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Earthquake early warning for Bucharest, Romania: Novel and revised scaling relations

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[1] The accumulation of strong earthquakes with resembling source mechanisms in the Romanian Vrancea zone, SE Carpathians, allows for designing a simple, cheep and robust earthquake early warning (EEW) system for Bucharest with leading times of about 25 s. A previously established scaling relation for EEW predicts in the range from 1–2 s a ten times higher ground motion amplitude in Bucharest than the maximum P-wave acceleration measured in the epicentral area. Using additional weak and strong motion data, we find that ground shaking in Bucharest is generally overestimated by this relation by a factor of two. However, the predicted amplitudes are within the 95% confidence interval of our revised relation. Additional predictive laws for EEW are determined for different ground motion parameters. The application of our scaling relations to the October 27, 2004 Vrancea earthquake (M_w = 6.0) supports the feasibility of the approach for EEW in Romania. **Citation:** Böse, M., C. Ionescu, and F. Wenzel (2007), Earthquake early warning for Bucharest, Romania: Novel and revised scaling relations, *Geophys. Res. Lett.*, *34*, L07302, doi:10.1029/2007GL029396.

1. Introduction

[2] Earthquake early warning (EEW) systems make use of differences in the propagation speed of seismic and electromagnetic waves and issue warnings, if necessary, to potential users before high-amplitude seismic waves arrive. Within a few seconds EEW systems must recognize the severity of impending ground shaking and trigger automatisms to reduce likely damage to structures and equipment caused by seismic waves. Pre-warning times are usually defined by the time window between P-wave detection at one or more EEW sensors and the arrival of S- or surface waves at the user site. Despite of significant progress in seismic real-time data processing and communication technologies during the last decades, there are only a few EEW systems in operation now, including systems in Japan [*Nakamura*, 1989], Taiwan [*Wu and Teng*, 2002; *Wu and Kanamori*, 2005], and Mexico [*Espinosa-Aranda et al.*, 1995]. In other countries, such as California [*Allen and Kanamori*, 2003], Turkey [*Erdik et al.*, 2003; *Böse*, 2006], or Romania [*Wenzel et al.*, 1999; *Ionescu and Marmureanu*, 2005], systems are under way.

[3] Within the last century Romania has experienced four strong earthquakes on November 10, 1940 (M_w = 7.7), March 4, 1977 (M_w = 7.4), August 30, 1986 (M_w = 7.1), and May 30, 1990 (M_w = 6.9) [*Oncescu et al.*, 1999]. The 1977 event was most damaging and caused 1,570 fatalities, more than 11,300 injured people - 90% of them in the Romanian capital Bucharest -, and USD 2 billion direct damage costs [*Sandi*, 2001]. All strong earthquakes aside from several small to moderate sized events occurred at depths between 70 and 180 km in a well-defined volume of about 40 km × 80 km × 110 km size in the Romanian Vrancea zone, SE Carpathians. This intermediate-depth seismicity coincides with the location of a lithospheric slab segment whose subduction took place 22 to 10 million years ago [*Sperner et al.*, 2001].

[4] The favorable geometry by the seismogenetic Vrancea zone and Bucharest accompanied by resembling source mechanisms of all strong Vrancea earthquakes, allows for the design of a simple, cheep and robust EEW system for the Romanian capital [*Wenzel et al.*, 1999]. The National Institute for Earth Physics (NIEP) in Bucharest and the Collaborative Research Center (CRC) 461 "Strong Earthquakes: A Challenge for Geosciences and Civil Engineering" (http://www-sfb461.physik.uni-karlsruhe.de/) at Karlsruhe University, Germany, have designed and installed key components of a prototype EEW system for Bucharest [*Ionescu and Marmureanu*, 2005]. Like the Mexican Seismic Alert System [*Espinosa-Aranda et al.*, 1995], the Romanian EEW system is designed as a front-detection system with seismic sensors installed close to likely source locations of future strong earthquakes. Three tri-axial strong motion sensors have been deployed in the epicentral Vrancea area with a satellite communication link to the Romanian Data Center at NIEP in Bucharest. Sensors have been installed in Vrancioaia (VRI) and in Plostina, about 8 km away (Figure 1). One of the Plostina stations (PLOR1), a FBA-23 sensor, is deployed in a 50 m deep borehole in order to avoid accidental triggering of the system; the other instrument (PLOR2) is an Episensor that is installed on top of the borehole. Average hypocentral distances of 160 km provide warning times of about 25 s for Bucharest for all intermediate-depth events.

