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HYBRID MODELLING OF GROUND MOTION

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SUMMARY

The Vrancea region (Romania) is one of the seismically most active regions in Europe. We try to understand the tectonic processes that are responsible for the strong intermediate depth earthquakes in order to develop realistic models and predictions of ground motion. However, as in other continental regions, the data base of large earthquakes is rather scarce. We develop a hybrid method to compute area-wide ground motion for a given magnitude. In our computation we include Fourier acceleration spectra computed from data recorded during the last large events in 1977, 1986 and 1990. Additionally, in our inversion we include spectra obtained from forward modelling with a) a Finite-Differences (FD) method and b) Irikura's method (EGF). Irikura's method makes use of small earthquakes as empirical Green's functions. In the spectral domain, we invert for the free parameters and use these parameters to model ground motion then with a stochastic method. Thus, this new approach allows us to model area-wide ground motion that integrates information obtained from large and small events, as well as our knowledge about the source and subsurface structure.

1. INTRODUCTION

The Vrancea region is located in the Carpathian Arc (Romania). The seismicity of the region is characterized by strong intermediate-depth earthquakes that occur in a narrow source volume. Bucharest, the capital of Romania is highly exposed to the seismic hazard from the Vrancea region. The sub-crustal earthquakes in the Vrancea region occur regularly with recurrence times typical for continental regions as 10 years for $M_W > 6.5$, 25 years for $M_W > 7.0$ and 50 years for $M_W > 7.4$ [Wenzel et al., 1999].

The work of the CRC 461 is dedicated to understand the tectonics of the region and the source processes that lead to the sub-crustal seismicity. In the SE-Carpathians, subduction was followed by continental collision. The descending oceanic lithosphere is in the process of decoupling which is considered the cause for the seismicity of the region [Sperner, 2005]. Seismic tomography [Martin, 2005, 2006] has shown that the slab is now in a sub-vertical position.

In order to quantify the hazard for Romania and Bucharest we use this knowledge and develop a hybrid method to model area-wide ground motion. The hybrid approach consists of two steps: First, an inversion of Fourier amplitude spectra is performed to receive spectral parameters. The parameters for which we invert are the corner-frequency fc, a high-frequency filter κ, the quality factor Q(f) and an exponent α that control anelastic attenuation, and a factor γ which controls geometrical spreading. In a second step those spectral parameters are used for stochastic forward modelling of ground motion [Boore, 2003]. As input to the inversion we use Fourier amplitude spectra from data recorded during the last large events in 1977 ($M_W = 7.4$), 1986 ($M_W = 7.1$) and 1990 ($M_W = 6.9$) as well as spectra computed with a 2D-FD-modelling method [Karrenbach, 1995] and spectra computed with Irikura's EGF-simulation-technique that uses empirical Green's functions as input [Hartzell, 1978, Irikura, 1983, Wu, 1978,].

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2. METHODOLOGY

After Boore [2003] the amplitude A(f) of Fourier spectra computed for the horizontal component of seismic data can be expressed as

$$A(F) = C \cdot S(f) \cdot D(f) \cdot P(f) \tag{1}$$

where C is a constant, S(f) is the source spectrum and D(f) and P(f) are spectral attenuation functions. The constant C can be written as

$$C = \langle R_{\Theta\Phi} \rangle \cdot FV / \left(4\pi \cdot \rho\beta^3\right). \tag{2}$$

$<R_{\Delta\Phi}>$ is the radiation pattern and is approximated by a standardised factor of 0.55. F accounts for the effect of the free surface and takes a value of 2. For V we take a value of $2^{-1/2}$. It stands for the fact that only a part of the shear-wave energy is contained in the horizontal component. ρ and β are the density and the shear-wave velocity at the source, respectively.

The source spectrum S(f) is commonly expressed after Brune [1970] as

$$S(f) = M_0 \cdot f^2 / (1 + f^2 / fc^2) \tag{3}$$

with the seismic moment M_0 and the corner frequency fc.

