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# UNCERTAINTIES IN SITE EFFECT ASSESSMENT - EXPERIENCE FROM WEAK MOTION OBSERVATIONS IN BUCHAREST

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## SUMMARY

The hazardous earthquakes for the Romanian capital Bucharest are the intermediate depth Vrancea events between 80 and 200 km depth, 130 km N of the city. Due to this geometry ground motion variations in Bucharest must be dominated by site effects as source and propagation effects at different sites within the city are almost identical. Thus ratios of Fourier Amplitude Spectra at those sites with the records of a reference station in the denominator contain only site effect terms and should not vary significantly for different Vrancea sources. However, the observed Fourier Amplitude Spectral Ratios differ significantly so that we have to conclude: The source site separation model is incorrect or incomplete and a significant amount of aleatory uncertainty exists in site effects so that they should be quantified in probabilistic terms. Aleatory uncertainties are inherent to the unpredictable nature of certain details in the complex process of ground motion. They cannot be reduced by collection of more data and information. One could certainly think of potential physical causes for the unexpected scatter in spectral ratios. Hydrogeological effects may play a role and thus modify ground motion via parameters such as soil moisture, water table, etc. However, these effects are hard to monitor systematically, inaccessible for previously observed ground motion and impossible to predict for future ground motion. Non-linearity cannot be responsible, as we use only weak motion data. Instead of speculating on causes we consider it more useful (a) to quantify the aleatory uncertainty in site effect amplification in a systematic way, and (b) to suggest that site-dependent prediction of future ground motion should be done by probabilistic means.

## INTRODUCTION

As a standard model for the assessment of site-effects (Borcherdt [1]) the Fourier Amplitude Spectrum (FAS) of a free surface accelerogram is de-composed into a source term, a propagation term, and the effect of the near-surface geology at the recording site. This model is utilized to synthesize FAS and subsequently time histories by assuming a source term, such as Brune's model [2], an attenuation law and an estimation of the site effect given by the geotechnical parameters of the near-surface layers. For reasons to be discussed later, it is believed that the observed variability in ground motion within Bucharest is predominantly caused by site effects. The regional geology does not suggest significant basin or basin edge effects (e.g. Ministerul Minelor, Petrolului si Geologiei / Institutul de Geologie si Geofizica [3]; Polonic [4]). As Bucharest is built on the fluvial plains of the Danube no significant surface topography

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exists (e.g. Ministerul Minelor, Petrolului si Geologiei / Institutul de Geologie si Geofizica [3]). Thus the model of Borcherdt [1] can be applied with confidence.

This paper discusses the lateral variation of ground motion within the Romanian capital Bucharest as observed in weak motion records of 23 recent events recorded by K2 accelerometers. Fourier Amplitude Spectra of the S-wave window are utilized to assess quantitatively the degree of variation and the spectral characteristics by scaling ground motion parameters with observations from a reference station. Studies on ground motion variation in Romania based on various data have been published by Lungu et al. [5], Bonjer et al. [5], Lungu et al. [7], Aldea et al. [8] and Bonjer et al. [9]. This paper focuses on the city of Bucharest and addresses uncertainties in site effect assessment.

## VRANCEA SEISMICITY AND GEOLOGY OF BUCHAREST

Romania is frequently hit by strong intermediate-depth earthquakes which occur beneath the SE Carpathian bending zone - the Vrancea area - between 80 km to 200 km depths in an amazingly narrow epicentral region of 20 by 80 km. The geodynamic frame and the tectonic boundary conditions of this unusual seismicity pattern have only recently been revealed. It is now recognized as the last stage of a plate break-off process that started in the Miocene (~16 Ma) in the Western Carpathians and is in its final stage today beneath Vrancea (Sperner et al. [10]).

How strong Vrancea earthquakes can become is a matter of speculation. Lungu et al. [11] estimated a maximum credible moment magnitude of 7.8. The Vrancea moment release rate is as high as the moment release rate of Southern California (Wenzel et al. [12]). The seismic risk for Romania and its neighbours Moldavia and Bulgaria is therefore very high and discussed in Lungu et al. [11]; Georgescu et al. [13]; Sandi [14], [15] and Georgescu [16].

During the last century four major Vrancea earthquakes occurred on November 10, 1940 (Mw = 7.7), March 4, 1977 (Mw = 7.4), August 30, 1986 (Mw = 7.1) and May 30, 1990 (Mw = 6.9). Moment magnitudes are taken from the ROMPLUS catalogue (Oncescu et al. [17]). The former two lead to disastrous impact on Romanian territory. According to official data (e.g. Sandi [15]) in the March 4, 1977 event, 1,570 people died, 11,300 were injured and 32,500 residential and 763 industrial units were destroyed or seriously damaged. Educational, medical and commercial networks as well as buildings related to culture and historical monuments, administrative buildings, various buildings and facilities in the agricultural sector were heavily affected. According to World Bank estimates the total direct economic loss amounted to 2 billion US dollars.

