers. Surface wave tests are typically devoted to the determination of a small strain stiffness profile for the site under investigation. Consequently the dispersion curve will be associated to the variation of medium parameters with depth.

The calculation of the dispersion curve from model parameters is the so called forward problem. Surface wave propagation can be seen as the combination of multiple modes of propagation, i.e. more than one possible velocity can be associated to each frequency value. Including higher modes in the inversion process allows the penetration depth to be increased and a more accurate subsoil profile to be retrieved.

If the dispersion curve is estimated on the basis of experimental data, it is then possible to solve the inverse problem, i.e. the model parameters are identified on the basis of the experimental data collected on the boundary of the medium. The result of the surface wave method is a one-dimensional S wave velocity soil profile.

The standard procedure for surface wave tests is reported in Figure 4. It can be subdivided into three main steps:

1. acquisition of experimental data;
2. signal processing to obtain the experimental dispersion curve;
3. inversion process to estimate shear wave velocity profile at the site.

It is very important to recognize that the above steps are strongly interconnected and their interaction must be adequately accounted for during the whole interpretation process.

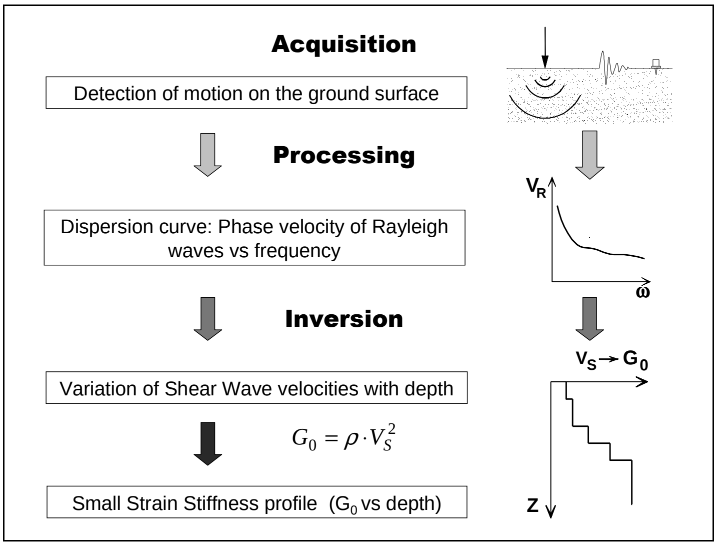

Figure 4 – Flow chart of surface wave tests.

2.1 Acquisition

Active (MASW) and passive surface wave tests at Catania (Piana) have been performed in May 2009 within the project S4 for the characterization of RAN sites.

Characteristics of sensors are reported in Table 1.

Test	GEOPHONE TYPE	NATURAL FREQUENCY	GEOPHONE NUMBER
MASW	vertical SENSOR SM-6/U-B	4,5 Hz	48
Passive surface wave tests	three components 3D HS1 GEO-SPACE	2 Hz	4
	vertical HS1 GEO-SPACE	2 Hz	12

Table 1 Catania (Piana): receiver characteristics

Acquisition geometry is shown in Figure 5. 48 receivers were used for active tests, with a spacing of 1.5 m between neighbouring geophones, so that the total length of the array is 70.5 m. The source is a 5kg sledge hammer. 16 receivers were used for passive tests: one three components geophones was placed at the centre of the array and three others were disposed along a circle whose radius is 9 m; 12 vertical geophones were arranged along the outer circle whose radius is 25 m. Acquisition parameters are summarized in Table 2