D(f) accounts for anelastic attenuation and attenuation due to geometrical spreading. It depends on the hypocentral distance $R = (h^2+d^2)^{1/2}$,with hypocentral depth h and epicentral distance d. Furthermore, it depends on the frequency-dependent quality-factor Q and two exponents, α and γ, which enable us to introduce exponentially variable ground motion attenuation with distance and frequency. D(f) can be expressed as

$$D(f) = \exp\{-\pi \cdot R \cdot f^{1-\alpha} / \beta \cdot Q\} / R^{\gamma}. \tag{4}$$

P(f), a high-cut filter expressed by an exponential function that includes the term κ is introduced in order to consider near-surface attenuation of seismic waves [Sokolov et al., 2004] and is given as

$$P(f) = \exp\{-\pi\kappa \cdot f\}. \tag{5}$$

We compute the natural logarithm of equation (1) and linearise the equation using Taylor's expansion receiving equation (6). It depends on 5 independent variables and reads like

$$G(fc, \kappa, \alpha, Q, \gamma) = G_0 + B \cdot \Delta fc + C \cdot \Delta\kappa + D \cdot \Delta\alpha + E \cdot \Delta Q + F \cdot \Delta\gamma \tag{6}$$

Here, G_0 is $G(fc_0,\kappa_0,\alpha_0,Q_0,\gamma_0)$, $\Delta x = (x-x_0)/x_0$ and fc_0, κ_0, α_0, Q_0, and γ_0 are the starting values for the inversion given below. Thus, the independent variables which are inverted for are the corner frequency fc, the high-frequency-filter κ, and the factors α, Q(f), and γ, that control the attenuation function D(f). B, C, D, E, and F are dependent on the frequency f and the hypocentral distance R. Furthermore they depend on the starting values for the inversion $fc_0 - \gamma_0$ which are compiled in Table 1.

Table 1: Starting values for inversion

fc_0 (Hz)	0.5
κ	0.04
α	0.01
Q	450
γ	1

3. DATA

For our inversion, we use three data-sets each having its own advantages.

The first data-set (DS1) consists of seismograms recorded during the last three large events in 1977, 1986 and 1990. Figure 1 shows the location of the epicentres. For the M_W = 7.4 event in 1977, only one record exists. It has been recorded at station INC at Bucharest using a SMA recorder. The Vrancea earthquake from August, 30, 1986 could be recorded at 20 SMA stations in Bucharest and all over the country (Figure 2). Similarly, the Vrancea earthquake from 1990 has been recorded at 17 SMA stations with three components each.

Our second data-set (DS2) contains ground motion computed with a 2D FD-technique [Karrenbach, 1995] by Miksat et al. [2006]. The simulations have been carried out for the M_W=7.1 Vrancea earthquake (August, 30, 1986) and for the M_W=5.9 event (October, 27, 2004), and could be computed for more than 20 slices within a 3D subsurface model. The grid spacing was 140 m both, horizontally and vertically (Figure 3). The FD-method, due to computational limitations, was in this case restricted to frequencies below 4.5 Hz.

The third data-set (DS3) is computed by Oth et al. [2006] for a suite of M_W=7.1 Vrancea earthquakes and for a suite of M_W=5.9 events using Irikura's EGF-simulation-technique [Hartzell, 1978, Irikura, 1983, Wu, 1978,]. Additionally, hypothetical earthquakes have been computed for M_W = 5.5, 6.0, 6.5, 7.0, and M_W = 7.5. The locations of epicentres and stations is shown in Figure 4. Irikura's simulation technique is based on the concept of self-similarity and assumes constant stress drop for small (M_W in the order of 5.0) and large (M_W up to 2 magnitude units larger) earthquakes. The small earthquakes are used as empirical Greens's functions to model ground motion of large events. The EGF-simulation-method allows us to model broad-band time-histories. Yet, with this method, ground motion is only available at those locations where small events have been recorded.

4. DISCUSSION

From the ground motions we compute Fourier amplitude spectra and invert for five unknown parameters fc, κ, α, Q, and γ. Tables 2 and 3 show results for an inversion computed for DS2 and DS3, respectively. The frequency content was restricted for all inversions to the range between 0.5 Hz and 4.5.