Bucharest with its high risk potential is located about 130 km south of the epicentral Vrancea region (Fig. 1). Typical hypocentral distances of the intermediate depth events that determine the hazard for the city are in the range of 180 km. Compared to such distances the spatial extent of Bucharest is relatively small. From this source-to-site geometry we conclude that the lateral variations of ground motion in the city are mainly caused by site effects. Furthermore this fairly large distance is responsible for the fact that the maximum ground motion that has been observed (in 1977) amounts to 0.2 g only. It is thus the potential of site specific amplification within the city and the vulnerability of the building stock that contribute most to the high damage potential.

Bucharest is situated in a Miocene alluvial basin with thick sedimentary formations, responsible for seismic site effects. Lungu et al. [5] emphasized the complex layering of the Quaternary deposits with several different sand and clay layers and explained it as a consequence of rapidly changing sedimentation processes during the silting of a Quaternary lake. The Quaternary deposits are reaching depths of 200 m to 300 m. The Tertiary layer beneath them is about 700 m thick.

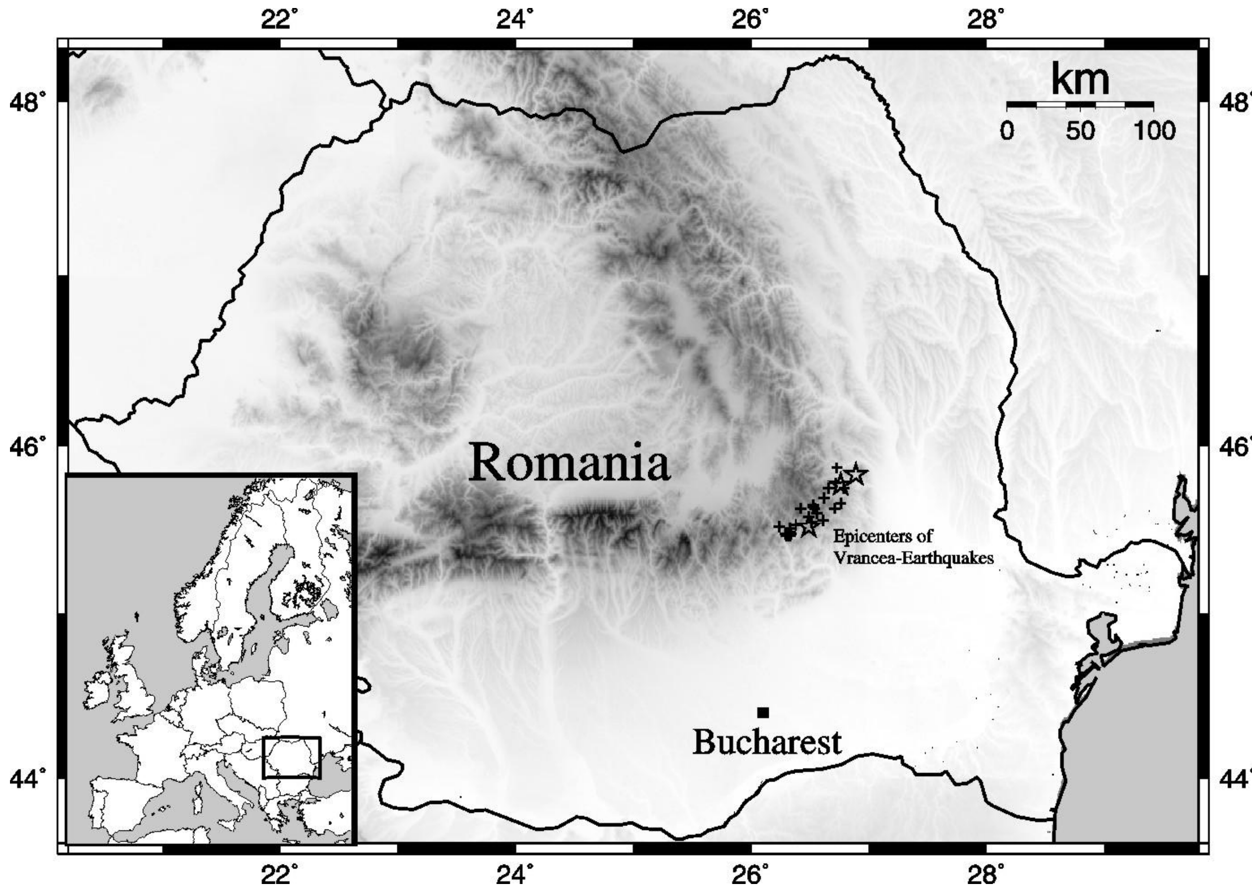


**Fig. 1: Topographic map of Romania with its capital Bucharest and the epicenters of the Vrancea earthquakes used in this study. Crosses mark 23 earthquakes with moment magnitudes between 3.6 and 5.3. The epicenters of the damaging earthquakes of 1977, 1986 and 1990 are indicated as stars. All Vrancea earthquakes occur within a narrow source volume at intermediate depths. Typical hypocentral distances for Bucharest are in the range of 250 km.**