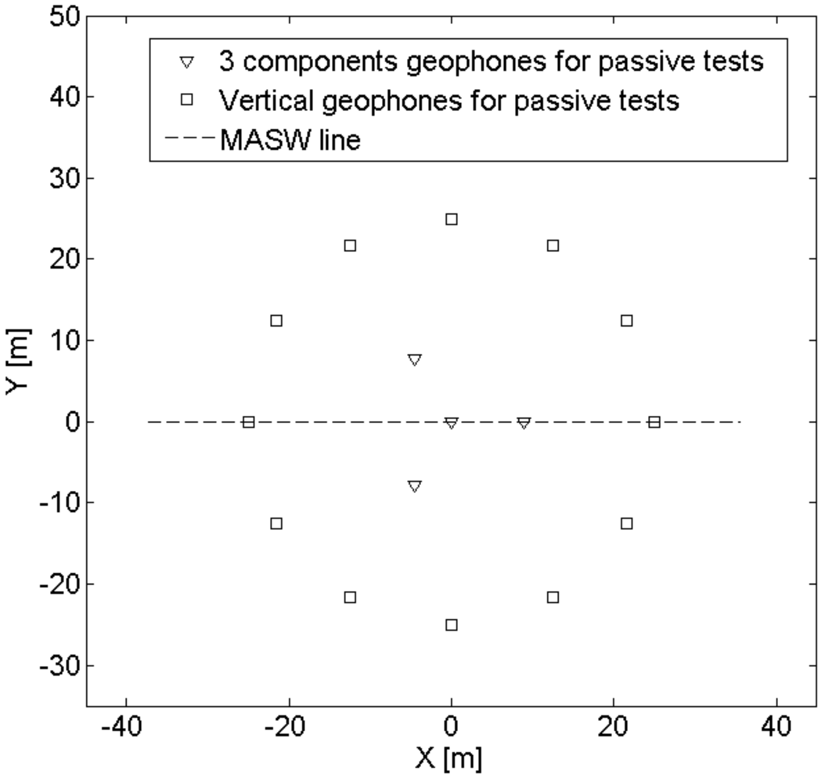

Figure 5 – Acquisition geometry.

Test	GEOF. N.	SPACING	SOURCE TYPE	ACQUISITION WINDOW	SAMPLING INTERVAL	STACK
MASW	48	1.5 m	Hammer	T = 2 s	Δt = 0.5 ms	10
Passive tests	16	-	-	T =524 s	Δt = 8 ms	1

Table 2 Catania (Piana): Acquisition parameters

2.2 Processing of active surface wave data

The processing allows the experimental dispersion curve to be determined.

Multichannel data are processed using a double Fourier Transform, which generates the frequency-wave number spectrum, where the multimodal dispersion curve is easily extracted as the location of spectral maxima.

2.3 Processing of passive surface wave data

The phase velocity of the surface waves can be extracted from noise recordings by using different methods: among them, the most frequently used are the Beam-Forming Method (BFM) (Lacoss et al., 1969) and the Maximum Likelihood Method (MLM) (Capon, 1969). Here we will illustrate the Beam-Forming Method which was used to process passive surface wave data. For further explanation on passive surface wave methodologies, see document: Project S4: ITALIAN STRONG MOTION DATA BASE, Deliverable # 6, Application of Surface wave methods for seismic site characterization, May 2009.

The estimate of the F-K spectra $P_b(f,\mathrm{k})$ by the BFM is given by:

$$P_b(f,k) = \sum_{l,m=1}^{n} \phi_{lm} \exp\{ik(X_l - X_m\} \ ,$$

where f is the frequency, k the two-dimensional horizontal wavenumber vector, n the number of sensors, ϕ_{lm} the estimate of the cross-power spectra between the l^{th} and the m^{th} data, and X_i and X_m, are the coordinates of the l^{th} and m^{th} sensors, respectively.

From the peak in the F-K spectrum occurring at coordinates k_{xo} and k_{yo} for a certain frequency f_0, the phase velocity c_0 can be calculated by:

$$c_0 = \frac{2\pi f_0}{\sqrt{k_{xo}^{\ 2} + k_{yo}^{\ 2}}}$$

so that, again, an experimental dispersion curve is retrieved.

Figure 6 shows an example of F-K analysis results obtained by processing passive surface wave data with Beam-Forming Method: white dots indicate the position of the maximum used to estimate the phase velocity while the white circle joins points with the same k values.

