

SITE CLASSIFICATION SCHEME FOR A COMPLEX GEOLOGIC AREA: THE STUDY CASE OF MT. ETNA

F. Panzera¹, E. Longo^{2,3}, H. Langer², G. Lombardo¹, S. Branca²

¹ Dipartimento di Scienze Biologiche, Geologiche e Ambientali, Università degli Studi di Catania, Italy

² Istituto Nazionale di Geofisica e Vulcanologia – Osservatorio Etneo, Catania, Italy

³ Department of Geosciences, University of Malta

Introduction. The features of near surface geology as well as the morphologic setting and the water content of layers play a key role in controlling ground motion. The most common technique of site response estimation is the standard spectral ratio (SSR) that consists in comparing earthquake recordings at two sites, the first of which is located on soft sediments (target site) and the other on hard rock (reference site) (Borcherdt, 1970). The method provides reliable evaluations if the “reference site” is free from any site effect, as for instance if it is located on an un-weathered, horizontal bedrock. Another extensively used technique, that does not need a reference station, consists in the spectral ratio between the horizontal and the vertical components of the shear wave part of the earthquake recordings (HVSr). This method, first applied by Lermo and Chavez-Garcia (1993) and subsequently by Lachet *et al.* (1996), exhibits very encouraging similarities with the SSR technique, especially in frequency values of resonant peaks, when the S-waves are used (see Riepl *et al.*, 1998; Parolai *et al.*, 2001 and references therein). According to the above mentioned studies HVSr is well correlated with surface geology, and much less sensitive to source and path effects. However, peak amplitudes depend on the type of incident waves; consequently, the determination of the absolute level of amplification only through HVSr is not straightforward (Field and Jacob, 1995). A quick estimate of the site effects role in the seismic motion observed at the surface can be provided by the horizontal to vertical noise spectral ratio technique (HVNR). Although many authors (e.g., Mucciarelli, 1998; Rodriguez and Midorikawa, 2002) have questioned the existence of simple direct correlation between HVNR spectral amplitude values and the site amplification, this method, put into practice by Nakamura (1989), became widely used in recent years since it provides a reliable estimate of the fundamental frequency of soft soil deposits (Lermo and Chavez-Garcia, 1993; Seekins *et al.*, 1996). The HVNR from ambient vibrations are sometimes “non-informative”, particularly in the case of significant lateral heterogeneity giving rise to 2D/3D effects and velocity inversion that influence the vertical component of motion (Di Giacomo *et al.*, 2005; Panzera *et al.*, 2013).

The selection of specific elastic response spectra according to “soil categories” is the easiest way to account for site effects in engineering projects and general-purpose hazard maps. Most of the international seismic codes make use of the average shear wave velocity of the upper 30 m ($V_{s,30}$) to discriminate soil categories (Eurocode, NEHRP). Some doubts arise about the

