DETERMINATION OF SITE AMPLIFICATION BASED ON NON-LINEAR INVERSION OF ACCELEROMETRIC DATA IN GREECE

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ABSTRACT:

Source, propagation path and site conditions are factors affecting seismic ground motion. Consequently, recordings acquired at a seismic station are formed by convolution of these three factors. In this work S-wave acceleration Fourier spectra of earthquakes recorded at local and regional scale, by the ITSAK accelerometric network for the period 2010-2016, are modeled as a product of source, propagation path (including geometric and anelastic attenuation) and site effects. The data set consists of 136 crustal earthquakes occurred in the broader Aegean area, with moment magnitudes $4.2 \leq M \leq 6.5$ and epicentral distances $20\text{km} \leq R \leq 350\text{km}$, recorded at 112 broadband accelerometric stations installed at sites with various geologic conditions. Based on this data set, an iterative Gauss-Newton inversion method to solve the non-linear problem and retrieve the different terms of source, propagation path and site, is used. This method uses an initial input model trying to find the best and at the same time a stable solution for the inverted parameters, which are, moment magnitude (M), corner frequency ($f_c$), anelastic attenuation quality factor ($Q=Q_0 f^\alpha$), slope of the geometric attenuation ($1/R^\gamma$) and site transfer function (S). The initial values of the starting model can be either known from other studies or inferred within a reasonable range. Results of the analyses exhibit satisfactory agreement of estimated source parameters with those proposed by seismological centers in Greece and propagation path properties similar to the ones determined in relevant previous studies for the same region. In addition, the site transfer functions obtained by the non-linear inversion and presented in this article are comparable with those calculated for the same sites using either standard spectral ratio (SSR) or horizontal-to-vertical spectral ration (HVSR-receiver function) techniques. The aforementioned results are encouraging in using such non-reference station methods for reliable site effect assessment in areas of intermediate to high seismicity.

KEYWORDS: Non-Linear Inversion, Site Amplification, Accelerograph Network, Greece

1. INTRODUCTION

One of the main objects in engineering seismology is the strong motion prediction, related to the energy of a seismic source and to its attenuation due to geometrical spreading. However, it is known that seismic waves also undergo anelastic attenuation along propagation path. In the last decades it is widely accepted that seismic
motion can be drastically modified (amplified or de-amplified) by surface geology, a phenomenon known as ‘site effects’.

Plethora of studies have been carried out, trying to estimate these factors, using the GIT (Generalized Inversion Technique), first introduced and applied by Andrews (1986) and Castro et al. (1990). This is a non-parametric method where the resolution is linear and split in two steps, where data are first inverted and corrected for attenuation, using a stable geometrical spreading factor and then resolved for source and site parameters. Other studies also used a similar method proposed by Scherbaum and Wyss (1990), which invert the earthquake spectra also in two different regression steps. However, these studies neither contain a frequency dependent anelastic attenuation, nor resolve at the same time parameters that are strongly correlated such as geometrical spreading parameter and quality factor, or seismic moment and corner frequency.

![Figure 1. Ray paths (green line) of 4.204 seismic records used in this study, from 136 earthquakes with 4.2 ≤ \( M_w \) ≤ 6.5 (red circle) and 112 accelerogram station (blue circle).](image)

Here we use a non-linear Gauss-Newton inversion method with initial model, first applied for these parameters by Drouet et al. (2008a) to data of the French accelerograph network. The use of a frequency dependent anelastic attenuation factor and the one step resolving process, are important advantages in resolution of the whole set of
parameters. However, this resolving becomes a non-linear problem because of its nature and the use of initial values for the parameters as well as for their one standard deviation space required. As has been seen from the results of this and from previous, similar studies, if the parameters are not known, we can successfully use high deviation values for the initial model, which shouldn’t differ dramatically from a realistic model. Starting from the priori model, this method finds the best solution for the parameters, reducing the misfit.

As it was mentioned above, this method has been applied by Drouet et al. (2008a) and Drouet et al. (2010) for France seismic data and also by Drouet et al. (2011) for French Indies data. In both cases, they found reliable and stable results for the parameters, comparable with other independent studies. It is positive that the calculated site effects are in agreement with those calculated from HVSR method, especially in dominant frequencies, but it is also observed a discrepancy at high frequencies. The distribution of the calculated residuals is normal with relative small standard deviation. This indicates a successful resolution of the parameters for the whole set of data. In Greece, this method has also been applied for the aftershock records of an $M_w=6.2$ earthquake in Lefkas island (Drouet et al., 2008b) and aimed mainly at site effect estimation where the results were also comparable and in a good agreement with corresponding results from HVSR and SSR methods.