**Weak Motion Data in Bucharest**

Installation of a modern network of digital Kinemetrics-K2 instruments by the University of Karlsruhe and NIEP (Bonjer et al. [18]) began in 1997. Fig. 2 shows the station distribution within the city by triangles and their two-letter code. For this study we utilize 23 Vrancea earthquakes that have been recorded between October 1997 and December 2001 by the K2-network in Bucharest (Bonjer and Rizescu [19]; Bonjer et al. [20]). In order to ensure a high signal-to-noise ratio, only earthquakes with moment magnitudes between 3.6 and 5.3 are considered. Higher moment magnitudes are not available in this period. Event dates and origin-times, hypocenter coordinates and moment magnitudes are listed in Table 1. The source parameters are taken from the ROMPLUS catalogue [17]. The epicenters for the events used in this study are shown by crosses in Fig. 1.

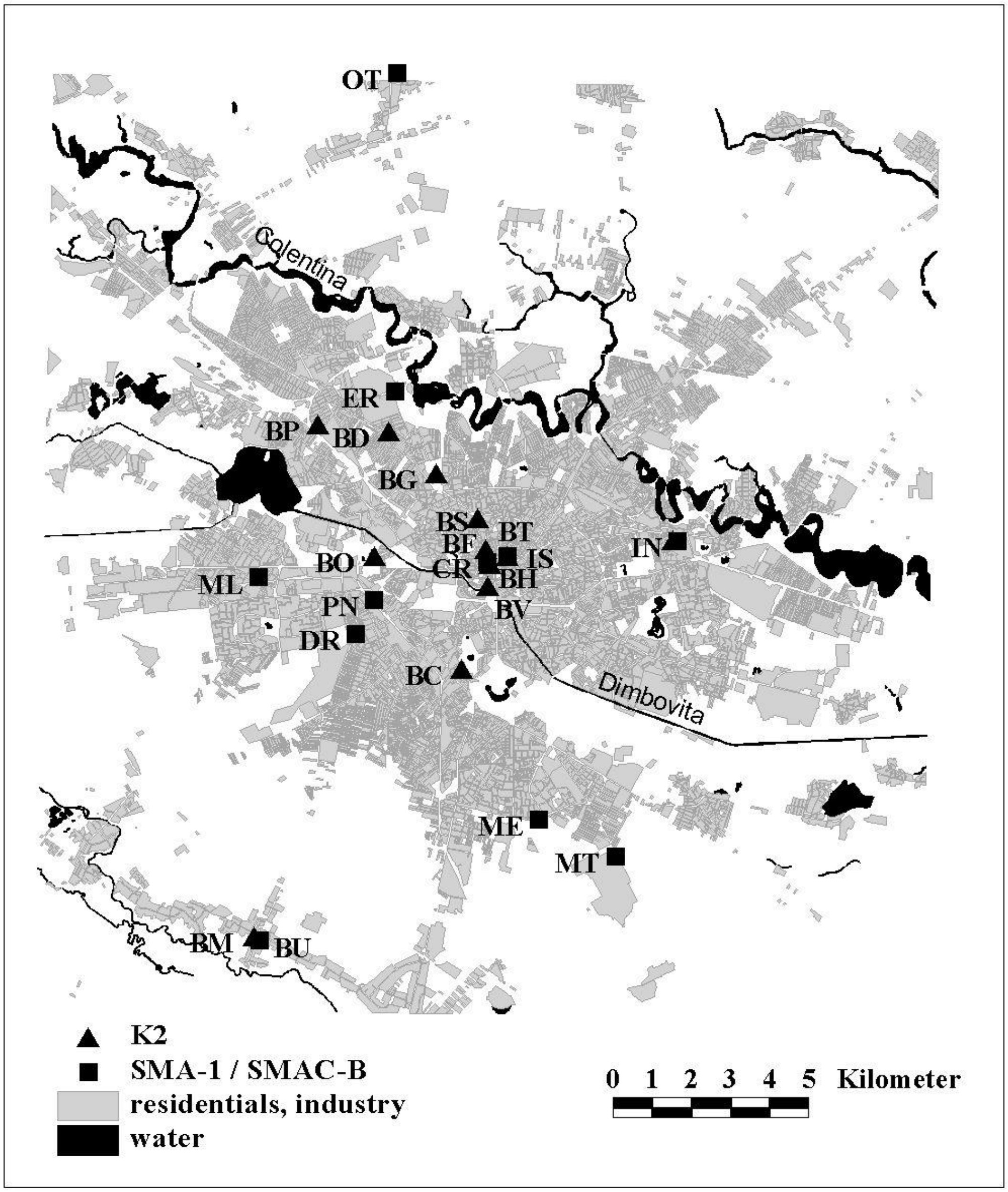


**Fig. 2: Distribution of strong motion accelerometers in Bucharest. Residential and industrial facilities are shaded grey, lakes and rivers black. SMA-1 and SMAC-B strong motion instruments (dark squares with two-letter code) recorded signals from all three major earthquakes: 1977, 1986, and 1990. They are operated by INCERC, NIEP and ISPH/GEOTEC. Installation of a network of digital Kinemetrics-K2 instruments by the University of Karlsruhe and NIEP began in 1997. These instruments are shown as triangles with a two-letter code.**