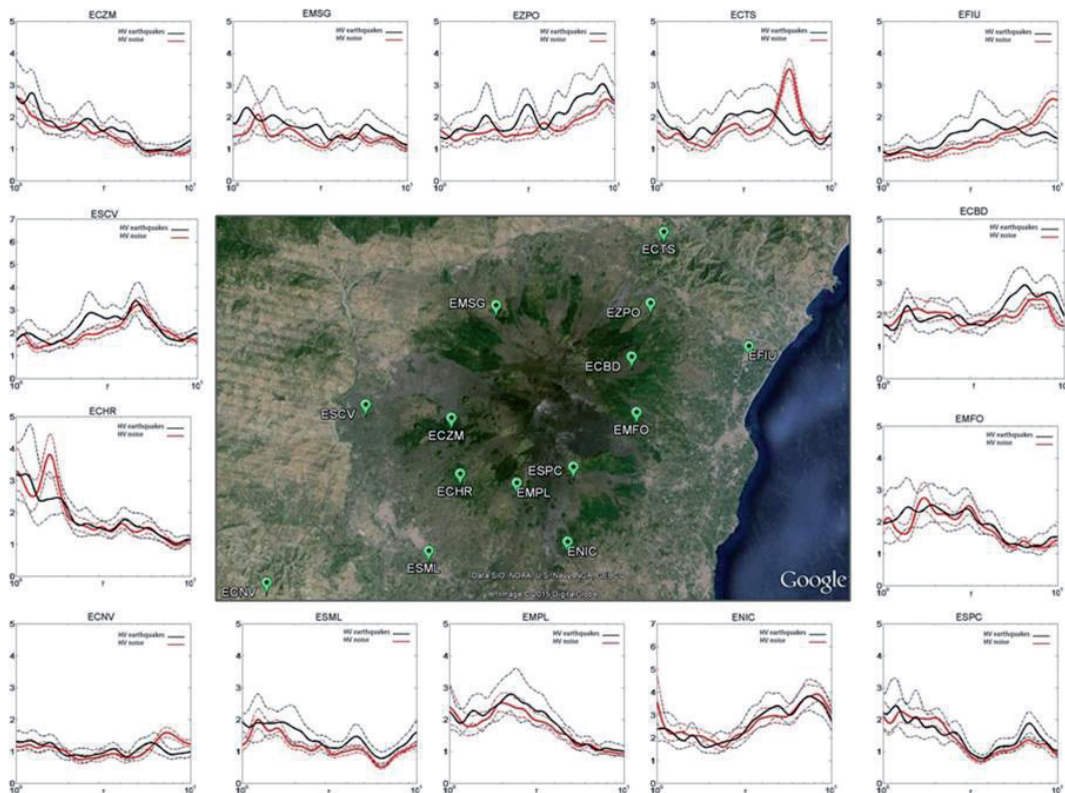


Fig. 1 – Mean HVSR (black line) and mean HVNR (red line) at each considered seismic station with the corresponding standard deviation, dashed black and red respectively.

aptitude of $V_{S,30}$ to predict actual soil amplification in Etna volcano as well as in different part of the world. Recent studies pointed out that the main problems are: alternating outcrops of sediment and lava (Panzeri *et al.*, 2011), oriented fractures linked to the fault fabric (Rigano *et al.*, 2008; Di Giulio *et al.*, 2009; Panzeri *et al.*, 2014, 2015), velocity inversion (Panzeri *et al.*, 2015). Then, a possible solution is to adopt a “Predominant-Period Site Classification”. In the present study we test the reliability of using both ambient noise and earthquake recordings in the lower eastern flank of Mt. Etna, a rather complex geologic and topographic setting, characterized by velocity inversion as well as strong vertical and lateral heterogeneities. The seismic site response of the study area was investigated by adopting the most commonly used techniques to evaluate the site response properties, such as the HVSR and the HVNR. Moreover, a detailed analysis of the geologic setting to reconstruct the stratigraphic sequence of 19 seismic stations of the INGV - Osservatorio Etna was performed (see location in Fig. 1). These data with a velocity model built through literature information were used to achieve 1D amplification function for the Etnaean area.

Earthquake and ambient noise spectral ratios. The HVSRs were performed selecting local earthquake records, extracted from the INGV - Osservatorio Etna database, whose location and magnitude were taken from the corresponding bulletins. The data set includes 30 earthquakes with local magnitude greater than 2.5, which occurred in the entire volcanic area. Recorded earthquakes were base-line corrected, with the purpose of removing spurious offsets and band-pass filtered in the range 0.08-20 Hz, with a fourth order causal Butterworth filter. The analysis was performed by using 20s time windows, starting from the S-wave onset, including part of the coda and using a 5% cosine-tapered window. First of all, Fourier spectra,

smoothed using a Konno-Ohmachi filter, of the S-wave time window were compared with the pre-event noise, in order to select good quality data on the basis of the signal/noise ratio. Only those signals with $s/n \geq 3$ were considered for analysis. The spectral ratio were evaluated at each station for the selected events and a geometric mean of all spectral ratios were computed to obtain the mean HVSr curve and the corresponding standard deviation.

Ambient noise recordings were selected from the stations of the INGV-Osservatorio Etno. The signal length was of about 1 hour at each stations. To check the stability of the HVNR the signals were selected in different days, taking into account both days with low level of noise and with an high level of noise, due to either weather conditions or to the presence of lava fountains. The microtremor recordings were de-trended, band-pass filtered and subdivided in 30 s, 5% cosine tapered, time windows. Through an anti-trigger algorithm based on STA/LTA (Short Time Average over Long Time Average) only the most stationary parts were selected and transients associated to very close sources were excluded. In particular, STA was settled to 1s and LTA to 20 s. After the necessary processes of signal cleaning were completed, the spectral ratio technique was applied to obtain the mean spectral ratios and corresponding standard deviation.

