A methodology to design bedrock input motion using noise measurements

Méthodologie pour construire de seisme de dimmensionnement au rocheu à l'aide des mesures de bruit des fonds

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ABSTRACT

Ambient noise measurements may be used under certain conditions to estimate characteristics of seismic response in a given site, namely the fundamental frequency and amplification at resonance. Both parameters depend on the geological structure and the dynamic properties of soils in the study area. The method known as Horizontal to Vertical Spectral Ratio technique, HVSR (Langston, 1979; Nakamura, 1989), provides a reliable estimate of the resonant frequency in most soil sites (Borcherdt, 1970), but the associated amplification is usually underestimated (Field & Jacob, 1995; Malagnini et al., 1996; Bard, 1997; Bard et al., 1997; Riepl et al., 1998). The aim of the present study is to elaborate a method for estimating design acceleration time histories in bedrock, combining theoretical and experimental site response estimates on the basis of 1D site response and microtremor measurements. The idea consists of selecting an accelerogram at bedrock and to modify it appropriately, using an heuristic transfer function, determined from ambient noise measurements at the same site. The modified accelerogram is then used to evaluate the seismic response of the investigated site using conventional 1D linear or equivalent linear method. With this procedure it is possible to estimate relatively accurate design ground motion time histories. The methodology is applied at three sites down-town Catania (Italy), and in one site in Euroseistest (http://euroseis.civil.auth.gr) where microtremor data and seismic events are available and geotechnical characterization of their soils are well known.

RÉSUMÉ

Le bruit des fonds peut être utilisé pour estimer les caractéristiques de la réponse sismique (fréquence fondamentale et de l'amplification à la résonance) sur un site donne. Ils dépendent de la structure géologique et les propriétés dynamiques des sols de l'étude. La technique HVSR (Langston, 1979; Nakamura, 1989) est une technique assez fiable pour estimer la fréquence de résonance pour les sols mous sites (Borcherdt, 1970), mais l'amplification associée est généralement sous-estimée (Field & Jacob, 1995; Malagnini et al., 1996, Bard, 1997; Bard et al., 1997; Riepl et al., 1998). L'objectif de ce travail est de développer une méthode d'estimation d'un accelerogramme de dimensionnement en combinant le calcul de la réponse théorique 1D et la réponse expérimentale obtenue à partir des mesures de bruit de font sur un site donne. L'idée est de sélectionner un accelerogramme rock de façon appropriée, en utilisant une fonction heuristique de transfert déterminée par les mesures du bruit de font.. Le accelerogramme ainsi adapte est ensuite utilisé pour évaluer la réponse sismique du site d'étude en utilisant une méthode conventionnelle de calcul 1D linéaire ou linéaire équivalent.. La méthode est appliquée en trois sites dans la ville de Catania (Italie) et au site expérimentale de Euroseistest (Grèce) où nous avons les données nécessaires.

Keywords : microtremor measurements, HV spectral ratios, heuristic transfer function

1 INTRODUCTION

The analysis of the seismic ground response is a key point for seismic hazard assessment in an urban area. Many methods exist for site response analysis (Field & Jacob, 1995). In common practice, site effects are often inferred using a 1D subsoil model and linear or non-linear site response analysis.

The microtremors have been frequently used in practice to estimate the natural frequency of subsoil. The Horizontal/Vertical Spectral Ratios technique (Langston, 1979; Nakamura, 1989) is one of the most commonly applied methods, as it is a simple and cost-efficient. The main problem of the such measurements is the lack of knowledge of the motion source, as the signal may be hindered by undesired anthropic noise, like cars and people movements, or natural events like wind gusts (Okada, 1997 & 1999).

Although the frequency characteristics of the HVSR, in particular the fundamental period, can be thought as reliable, the estimation of the amplification factor is considered as uncertain (Field & Jacob, 1995; Malagnini et al., 1996; Bard, 1997; Bard et al., 1997; Riepl et al., 1998).

The aim of this paper is to investigate the possibility to use the experimental records in a given site, obtained from ambient noise measurements, to improve the accuracy of the local seismic response calculated in a conventional 1D analysis.