Table 2: Inversion results DS2 (0.5 – 4.5 Hz)

Parameter	M_W = 5.9	M_W = 7.1
fc (Hz)	16.6	6.4
κ	0.09	0.16
α	0.01	0.01
Q	5.1e3	8.4e3
γ	5.1	2.4

Table 3: Inversion results DS3 (0.5 – 4.5 Hz)

Parameter	M_W = 5.5	M_W = 5.9	M_W = 6.0	M_W = 6.5	M_W = 7.0	M_W = 7.1	M_W = 7.5
fc (Hz)	10.1	7.7	5.8	4.3	3.3	7.1	1.0
κ	0.01	0.01	0.02	0.04	0.04	0.07	0.05
α	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Q	6.3e3	4.4e3	4.0e3	3.5e3	3.2e3	5.4e3	1.0e3
γ	3.2	2.6	1.9	1.5	1.4	2.8	0.2

The corner frequency fc computed with our inversion scheme decreases with increasing magnitude, in good agreement with theoretical source spectra [e.g. Stein and Wysession, 2003]. An exception are the results for the M_W = 7.1 events which will need further inspection. Furthermore, our values for fc are higher than one would expect from the theoretical curves, especially our results for spectra computed with the 2D-FD-method. One possible explanation could be that the rupture time used in the FD-computations was possibly shorter than in reality. Also, large corner frequencies could arise from the fact that it could be due to the fact that the stress drops used in the forward modelling are rather high (e.g. 100 Mpa for the 2D FD modelling) in accordance with literature (e.g. [Sokolov et al., 2004]).

The κ -value computed with our inversion method takes values of 0.09 (M_W = 5.9) and 0.16 (M_W = 7.1) for the FD-simulations and ranges from 0.01 (M_W = 5.5, M_W = 6.0) to 0.07 (M_W = 7.1) for the EGF-simulations. Atkinson and Silva [1997] showed that the parameter should be considered as magnitude-dependent due to the nonlinear behaviour of the rock. Sokolov et al. [2004] suggest for the Vrancea region to use $\kappa = 0.04$ for small and intermediate earthquakes, and $\kappa = 0.08$ for large earthquakes in the Vrancea region. Our inversion results are in good agreement with this suggestion and confirm it numerically.

Anelastic attenuation as described by eq. 4 comprises factor α. It turns out that α received from the inversion is constantly 0.01 alike the input value α_0. This shows that there is no obvious magnitude dependence of α.

The damping factor Q is a frequency-dependent value. Tables 2 and 3 show an average value from 0.5-4.5 Hz. We find average values between 1.0e3 and 8.4e3. The variation of Q with frequency is shown in Figure 5. It displays a common inversion for DS2 and DS3 in the frequency range from 0.5 – 4.5 Hz. It can clearly be seen that Q decreases with increasing frequency leading to stronger damping for higher frequencies.

The inversion for γ shows that γ decreases slightly with increasing magnitude, apart from the event M_W = 7.1. This indicates that ground motion from smaller events experiences higher damping due to geometrical spreading than ground motion from larger events.

5. SUMMARY

In continental regions recurrence intervals for strong earthquakes are in general larger than close to plate boundaries. Therefore, the amount of recorded data of strong events is usually limited for continental regions. For hazard assessment purposes, however, it is necessary to access a comprehensive and reliable data base. In order to augment the data base for the Vrancea Region in the Carpathian Arc (Romania) we develop a hybrid method for ground motion modelling. This method consists of two steps. In a first step we combine real data with modelled time histories computed with a 2D FD method and with Irikura's EGF simulation technique in an inversion. In the spectral domain, we invert for parameters as the corner frequency fc, the high-energy damping term κ, the quality factor Q(f), and two exponents responsible for anelastic attenuation and attenuation due to geometrical spreading, α and γ. In a second step we will use those parameters to model ground motion with a stochastic method. This allows us to model time-histories for a broad frequency range and for a wide area, unlike when using only one conventional simulation technique. The new data base includes information about the subsurface structure and contains the source complexity. It can be used as basis for hazard assessment, e.g. for computing attenuation functions. Our hybrid method can easily be applied to other continental regions and provides therefore a powerful tool for hazard assessment in regions with scarce data bases.