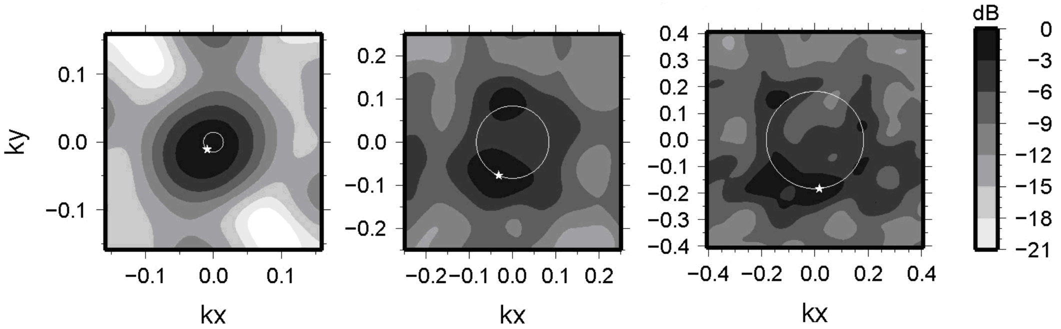

Figure 6 – Example of results from F-K analysis s for 2.5 Hz, 3.9 Hz, and 6.5 Hz. White dots indicate the position of the maximum used to estimate the phase velocity. The white circle joins points with the same k

2.4 Inversion of surface waves

The solution of the inverse Rayleigh problem is the final step in test interpretation. The solution of the forward problem forms the basis of any inversion strategy; the forward problem consists in the calculation of the function whose zeros are dispersion curves of a given model. Assuming a model for the soil deposit, model parameters of the best fitting subsoil profile are obtained minimizing an object function.

The subsoil is modelled as a horizontally layered medium overlaying a halfspace, with constant parameter in the interior of each layer and linear elastic behaviour. Model parameters are thickness, S-wave velocity, P-wave velocity (or Poisson coefficient), and density of each layer and the halfspace. The inversion is performed on S-wave velocities and thicknesses, whereas for the other parameters realistic values are chosen a priori. The number of layer is chosen applying minimum parameterization criterion.

In surface wave analysis it is very common to perform the inversions using only the fundamental mode of propagation. This approach is based on the assumption that the prevailing mode of propagation is the fundamental one; if this is partially true for normal dispersive sites, in several real cases the experimental dispersion curve is on the contrary the result of the superposition of several modes. This may happen in particular when velocity inversions or strong velocity contrasts are present in the shear wave velocity profile. In these stratigraphic conditions the inversion of the only fundamental mode will produce significant errors; moreover all the information contained in higher propagating modes is not used in the inversion process. Therefore, the fundamental mode inversion does not use all the available information, and this affects the result accuracy.

The use of higher modes in the inversion can be helpful both in the low frequency range, in order to increase the investigation depth and to avoid the overestimation of the bedrock velocity, and in the high frequency range in order to provide a more consistent interpretation of shallow interfaces and increase model parameter resolution.

In this work a multimodal misfit function has been used. This function is based on the Haskell-Thomson method for dispersion curve calculation (Thomson 1950, Haskell 1953, Herrmann e Wang 1980, Herrmann 2002). For a given subsoil model, and an experimental data, the misfit of the model is the L^1 norm of the vector containing the absolute value of the determinant of the Haskell-Thomson matrix (which is zeros in correspondence of all the modes of the dispersion curves of the numerical model) evaluated in correspondence of the experimental data (Maraschini et al. 2008). The misfit function adopted has the advantage of being able to include any dispersive event present in the data without the need of specifying to which mode the data points belong to, avoiding errors arising from mode misidentification, in particular in the low frequency range.

This misfit function is applied in a Global Search Methods (GSM), in order to reduce the possibility of falling in local minima. A uniform random search is applied; ranges for the inversion have been chosen, for the different sites, based on the experimental dispersion curves; in particular the range of the S-wave half space velocity is close to the maximum surface wave velocity retrieved on experimental data.