[5] *Wenzel et al.* [1999] have developed a scaling relation for the real-time prediction of seismic ground shaking in Bucharest with leading times of 20 s to 25 s. Based on 18 weak motion (FBA23, S13/SH-1, S13) and 2 strong motion records (1986 M_w = 7.1 and 1990 M_w = 6.9, SMA-1) the authors find that

$$PGA_{filt} \approx 10P_{epi}, \qquad (1)$$

where P_{epi} is the maximum 1–2 s filtered P-wave amplitude on the vertical component of acceleration at epicentral station MLR in Muntele-Rosu; PGA_{filt} is the 1–2 s filtered peak horizontal acceleration at station BUC in Bucharest

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Figure 1. Distributions of strong motion sensors in the Romanian EEW system and additional stations used for the definition of scaling relations. The star indicates the location of the October 27, 2004 Vrancea earthquake (M_w = 6.0).

(Figure 1). In this paper, relation (1) will be revised on the basis of additional weak and strong motion data, as well as simulated ground motion records. Novel scaling relations for peak ground acceleration *PGA*, spectral response at different periods ($PSA_{0.3s}$, $PSA_{1.0s}$, $PSA_{2.0s}$) at 5% damping, and seismic intensity *I* will be established and tested by application to the October 27, 2004 Vrancea earthquake (M_w = 6.0).

2. Database and Method

[6] We use a dataset of 19 weak motion records ($3.7 \leq M_w \leq 5.3$) of the Romanian K2 strong motion network [*Bonjer et al.*, 2000], aside from 2 strong motion records (1986 M_w = 7.1, 1990 M_w = 6.9, SMA-1). Due to the lack of further strong motion data we use in addition 36 simulated acceleration records ($5.6 \leq M_w \leq 8.0$) obtained from Empirical Green's Functions (EGF) modelling after *Irikura* [1983]. The EGF method is based on the self-similarity concept of earthquakes of different magnitudes

$$\frac{L}{l} = \frac{W}{w} = \sqrt[3]{\frac{M_0}{m_0}} = N, \tag{2}$$

assuming constant stress drops of all events [*Kanamori and Anderson*, 1975]; *L* and *W*, and *l* and *w* are the length and width of the target event and small EFG earthquake, respectively, M_0 and m_0 are the seismic moments, and *N* is the scaling factor. This concept allows up-scaling small EGF earthquakes to obtain strong motion time series of large events at the same sites where the EGFs have been recorded. The benefit of the EGF method is that propagation and site effects are already included in the small EGF event, presuming linear soil behaviour. For the simulation of large events we up-scale four small Vrancea earthquakes recorded by the K2 strong motion network on October 11, 1997 (Mw = 4.5, 110 km depth), November 8, 1999 (Mw = 4.6, 137 km depth), November 14, 1999 (Mw = 4.6, 132 km depth), and April 6, 2000 (Mw = 5.0, 143 km depth) (ROMPLUS catalogue [*Oncescu et al.*, 1999]).

[7] As proposed by *Wenzel et al.* [1999] the data is bandpass-filtered between 1–2 s by application of a 3rd order Butterworth-filter. Site effects in Bucharest show a significant amplification in this period range [*Wirth et al.*, 2003]; in addition, estimated ground motions in this interval are meaningful for engineering problems because they cover the range of eigenperiods of medium to high-rise structures in Bucharest [*Wenzel et al.*, 1999]. The filtering reduces also the probability of false alerts caused by small high-frequency events close to the seismic device or by site effects in the epicentral area.