The procedure consists of modifying the design input motion accounting for the results of the ambient noise measurement at the same site; in this pilot study, it was applied to three sites selected in Catania (Italy) and at the Euroseistest site in Greece.

The three sites in the urban area of Catania have been selected among representative test-sites for the microzonation study of the city ("Progetto Catania", Maugeri, 2005). Different subsoil conditions are present at these sites: sandy clay (Piazza Palestro), volcanic rock overlain by a rubble layer (Via Monterosso) and silica sand (Boschetto Playa).

Euroseistest was selected on the basis of available microtremor data and high-quality earthquake recordings on both soil and rock conditions. The geometry and the dynamic properties of soils at Euroseistest were investigated by several geophysical and geotechnical surveys (Raptakis et al., 1998; Pitilakis et al., 1999; Raptakis et al., 2000; Manakou, 2007).

2 NOISE RECORDING AND DATA PROCESSING

The microtremor measurements in the Catania sites (Figure 1) were taken by four Nanometrics Taurus data loggers together with broadband seismometers (Lennartz LE-3D with 20sec natural period) and GPS time coding. The stations were

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-945

arranged in a square geometry and records were taken for 120 min, with a sampling frequency of 100 Hz (Condarelli, 2008).

Although the measurements were carried out during night (from 1 to 3 am), the microtremor records in Piazza Palestro (located in the historic centre of Catania) were affected by unavoidable external disturbances; a statistical analysis of the fluctuation of the signals was used to clear the records.

The Fourier amplitude spectra of the three components and the HV spectral ratio applying Nakamura's (1989) technique were then calculated. The spectral ratios of the EW component were selected, because of its higher amplitude. The technique was applied to all records (4 stations x 3 sites = 12 records).

The spectral ratios show evident differences between the different sites (Figure 1). A dominant frequency peak is observed at 3Hz in Piazza Palestro and Boschetto Playa sites. The peak at 3Hz is higher than that computed on the basis of the geotechnical parameters in a 1D response analysis. In Via Monterosso site, no evident peak is observed in the spectral ratio (Figure 1). The increase of the spectral amplitudes in the high frequency range may be attributed to the presence of a surface layer of debris materials.

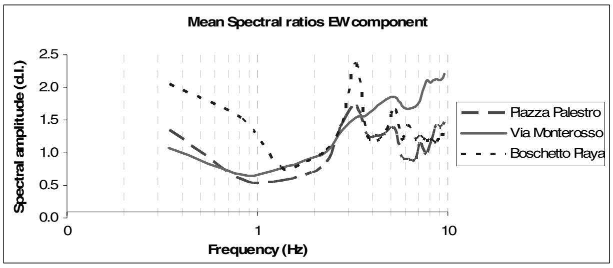

Figure 1. Mean spectral ratios calculated for the EW component of microtremor measurements for all stations used in the three sites in Catania.

Euroseistest is one of the longest running worldwide test-sites, located 30km E-NE of the city of Thessaloniki. It consists of many surface and downhole accelerographs installed in different geological conditions (http://euroseis.civil.auth.gr).

In the central part of the Euroseistest, a down-hole array of five 3D accelerographs is installed at site TST. The stations are installed in alluvial deposits at different depths, while the station at 200m depth is installed in rock conditions (bedrock). The soil classification and the shear-wave velocities for the TST site have been reported in detail by Raptakis et al. (2000).

Microtremor measurements at Euroseistest were recorded with four Guralp broadband seismometers (CMG-40T with 30sec natural period), connected to Reftek recorders (72A-07) and GPS units. A circular array of stations with radius of 25m was deployed. The ambient noise was recorded for 30 to 35min at 125Hz sampling rate (Apostolidis, 2002).

As for Catania sites, Fourier amplitude spectra and HV spectral ratios for all stations of the array were calculated. The predominant frequency at this site is about 0.7Hz, while the associated spectral amplitude ranges from 5 to 7 (Figure 2).

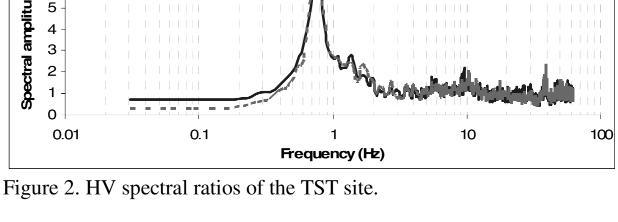

Figure 2. HV spectral ratios of the TST site.