| Date | Origin-Time | Latitude | Longitude | Depth | Mw |
|---|---|---|---|---|---|
| 1997/11/18 | 11:23:16.3 | 45.76N | 26.71E | 123.0 | 4.7 |
| 1997/12/18 | 23:21:21.4 | 45.52N | 26.26E | 135.5 | 3.9 |
| 1997/12/30 | 04:39:30.3 | 45.54N | 26.32E | 139.1 | 4.6 |
| 1998/01/19 | 00:53:50.4 | 45.64N | 26.67E | 104.9 | 4.0 |
| 1998/01/31 | 21:14:48.5 | 45.47N | 26.33E | 136.6 | 3.6 |
| 1998/03/13 | 13:14:38.8 | 45.56N | 26.33E | 154.8 | 4.7 |
| 1998/04/14 | 01:03:52.1 | 45.73N | 26.57E | 141.3 | 3.8 |
| 1998/07/03 | 06:14:49.6 | 45.67N | 26.76E | 135.7 | 4.2 |
| 1998/07/27 | 15:02:18.5 | 45.67N | 26.53E | 135.4 | 4.4 |
| 1999/03/22 | 19:25:53.3 | 45.52N | 26.31E | 144.5 | 4.4 |
| 1999/04/04 | 01:21:12.6 | 45.70N | 26.44E | 146.0 | 3.7 |
| 1999/04/28 | 08:47:56.0 | 45.49N | 26.27E | 151.1 | 5.3 |
| 1999/04/29 | 18:44:12.9 | 45.62N | 26.40E | 147.7 | 4.0 |
| 1999/05/25 | 09:35:53.8 | 45.59N | 26.49E | 122.3 | 3.9 |
| 1999/06/29 | 20:04:07.4 | 45.61N | 26.52E | 131.0 | 4.2 |
| 1999/11/08 | 19:22:52.4 | 45.55N | 26.35E | 137.9 | 4.6 |
| 1999/11/14 | 09:05:59.0 | 45.52N | 26.27E | 132.0 | 4.6 |
| 2000/03/08 | 22:11:29.1 | 45.87N | 26.72E | 74.2 | 4.4 |
| 2000/04/06 | 00:10:38.8 | 45.75N | 26.64E | 143.4 | 5.0 |
| 2001/03/04 | 15:38:45.2 | 45.51N | 26.24E | 154.5 | 4.8 |
| 2001/05/24 | 17:34:02.5 | 45.63N | 26.42E | 143.7 | 4.9 |
| 2001/07/20 | 05:09:40.3 | 45.75N | 26.79E | 132.5 | 4.8 |
| 2001/10/17 | 13:01:32.8 | 45.60N | 26.56E | 86.6 | 4.2 |

**Table 1: Origin-times, hypocenter and moment magnitudes of the 23 earthquakes used in this study. (Source: ROMPLUS, Oncescu et al. [17]).**

The data consist of three-component acceleration records but as horizontal ground motion is mainly responsible for the earthquake damage, only NS- and EW-components are used. Wherever possible we use a 15 s time window starting about 1s before the onset of the S- waves. We remove the time average (DC shift). No additional filtering is applied.

The horizontal components at each site display about the same amplitudes, with a tendency of slightly higher values on the NS-component. Comparing records at different sites a significant variability in maximum amplitude by a factor of about 4 within the city is obvious. Stations with low amplitudes such as BF, BM and IN also show simple waveforms in comparison to the more complex wave patterns at stations BO and BP where the amplitudes are higher.

## OBSERVED GROUND MOTION VARIATION

In order to quantify the lateral variations of ground motion in Bucharest we study Fourier Amplitude Spectra (FAS). As no hardrock site is available for the city we scale the FAS with the observation from a reference station in order to compare different earthquakes. Station INCERC (IN) is the natural choice, because it recorded strong motion data of 1986 and 1990 with a SMAC-B instrument as well as weak motion data with a K2 unit. These criteria apply to station Bucharest-Magurele (BU), too. We repeated all computations presented in this paper with Bucharest-Magurele as reference in order to test whether results depend on this choice. We found that they do not.

The FAS of the observed weak motion data are studied by forming spectral ratios with respect to station INCERC. In order to minimize the effects of the finite time window the first and last 5 % of the signal were tapered with a cosine function before computing the FAS. The resulting FAS were smoothed with a moving average filter with 0.5 Hz half-width. To avoid artefacts in the spectral ratios that can occur at notches of a reference spectrum in the denominator a threshold (water-level) is defined at 10% of its maximum value. This technique is standard procedure for the computation of receiver functions (Langston [21]). We investigate resulting horizontal components. At the K2 sites we compute mean spectral ratios with respect to INCERC from the 23 earthquakes. In the following they are simply referred to as the mean spectral ratios.