In this study, based on a joint inversion approach which relates seismic source, attenuation and site effects with earthquake ground motion, we try to resolve for these three factors using a dataset of acceleration time histories from earthquakes in the Aegean and broader area, recorded by the ITSak accelerograph network. To this purpose, we use Fourier amplitude spectra of body S-wave windows. More specifically, in this article as part of a dissertation thesis (Grendas 2017), site effects in terms of ground amplification as a function of frequency for each accelerograph station, are presented. In addition, comparison of the inversion based on amplification functions with corresponding HVSR and SSR results for the same stations is attempted and shows a satisfactory agreement.

2. DATA

Data used in this study are S-wave acceleration Fourier spectra. Recordings come from 136 shallow (depth<30km) earthquakes with moment magnitude $4.2 \leq M_w \leq 6.5$ occurred during the period 2010-2016, in the broader Aegean area (Figure 1). These earthquakes were recorded at 112 accelerograph stations in hypocentral distances $10 \text{ km} \leq R_{\text{hyp}} \leq 350 \text{ km}$. Instruments belong to the permanent ITSak accelerograph network. Since 2010 additional 118 three component broadband accelerographs have been installed in the area of Greece.

The initial choice of earthquakes is based on local magnitude which is calculated by manual analysis from Seismological Station of Aristotle University of Thessaloniki, with $M_L \geq 4.5$. As moment magnitude is exported from source parameter inversion results we also use it in the initial source values, so that the comparison between them is compatible.

S-wave strong motion duration depends on magnitude and distance (among others, Hermann 1985, PEER 2016). S-wave window length is determined by the formula (Hermann 1985):

$$T_d = \frac{1}{f_c} + 0.05 R$$  \hspace{1cm} (1)

where $T_d$ is the duration of S-wave window, $R$ is the epicentral distance and $f_c$ is the corner frequency. $1/f_c$ ratio corresponds to S-wave duration to zero epicentral distance, related with source duration (Hanks and McGuire, 1981). Here we use this ratio as source duration approximately and is calculated (Table 1) simply using the fault
length vs magnitude (Wells and Coppersmith 1994), in combination with the rupture velocity $V_{Rup} = 0.75 V_s$ given by Madariaga (1976), for unilateral rupture, with $V_s = 3.5$ km/sec.

Table 1. Source duration and fault length as they calculated for the ranges of moment magnitude and used for S-wave window estimation.

<table>
<thead>
<tr>
<th>Moment magnitude ($M_w$)</th>
<th>Fault length (maximum $M_w$) (km)</th>
<th>Source duration (maximum $M_w$) (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\leq 5.0$</td>
<td>3.2</td>
<td>$\sim 1$</td>
</tr>
<tr>
<td>5.1 – 6.0</td>
<td>12.6</td>
<td>$\sim 5$</td>
</tr>
<tr>
<td>6.1 – 6.5</td>
<td>24.8</td>
<td>$\sim 9.5$</td>
</tr>
</tbody>
</table>

Calculated Fourier spectra are smoothed using the “weighted” smoothed function $W(f_c, f)$ proposed by Konno and Ochmachi (1998) with $b=40$. We study 20 specific frequencies between 0.25-15 Hz, equally distributed in logarithmic scale. Their spectral value is the mean amplitude of the half distance of two consecutives frequencies in both sides of the study frequency range. Subsequently, testing the reliability of the strong motion records, we compare the spectral amplitudes of the 20 frequencies to the corresponding ones of the selected noise with signal-to-noise ratio criterion 3:1, respectively. We use as noise of the signal, the 15 sec part of the recording before P-arrival, if possible, which is obviously not part of the record. This is a common approach used for S-wave studies (among others, Drouet et al. 2008a, Kastelic et al. 2010, PEER 2014). However, it is reasonable to consider that a part of P-wave “contaminates” S-wave. This issue constitutes a subject of investigation that however is not studied in this work. Another restriction of the data set is the minimum hypocentral distance which relates to the reliability of the lower frequency and wavelength. In this study, considering the mean shear wave velocity of the upper layers of the crust $V_s=2.5$km/sec (Novotny et al. 2001, Papazchos 1998, Karagianni et al. 2005, Karagianni and Papazchos 2007), the wavelength of the frequency 0.25 Hz is $\lambda=10$ km ($\lambda=V_s/f$) and the minimum hypocentral distance has been chosen to be at least two wavelengths (Aki and Richards, 2002).