3 CORRECTION PROCEDURE

The proposed procedure consists of using the microtremor measurements to find a *heuristic transfer function* (i.e. a "weighting function") in order to scale an accelerogram, either synthetic or recorded, to a 'conventional bedrock'. The scaling affects both frequency and amplitude, despite this latter results, in general, underestimated (Bonnefoy et al., 2006).

The *heuristic transfer function* was obtained re-sampling the microtremor spectra in such a way to get the same spectral resolution of that of the accelerogram chosen as input motion. The term "heuristic" is used, as it is assumed that the microtremors have properties comparable to those of the earthquakes (Condarelli, 2008).

The weighting function was used to modify the input motion accounting for the main spectral features of microtremors. A similar methodology was proposed by Nakamura (2000) to adjust the vulnerability factor of buildings.

The steps for modifying the seismic input are the following:

- Selection of the accelerogram (or seismogram) representing ground motion for conventional bedrock conditions.
- Elaboration of the *heuristic transfer function* (weighting function) based on the HV ratio of microtremors records
- Adjustment of the Fourier spectrum of the original accelerogram with the estimated transfer function (weighting function) and calculation of the inverse FFT to obtain a modified accelerogram at the bedrock.

Thereafter, the modified accelerogram at bedrock can be used to predict the ground motion at surface with a 1D site response analysis.

4 GEOTECHNICAL CHARACTERIZATION OF THE TEST SITES

The three test sites in Catania are characterised by different geotechnical properties. Figure 3 shows the profiles of shear wave velocity and total unit weight for each site, as resulting from previous investigations (Maugeri, 2005).

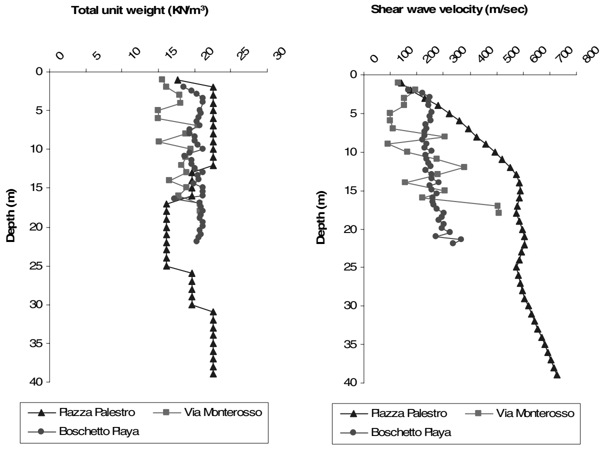

Figure 3. Total unit weight (left) and shear wave velocity (right) profiles of the three test sites in Catania.

The dynamic non-linear behaviour of the soil was described by the relationships proposed from Yokota el al. (1981):

$$\frac{G(\gamma)}{G_0}=\frac{1}{1+\alpha\cdot\gamma(\%)^{\beta}} \qquad \xi(\gamma)(\%)=\eta\cdot exp\left[-\lambda\cdot\frac{G(\gamma)}{G_0}\right] \tag{1}$$

where G_0 is the initial shear modulus resulting from the above described profiles, the strain-dependent shear modulus $G(\gamma)$ and damping ratio $\xi(\gamma)$ were measured by means of resonant column tests. The parameters α, β, η, λ for the main soil types present in the three layerings are reported in Table 1.

Table 1. Parameters describing non-linear behaviour of several soil types in the city of Catania: (a) clay, (b) sandy clay, (c) silica sand, (d) volcanic sand (Maugeri, 2005).

Site	α	β	η	λ
sandy clay (piazza Palestro)	6.9	1	23	2.21
silica sand (Playa)	9	0.82	80	4
clay (via Dottor Consoli)	16	1.2	33	2.4
volcanic sand (S. Nicola alla Rena)	7.5	0.90	90	4.5

In the Euroseistest TST site, the shear wave velocity profile was as deep as 200m (Figure 4a). The non-linear dynamic soil properties were described by the curves shown in Figure 4b (Raptakis et al, 2000; Pitilakis, 2004).