Once the HVSr and HVNR were performed, they were overlapped and it was observed a strong similarity between the obtained results (Fig. 1), therefore confirming the reliability of the peak frequency found through both the techniques.

Numerical modelling. *HVSr inversion.* The ModelHVSr Matlab routines (Herak, 2008) were adopted to compute theoretical HVSr in homogeneous and isotropic layers. The soil model consists of a number of visco-elastic layers, stacked over a half-space, each of them being defined by the thickness (h), the velocity of the body waves (V_p and V_s), the density (ρ), and the Q-factor, which controls the inelastic properties. The incoming waves are assumed to be travelling vertically and without amplification at the bedrock of the horizontal and vertical motions. The HVSr at the surface is then obtained as the ratio between the theoretical transfer functions of S and P waves. In particular, the observed HVSr is inverted through a Monte Carlo simulation aiming to find soil models that minimize the misfit function with theoretical HVSr. The Monte Carlo search is started with an initial model whose parameters are then randomly perturbed within the bounds defined by the user. In our case, the number of random tries was settled to 10,000 and the initial model of body wave velocities (V_p and V_s) and layers thickness was perturbed by $\pm 5\%$ and $\pm 25\%$ respectively, to obtain a good fit with the experimental results. For all the considered seismic stations of Mt. Etna, stratigraphic sequences were made by integrating observations and literature information (Branca *et al.*, 2011; Branca and Ferrara, 2013). Such procedure allowed us to estimate the thicknesses of the layers and then, by using geotechnical and geophysical literature data (Azzaro *et al.*, 2010; Priolo, 1999), a initial velocity model as well as density, Q_p and Q_s were assigned to each layer.

Site amplification functions. The amplifications were computed from frequency-domain calculations, using the programs Site_amp and Nratte (Boore, 2003). In particular, using as input parameters V_s , density (ρ), and Q, the Nratte Fortran routine calculates the Thomson-Haskell plane SH-wave transfer function for horizontally stratified constant velocity layers at a specific incidence angle, within a uniform velocity halfspace settled equal to the deepest measured layer. The code compute amplifications at specified frequencies or at frequencies corresponding to the “breakpoints” in the velocity model. To compile the input file for the Site_amp and Nratte codes we used the output model of HVSr obtaining as input the amplification function (AF) for 14 seismic stations, showing the best convergence between experimental and theoretical models. We adopted a classification scheme different from those based on V_{s30} , so that following the one proposed by many authors (Luzi *et al.*, 2011; Di Alessandro *et al.*, 2012; Zhao *et al.*, 2006), we used the predominant soil period to discriminate among classes. The following Amplification Function classes were obtained taking into account the dominant frequency peak in the HVSrs:

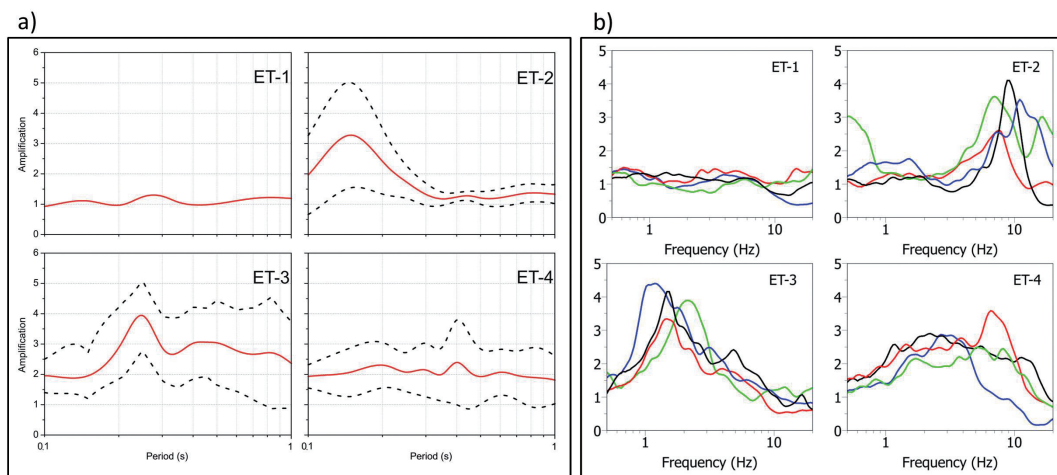


Fig. 2 – a) Mean site amplification (red curve) and standard deviation (dashed black curve) for the Etna area. b) Examples of classification based on the use of HVNR.