The corner frequency fc computed with our inversion takes values between 1.0 and 16.6 Hz and gets larger for stronger earthquakes. This second result is in accordance with literature, however the values are larger than one would expect from other observations. One possible explanation for the high values could, however, be the high stress drop σ that is used in the forward modelling (e.g. 100 MPa in 2D FD modelling). The inverted values for the high-frequency filter κ fit very well with values in literature and take values between 0.01 and 0.16. α computed in our inversion is constantly low and takes a value of 0.01. In a next step we could try to invert the spectral parameters leaving α fixed. The quality factor Q(f) we receive from our inversion takes average values between 1.0e3 and 8.4e3. It decreases monotonically with frequency. For γ we find values between 5.1 and 0.2. We can see a dependence on magnitude where γ decreases with increasing magnitude of the event.

6. FIGURES

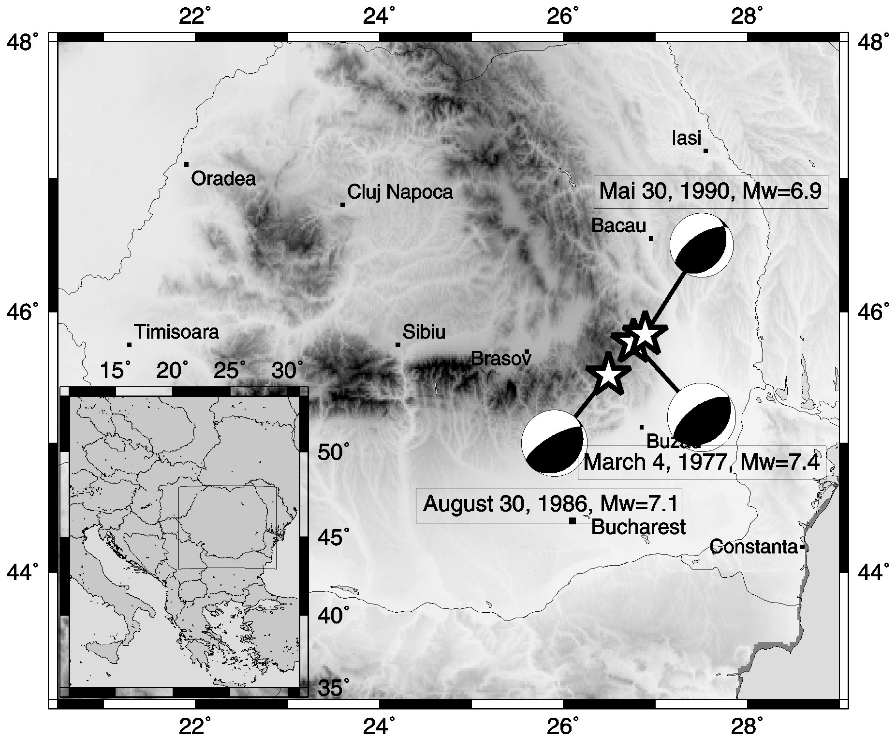

Figure 1: Map of the Carpathian Arc (Romania) and the Vrancea region where strong intermediate-depth earthquakes took place in 1977, 1986, and 1990. The epicentres of the earthquakes are indicated as stars. The focal mechanisms are displayed as beach-balls. Date and magnitude of each event is given in the figure.

