DYNAMIC CHARACTERIZATION AND DECONVOLUTION ANALYSIS FOR SOME SITES OF THE NATIONAL ACCELEROMETRIC NETWORK (RAN)

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Introduction. This work is part of the DPC-INGV-S2 research project devoted to improving mid-long term seismic hazard assessment in Italy (https://sites.google.com/site/ingvdpc2012progettos2/home). One of its main aims is the empirical testing of seismic hazard estimates proposed so far for the Italian area (Albarello *et al.*, 2015). To this purpose, several sites belonging to the Italian accelerometric network (RAN) active for a long time (at least 25 years) are considered and the probabilistic "forecasts" provided by each hazard estimate for that sites is compared with observations (for a general discussion of the testing methodology see Albarello and D'Amico, 2015).

Since hazard estimates are generally provided for reference soil conditions, sites of type A (by following NTC, 2008) only, which represent a subset of the considered sites. Furthermore, site soil classification for the most part of these stations was provided on the basis of large-scale (1:100,000) geological maps only, and this inaccurate soil classification may bias results of testing. To face this problem, the first phase of the work has been devoted to estimate the S-wave velocity (V_S) profile at all the sites and to provide a site characterization in terms of $V_{S,30}$. Thus, to exploit as much as possible available information, observations at non-reference sites were deconvolved (*e.g.*, Kramer, 1996) for the local seismic response to obtain accelerometric records "equivalent" to those relative to reference site conditions.

Results relative to nine accelerometric sites are presented here: eight of them are located in Central Italy (Cagli, Cascia, Castel Viscardo, Matelica, Peglio, Rincine, Senigallia, Sirolo) and one in southern Italy (Gildone). By following the procedure described in Pileggi *et al.* (2011), the V_S profile at these locations has been estimated by performing ambient vibration measurements both in single-station and multiple-station configuration. For each non-reference site, the free computer program STRATA (https://nees.org/resources/strata) has been used to deconvolve the ground motion by considering the mono-dimensional seismo-stratigraphical model obtained by the passive seismic study.

Ambient vibration monitoring and dynamic characterization of the sites. The ambient vibration monitoring has been carried out by performing, in each of the above-mentioned accelerometric sites, a number of single-station as well as a multiple-station (seismic array) measurements. In one site, two arrays have been realized, while in another one, an active MASW measurement has also been carried out (*vide infra*). As concerns single-station acquisitions, ambient vibrations have been recorded using a three-directional digital tromograph Tromino® *Micromed* (http://www.tromino.eu/); for seismic arrays, vertical geophones (4.5 Hz) and a BrainSpy 16 channel digital acquisition system by *Micromed* have been used. Acquisition duration of single-station measurements was of 20 or 30 minutes, with a sampling frequency of 128 Hz, while passive seismic arrays recorded at 128, 256 or 512 Hz, in any case for 20 minutes. Each acquisition by single-station measurements has been processed in order to obtain the HVSR curve (Nakamura, 1989; SESAME, 2004), which allow to evaluate the possible presence of seismic resonance phenomena. Acquisitions by seismic arrays have been analysed by both ESAC (Ohori *et al.*, 2002; Okada, 2003) and f-k (Lacoss *et al.*, 1969; Capon, 1969) techniques, in order to obtain relative Rayleigh-wave dispersion curves.

Jointly with each ambient-vibration monitoring, a geological/geomorphological survey has been carried out at a local scale (1:5000 or 1:10000), with the aim to better identify the geometry and to characterize the main lithological units where seismic impedance contrasts may occur (cf. Pileggi *et al.*, 2011).

In the cases where the accelerometric station is located on outcropping stiff soil (Cagli, Cascia, Rincine), it has not been possible to deploy seismic arrays in exact correspondence of the stations, due to the rough topography: in these situations, geologic survey was particularly useful to identify alternative sites characterized by a strict geologic correspondence with the site of interest. Topographical conditions have caused a similar problem for the station of Peglio.