[8] Due to the larger database of available ground motion records, scaling relations in this paper refer to epicentral station VRI instead of EEW sensors PLOR1 and PLOR2 (Figure 1). Though being 8 km far away, P-wave amplitudes on the vertical components at the EEW sensors and station VRI are almost equal after bandpass-filtering (Figure 2). Scaling laws for station VRI are therefore assumed to be also applicable to PLOR1 and PLOR2.

[9] Scaling laws for *PGA*, PGA_{filt}, $PSA_{0.3s}$, $PSA_{1.0s}$, and $PSA_{2.0s}$ are expressed by logarithmic relations of form

$$\log IM = a + b \log P_{epi}, \tag{3}$$

and for instrumental intensity *I* of form

$$I = a + b \log P_{epi}. \tag{4}$$

[10] P_{epi} is the maximum filtered P-wave amplitude of vertical acceleration (in [cm/s^2]) at station VRI, *IM* is the ground motion parameter of interest (in [cm/s^2] for *PGA* and *PSA*). *IM* refers to the larger value of both horizontal components of acceleration at station INCERC (INC, later renamed RBA) in Bucharest. Instrumental intensity *I* (MMI or MSK scale) is determined from the Fourier amplitude

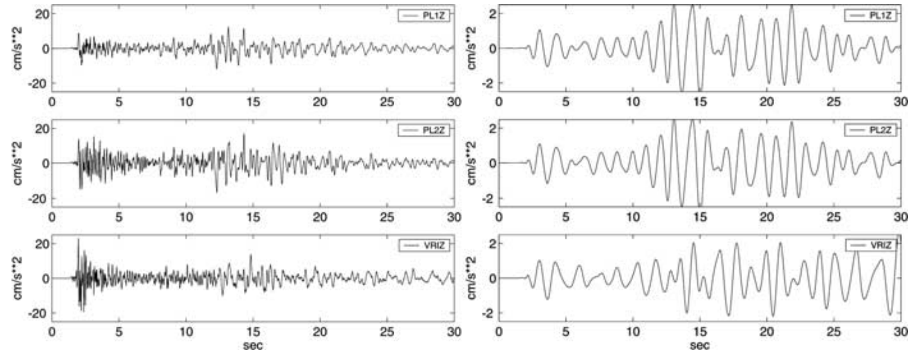

Figure 2. Vertical components of recorded ground acceleration during the October 27, 2004, Vrancea earthquake ($M_w = 6.0$) at (top to bottom) station PLOR1 (borehole sensor) and PLOR2 in Plostina, and at station VRI in Vrancioia. Shown are (left) unfiltered records and (right) filtered records after application of a 3rd order Butterworth-filter between 1–2 s. P-wave amplitudes are almost equal at all three sensors implying the applicability of the same scaling relations to all epicentral sites.

spectrum (FAS) of acceleration applying an empirical method developed by *Chernov and Sokolov* [1988] and refined by *Sokolov* [2002]. Coefficients *a* and *b* are determined by regression from the described database.

3. Results

[11] The regression results for coefficients *a* and *b*, as well as the unit standard deviation σ of the obtained scaling relations are summarized in Table 1 (left) and visualized in Figure 3. For all ground motion parameters the determination coefficient R^2 is very high with $R^2 = 0.87$ to $R^2 = 0.98$ (Table 1, left).

[12] Note that in case of seismic intensity most weak motion events had to be excluded from the database because the method proposed by *Sokolov* [2002] is only calibrated for $I > 3.5$ events. This leads to a dominance of synthetic records in the database. The simulations appear to overestimate seismic intensities in Bucharest by one to two units. This disagreement of seismic intensities determined from the EGF simulations (I_1) with values determined from observational strong motion data (I_2, Figure 3) may be caused by inappropriate spectral contents of the synthetics. In contrast to the other ground motion parameters studied in this paper, that show a clear conformity of EGF simulations with observational data with respect to the level as well as to variability of ground shaking, seismic intensities are susceptible to the full bandwidth of frequencies as they are directly determined from FAS [*Sokolov*, 2002].

