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EFFECTS OF THE SEISMIC ATTENUATION PATTERN AT THE BEND OF THE SOUTHEASTERN CARPATHIANS ON THE PEAK GROUND MOTIONS FROM LOCAL CRUSTAL EARTHQUAKES

L. ARDELEANU, C. NEAGOE

National Institute for Earth Physics,
12 Calugareni Str., P.O.Box MG-2, RO-077125, Magurele, Ilfov, Romania
E-mails: ardel@infp.ro; cristian.neagoe@ infp.ro

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Abstract. The effects of the seismic attenuation pattern observed at the bend of the Southeastern Carpathians on the peak ground motions (PGMs) produced by local crustal earthquakes are analyzed using theoretical experiments. The synthetic seismograms – ground velocity time histories, vertical component – are calculated by the multimodal summation method in layered inelastic media. The theoretical waveforms evidence that the lateral variations of the attenuation structure may result in higher peak amplitudes at larger epicentral distances, in other words, the wave attenuation may dominate the wave spreading in the study area, within epicentral distances up to a few tens of km. The result is in good agreement with the observations, and emphasize the substantial contribution of the crustal attenuation to the pattern of ground motions caused by crustal, as well as intermediate-depth earthquakes of Vrancea.

Key words: seismic attenuation pattern in Vrancea region, synthetic seismograms, peak ground motions.

1. INTRODUCTION

The amplitude of the seismic ground motion at a site is dependent on the parameters of the seismic source that generates the shaking, the loss of the seismic energy radiated from the source, during the wave propagation through the Earth, and the site near-surface geology (local effects).

When traveling in elastic media, the wave motion is spatially attenuated as waves spread away from the source region, and for body waves in homogeneous isotropic media the wave-amplitude decay is proportional to the distance from the source.

In real materials, because of imperfections in the elasticity, the wave amplitudes attenuate also as a result of a variety of processes, usually summarized macroscopically as “internal friction”. The gross effect of internal friction is measured by a dimensionless quantity, inversely proportional to the attenuation, the quality factor Q [1–2].

In a simplified way, the spatial decay of wave amplitudes can be written:

$$A(r) = (A_0 / r) * \exp(-\omega\, r / 2\, Q\, v). \quad (1)$$

where A_0 / r represents the geometrical spreading term, and $\exp(-\omega\, r / 2\, Q\, v)$ – the (anelastic) attenuation term; A_0 is the source amplitude, ω – the angular frequency of the wave, r – the distance from the source, v – the wave propagation velocity.

Considerable lateral variations of attenuation have been observed in different regions all over the world, in Eurasia [3], North America [4–5], Australia [6], China [7], East Africa [8], Himalaya [9], the tectonically active zones showing greater seismic wave attenuation than the stable regions [10].

At the bend of the Southeastern Carpathians – in the Vrancea region – the tectonic setting is complex, with three tectonic units in contact: the East-European Platform, the Moesian Platform and the Intra-Alpine subplate (see Fig. 1). Here the seismicity occurs in two distinct segments: a subcrustal segment, located in the depth range 70 - 180 km, that hosts strong earthquakes (magnitude M_w 7 and above) with significant damaging effects over large areas, and a crustal segment that hosts only moderate-sized events (not exceeding magnitude 5.6), at depths less than 40 km [11]. The intermediate-depth seismicity of Vrancea region is the main source of seismic hazard in the extra-Carpathian area of Romania (*e.g.* [12–14]).

The attenuation of the seismic waves beneath the Vrancea region and surrounding zones has been approached in several studies, which used diverse data sets and various methodologies (*e.g.* [15–20]); a comprehensive review is given in [21]. The investigations revealed notable lateral variations, with low attenuation in the stable East European, Scythian and Moesian Platforms, and high attenuation in the Carpathian Orogen, and in the sedimentary Transylvanian and Focşani Basins.