At stations in the central part of the city (BF, BH, BS, BT and BV) the mean spectral ratio is about one in the entire frequency range between 0 Hz and 10 Hz. These stations exhibit similar site effects as INCERC. At BC, BD, BG and BM a plateau of the mean spectral ratio between 2 Hz and 5 Hz indicates a slight amplification relative to the reference site. It does not exceed a factor of 2. These stations form a belt that runs west of the previously mentioned group of stations from NNE to SSW. Mean spectral ratios with similar shapes but higher amplification values are observed at stations BO and BP. At station BP the amplification reaches a factor of about 3. At station BO there is a prominent peak in the mean spectral ratio at about 4.5 Hz with a relative amplification up to a factor of 4.5. BP and BO mark a wedge of high amplification sites protruding from the NW towards the city center. Fig. 3 shows the mean spectral ratios of BF, BC and BP and their standard deviations as examples for the three categories specified above. Station BO is also shown in order to illustrate its exceptional behaviour.

Site effect variations show different characteristics for frequencies below 2 Hz and above 2 Hz and are thus analyzed separately. For the higher frequency range we characterized them by the height of the FAS between 2 Hz and 5 Hz. Consequently we define a relative high frequency amplification factor $AF_h$ for each K2 station as the mean spectral ratio averaged over the frequency range between 2 Hz and 5 Hz (Fig. 4). The vertical bars in the figure indicate one standard deviation. At BF, BH, BS, BT and BV the value of $AF_h$ is only slightly higher than one. At BC, BD, BG and BM it amounts to 1.5 to 1.6. The highest values are observed at BP and BO with 2.5 and 3.3 respectively. With 20 % to 40 % of the absolute values the standard deviations are unexpectedly high.