As fully described in Pileggi *et al.* (2011), passive seismic surveys on stiff-rock sites suffer of significant drawbacks. In fact, in these geological settings, ambient vibrations are characterized by very low powers of surface waves (particularly evident in vertical ground motion) in the whole frequency range of interest (1-20 Hz). Moreover, when relatively high phase velocities exist (such as the ones expected at stiff-rock sites), ambient vibrations can be characterized by large wavelengths with respect to the overall dimension of the array (Foti *et al.*, 2011; Pileggi *et al.*, 2011). These effects may hamper retrieving clear dispersion curves in some of the analysed rock sites. At Cagli, a reasonable dispersion curve has been obtained for relatively high frequencies (10-25 Hz) only, while at Rincine it has not been possible to obtain any kind of dispersion curve, both using ESAC and f-k procedures. In this latter case, an active seismic prospecting has been necessary: by using the MASW technique (Park *et al.*, 1999), a dispersion curve that confirm the presence of Rayleigh-wave velocity values greater than 800 m/s at high frequencies (about 20 Hz) has been obtained.

As concerns the seismic array analysis, dispersion curves obtained by ESAC and f-k technique are, in general, very similar. Just in one case (Sirolo) the curves produced by these two techniques have been merged to "build" a single curve, because the ESAC curve is acceptable for relatively low frequencies (3-6 Hz) while the f-k one is so for higher frequencies (6-14 Hz). In the remaining cases, the choice of the dispersion curve to be used in the joint inversion procedure (*vide infra*) has been done by considering the shape regularity and the frequency coverage of the obtained ones.

To assess the V_S profile for the sites whose Rayleigh-wave velocity values are lower than 800 m/s, a joint inversion of a site-representative HVSR curve and of the Rayleigh-wave dispersion curve has been performed in each of them, by using a Genetic Algorithm procedure (*e.g.*, Albarello *et al.*, 2011). Since other geophysical measurements and borehole data are not available in the studied places, information provided by geological/geomorphological surveys has been used to constrain the inversion process. At each site, the inversion procedure has been repeated several times (>10) in order to estimate possible uncertainties affecting the resulting profiles. The overall variability for the S-wave velocity profile of each site has been assessed by using the extreme values of the set of solutions (profiles obtained by the inversion procedure) whose misfit is not greater than two times the misfit value associated to the best fitting model. These variability ranges have then been used in the deconvolution procedure (*vide infra*).

In the sites where placing the seismic array in the same position of the accelerometric station was not possible, obtained best profiles have been manually adapted in order they were able to reproduce the HVSR curves obtained in correspondence of the stations. As these adapted profiles have always shown to be included in the correspondent variability ranges given by the inversion procedures, these variability ranges have been reputed valid for the relative accelerometric stations too.

In any case, the best profile of each site has been used to estimate the $V_{S,30}$ and therefore to reclassify the site.

A summary of obtained results is shown in Tab. 1.

Tab. 1 - Synthesis of the results of the dynamical characterization of the studied acceleorometric stations.

station code	municipality	$V_{S,30}$ (m/s)	new soil class	*old* soil class	seismic bedrock depth min – max (m)	average V_S to the seismic bedrock (m/s)	f0 (Hz)
CGL	Cagli (PU)	> 800	A	*B*	0	-	20.2
CSC	Cascia (PG)	698	B	*B*	8 - 13	530	3.7
CSD	Castel Viscardo (TR)	484	B	*B*	22 - 189	454	3.9
GLD	Gildone (CB)	470	B	*B*	18 - 74	423	2.8
MTL	Matelica (MC)	579	B	*C*	33 - 82	578	2.0
PGL	Peglio (PU)	358	C	*B*	23 - 68	365	2.9
RNC	Rincine (FI)	871	A	*B*	9 - 12	570	no
SNG	Senigallia (AN)	258	C	*B*	65 - 159	420	1.4
SRL	Sirolo (AN)	270	C	*B*	54 - 296	515	5.8

Deconvolution analysis. When the stations are located, according with the realized reclassification, on reference sites, the ground-motion recorded by them can be directly used for validating seismic hazard estimates.