The attenuation solely in the crust has been less analyzed [22, 21, 23], nevertheless, the observed lateral variations – high attenuation in the Carpathians Mountains and in the sedimentary basins, and low attenuation in the Platform zones – evidence the important contribution of the crustal structures to the overall seismic attenuation pattern in the region.

In this study we analyze, by theoretical experiments, the effects of the observed attenuation pattern on the peak amplitudes of waveforms generated in the Vrancea region and adjacent extra-Carpathian zone by local crustal earthquakes.

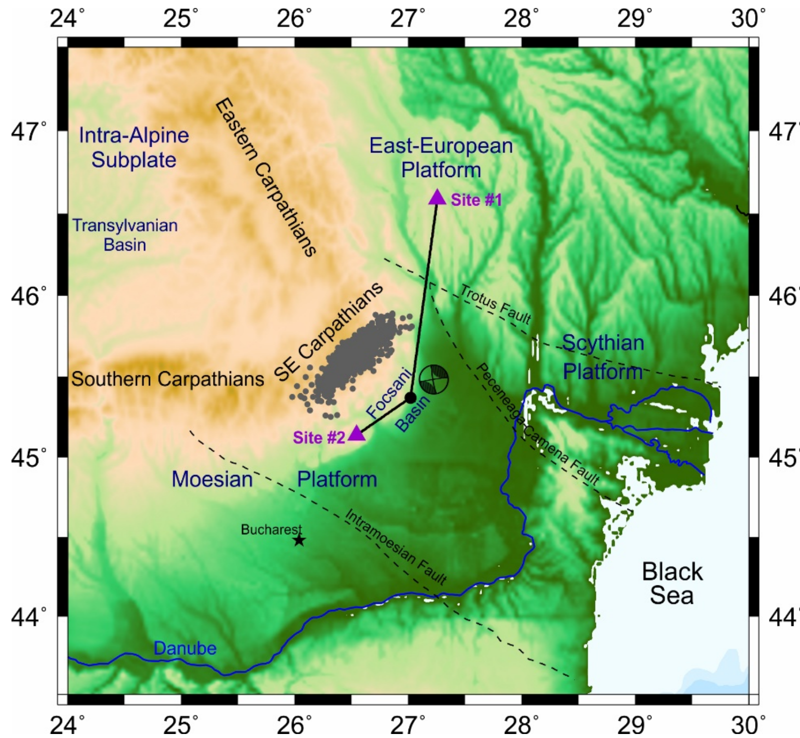

Fig. 1 – Tectonic setting of the study region. The grey dots illustrate the intermediate-depth seismicity (epicenters of earthquakes with magnitude $M_w \geq 3.0$ recorded in the period 2010-2023). Black full circle – the epicenter of the crustal seismic source of Table 1; the source mechanism (Table 2) is also displayed. Triangles – locations of observation points.

2. SYNTHETIC SEISMOGRAMS

The synthetic experiments were carried out using seismic sources with locations and mechanisms of recorded events [24–25] and observation points localized at the sites of existing seismic stations.

The theoretical seismograms – ground velocity time histories, vertical component – were generated by multimodal summation in layered inelastic media [26–27]. The synthetics were calculated up to the frequency of 10 Hz, then filtered by low-pass, with cut-off frequency at 5 Hz.

The 1-D structures of wave velocities and medium density, needed to compute the synthetic waveforms, were compiled following [25], by integrating and harmonizing the available seismological data and studies [28–37]. The sedimentary cover is modeled by several layers representing the local structure in the zone of the recording point, while the crystalline crust is modeled by two layers – the upper and the lower crust – representing average models along the individual paths from the seismic source to the recording station.

For the seismic attenuation we used the models of the quality factor *Q* presented in [22, 25], which were developed using an approach proposed in [38]. These structures do not differentiate scattering from anelastic attenuation – they reflect, most likely, a combination of both attenuation mechanisms – and they were successfully applied in high-frequency waveform inversions for source parameters [25], contributing to obtaining better constrained fault plane solutions of the analyzed weak shallow earthquakes.