- ET-1: Flat spectral ratios showing amplitude values not exceeding 2 units;
- ET-2: HVSR having fundamental period $T \leq 0.2$ s with amplitude exceeding 2 units;
- ET-3: HVSR with fundamental period $0.2 < T \leq 1.0$ s with amplitude exceeding 2 units;
- ET-4: HVSR showing broad band amplitude exceeding 2 units;

The AF of each class were then obtained by averaging the AF of all the stations included in the considered classes (Fig. 2a). The obtained curves show a good match with those proposed by Luzi *et al.* (2011) for the whole Italian territory. It has to be specified that the long period seismic site effects were not considered and the predicted amplification functions for the Etna area display higher values compared to Luzi's functions, as a consequence of the low shear wave velocity assigned to the fractured lavas.

Application of the proposed classification on low eastern Etna flank. The comparison of HVSR and HVNR on the 19 seismic stations all around the Etna volcano allowed us to verify that the noise can replace the earthquakes data in seismic site response estimate. Then in order to evaluate the fundamental period of an investigated site, required for a predominant period classification, it is possible to use the fast and inexpensive HVNR technique. An attempt to use the achieved classification with an extensive noise measurements field, in the eastern flank of Mount Etna, was therefore made. Using a three components velocimeter, 130 noise measurements, georeferenced by means of a GPS instrument, were almost homogeneously spaced along a grid having size of about 1x2 km, extended from north to south of the eastern side on Mt. Etna.

Time series of 30 minutes length were recorded using a sampling rate of 128 Hz and processed through the HVNR technique. Time windows of 30 s were considered and the most stationary part of the signal was selected excluding transients associated to very close sources. In this way the Fourier spectra were calculated in the frequency range 0.1-30.0 Hz and smoothed using a proportional 20% triangular window. Following the criteria suggested by the European project Site EffectS assessment using AMbient Excitations (SESAME, 2004), only the spectral ratio peaks having amplitude greater than two units, in the frequency range 0.5-10 Hz, were considered significant. To summarize the obtained results, the HVNR were subdivided into 16 groups showing a similar shape using the cluster analysis. Finally, a further classification of the HVNRs was manually performed using the adopted predominant period classification (see results in Fig. 2b).

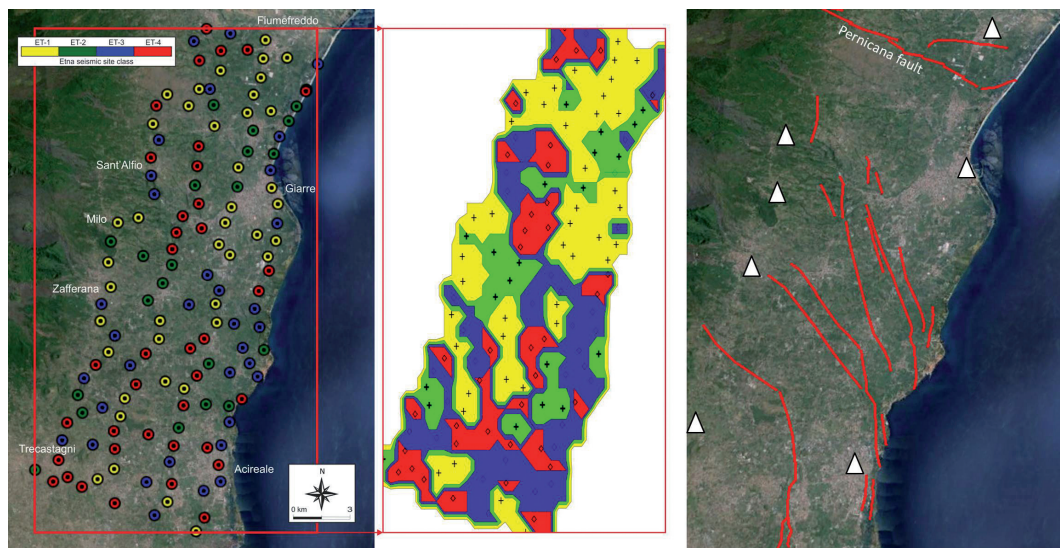


Fig. 3 – Left panel, map showing the class assigned to each measurement point. Central panel, map of the studied area obtained by interpolating the class assigned at each measurement point using the Nearest Neighbor algorithm. Right panel, shows the main faults in the studied area.

