Characterization of seismic soil effects

Author: Berta Vilacís Baurier.
Facultat de Física, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain.

Advisor: Dr. Pilar Queralt Capdevila
Co-advisor: Dr. Sara Figueras Vila (ICGC)

Abstract: It is widely known that local site effects can have a drastic influence on seismic hazards. Consequently, in vulnerable areas such as highly urbanized zones it is a major issue to characterize them. In the present study I characterize the soil effects in several places of Barcelona and Girona cities for the 29^{th} October, $M_l = 4.3$, earthquake located in Alt Empordà Coast. The soil effect assessment has been estimated using two approaches. In one hand, the soil transfer function and response spectra are obtained from real recordings in rock and soil sites and also from ambient seismic soil measurements. In the other hand, using one dimensional (1D) numerical modelling. These methods provide parameters used to estimate the expected seismic ground motion during earthquakes. Among them, the soil fundamental frequency, the soil transfer function, the response spectra and the macroseismic intensity increment will be analysed in this work.

I. INTRODUCTION

Most of the earthquakes are being registered everyday around the world. The released energy is propagated through the ground by means of seismic waves. The geological, geotechnical and topographic characteristics of the subsoil can modify amplitude, duration and frequency content of the seismic motion. This phenomenon is known as local effect and it includes soil, topographical and induced effects.

Soil effects can produce destruction on surface even in areas located more than hundred kilometres away from the epicentre. The importance of estimating the seismic ground motion in such areas for risk mitigation is worldwide accepted.

The aim of this study is the soil effects characterization in the accelerometer stations located in Barcelona and Girona cities. I propose the application of empirical methods based on real recordings and seismic noise measurements and also a 1D numerical modelling. The results have been used to estimate the soil transfer functions and intensity increments.

II. METHODOLOGY

Methods for soil effects characterization are classified by empirical and numerical. The empirical methods use real recordings to provide the transfer function (FT), the soil fundamental frequency (f_0) or the response spectrum (RS). This information is obtained directly from a real earthquake recorded in a seismic network, or from seismic noise measurements using indirect methods.

On the other hand, the numerical methods allow seismic soil characterization in low seismicity areas or when there is a lack of measure instruments. A comparison between synthetic and real records will be established in this report.

A. Empirical methods

1. H/V Theory

The H/V method [1] is an experimental non-reference site technique that has been proven to be useful for the identification of the fundamental frequency in soil deposits, but the H/V ratio amplitudes cannot be related to soil amplification factors in a reliable way [2]. It consists of computing a Fourier spectral ratio of the horizontal over the vertical components of seismic noise (microtremors) recorded at surface.

The FT is defined as the quotient between soil and bedrock component (reference site). Considering that ambient vibrations are composed by waves that are similar horizontally and vertically in the bedrock and the surface components are being affected by the Rayleigh waves and the bedrock does not. Seismic noise FT is computed as:

$$\frac{H}{V} = \frac{S_{HS}}{S_{VS}} = \frac{S_{NS} + S_{EW}}{2S_V}, \tag{1}$$

where S_{HS} is the median of the surface horizontal components and S_{VS} is the vertical one. The H/V method has been widely tested and an exhaustive list for its application is available [3].

2. Instrumental methods

One of the most widely used instrumental methods for site effects estimation was proposed by Borcherdt [4]. It is know as the reference site technique and consists in computation of the spectral ratio of simultaneous records obtained on rock (RR) and soil stations (SR). It provides the FT of the soil location if the distance between stations is negligible compared to epicentral distance, FIG. 1. In this case assuming that the source and propagation effects are the same for soil and rock recordings. The FT is obtained:

$$FT = \frac{SR}{RR} = \frac{S \cdot P \cdot L}{SC \cdot P} = L, \quad (2)$$

where SR is the soil register, the RR is the rock register, S is the seismic source, P is the propagation and L is the soil effect. The FT gives us the values of the soil amplification in a frequency rank. The fundamental frequency normally corresponds to the first amplification frequency in the FT. Although the maximum amplification is normally observed at this frequency, in some subsoil conditions the peak of amplification has been obtained at higher frequency values [3], [5], [6].

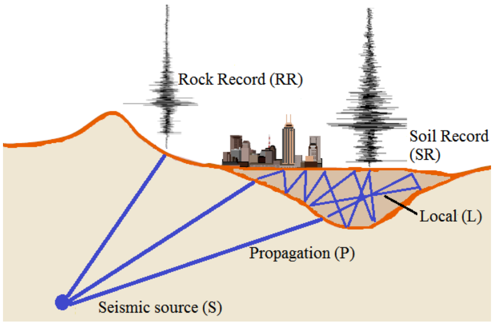

FIG. 1: Representation of the site effects in a seismic motion

Also in this work I use the response spectra. They are computed from accelerometers and considering a selected frequency values. The RS provide information about the maximum absolute response (acceleration, velocity or displacement) of single-degree-of-freedom oscillators with different natural periods and damping values. They give a good indication of the potential effects of the ground motion on different structures.