The considered *Q*-models show significant variations of the shear wave attenuation in the study area: *Q*-values of 100-150 in the crystalline upper crust, and less than 100 in the layers above, for the paths beneath the Vrancea Orogen and the Focşani foredeep basin, and values of 600 to 800 in the crystalline upper crust, and between 100 and 400 in the shallower layers, for the profiles that cross portions of the Moesian, Scythian and East European Platforms.

Fig. 2 shows an example of synthetic waveforms, computed for a seismic source located in the Focşani Basin (in the Râmnicu Sărat zone), at 12 km depth, having the seismic moment $M_0 = 4.0*10^{13}$ Nm (the moment magnitude M_w 3.0) (Table 1). The focal mechanism (Table 2 and Fig. 1) is a dominant strike-slip faulting, with the nodal planes orientated NNW-SSE and ENE-WSW, respectively, and the compressive axis oriented SE-NW. The observation points are situated at the sites of the seismic stations Coloneşti CLI (site #1) and Istriţa ISR (site #2) (Fig. 1). We remark that for the considered source – station configuration the larger peak amplitude is observed at the more distant site.

Table 1

The seismic source hypocenter (epicenter coordinates and depth), and moment magnitude

Latitude [°N]	Longitude [°E]	Depth [km]	M_w
45.37	27.02	12	3.0

Table 2

The seismic source mechanism

Plane 1			Plane 2			P-axis		T-axis	
strike [°]	dip [°]	rake [°]	strike [°]	dip [°]	rake [°]	strike [°]	plunge [°]	strike [°]	plunge [°]
170	85	359	261	89	185	126	5	35	3