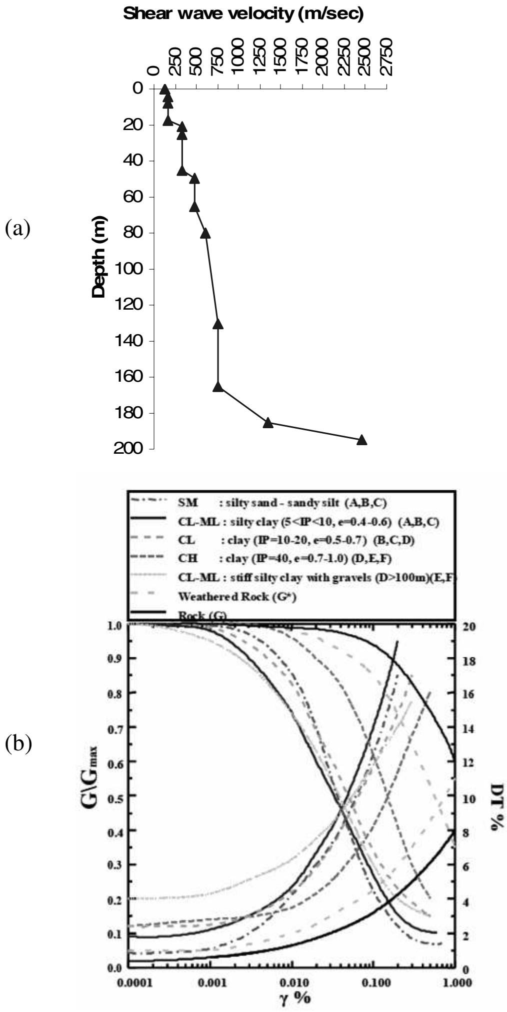

Figure 4. Downhole array and dynamic soil proprieties for TST site in Euroseistest (Raptakis et al, 2000; Pitilakis, 2004)

5 EFFECTS OF CORRECTIONS ON SITE RESPONSE

5.1 *Catania sites, Italy*

For the Catania sites, an estimated synthetic accelerogram representing bedrock ground motion during the January 11th 1693, M=7 earthquake was used (Laurenzano e Priolo, 2002).

The seismogram was modified in the frequency domain, applying the weighting functions calculated from the in situ noise HV spectral ratios. For each HV spectral ratio, different weighting functions and modified accelerograms were obtained.

Figure 5 shows the difference between the original and the modified accelerogram at bedrock for the HV spectral ratio of a station at Piazza Palestro site. Compared to the original accelerogram, the modified signal is amplified and has a longer duration. Similar changes in amplitude and duration were observed for the other sites.

Using the computed time history as input motion and the above described geotechnical data, the seismic response at surface for each site was calculated by the non-linear code NERA (Bardet and Tobita, 2001).

Tables 2 & 3 show the dominant frequency and the associated amplification factor, as computed by the original and the modified accelerograms. The differences in the fundamental frequencies for the two cases are not negligible at least at the Via Monterosso site, where the modified accelerogram gives a higher fundamental frequency; the amplification factor is lower because of the presence of the fractured rock.

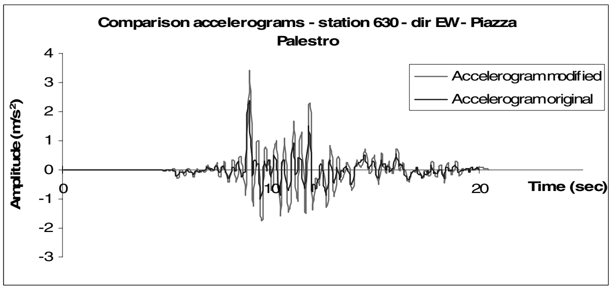

Figure 5. Comparison between original and modified accelerograms at bedrock for the earthquake of January 11th 1693.

Table 2. Comparison between fundamental frequencies (Hz) calculated with the original and modified input accelerograms.