[13] The revised scaling relation for PGA_{filt} with coefficients taken from Table 1 (left) gives in rearranged form

$$PGA_{filt} \approx 5P_{epi}. \tag{5}$$

[14] That is, values predicted from relation (1) following *Wenzel et al.* [1999] are twice as large as if determined from our new relation (5). Note, however, that the uncertainty of our scaling relation is of the same order; both relations are therewith not mutually exclusive.

[15] We test our proposed scaling relations by application to the October 27, 2004, ($M_w = 6.0$) Vrancea earthquake, the largest earthquake in Romania since installation of the K2 network in 1997 [*Radulian et al.*, 2007]. This event was not used for the establishment of scaling relations. The peak filtered P-wave amplitude of the event at station VRI is $P_{epi} \approx 1.2$ cm/s^2. Inserting this value into (3) and (4) with coefficients taken from Table 1 (left) allows predicting ground motion in Bucharest for different *IM*. Observed levels of ground shaking IM_{obs} and prognostics IM_{est} are compared in Table 1 (right). In general, ground motion is well-predicted, whereby most parameters are slightly overestimated. Considering the 95% confidence intervals of the relations approximated by 2σ, all predictions give satisfying results; that is, ground motion in Bucharest can be well approximated by the explored relations. Slight discrepancies are observed for seismic intensity that is overestimated by one to two units using the first relation (I_1), and half to one unit using the second relation (I_2).

4. Discussions and Conclusions

[16] In this paper we have revised a scaling relation for EEW in Romania proposed by *Wenzel et al.* [1999] and established novel relations for different ground motion parameters on the basis of (1) weak motion data recorded by the Romanian K2 network, (2) records of two large Vrancea earthquakes (1986 $M_w = 7.1$, 1990 $M_w = 6.9$), and (3) synthetic strong motion records obtained from EGF simulations after *Irikura* [1983].

Table 1. Coefficients in Scaling Relations (3) and (4) for Different Ground Motion Parameters *IM* (Left) and Application of Scaling Relations to the October 27, 2004 Vrancea Earthquake ($M_w = 6.0$) (Right)[a]

IM	a	b	σ	R^2	IM_{est} 2σ	IM_{obs}
PGA_{filt}	0.6643	0.9929	0.1618	0.98	5.5 ± 2.9	2.4
PGA	1.4331	0.6310	0.1508	0.92	30.4 ± 15.2	23.7
$PSA_{0.3s}$	1.5966	0.6286	0.1660	0.89	44.3 ± 23.7	56.3
$PSA_{1.0s}$	1.3889	0.9696	0.1469	0.96	29.2 ± 14.4	15.8
$PSA_{2.0s}$	0.8914	1.0301	0.2025	0.93	9.4 ± 5.7	3.2
I_1	6.3375	2.7169	0.4468	0.87	6.6 ± 0.9	4.4
I_2	1.6435	5.2626	0.1452	0.92	5.4 ± 0.3	4.4

[a] Here σ is the unit standard deviation, R^2 is the determination coefficient. IM_{est} are estimated values of ground shaking and IM_{obs} are observed values (in cm/s^2). Using the 95% confidence intervals - approximated by 2σ - almost all parameters are well predicted; intensity is overestimated by both intensity relations I_1 and I_2.