For the other stations, recorded ground-motion has been deconvolved by considering the seismic response of shallow low-velocity layers from the surface to the seismic bedrock where the ground motion has to be assessed.

The deconvolution has been performed, in a 1D scheme (in which the shallow subsoil is constituted by a stack of horizontal homogeneous and isotropic viscoelastic layers), by means the free software STRATA (https://nees.org/resources/strata), doing both linear and equivalent linear analysis. STRATA requests the definition of a stratigraphy where each stratum is characterized by: thickness, some statistical properties of S-wave velocity (extreme values, means and variance), the kind of the material and its viscosity properties. Results exposed in previous section have been used to fix these parameters.

First of all, a seismo-stratigraphical profile has been built by correlating the geological section of the area around each station with the V_S profiles derived from the relative inversion process. This step has been useful in order to link each geological unit to a density value as well as to a damping and a bulk modulus reduction curves. Density values and dynamic curves have been chosen from data derived from seismic microzoning studies in similar lithological units, in the same geological context and geographic area. Only for depths exceeding 40 m, dynamic curves by EPRI (1993) have been used, in order to not overestimating damping values (usually derived from analysis in shallow samples). Variability ranges in S-wave velocity profiles have been used to establish minimum and maximum values for the bedrock depth, as well as the statistical properties of V_S in each strata. Variability of modulus reduction and damping curves have been reproduced by following Darendeli (2001).

For each station where the deconvolution has been made, the ground motion to be deconvolved has been provided by other research units participating in the project, and consists in a set of selected earthquake events.

Statistics about peak ground acceleration (PGA) and acceleration spectral amplitude (SA) at 0.15, 1 and 2 s have been extracted for each site, based on an *ensemble* of 100 deconvolution runs for each earthquake record, to account for uncertainty affecting the local seismic stratigraphy. For each earthquake, the two horizontal components have been considered separately, taking into account both the geometric mean and the maximum of PGA and SA of each run. Then the median and the 75th percentile of the *ensemble* have been computed.

An example: the station of Peglio. The accelerometric station "PGL" is located within Peglio, a village in the Marche region (central Italy). The station is near the top of the hill where the village is situated (468 m a.s.l.), on a not very steep slope (< 15°) above the Metauro River valley.

The station lies on syn/post-evaporitic deposits characterized by a siliciclastic succession consist of marl, clay-marl, gypsum, clay, sandstone and silt. The station is situated on a unit (*Formazione a Colombacci*; FCO) formed by clay and marl, dipping with an inclination of about 15° northward and situated on a anticline flank. Due to the nature of these lithologies, this area is characterized by the presence of several landslides, active too (MUSa1q, MUSa). The FCO formation lies on *Gessoso-Solfifera* Formation (GES) with unconformity relationship; this latter unit, mainly composed by gypseous sandstone and marl, lies on Miocenic torbiditic sandstone and marl (*Marnoso-Arenacea Marchigiana* Formation; FAM) with the same stratigraphic relationship. The village historical centre is situated on a *Gessoso-Solfifera* Formation facies mainly composed by alabastrine gypsum (GESa). Peglio is located in the north of the major north Apennine bending. The main structures are anticlines, synclines and thrusts trending mainly NW-SE (Apennine direction), sometimes cut-off by normal fault with N-S trend. However, the tectonic setting is dominated by Mio-Pliocenic compressive structures.

Due to the position of the station "PGL", it was not possible to deploy a seismic array near the station, so it was decided to realize two arrays in the neighbourhood: one in the same geological unit and the other one on a different unit. However, the first one did not give any readable dispersion curve, so just the curve obtained by the second array was available for the inversion procedure. In the area including the station and the two seismic arrays, 21 single-station ambient-vibration measurements were also performed.

A set of joint inversions of the dispersion curve and a HVSR curve obtained by a single-station measurement located near the relative array was performed, by using the above-mentioned Genetic Algorithm procedure. Each result of the inversion set is the best profile produced by an independent run. The best resulting group, which contains the profile with minimum global misfit value (in red) and the ones whose misfit values are no greater than its double (in green), is shown in Fig. 1.