B. Numerical methods

In low seismicity areas it is often difficult to record a convenient number of events in a short period of time. In these cases numerical techniques are recommended to estimate the soil response.There are numerical programs in 1D, 2D and 3D. Therefore as the dimensions increase, the detail in the knowledge of the structure and the computing costs are higher. In this report I used the ProShake 1D simulation program [7].

Proshake estimates the soil response to vertically propagated shear waves solving the wave equation in a linear viscoelastic system. For this purpose, a 1D semi-infinite horizontally layered medium composed of homogeneous layer is considered. The soil non-linearity behaviour is taken into account using an iterative process which fits shear modulus and damping factors for each layer until they are consistent with the effective stress and strain levels induced in the soil. The input data are a soil column defined for N homogeneous and isotropic layers characterized by thickness h, mass density ρ, shear-wave velocity and also damping and shear modulus curves versus strain for each layer. Two main output parameters are the soil TF from with fundamental frequencies as well as soil amplification factors are estimated for each site and acceleration, velocity and displacement records to characterize the seismic motion in surface.

C. Intensity increment assessment

Taking into account the energy contained in the records it is defined the Arias intensity (AI) as an estimation of potential damage.

$$AI = \frac{\pi}{2g} \int a_i^2(t)dt, \quad (3)$$

were $a_i(t)$ is the acceleration in each components and g is the gravity acceleration. Arias intensity can be related to macroseismic intensity using empirical relationships, applying those proposed by [8] in soil and rock records we can obtain the intensity increment:

$$\Delta I = 0.66 \ln \left(\frac{AI_S}{AI_R} \right), \quad (4)$$

where AI_S is the Arias intensity for the soil record and AI_R is the Arias Intensity for the rock record [9].

III. APPLICATION

A. Study area

The areas selected in this study are located in the Barcelona and Girona stations of the accelerometric network of Catalonia. In Girona we have one accelerometer in soil (GIRS) above a Quaternary alluvial formation of mudstones and gravels and one in rock (GIRR) in a calcareous Paleozoic outcropping. Moreover in Barcelona we have two stations in soil, BAJU and BINT, placed above alluvial Quaternary gravel and clay layer with different thickness. Finally, the rock station, FBRR is located at Tibidabo mountain in a Paleozoic slates outcrop.

B. Earthquake

The earthquake chosen is the Empordà Coast, October 29^{th} 2015, with local magnitude $Ml = 4.3$, UT: $00:37:47.60$h. It was felt in a large area, including Barcelona and Girona cities. Accelerograms recorded in the study area, are used in the soil effects characterization with instrumental methods. Rock recordings are used as input motion in the numerical methods. Results obtained from the two approximations are compared and analysed.

C. Processing

The processing to obtain the H/V spectral ratios has been done applying *Geopsy* software to seismic noise recordings, equation (1). As is recommended in SESAME [3], accelerometer noise recordings are not useful for the application of the H/V method because they have not good resolution for noise signals under 1 Hz. Therefore, for Barcelona soil stations I performed a field survey to obtain seismic noise recordings in the two soil sites. In GIRS, I processed the seismic noise recorded in a former geophysical survey done near the site [5].

Empirical transfer functions have been obtained applying the equation (2) to the accelerograms recorded in soil and rock sites in both study areas. I have used a Fortran program for provide the three empirical component averaged FT and the standard deviation. RS (5% damping) of the three component accelerograms obtained in soil and rock sites have also been computed. The simulated FT and RS have been computed in both study areas. The different parameters have been defined after one analysis of the information available from previous geological, geotechnical and geophysical studies conducted in the study areas [6] and [5], Table I.

Layer	Thickness (m)	Density (g/cm^3)	v_s (m/s)	Damping and module reducction curve
GIRS				
1	35	1.79	370	Clay -PL=5-10
2	Infinite	2.24	1500	Rock
BAJU				
1	20	1.8	395	Gravel
2	30	2.1	650	Clay
3	70	2.4	900	Altered Rock
4	Infinite	2.6	2000	Rock
BINT				
1	40	1.7	300	Gravel
2	60	1.9	650	Clay
3	90	2.4	900	Altered Rock
4	Infinite	2.6	2000	Rock

TABLE I: Definition of the columns for Girona and Barcelona soil stations

Results from numerical simulation are accelerograms, TF and RS for each soil columns defined in Table I.

IV. RESULTS

In this section we analyse the results obtained after the application of different methodologies proposed for soil effects evaluation in the study areas.