In Fig. 3 left panel, it is shown the areal distribution of site classes for the investigated area, whereas in the central panel, by interpolating these information through the Nearest Neighbor algorithm, a macro-zones map of the studied area was attained. The obtained results highlight that the main faults system in the studied area (Fig. 3, right panel) plays an important role in the seismic site response features of the lower eastern flank of Mt. Etna.

Concluding remark.

- A preliminary characterization of the local seismic response in the Etnean territory was made;
- literature data were achieved in order to get information on the elastic parameters and lithology;
- HVSR and HVNR were compared to test the reliability of ambient noise in Etnean area to obtain information on the soil fundamental periods;
- through a simple 1D model, preliminary site amplification functions were attained and classified into 4 classes of a predominant-period site classification, trying in this way to overcome the limits usually showed by the average shear wave velocity of the upper 30 m ($V_{s,30}$);
- a map site effects for the lower eastern flank of Mt. Etna was drawn up using the obtained classification;
- long period seismic site effects corresponding to ET3 and ET4 classes seem to match the area of Timpe faults system and Pernicana fault;
- the results highlight a strong contribution due to the presence of the oriented fractures linked to the fault fabric, and not only to stratigraphic effects, in causing local site effects. This imply that further analysis are needed to better constrain the obtained amplification functions.

Acknowledgements. The present study was performed in the frame of the Volcanologic Project DPC-INGV 2013-2015 “Multi-disciplinary analysis of the relationships between tectonic structures and volcanic activity” financially supported by the Italian Civil Protection Department (DPC). This paper does not necessarily represents the official opinion of the DPC.

References

- Azzaro R., Carocci C.F., Maugeri M., Torrisi A. (2010). *Microzonazione sismica del versante orientale dell'Etna studi di primo livello*. Ed. Le nove Muse, Catania, pp. 181
- Boore D.M. (2003). *Prediction of ground motion using the stochastic method*. Pure Appl. Geophys. 160, 635–676.
- Borcherdt R.D. (1970). *Effects of local geology on ground motion near San Francisco Bay*. Bulletin of the Seismological Society of America 60, 29–61
- Burnham K.P., Anderson D.R. (2002). *Model selection and multimodel inference: a practical information-theoretic approach*, 2nd edn. Springer, New York
- Branca S., Coltelli M., Groppelli G. (2011). *Geological evolution of a complex basaltic stratovolcano: Mount Etna, Italy*. Ital. J. Geosci., 130 (3), 306–317, DOI: 10.3301/IJG.2011.13
- Branca S., Ferrara V. (2013). *The morphostructural setting of Mount Etna sedimentary basement (Italy): implications for the geometry and volume of the volcano edifice and its flank instability*. Tectonophysics, doi: 10.1016/j.tecto.2012.11.011
- Di Alessandro C., Bonilla L.B., Boore D.M., Rovelli A., Scotti O. (2012). *Predominant Period Site Classification for Response Spectra Prediction Equations in Italy*. Bulletin of the Seismological Society of America 102(2), 680–695.
- Di Giacomo D., Gallipoli M.R., Mucciarelli M., Parolai S., Richwalski S.M. (2005). *Analysis and Modeling of HVSR in the Presence of a Velocity Inversion: The Case of Venosa, Italy*. Bull. Seism. Soc. Am. 95(6), 2364–2372.
- Di Giulio G., Rovelli A., Cara F., Azzaro R. M., Marra F., Basili R., Caserta A. (2003). *Long-duration asynchronous ground motions in the Colfiorito plain, central Italy, observed on a two-dimensional dense array*. J. Geophys. Res. 108(B10): 2486, doi:10.1029/2002JB002367.
- Eurocode8 (2003). *Design of structures for earthquake resistance-Part 1: general rules, seismic actions and rules for buildings*, EN 1998. European Committee for Standardization, Brussels.
- Field E.H., Jacob K. (1995). *A comparison and test of various site response estimation techniques*. Bull. Seism. Soc. Am., 85(4), 1127–1143.
- Herak M. (2008). *ModelHVSR-A Matlab® tool to model horizontal-to-vertical spectral ratio of ambient noise*, Computers Geosciences, 34, 1514–1526.
- Lachet C., Bard P.-Y. (1994). *Numerical and Theoretical Investigations on the Possibilities and Limitations of Nakamura's Technique*. J. Phys. Earth, 42, 377–397.
- Lermo J., Chavez-Garcia F.J. (1993). *Site effect evaluation using spectral ratios with only one station*. Bulletin Seismological Society of America, 83, 1574–1594.
- Lermo J., Chavez-Garcia F.J. (1994). *Are microtremors useful in the site response evaluation?* Bulletin Seismological Society of America, 84, 1350–1364.
- Luzi L., Puglia R., Pacor F., Gallipoli M.R., Bindi D., Mucciarelli M. (2011). *Proposal for a soil classification based on parameters alternative or complementary to VS30*. Bull. Earthquake Eng. doi 10.1007/s10518-011-9274-2.
- Mucciarelli M. (1998). *Reliability and applicability of Nakamura's technique using microtremors: an experimental approach*. J. Earth. Eng., 2, 625–638.
- Nakamura Y., (1989). *A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface*. Quarterly Rept. Railway Tech. Res. Inst., 30, 25–33.
- Panzerà F., D'Amico S., Lotteri A., Galea P., Lombardo G. (2012). *Seismic site response of unstable steep slope using noise measurements: the case study of Xemxija bay area, Malta*. Natural Hazard and Earth Science System 12, 3421–3431.
- Panzerà F., D'Amico S., Galea P., Lombardo G., Gallipoli M.R., Pace S. (2013). *Geophysical measurements for site response investigation: preliminary results on the island of Malta*, Bollettino di Geofisica Teorica ed Applicata 54 (2), 111–128
- Panzerà F., Lombardo G., Monaco C., Di Stefano A. (2015). *Seismic site effects observed on sediments and basaltic lavas outcropping in a test site of Catania, Italy*. Natural Hazards, doi: 10.1007/s11069-015-1822-7
- Panzerà F., Pischiutta M., Lombardo G., Monaco C., Rovelli A. (2014). *Wavefield polarization in fault zones of the western flank of Mt. Etna: Observations and fracture orientation modeling*. Pure and Applied Geophysics 171 (11), 3083–3097
- Panzerà F., Rigano R., Lombardo G., Cara F., Di Giulio G., Rovelli A. (2011). *The role of alternating outcrops of sediments and basaltic lavas on seismic urban scenario: the study case of Catania, Italy*. Bulletin of Earthquake Engineering 9 (2), 411–439
- Parolai S., Bindi D., Troiani L. (2001). *Site response for the RSM seismic network and source parameters in the central Apennines (Italy)*. Pure Appl. Geophys., 158, 695–715.
- Priolo E. (1999). *2-D spectral element simulation of destructive ground shaking in Catania (Italy)*. J. Seismol., 3, 289–309.