For each station and earthquake, a single spectrum $FA(f)$ is used, calculated from two horizontal Fourier spectra as follows:

$$FA(f) = \sqrt{NS^2(f) + EW^2(f)}$$  \hspace{1cm}(2)$$

where $NS(f)$ and $EW(f)$ are the north-south and the east-west components, respectively.

Finally, as we aim to reliable parameter resolution, a criterion of a minimum number of 5 records per earthquake and 5 earthquakes per station, is applied. The final data are consisted of 4,204 average, horizontal component Fourier spectra calculated from their corresponding records (Figure 1). In Figure 2, the distribution of data used in this study per station and earthquake as a function of hypocentral distance is shown. A satisfactory coverage for the investigated distance range, $20\text{km} \leq R_{hyp} \leq 350\text{km}$, both for stations and earthquakes, is observed.
3. METHOD

3.1. Non-linear Inversion

Following the non-linear inversion method applied by Drouet et al. (2008a, b), it is a common approach that S-wave displacement spectra $A_{ijk}$ is the product of seismic source spectrum $\Omega_{ik}$, of an attenuation function $D_{ijk}$ and of a site transfer function $S_{jk}$ as follows:

$$A_{ijk}(f) = \Omega_{ik}(f) \times D_{ijk}(f) \times S_{jk}(f)$$  \hspace{1cm} (3)

where $i$ is an earthquake, $j$ is a station and $k$ is the number of frequency used. Initially, the displacement Fourier spectra can easily be calculated from acceleration Fourier spectra divided with $\omega^2$ where $\omega=2\pi f$. For the function of the source, is used the Brune’s model (Brune 1970, 1971):

$$\Omega_{i}(f_k) = \frac{M_{0i}}{[1+(f_k/f_{c,i})^2]^\frac{3}{2}}$$ \hspace{1cm} (4)

where $M_{0i}$ is the seismic moment and $f_{c,i}$ is the corner frequency. Attenuation factor $D_{ij}$, analyzed in:

$$D_{ijk}(r_{ij}, f_k) = \exp \left(-\frac{\pi r_{ij} f_k}{Q(f) v_s}\right) \times \frac{1}{r_{ij}^\gamma}$$ \hspace{1cm} (5)

with the first part of the product refers to anelastic attenuation function such as the one given by Futternman, (1962) and the second part is the common approach of geometrical spreading. $r_{ij}$ is the hypocentral distance, here calculated simply using epicenter and source depth, $v_s$ is the average shear wave velocity across the propagation path, $\gamma$ is the parameter that controls the geometrical spreading of the seismic wave which can differs from typical 1 ($\gamma=1$, spherical spreading) and:

$$Q(f_k) = Q_s \times f_k^a$$ \hspace{1cm} (6)
is the frequency dependent quality factor depends on $Q_s$ and $a$ parameters. Site transfer function $S_j(f)$ constitute amplification coefficient.

Concerning the site effect parameters, reference condition is needed, so as to remove a degree of freedom in the solution (Boatwright et al. 1991, Field and Jacob 1995). Following Drouet et al. (2008a,b) the mean response of a set of possible reference stations is a good reference. The choice of these stations is based on the corresponding results of a first inversion applied with all the stations as reference and on a priori HVSR results calculated in this study and mentioned below. Finally, the $ATH5, KYP2, NAX1, SEIS, VSK1$ stations used as reference ones from 0.25Hz up to 4 Hz.

In addition, crustal amplification in order to improve the absolute values of site amplification, is also used. Thus, in the inversion procedure, a generic rock velocity profile $v_{s30}$ of 2000m/s (Boore and Joyner, 1997) is considered along with the site transfer functions.

3.2. HVSR

Horizontal to Vertical spectral ratio is a widely used technique to estimate properties of site response at a site. This method first introduced by Nakamura (1989) using ambient noise recordings which include mainly surface waves, based on the hypothesis that the vertical component of the ground motion is not amplified, in contrast with the horizontal one (Nogoshi & Igarashi 1971). This method extended in seismic records by Lermo and Chavez-Garcia (1993), Theodoulidis and Bard (1995), especially for the S-wave strong motion part of the time history.

Here, the HVSR method has been applied for each one of the 112 stations for the whole set of spectra used in inversion, without any constraint criterion. Finally, the logarithmic average and the corresponding standard deviation are calculated for each station. The results of this method used as mention above for the a priori estimation of reference station and for the comparison with the corresponding inversion results.