A. Girona area

In FIG. 2 I present the East-West component response spectra obtained from the accelerograms recorded in rock and soil sites in Girona and the response spectrum simulated in soil site. Regarding the real spectra, it is observed an amplification of the soil spectrum in relation to the rock one. This amplification is also observed in the simulated soil response spectrum. Similar results have been obtained in the other components. Analysing the recordings obtained in GIRR site I detected an amplification in the North component. A complementary study, considering other earthquakes with different magnitudes and azimuths recorded in the GIRR station provided the same result. Therefore I conclude that it could be an issue related to the accelerometer calibration.

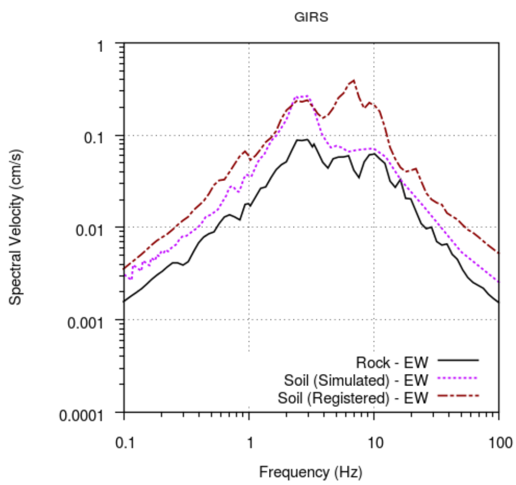

FIG. 2: Comparison between real soil and rock RS, EW component, recorded in GIRS stations, and simulated soil RS

On the other hand the FT allows us to evaluate the soil amplification values and the associated frequencies. In FIG 3 I present the comparison between the numerical and empirical ($\pm\sigma$) TF of the GIRS site. The H/V f_0 obtained in this site is also depicted. The fundamental frequencies have a close value in the transfer function calculated and simulated and the provided by H/V method, have a good fit, the f_0 value is 2.5 Hz with an amplification value of 4.5. It is observed that the maximum amplification in the real transfer function is not obtained in the f_0. The predominant frequency is around the 7.5 Hz, in this case, this frequency will present more amplification than the fundamental frequency, owing to the distribution of the layers in the soil not included in the soil column used in the simulations.

B. Barcelona area

FIG. 4 presents the East-West component response spectra obtained from the accelerograms recorded in rock

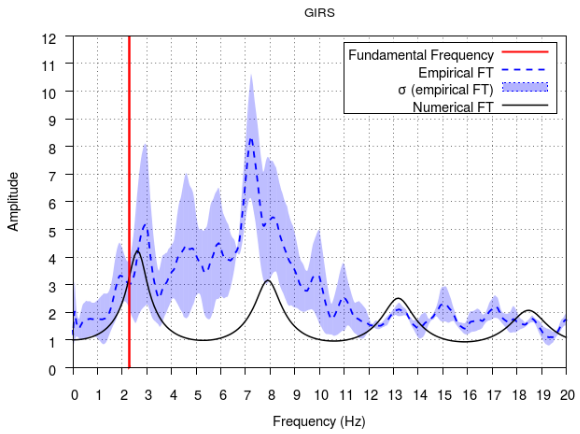

FIG. 3: Comparison between real($\pm\sigma$) and simulated TF in GIRS. Vertical red line indicates f_0 obtained from the H/V seismic noise spectral ratio

and soil sites in Barcelona and the response spectrum simulated in soil site. Observing the real response spectra comparisons it is observed an amplification in soil curves at low frequencies. However in the high frequency range the rock curves exceed the soil curves, so we detect an amplification in the rock. This unexpected behaviour is owing to the FBRR station. I suggest that it has a topographic effect, due to is in a steep slope. The simulated soil response spectra shows an amplification in all the frequency range. In the simulations with Proshake, the FBRR accelerogram has been used to propagate the motion from rock to surface. The simulated soil response spectrum shows the amplification computed in the BINT soil site.

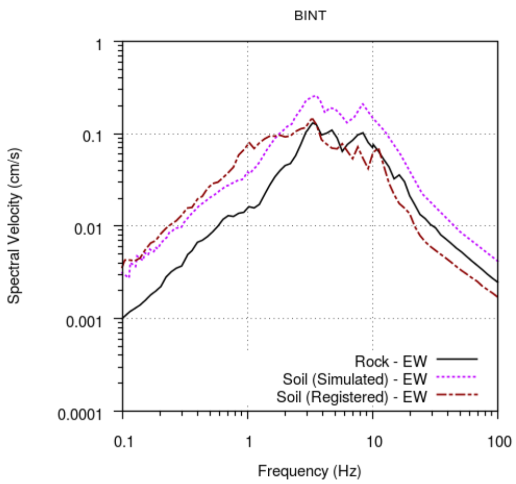

FIG. 4: Comparison between real soil and rock RS, EW component, recorded in BINT stations, and simulated soil RS

Regarding the TF comparisons in Barcelona, shown the results obtained in BINT (FIG. 5) and in BAJU (not shown).