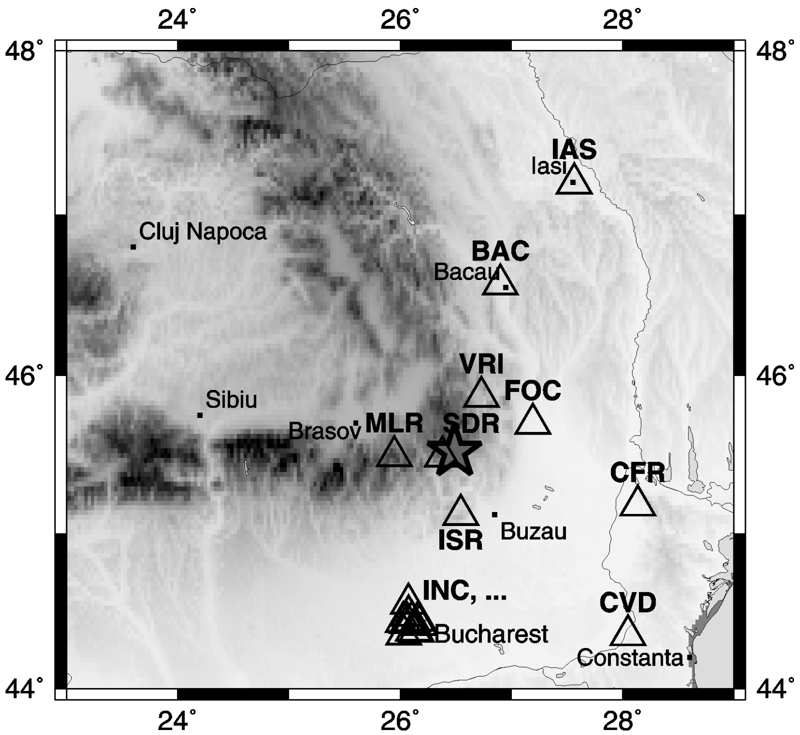

Figure 2: Map of the stations of the SMA-network that recorded the M_W = 7.1 event on August, 30, 1986. The stations are displayed as triangles and their names are given in the figure. The location of the epicentre is indicated as a star.

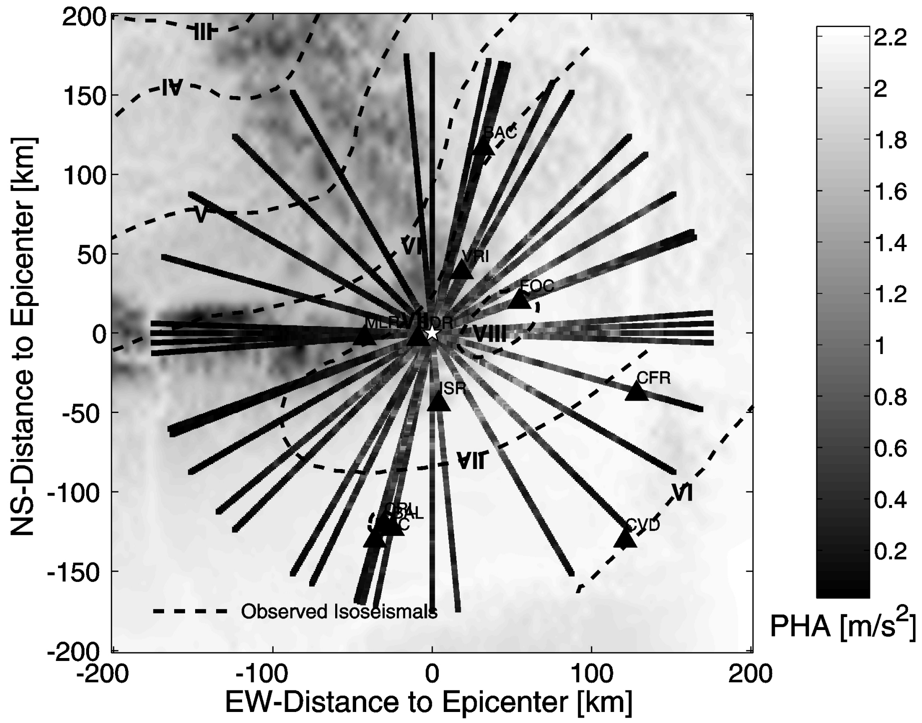

Figure 3: Peak horizontal acceleration (PHA) computed from FD-ground motions for the M_W = 7.1 event on August, 30, 1986. The ground motions have been calculated on 20 slices through the 3D-model. The epicentre of the earthquake is indicated as a white star. The observed isoseismals are plotted as dashed lines. SMA-station locations are indicated as black triangles.