3.3. SSR

Standard Spectral Ratio (SSR) is the most commonly used empirical transfer function estimation technique. Fourier amplitude spectra of an earthquake recorded at a site are divided by the corresponding one at a nearby site located on rock, that is called ‘reference site’ (Borcherdt, 1970). By dividing these two spectra and considering that in reference site there is no amplification, source and attenuation factors are eliminated and their spectra ratio corresponds to site amplification. In this study we choose the hypocenter-to-station distance to be at least 10 times greater than the distance between the examined stations.

Only SEIS and ATH5 stations are characterized as reference at least up to 4 Hz for which there are adjacent stations. Site tested by this method for these two reference station are: $KLR1, LSM0, ITS1, PLA1, PRF0, STL1$ και οι $KIF1, MOS1, PER1, PIR1, PIR2, PIR3$, respectively. Data used are the same as in HVSR and SSR methods. The SSR results are separately calculated for horizontal and vertical component (Fig. 4).
4. RESULTS ON SITE AMPLIFICATION

The results of inversion regarding site effect factor are presented in Fig. 4. Their values clearly differ from the starting input ones for all stations ($S_{jk} = 1 \pm 10$). This is an encouraging result for the system resolving with respect to estimation of the site effect factor.

In general amplification transfer functions are in a good agreement with those calculated using HVSR and SSR method (Figure 4) especially in estimating the fundamental frequency and the “shape” of the transfer function except for high frequencies ($f>4$Hz). It is well known that the HVSR method provides reliable results for site transfer function, especially in determination of fundamental frequency (among others; Theodulidis and Bard 1995, Lachet et al. 1996, Bonilla et al. 1997, Triantafyllidis et al. 1999, Haghshenas et al. 2008). The aforementioned studies compared HVSR with SSR transfer functions for the same site and showed very good agreement with respect to site fundamental frequency and in some cases to amplification of ground motion.

Flat shape of transfer function indicates mainly stations located on rock sites, while intense amplifications can be related to stations installed on sediment valleys. For instance, $AGR3, HER1, HER2, HER3, ITE1, KMT1, LAR4, LAR5, LEF2, MOS1, LXRI, PIR2, PTO1, SFK1, SFL1, SIT2$ are among the stations that present intense ground amplifications in certain frequency range and all of them are deployed on alluvium valleys. On the other hand, there are stations as $KSS1, LEO1, SEIS, VSK1, NAX1, FRS1, ART2$ which present flat response and are installed on geologic bedrock. For the 12 stations where inversion amplification transfer functions are compared with the corresponding ones resulting from HVSR and SSR methods the observed good agreement is noteworthy and encouraging for the application of the non-linear inversion method in determining site factor.
5. DISCUSSION AND CONCLUSIONS

In this study, source, propagation path and site effect factors are determined at the same time, by non-linear inversion using a large data set of 4,204 Fourier spectra from 136 earthquakes and 112 accelerograph stations. Brune’s source model, frequency dependent quality factor and geometrical spreading are used in seismic model for the non-linear inversion. Site effects are calculated as amplification coefficients in discrete frequencies between 0.25Hz to 15Hz, for each station without following a specific model of amplification or attenuation. Scattering model of attenuation due to discontinuities in propagation path is not included in the model. Source characteristics as focal mechanism, directivity and dimension of faulting or stress drop are not also taken into account in the inversion. For the non-linear inversion site effect factor includes crustal amplification with a generic rock velocity profile with $v_{s30}=2000m/s$.

The empirical transfer functions calculated by the non-linear inversion for accelerograph stations in Greece show qualitatively good correlation with surface geology at the sites of the stations; amplified in certain frequencies for sediment valleys or almost flat curves for rock sites. Comparison of these transfer functions with those based on independent HVSR or/and SSR methods show very good agreement in ‘shape’ and fundamental frequency and they are in satisfactory agreement regarding amplification level. However, in several stations amplification functions based on non-linear inversion exhibit higher slope of attenuation for frequencies $f>4Hz$, compared to those based on HVSR or SSR methods. The latter observation needs further investigation. Finally, taking into account the reliability of HVSR in determining the fundamental frequency and SSR methods in determining both fundamental frequency and amplification level, we may consider that empirical transfer functions calculated by the non-linear inversion method are satisfactorily reliable. That is, this ‘non-reference’ station method presented in this work could be safely used in microzoning studies in areas of moderate to high seismicity.

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Figure 4. Site amplification transfer functions calculated from inversion (blue) and from HVSR (red) methods for all stations and from SSR (black: horizontal, green: vertical component) method only for 12 stations. (continue)
Figure 4. (continue)
Figure 4. (end)
REFERENCES