- Riepl J., Bard P.-Y., Hatzfeld D., Papaioannou C., Nechtschein S. (1998). *Detailed evaluation of site response estimation methods accross and along the sedimentary valley of Volvi (EUROSEISTEST)*. *Bull. Seism. Soc. Am.*, 88(2), 488-502.
- Rigano R., Cara F., Lombardo G., Rovelli A. (2008). *Evidence for ground motion polarization on fault zones of Mount Etna volcano*. *J. Geophys. Res.* 113, B10306, doi: 10.1029/2007JB005574.
- Rodriguez V. H., Midorikawa S. (2002). *Applicability of the H/V spectral ratio of microtremors in assessing site effects on seismic motion*. *Earthqu. Eng. Struct. Dyn.*, 31(2), 261–279.
- Schnabel, P. B., Lysmer, J. and Seed, H. B. (1972). *Shake a computer program for earthquake response analysis of horizontally layered sites*. Report No. EERC 72 - 12, Earthquake Engineering Research Center, University of California, Berkeley, California.
- Seekins L.C., Wennerberg L., Marghereti L., Liu H.-P. (1996). *Site amplification at five locations in San Fransico, California: a comparison of S waves, codas, and microtremors*. *Bull. Seism. Soc. Am.*, 86(3), 627–635.
- SESAME (2004) - *Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations: Measurements, processing and interpretation*. SESAME European Research Project WP12, deliverable D23.12, at <http://sesame-fp5.obs.ujfgrenoble.fr/Deliverables>, 2004.
- Zhao J.X., Irikura K., Zhang J., Fukushima Y., Somerville P.G., Asano A., Ohno Y., Oouchi T., Takahashi T., Ogawa H. (2006). *An empirical site-classification method for strong-motion stations in Japan using H/V response spectral ratio*. *Bull. Seismol. Soc. Am.*, 96, 914–925.