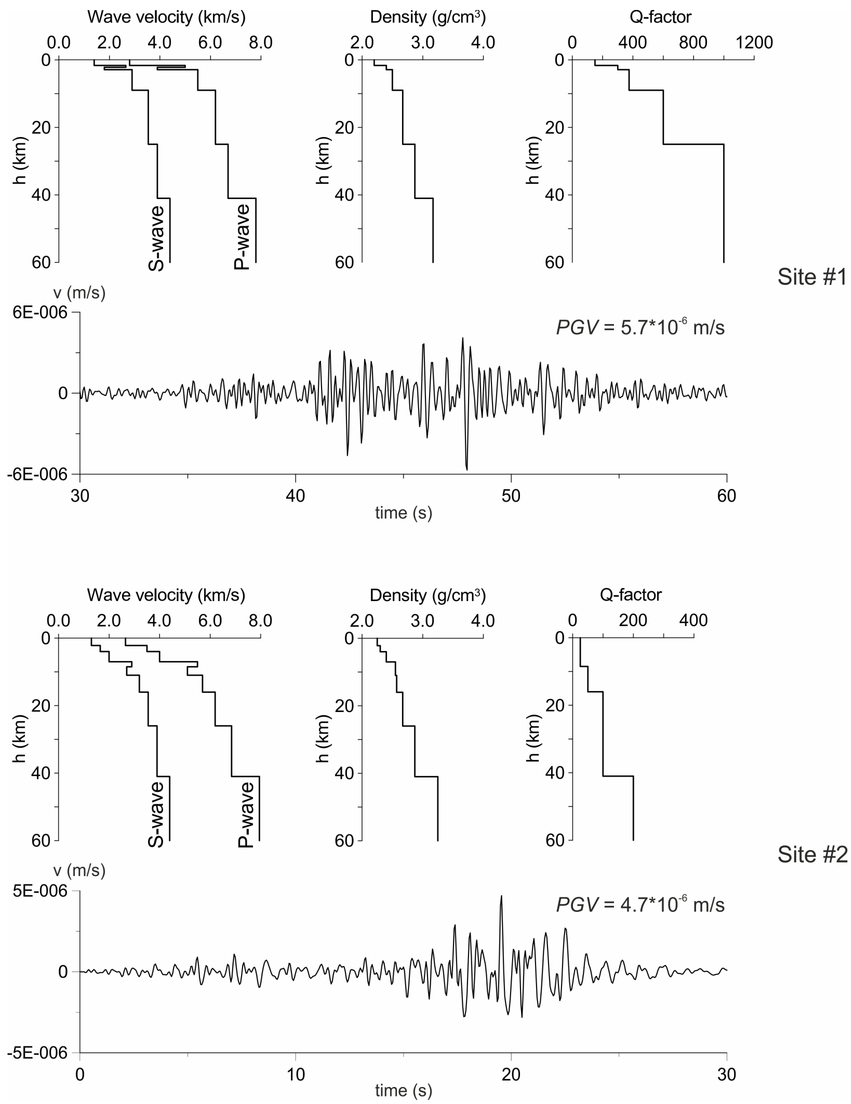

Fig. 2 – Simulations of the ground motion for the configuration seismic source – observation points of Fig. 1. Structural models along the source – station paths (up), and synthetic seismograms – ground velocities, vertical component – generated with the source defined in Tables 1 and 2 (down); the waveforms are aligned relative to the origin time, and the peak ground velocities (*PGV*s) are also specified.

3. DISCUSSION

We performed experiments with several sources located at the bend of the Carpathians arc – beneath the Vrancea mountain range and the Focşani basin – by considering observation points placed in the Carpathian Orogen, and in the extra-Carpathian area – in the Carpathian foredeep and in Platform zones.

The simulated vertical ground velocities at the investigated sites exhibit a significant variability related to the source location (epicenter and depth) and its focal mechanism, emphasizing the prominent contribution of the seismic source features to the spatial distribution of the peak ground motions.

The results point also out a substantial signature of the medium structure along the wave travel paths on the level of peak amplitudes of ground shaking. Thus, for the crustal earthquakes of Vrancea, the local and regional geological conditions (modelled by the structures used in the computation of the synthetic waveforms) can control the amplitudes of ground motion to a larger degree than the distance; in other words, in the study area the wave attenuation may dominate the wave spreading, at epicentral distances up to a few tens of km. In the example displayed in Figs. 1-2, the lateral variations in attenuation (reflected by the adopted *Q*-models) result in larger peak ground velocity at site #1 than at site #2, although the site #2 is noticeably closer to the source.

The finding is in good agreement with the observations – velocity records of small shallow events, but also with the ground motion space distributions from strong and moderate-size intermediate-depth earthquakes of Vrancea. These distributions exhibit prominent asymmetries with respect to the epicenters, and reveal large values of the instrumental, as well as macroseismic parameters, over wide areas orientated predominantly NE-SW (*e.g.* [39–43, 13, 44–46]). The rather unusual feature – largest peak ground motion values recorded at considerable epicentral distances, in the Extra-Carpathian area – is commonly attributed to dominant local site effects, the near surface elastic properties beneath a site playing a considerable role in the amplification of horizontal components of *S*-waves.

Our synthetic seismograms are vertical components of ground velocity (therefore the site effects can be ignored, as the amplification of vertically propagating *S*-waves may be neglected – see *e.g.* [47, 18]). The theoretical waveforms reveal the substantial contribution of the lateral variations of seismic attenuation in the crust – modelled by the *Q*-structures developed for the area of interest – to the pattern of peak amplitudes at the Earth's surface. The high attenuation (low *Q*-factor) beneath the Vrancea Orogen and the adjacent Focşani Basin supports the observed peculiarities of ground shaking caused by the earthquakes from the bend of the Southeastern Carpathians (crustal, as well as and intermediate-depth events).

The attenuation structure is also important in the assessment of the seismic hazard, for correctly predicting the amplitude of ground motions from future strong earthquakes. In the sedimentary basin Focşani, the low seismic velocities [32], that amplify the seismic waves, correlate with high attenuation, which reduces these amplitudes. Therefore, failing to adequately account for the lateral variations of the attenuation structure may lead to overestimated predictions of the ground motion amplitude (see *e.g.* [48–49]).

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