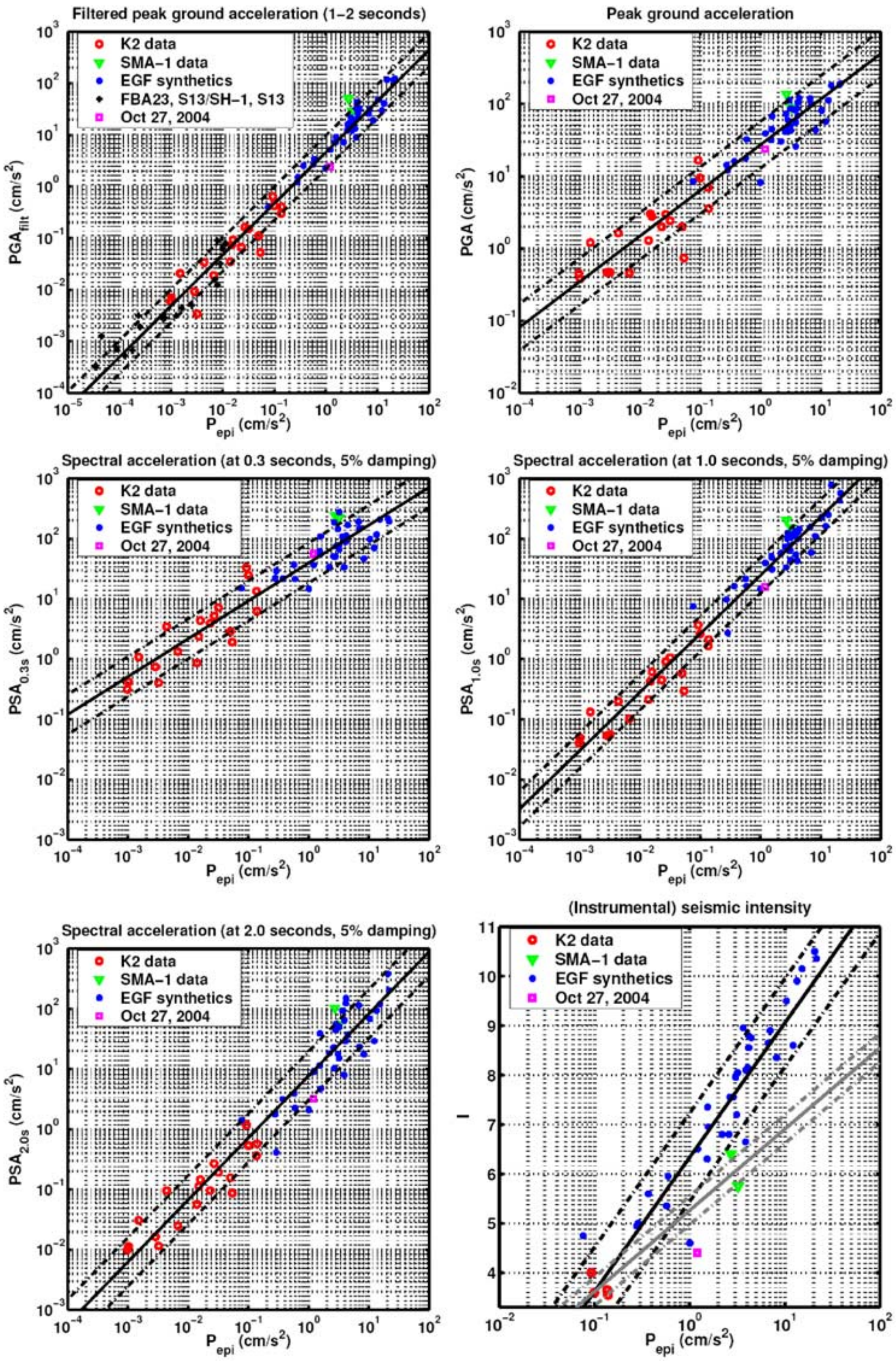

Figure 3. Correlation between maximum filtered epicentral P-amplitude and different ground motion parameters in Bucharest: filtered peak ground acceleration (PGA_{filt}), peak ground acceleration (PGA), spectral response (PSA) at 0.3 sec, 1.0 sec and 2.0 sec at 5% damping, and instrumental intensity I. Solid lines show the determined scaling relations, dashed lines the corresponding 95% confidence intervals (= 2σ). The relations have been derived from different datasets as indicated in the legends.