In both sites, the H/V f_0 has values around 1 Hz and are similar to the f_0 values of the numerical and empirical ($\pm\sigma$) transfer functions. In the BAJU and BINT, H/V ratios a $f_0 \simeq 0.5$ Hz was detected. After the analysis performed in the three components of the recordings I concluded that it was a peak of industrial origin and the f_0 was identified at 1 Hz, this result fits those obtained in former studies in the area. As FBRR record is probably affected by topographical amplification, real transfer functions could not be representative of the soil response. At frequencies higher that 3 Hz the real transfer function presents a similar shape than the numerical but the amplification values are lower in both sites reaching values of 1 or lesser.

Looking at the numerical transfer functions, the maximum amplification has a value of 4 at 3 Hz in BAJU site and of 5 at 7.5 Hz in BINT site. In both cases they are not associated to the f_0 and this is a difference with the real TF in which I obtain an amplification value between $6-7$ at the fundamental frequency. The behaviour observed in the simulated curves could be related to the impedance contrast ($\rho \cdot v_S$) between the 4 and 3 layers in the soil columns defined for the numerical simulation. To clarify this differences, additional geophysical data should be obtained in both accelerometer sites in order to provide a soil column more realistic to be used in the simulations. The evaluation of the topographical effects in the FBRR site could be useful to provide a better recordings to be used as a reference site.

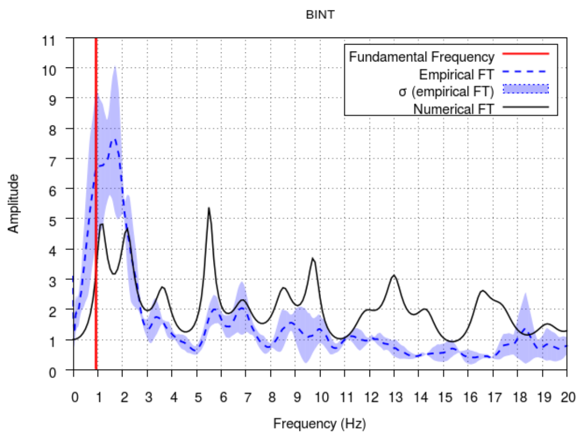

FIG. 5: CComparison between real($\pm\sigma$) and simulated TF in BINT. Vertical red line indicates f_0 obtained from the H/V seismic noise spectral ratio.

C. Soil effects evaluation

I propose a soil effect evaluation in terms of intensity increment. In each soil site studied, AI values (Table II) in the surface and the bedrock have been obtained applying the equation (3) to real and simulated records. Finally, intensity increments for each columns are obtained from (4).

	Real	Simulated
GIRS	0.8869	0.6393
BAJU	-0.0527	1.0861
BINT	-0.2068	1.0059

TABLE II: Intensity increment for each soil station, calculated from the real and the simulated records

Real and simulated ΔI in GIRS have similar values, differences observed can be attributed to the anomalous behaviour observed in the North component of the accelerogram recorded in rock. Otherwise in Barcelona the simulated values have better approximation than the real due to the amplification in the high frequencies in FBRR. This gives us Arias intensity values in rock higher than in soil and ΔI real values are negative.

V. CONCLUSIONS

The aim of this project was to learn about seismic soil effects and to acquire experience in methodologies for their evaluation. Working in the project I've been involved in signal processing techniques in time and frequency domain, I have participate on a field survey for seismic noise acquisition in Barcelona soil sites and, finally, I have acquired experience in a one dimensional numerical simulation method for seismic response characterization and soil effects evaluation. From this experience the following conclusions and recommendations are proposed:

- Values obtained for soil effects characterization in the study areas are $f_0 = 2.5\ Hz$, $\Delta I = 0.9$ in Girona and $f_0 = 1\ Hz$, $\Delta I = 1$ in Barcelona.

- The methods used to obtain real and numerical TF and soil response will be improved increasing the number of earthquakes records used. Results from numerical methods could be improved too obtaining geotechnical and geophysical parameters for the soil-columns definition with more accuracy.

- The H/V method has limitations working with noise recordings in accelerometers. They do not have enough resolution under 1 Hz, the spectral ratios have lot of dispersion under that value. Thus is not recommendable to use this kind of sensors.

- FBRR is not a good rock reference site for empirical and numerical site effects characterization due to topographic effect. For later studies it is recommendable to select another rock reference site or to evaluate the topographic effect in FBRR and correct it in the records.

- GIRR presents an anomalous behaviour in the north component. After a careful analysis of different earthquakes recorded in the station in different years and with different magnitudes and azimuths I associate this behaviour to a calibration issue. For future studies it is recommended to calibrate the station.

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