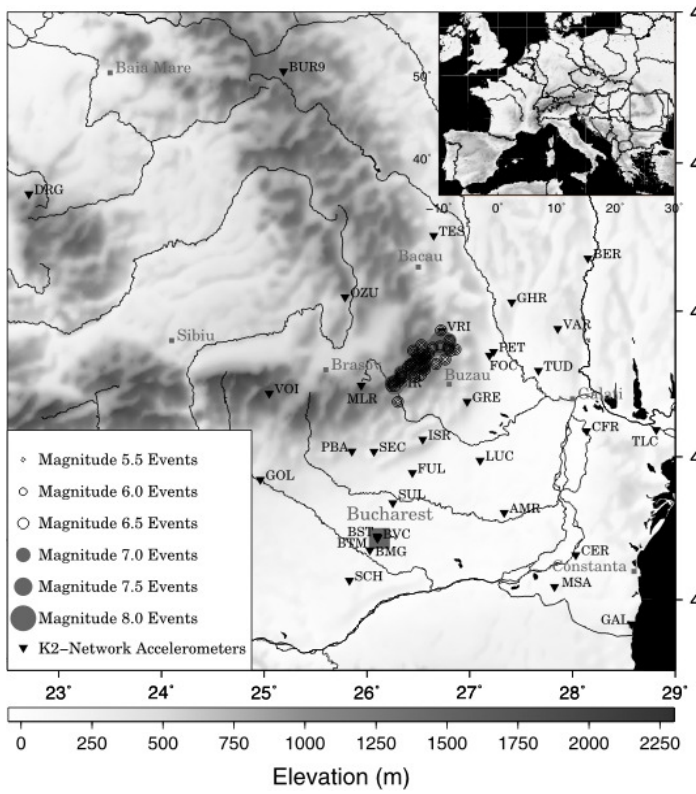

Figure 4: Map of the Carpathian Arc, and location of events modelled with the EGF-method. The epicentres of the events are displayed as circles and dots. Station locations of the K2-network are indicated as triangles.

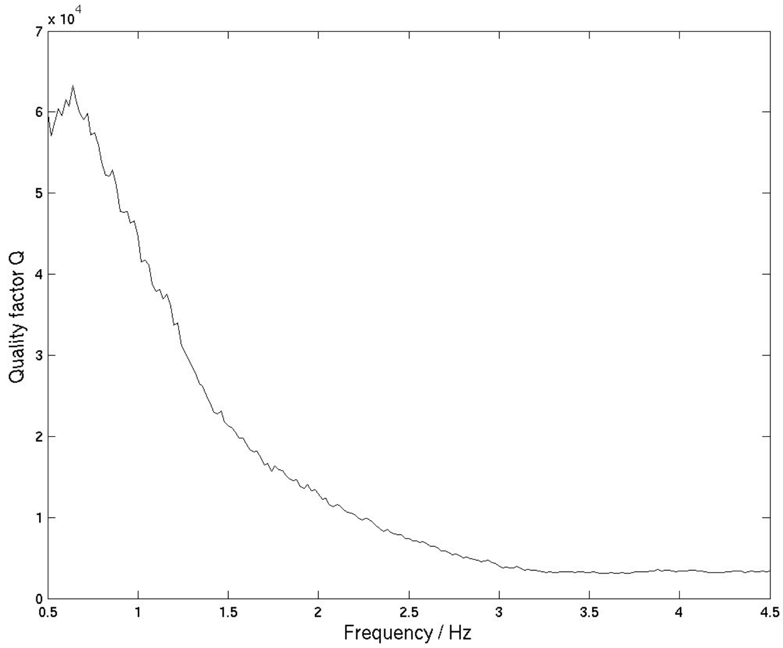

Figure 5: Variation of the quality factor Q(f). Common inversion for DS2 and DS3 in the frequency range from 0.5 – 4.5 Hz.

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