The best fit profile obtained by the inversion (characterized by the minimum misfit value and represented by red lines in Fig. 1) has been chosen as reference to perform a geological interpretation of the subsoil configuration in the place where the seismic array was deployed: this interpretation is exposed in Tab. 2.

The whole *ensemble* of best results (represented by red and green lines in Fig. 1) is considered as representative of the result variability. Consequently, the depth of the seismic bedrock top is estimated to be between 23 and 68 m.

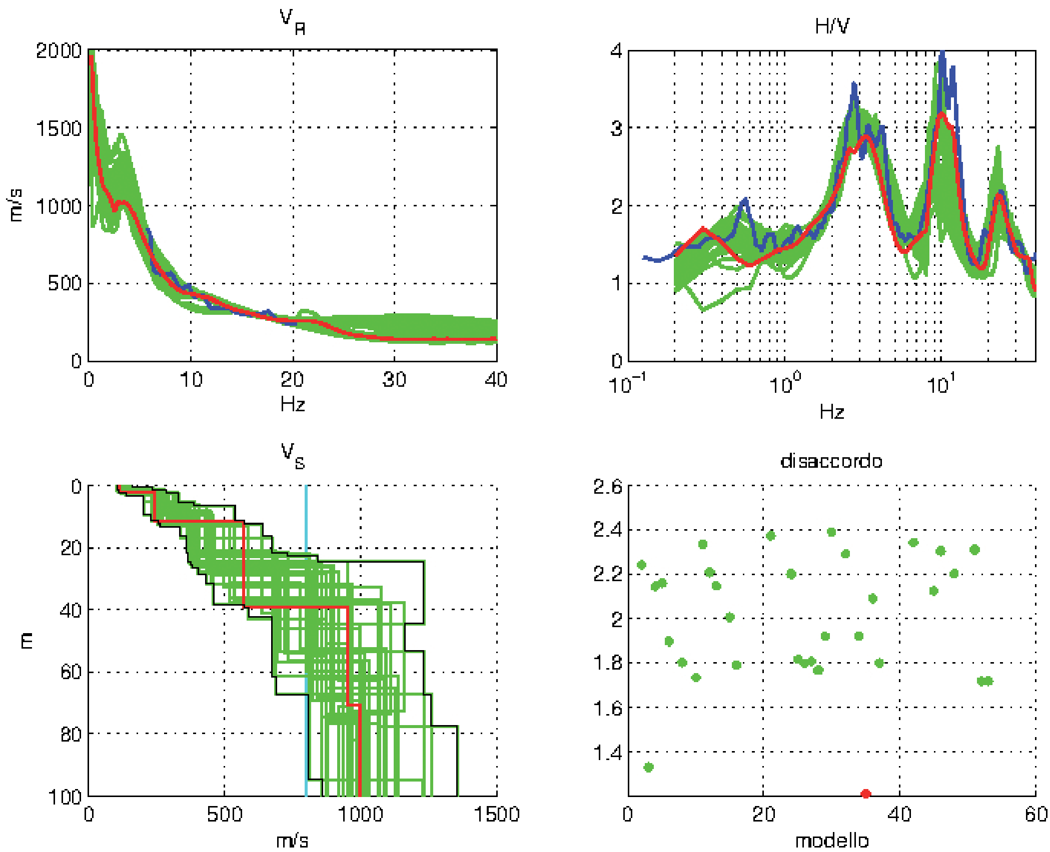

Fig. 1 – Inversion results for the accelerometric station of Peglio: blue lines represent the experimental data, red lines mark the best profile (the minimum misfit one), green line describe the profiles whose misfit is no higher than the double of the minimum one, black lines mark the variability range of the results and cyan line is the reference velocity of 800 m/s.