[17] The present EEW system in Romania belongs to the group of on-site warning systems [*Kanamori*, 2005] that relies essentially on the information of a single station. Thus shortcomings of this type of EEW system [e.g., *Rydelek and Horiuchi*, 2006] apply to our system in general, too. However, the specifics of Vrancea seismicity qualify the system as far more reasonable and reliable than most of the other on-site systems: earthquake sources are located in a

small volume so that the epicentres of Vrancea earthquakes are essentially in one location. Almost all events are of thrust type with the rupture plane oriented SW-NE; they radiate always similar percentages of energy to the epicenter and to Bucharest [*Wenzel et al.*, 1999]. Earthquakes in Vrancea have repeatedly demonstrated that their source mechanisms are not very complex [e.g., *Radulian et al.*, 2007]. Compared to crustal events in other seismic active regions, source areas of Vrancea earthquakes are fairly small at concurrent very high stress drops [*Oth et al.*, 2007]. We utilize this empirically established and tectonically understood feature of Vrancea earthquakes for our EEW approach. We are aware that there is a potential for failure if an earthquake occurs that violates these rules. Therefore, work on EEW for Bucharest will continue and include more stations in the future.

[18] Sensors of the Romanian EEW system are installed on rock and are therewith hardly affected by site amplifications due to soft soils. In addition, we consider only 1–2 s filtered data at stations in the epicentral area: this band is usually not much affected by site amplification [*Sokolov et al.*, 2005]. The EGF method presumes linear soil behaviour [*Irikura*, 1983]. We consider linearity as a justified presumption due to two reasons: first, the influence of nonlinearities becomes important only for very strong motion amplitudes. The majority of our amplitudes is <0.1 g so that the effect of non-linearities should be negligible [*Borcherdt*, 1994]. Secondly, aside from the EGF simulations we use 19 weak motion and 2 strong motion observations for the definition of our scaling relations. Except for seismic intensities we found a good agreement between EGF simulations and observational data with respect to the level of ground shaking as well as to the degree of their variability (Figure 3).

[19] For ground motion parameters $PSA_{1.0s}$, $PSA_{2.0s}$, and PGA_{filt} that just as P_{epi} depend on long-period shaking, the b-value in relation (3) (see Table 1, left) is almost 1.0 indicating a linear relationship between long-period motions in the epicentral area and Bucharest. In contrast, we do not necessarily expect that $b \approx 1.0$ in case of high-frequency parameters PGA and $PSA_{0.3s}$. This is because long- and short-period motions undergo different attenuation and scattering effects during wave propagation. A b-value distinct from 1.0 (here: $b \approx 0.6$) is not evidence for nonlinearity of seismic site effects.

[20] Figure 3 indicates that our scaling relations slightly underestimate PGA and PSA for the 1986 event. However, the level of precision required for EEW information depends very much on the user. For instance Civil Protection may require nothing but the information that a large earthquake is impending whereas automatic switch-off for industrial facilities may require higher precision.

[21] So far, the Romanian EEW system focuses on Vrancea events. For future operation, the system must include redundancy to make it insusceptible to small crustal events close to the sensors or to ambient noise that might cause false alerts. We therefore encourage the installation of further sensors between Vrancea and Bucharest (such as at Montele-Rosu MLR, Figure 1). As a first step, we suggest the usage of P-phases of seismic signals in Bucharest for the judgment whether the detected earthquake has been generated in Vrancea: if so, then the P-wave should arrive in Bucharest approximately 10 s after detection at the EEW sensors. Alternatively *Wenzel et al.* [1999] proposed the usage of a scaling relation between epicentral S- and P-wave amplitudes to decide whether the alarm should be cancelled or confirmed. In both cases, warning times for Bucharest are reduced to about 15 s.

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