The results of the inversion are reported as the ensemble of the best shear wave velocity profiles chosen according to a chi-square test (see Socco et al., 2008). It can be assumed that the experimental dispersion curve is affected by a Gaussian error with a known standard deviation, so that the probability density function of data $\rho_D(d)$ can be described by a discrete m-dimensional Gaussian (where m are the model parameters) and the sample variance variable of each random vector (dispersion curve) extracted from the data pdf is distributed according to a chi-square probability density. According to these assumptions we adopt a misfit function with the structure of a chi-square and this allows a statistical test to be applied to the variances of the synthetic dispersion curves with respect to the experimental one d_{obs}. Assuming that the best fitting curve d_{opt} belongs to the distribution $\rho_D(d_{obs})$ all models belonging to the distribution $\rho_D(d_{opt})$ and consistent with the data within a fixed level of confidence α are selected. As the ratio between chi-square variables follows a Fisher distribution a one–tailed F test can be performed:

$$F_{\alpha}(dof_{dopt}, dof_{g(m)}) < \frac{\chi^2{}_{dopt}}{\chi^2{}_{g(m)}}$$

where α is the chosen level of confidence, dof_{dopt} and $dof_{g(m)}$ are the degrees of freedom of the Fischer distribution and $\chi^2{}_{dopt}$ and $\chi^2{}_{g(m)}$ are the misfit of the best fitting curve and the misfit of all the others respectively. All models passing such test are selected. In the figures reported a representation based on the misfit is adopted for velocity profiles, so that the darkest colour corresponds to the profile whose dispersion curve has the lowest misfit and better approximation to the reference one; instead for dispersion curves the coloured surface under imposed to the experimental one is a misfit surface, whose zeros are synthetic dispersion curve of the best fitting model.

2.5 Numerical code

The numerical codes used for processing and inversion of surface waves are non commercial codes, implemented at Politecnico di Torino.

3 Catania (Piana) – Surface wave results

In Figure 7 an example of the f-k spectrum from active data collected at Catania (Piana) is presented.

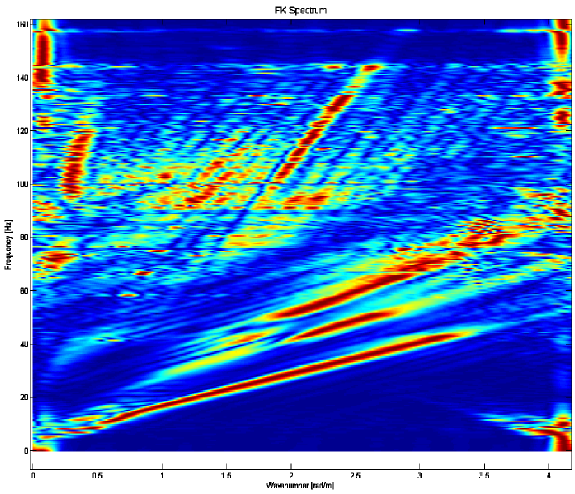

Figure 7 Catania (Piana) – example of f-k spectrum

From the f-k spectra of active and passive data, several dispersion curves can be retrieved. From all these curves an average curve is estimated (Figure 8).

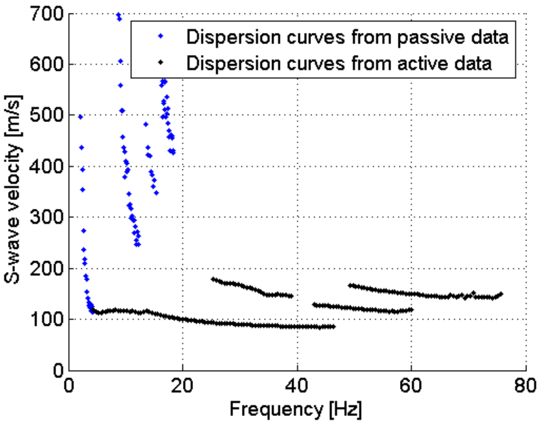

Figure 8 – Catania (Piana) -Average apparent dispersion curve

Very likely the apparent dispersion curve is characterized by the presence of four propagation modes: all of them show a steep velocity increase in the low frequency range. It should also be noticed that the low frequency part of the dispersion curve has been retrieved by processing passive data which allow a greater investigation depth.