Tab. 2 - Geological interpretation of the best-profile shallow strata obtained beneath the array position: for each layer, depth, thickness, S-wave velocity, type of material and corresponding geological formation are reported.

depth (m)	thickness (m)	V_S (m/s)	lithology	geological unit
2	2	116	debris	MUSa
11	9	241	marl and clay marls *(Colombacci)*	FCO
38	27	571	gypsum	GES
70	32	952	marl	FAM1c
144	74	995	sandstone and marl	FAM1

Although the seismic array was deployed not so far from the accelerometric station location, it lays on a different geological unit with respect this one, so an adjustment of the obtained seismo-stratigraphical profile (Tab. 2) was necessary, in order to better represent the subsoil beneath the accelerometric station. As the sole information in this last site is provided by HVSR curves, the best quality one of them was chosen as representative of this place. After removed the shallowest layer, this adjustment involved changes in layer thickness and velocity values. These values were changed by hand, by using a surface-wave model (which is used in the inversion

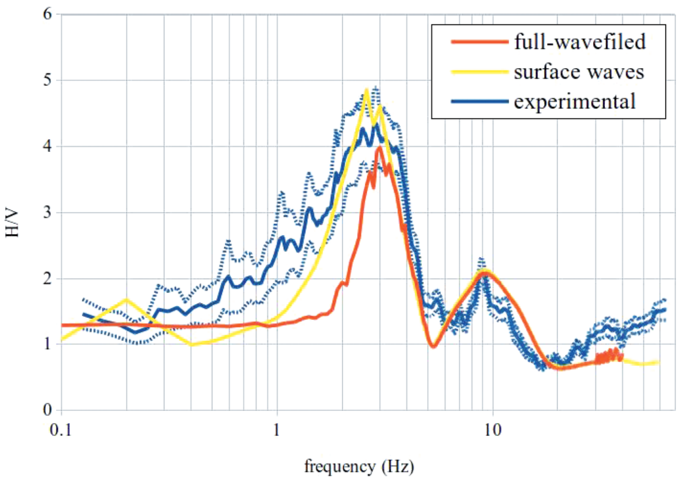

Fig. 2 – Results, with respect the HVSR curve representative of the "PGL" station site, of the manual adjustment of the resulting stratigraphical profile, by using both a full-wavefiled and a surface-wave approximation models.

procedure) as well as a complete wavefield model. A good agreement between experimental and theoretical curves, which is shown in Fig. 2, was obtained with the profile in Tab. 3, which is assumed as representative of the PGL station site.

Tab. 3 - Seismo-stratigraphical profile under the accelerometric station PGL.

depth (m)	thickness (m)	V_s (m/s)	lithology	geological unit
5	5	220	marl and clay marls *(Colombacci)*	FCO
35	30	410	gypsum	GES
65	30	950	marl	FAM1c
140	75	1000	sandstone and marl	FAM1

In terms of NTC (2008) seismic classification, the site where the "PGL" station lays is a class C soil type, being the $V_{S,30}$ value (obtained by results of Tab. 3) lower than 360 m/s.

The deconvolution process was realized by using 4 accelerograms and the variability intervals shown, in the shallower part, in Fig. 1, as above explained. Statistics about peak ground acceleration (PGA) and acceleration spectral amplitude (SA) at 0.15, 1 and 2 s have been extracted, based on an *ensemble* of 100 deconvolution runs for each earthquake record. For each earthquake, the two horizontal components have been considered separately, taking into account both the geometric mean and the maximum of PGA and SA of each run. Then the median and the 75th percentile of the *ensemble* have been computed. An example of the obtained results is reported in Tab. 4.

Tab. 4 - Results for the station of Peglio: 75th percentile of PGA and SA values are reported for the maximum of horizontal components; surface values are derived from the accelerometric registrations, while bedrock values are derived from equivalent linear analysis with STRATA; in the last column is reported the ratio between each couple of values.

	earthquake event	surface (cm/s²)	bedrock (cm/s²)	surface / bedrock
PGA	IT-1997-0006	67.959	38.812	1.751
SA at 0.15s	IT-1987-0003	164.027	91.022	1.802
SA at 1s	IT-1997-0006	19.591	16.960	1.155
SA at 2s	IT-1997-0006	8.350	8.001	1.044

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