Type of input	P. Palestro	V. Monterosso	B. Playa
Accel original	2.32	1.71	2.37
Accel modified	2.48	2.33	2.72

Table 3. Comparison between amplification factors (calculated as peak acceleration ratio) with the original and modified input accelerograms.

Type of input	P. Palestro	V. Monterosso	B. Playa
Accel original	2.52	1.32	2.29
Accel modified	2.51	1.24	2.20

5.2 *Euroseistest site, Greece*

The same methodology previously described was applied to the three local earthquakes recorded in all stations of the vertical TST array (November 19th 2004 40.53°N, 23.22°E, M_L2.8; September 12th 2005 40.69°N, 23.36°E, M_L4.3; October 9th 2005, 40.70°N, 23.35°E, M_L2.5). The records of the stations at surface and at 200m depth have been used. Using the characteristics of the site response (frequency and amplification at resonance), as determined by HV technique, the weighting transfer function for TST site has been calculated. By multiplying this function for the Fourier spectra of the three component recordings of the deep station, the modified accelerogram for each earthquake were obtained. The difference observed between the original and the modified accelerograms at the bedrock for the earthquake November 19th 2004 is shown in Figure 6.

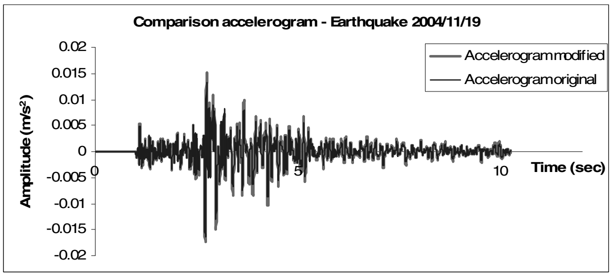

Figure 6. Comparison between original and modified accelerograms at the bedrock for the earthquake November 19th 2004.

Thereafter, the resulting modified accelerograms have been used to calculate the seismic response at TST using a non-linear 1D analysis. The mean frequency values of the Fourier spectra at surface are around 2÷4Hz, higher than the noise frequency; maybe because the bedrock of 1D model is at 200m depth. Table 4 shows the amplification factor as determined from the ratio between the peak acceleration at surface and at the bedrock, for the original and modified accelerograms.

Table 4. Comparison between the 1D amplification factor computed using as input motion the modified (Stat1, Stat2, Stat3) and the original accelerograms of the November 19th 2004 earthquake.

Input	Stat1	Stat2	Stat3	Orig accel
Amplification factor	1.68	1.76	1.77	1.26

6 CONCLUSIONS

A procedure to estimate the input bedrock ground motion has been proposed, using the HV spectral ratio of the microtremor measurements.

At Catania, the input accelerograms modified by the microtremors-based correction presents relatively higher amplitude and longer duration.

At Euroseistest, the difference between the two accelerograms is lower than at Catania, since the non-linear behavior soil did not affect the soil response.

The proposed procedure is very useful for site response analysis in the Catania urban area, because there are no available recording stations on rock, either at depth or at surface. The synthetic accelerograms are affected by inaccuracy of the shallower stratigraphic details since the 2D soil model adopted for the simulations extends until 20 km depth (Laurenzano & Priolo, 2002). Therefore, the use of the proposed procedure, based on the values of the fundamental frequency and the resonance amplification, allows a correction of the synthetic accelerogram at the conventional bedrock, taking into account the spatial soil variability.

At Euroseistest the approach was practically pointless, because the accelerograms recorded at surface and at the bedrock are available. However, the test site was useful to assess the proposed procedure.

Considerable uncertainties of site amplification were also encountered with methods of synthetic seismogram simulation, for instance, in the Turkey Flat blind prediction project (Cramer, 1995; Real et al, 2006), for which detailed investigations on the geotechnical properties were available. In this context, the proposed approach based on ambient noise analysis provides anyway appreciable information, yielding at least an estimation of a lower threshold for site amplification; this information might be useful in those cases where geotechnical information are not available.

ACKNOWLEDGEMENT

The authors are grateful to Mr. S. Rapisarda and to Mr. A. Messina for the support during the microtremor measurements and to Dr. D. Patanè for the use of the INGV instruments. The authors wish also thank the reviewers for the helpful contribution to the final editing of the paper.

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