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SEISMIC EXPOSITION OF THE WEST BOHEMIA SPA REGION

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Abstract: In West Bohemia the natural seismicity and strong blasts in quarries and open-pit mines may endanger the function of the mineral springs. In order to quantify and compare the effect of both seismic sources the seismic energy radiated by earthquakes and blasts was determined in the period March 1991 - June 1992. For this purpose the effects of all parameters affecting the values of energy obtained were discussed firstly. The seismic energy of blasts was up to 10^7 J while the energy of earthquakes reached the order of 10^8 J.

Key words: seismicity; quarry blast; seismic energy; attenuation

1. INTRODUCTION

The region of West Bohemia with a number of spa springs is typical by two other features which may endanger the function of the springs. The first danger, the local seismicity manifesting itself in the form of earthquake swarms, had local magnitudes up to 4.5 in the past. The second danger is represented by strong blasting in quarries and open-pit coal mines of the neighbouring Sokolov basin.

To monitor the effect of local seismicity and industrial explosions upon the system of spa springs, a local seismic network was installed in this area. It consists of five digital stations MARS-88 and one station PCM-5800 (all manufactured by Lennartz electronic) situated mostly in the vicinity of the spa springs (see Fig.1).

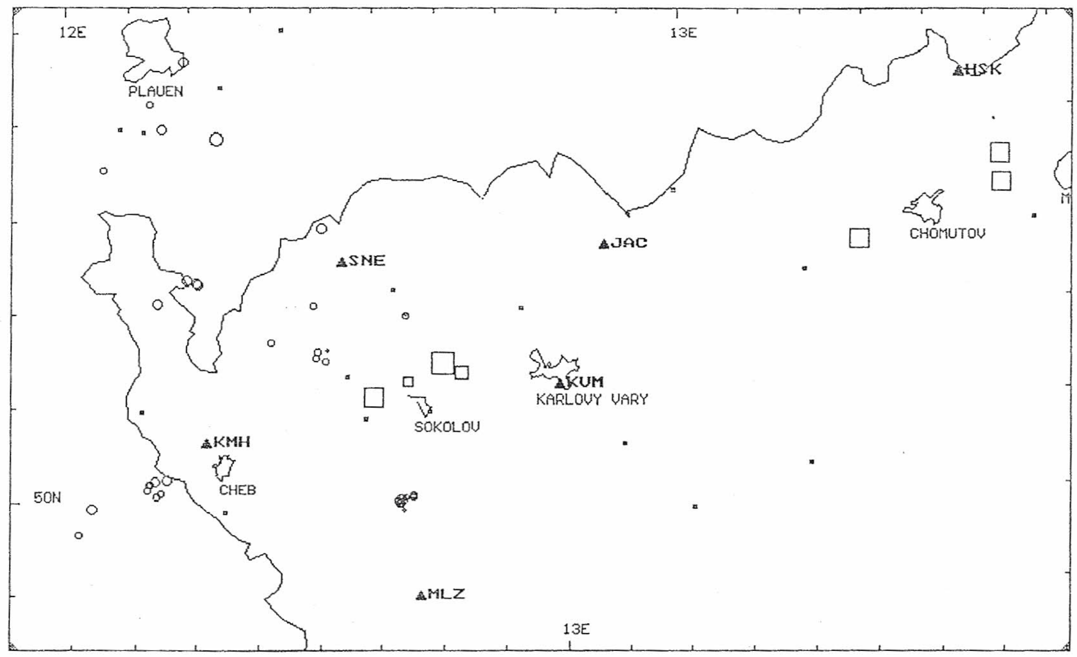

Fig. 1. The region of West Bohemia. Symbols: triangles - seismic stations, small squares - quarries, big squares - open-pit mines, open circles - epicentres of local earthquakes in 1991 and 1992.

One of the aims is to estimate a seismic exposition of the region in order to correlate it with the parameters of the spa springs. The seismic exposition of the area may be represented by the seismic energy radiated from the seismic sources during a particular time.

Since the seismic energy determination is sensitive to many parameters, this paper deals with the methodology in order to design a uniform method of the energy estimating of both earthquakes and blasts. Results of the energy estimation for events in the period March 1991 - June 1992 are given, too.

2. THE DATA AND THE METHOD

In the period March 1991 - June 1992 altogether 837 events were registered and identified by the network while 44 of them were local shallow earthquakes with depths around 8 km. In order to get a rough comparison of the energy of earthquakes and blasts when processing such a big amount of data a simple method should be used which holds for both types of events.