Data were inverted using a multimodal stochastic approach, the best fitting profiles are plotted in Figure 9 a), profile colour depends on the misfit, from yellow to blue (best fitting profile). In Figure 9 b) the best fitting profile is compared with the results of a DH test previously performed on the same site. In Figure 10 the experimental dispersion curve is compared with the determinant surface of the best fitting model. Moreover it can be noted that the surface wave method results are in fairly good agreement with the DH test profile, particularly in the shallower part of the profile itself.

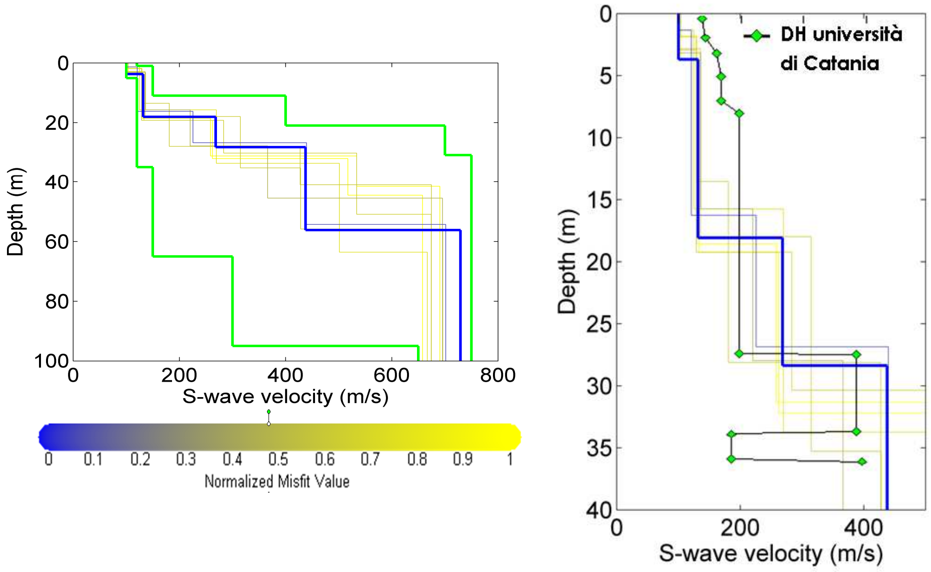

Figure 9 Catania (Piana) – a) Monte Carlo results (from yellow to blue) of the inversion with the boundaries (green). b) Catania (Piana) – Best fitting profiles compared with the refraction result (black).

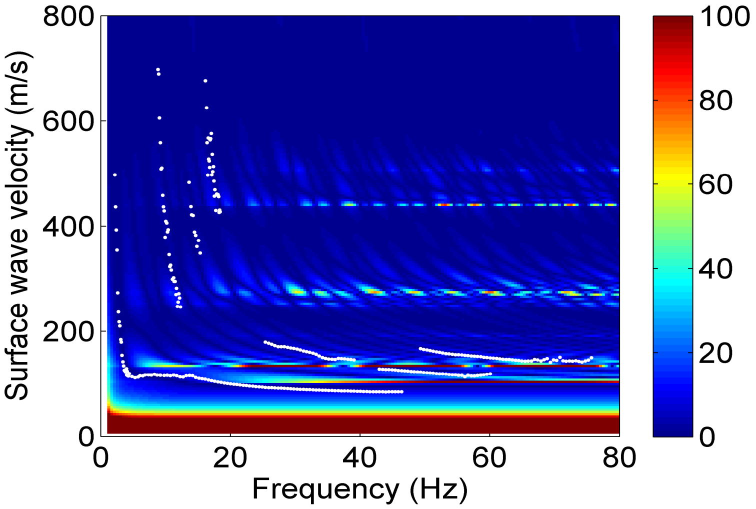

Figure 10 Catania – Experimental dispersion curve compared with the misfit surface of the best fitting model

The parameters of the best fitting profile are summarized in Table 4.

Vs (m/s)	Thickness (m)	Poisson coefficient	Density (T/m^3)
100	3.7	0.3	1.8
132	14.4	0.3	1.8
268	10.3	0.3	1.8
438	27.8	0.3	1.8
730	-	0.3	1.8

Table 3 Catania (Piana): subsoil parameters of the best fitting profile.

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