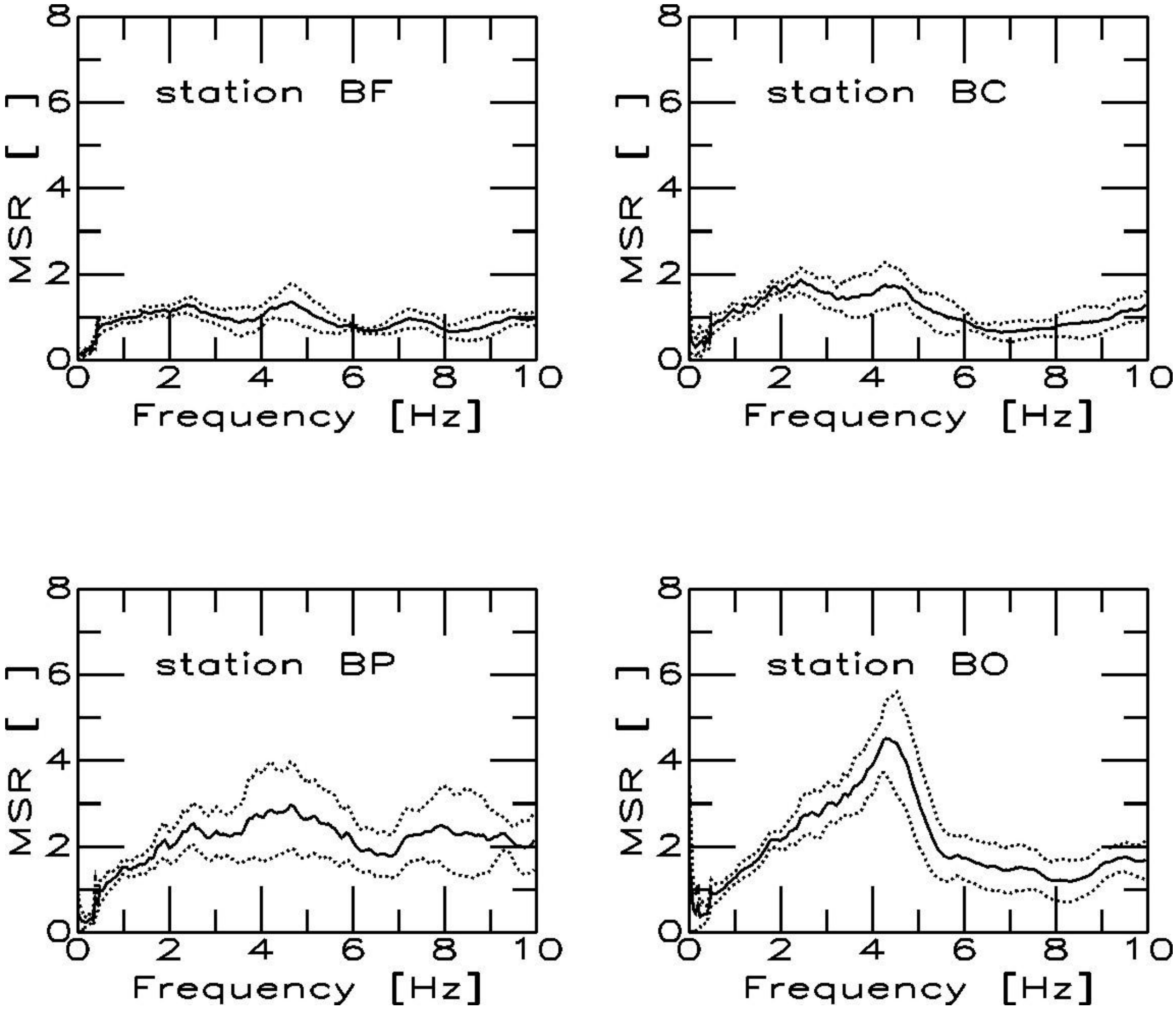


**Fig. 3: Mean spectral ratios (MSR) of the Fourier Amplitude Spectra with respect to INCERC at stations BF, BC, BP, and BO from all 23 small earthquakes. The dashed lines indicate one standard deviation. At station BF located in the central part of the city the mean spectral ratio is about one in the entire frequency. Station BC, in the south of BF, shows elevated values between 2 Hz and 5 Hz. However, they do not exceed a value of 2. Mean spectral ratios with similar shape but higher values between 2 and 5 Hz are observed at BO and BP in the west and NW of Bucharest. Station BO is characterized by a prominent peak at about 4.5.**

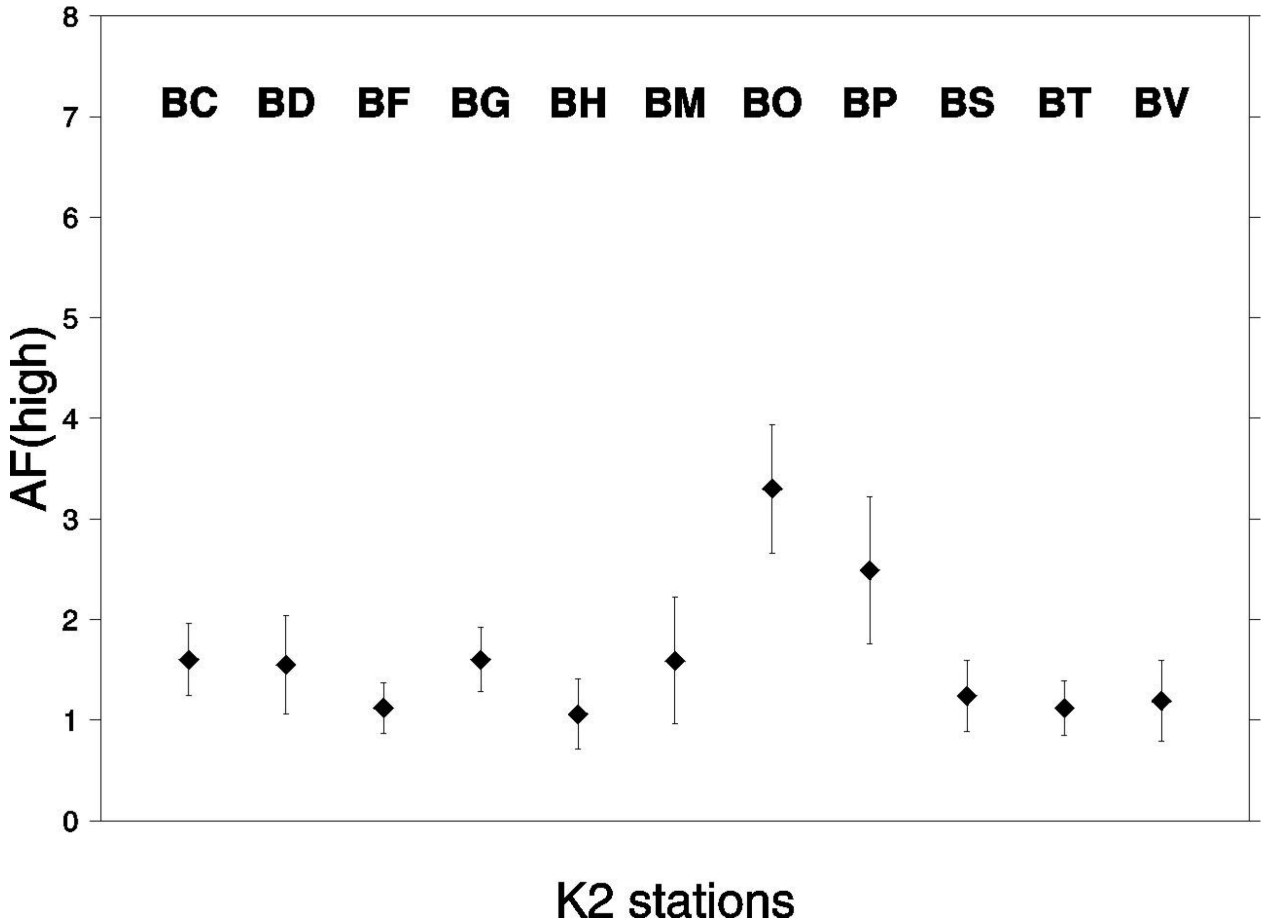


**Fig. 4: $AF_h$ (indicated as AF(high) in the figure) defined as the average of the mean spectral ratio with respect to INCERC between 2 Hz and 5 Hz. Vertical bars indicate one standard deviation. In the central part of the city (BF, BH, BS, BT and BV) $AF_h$ are about one. In the west (BC, BD, BG and BM) values are slightly higher (1.5 to 1.6). The highest values are observed at BO and BP, in the west and NW of Bucharest, with 3.3 and 2.5 respectively. The standard deviations amount to 20 % to 40 % of the absolute values.**

## AMPLIFICATION OF GROUND MOTION BY SITE EFFECTS

The influence of earthquake source, propagation path, and site effect on the observed ground accelerations in the frequency domain is usually modeled as:

$$A(f) = F(f) \cdot P(f) \cdot S(f) \tag{2}$$

where
A(f) = spectrum of ground acceleration
F(f) = source radiation term
P(f) = propagation term
S(f) = site effect term

If we consider one earthquake and a set of records from stations in approximately the same distance and azimuth from the source, the source and propagation functions F(f) and P(f) should be similar. Spectral ratios with respect to a reference station should then only reflect the ratio of site effect amplification functions. They should be independent of a specific earthquake and should not change if computed for different events. With station INCERC as reference the ratio reads as

$$\frac{A_{ik}(f)}{A_{0k}(f)} = \frac{F_{ik}(f)P_{ik}(f)S_i(f)}{F_{0k}(f)P_{0k}(f)S_0(f)} \approx \frac{S_i(f)}{S_0(f)} \tag{3}$$

with station index i, source index k and i=0 indicating station INCERC.

For Vrancea earthquakes of typically 100 km depth recorded at the K2 stations in Bucharest one would expect that the conditions used to establish the model of equations (2) and (3) are very well satisfied.

The source radiation term can vary to a small degree only, if we assume that it is controlled by an azimuth-independent source time function and a radiation pattern that is differently sensed by the various stations. Using the common double couple point source approximation, F(f) for S-waves in the far field is proportional to a radiation pattern factor R. In a geographical coordinate system it can be separated into

$$\begin{aligned} R_{SH} &= (\cos\lambda\cdot\cos\delta\cdot\cos i\cdot\sin\Phi)+(\cos\lambda\cdot\sin\delta\cdot\sin i\cdot\cos 2\Phi)+\\ &(\sin\lambda\cdot\cos 2\delta\cdot\cos i\cdot\cos\Phi)-(0.5\cdot\sin\lambda\cdot\sin 2\delta\cdot\sin i\cdot\sin 2\Phi) \end{aligned} \tag{4}$$

and

$$\begin{aligned} R_{SV} &= (\sin\lambda\cdot\cos 2\delta\cdot\cos 2i\cdot\sin\Phi)-(\cos\lambda\cdot\cos\delta\cdot\cos 2i\cdot\cos\Phi)+\\ &(0.5\cdot\cos\lambda\cdot\sin\delta\cdot\sin 2i\cdot\sin 2\Phi)-(0.5\cdot\sin\lambda\cdot\sin 2\delta\cdot\sin 2i\cdot(1+\sin^2\Phi)) \end{aligned} \tag{5}$$

both depending on rake λ and dip δ of the fault plane solution, the difference Φ between the strike of the fault and the azimuth of the investigated station and the source take off angle i. The definition of the angles follows Lay and Wallace [22].

Then F(f) is proportional to

$$R = \sqrt{R_{SH}^2 + R_{SV}^2} \tag{6}$$

The ratios of the source radiation terms to their reference values at INCERC follow from the fault plane solutions in Table 2 (taken from Bonjer et al. [23]) and the hypocenters in Table 1 by applying equations (4), (5) and (6). The expected relative standard deviations of these ratios are 10 % at station BC, 6 % at station BF, 11% at station BO and 12 % at station BP. Only stations where fault plane solutions are available for all recorded events are used as examples. It should be mentioned that the effect of the source radiation pattern on high-frequency seismograms is probably highly overestimated as scattering during wave propagation in the frequency range larger than 1 Hz tends to smooth the radiation effects significantly.

| Date | strike | dip | Rake |
| --- | --- | --- | --- |
| 1997/11/18 | 154 | 44 | 93 |
| 1997/12/18 | 120 | 25 | 108 |
| 1997/12/30 | 260 | 44 | 132 |
| 1998/01/19 | 197 | 29 | 73 |
| 1998/01/31 | 225 | 45 | 95 |
| 1998/03/13 | 225 | 21 | 129 |
| 1998/04/14 | 354 | 36 | 127 |
| 1998/07/03 | 194 | 17 | 107 |
| 1998/07/27 | 290 | 38 | 87 |
| 1999/03/22 | 220 | 45 | 65 |
| 1999/04/04 | 315 | 38 | 116 |
| 1999/04/28 | 343 | 35 | 103 |
| 1999/04/29 | 114 | 57 | 146 |
| 1999/05/25 | 59 | 44 | 105 |
| 1999/06/29 | 219 | 46 | 72 |
| 1999/11/08 | 254 | 39 | 109 |
| 1999/11/14 | 242 | 43 | 84 |
| 2000/04/06 | 75 | 19 | 120 |

**Table 2: Fault plane solutions of earthquakes that were recorded in Bucharest (Source: Bonjer et al. [23]). Only one nodal plane is given respectively.**

The small differences in hypocentral distance can cause only minor differences in amplitude attenuation during propagation. In order to assess the effect of amplitude attenuation during propagation we parameterize the propagation term as

$$A(r) = \frac{A(0)}{r} \cdot e^{-\frac{f \cdot \pi \cdot r}{Q_\beta(f) \cdot v}} \qquad (7)$$

where
A(r) = Ground acceleration at hypocentral distance r
A(0) = Acceleration in the vicinity of the source
f = frequency
$Q_\beta$ (f) = quality factor for shear waves
v = shearwave velocity
r = hypocentral distance

We use the result of a coda wave study by Oncescu et al. [24] to determine $Q_\beta(f)$:

$$Q_\beta(f) = 109 \cdot f^{0.81} \qquad (8)$$

We study a frequency of 5 Hz, which suffers higher attenuation than lower frequencies at which pronounced ground motion variations are observed. According to equation (8) this corresponds to a $Q_\beta(f)$ of about 400. v is estimated as 4.5 km/s. Relative standard deviations of 1 % at station BC, 0 % at station BF, 1 % at station BO and 1 % at station BP for the ratios of the propagation terms to their reference values at INCERC are estimated with equation (7). Thus the variance of the ground acceleration ratio is mainly controlled by the source radiation terms, while the variance of the propagation terms is negligible.

An exact calculation of the expected relative standard deviation of the ground acceleration ratio is achieved by applying Gauss' law of error propagation to equation (2). This results in 10 % for station BC, 6 % for station BF, 10 % for station BO and 12 % for station BP.

The results of spectral ratios for 23 different earthquakes have been presented above and examples are shown in Fig. 3. For frequencies in excess of 2 Hz the scatter for some of the stations is amazingly high. Stations BC, BF, BG, BO and BP show a similar behaviour. Below 2 Hz the standard deviations amount to 10 % to 20 % of the absolute spectra. Above 2 Hz the ratios of standard deviations and the mean values successively increase and reach maximum values of about 40 % at 4 Hz to 5.5 Hz. This is about three times higher than the highest theoretical relative standard deviation computed for a frequency of 5 Hz (see above). At higher frequencies the relative standard deviations behave less systematic but undulate around this maximum without a further systematic increase. At BM the relative standard deviation is generally higher and starts increasing at the comparatively low frequency of 1.5 Hz. Below 1.5 Hz it amounts to 25 % to 30 %. It reaches its maximum of 45 % already at 3 Hz. At the other K2-stations (BD, BH, BS, BT and BV), where only 5 or less earthquakes were recorded, the standard deviation behaves less systematic. We ascribe that to the low redundancy. However, it never exceeds 60 % of the absolute spectra.

## DISCUSSION AND CONCLUSION

The computation of ratios of FAS of weak motion records shows an unexpected high scatter at above 2 Hz. Unexpected because validity of equation (2) and (3) demands a sufficiently large distance from the source and the absence of basin and basin edge effects. For Bucharest these conditions hold. Thus the parameterization of ground motion in equation (2) does not represent a complete model. Site effect prediction by equation (3) in the case of Bucharest can cause errors as large as a factor of about 1.5. Even if we assume that the theoretical source radiation terms are realistic, only about one third of this error can plausibly be explained in accordance with the model of equations (2) and (3). The rest is caused by other factors and circumstances. It belongs to the class of aleatory uncertainties. Aleatory uncertainties are inherent to the unpredictable nature of certain details in the complex process of ground motion (Toro et al. [25]). They cannot be reduced by collection of more data and information, as the model seems to be adequate in the description of ground motion. One could certainly think of potential physical causes for the unexpected scatter in spectral ratios. Hydrogeological effects may play a role and thus modify ground motion via parameters such as soil moisture, water table, etc. However, these effects are hard to monitor systematically, inaccessible for previously observed ground motion and impossible to predict for future ground motion. The latter also holds for the effects of inclined sediment interfaces, which can cause ground motion variations to be sensitive to the hypocenter location. They are ignored in the one-dimensional approach of equations (2) and (3).

Site effect predictions on the basis of the parameterization of ground motion in equation (2) causes high errors, because equation (2) does obviously not represent a complete model. Although it is possible to think of physical explanations we categorize these uncertainties as aleatory. Instead of speculating on causes we consider it more useful (a) to quantify the aleatory uncertainty in site effect amplification in a systematic way, and (b) to suggest that site-dependent prediction of future ground motion should be done by probabilistic means.

## ACKNOWLEDGEMENTS

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