Generally, the total seismic energy is a sum of energy radiated by P- and S-waves. The P-wave energy may be determined using the velocity of ground motion $\dot{u}$ as

$$E_P = \frac{4\pi \alpha \rho r^2}{A^2 F_P^2 K^2 R^2} \int_0^T \dot{u}^2 dt \qquad (1)$$

where α is the P-wave velocity, ρ is the density, r is the epicentral distance, F_P is the P-wave source radiation pattern, K is the free-surface conversion coefficient, R is the site amplification factor, and the attenuation factor A is given as

$$A = \exp\left(-\frac{\pi f}{\alpha Q} r\right) \qquad (2)$$

where f is the frequency and Q is the quality factor.

For the S-wave energy a similar formula may be used using the S-wave velocity and different integration interval. The ratio of S-wave to P-wave energy is commonly denoted as q.

In the next section the influence of all the parameters upon the energy determination will be discussed in order to obtain an efficient procedure for energy estimation of a large set of events.

Time window for integration: Generally, only the direct wave energy should be included in integration. In the case of earthquakes, the direct wave impulse is usually short and its determination is simple. This does not hold for blasts which are performed by means of a number of subexplosions and due to the interference effects the impulse is not well defined. To resolve this problem a longer time window was used which included the scattered wave, too. In principle this approach is possible because the volume responsible for scattering is common for all events from the same region when using a sufficiently long time window. Then the energy increment due to time window prolongation is similar for all the events, especially when one uses a "flexible" window - its length is proportional to the P-wave travel time t_T. On the basis of these assumptions an interval $\langle t_T, 1.5t_T \rangle$ was used.

S-wave energy: For a number of blasts the integration of the S-wave group was not possible. This was caused by the fact that the S-phase is not present in all seismograms of explosions, or it is very weak. Therefore the scattered P-coda waves would be integrated instead of the S-wave. Because of this, the integration was made for the P-phase only and the total energy was estimated for both earthquakes and blasts by means of the q coefficient. The value of q depends on the source mechanism and for the West Bohemian earthquakes Kolář (1992) gives q = 20.

In the case of blasts the primary S-wave energy should be zero. In practice, the presence of inhomogeneities in the vicinity of the source may generate secondary S-waves. To obtain an empirical value of q for blasts, a test was made using 62 explosions from seven quarries

TABLE 1

Mean ratios E_S/E_P for blasts in selected quarries

Quarry (open-pit mine)	Num. of data	$q = E_S/E_P$
Nové Sedlo	6	7.1 ± 2.9
Vintířov	25	6.1 ± 3.2
Děpoltovice	4	5.2 ± 1.7
Ratiboř	2	3.3 ± 0.9
Tašovice	5	1.4 ± 0.9
Medard	16	0.9 ± 0.5
Šverma	4	0.8 ± 0.3
Total	62	3.24 ± 3.08

and open-pit mines. The results (Tab. 1) show a big scatter of the *q* values and systematic differences in *q* among particular quarries. This may be a result of a different local geology in the vicinity of the quarries. The average value 3.24 is a rough approximation for all the quarries and open-pit mines and was used for the energy estimation of blasts.

Radiation pattern: The radiation pattern of explosions is supposed to be spherical, which implies that there is no need to take it into account. On the other hand, when determining the seismic energy of earthquakes from a single-station recording the knowledge of the source radiation pattern is essential. For its determination a number of recording stations is needed. The data used in this study were not homogeneous, the number of triggering stations ranged from two to six, and so they did not enable us to determine the radiation pattern. The task was solved simply by averaging the energy of a particular event from all the stations.

Conversion coefficients: The conversion coefficient of the free surface depends on the incidence angle of the incoming wave. When processing a big amount of data it is rather laborious to determine the incidence angle and to compute the conversion coefficient for each of the recordings. In order to simplify the problem the stability of the incidence angle was tested at the stations JAC, KVM, MLZ, SNE which triggered most frequently. For a sample of 20 earthquakes and 40 blasts the incidence angles were determined. Table 2 shows the results; the incidence angles were measured from the vertical axis.

TABLE 2

Incidence angles for blasts and earthquakes

Station	Incidence angle	
	Blasts	Earthquakes
JAC	68° ± 9°	62° ± 13°
KVM	47° ± 6°	43° ± 19°
MLZ	49° ± 10°	26° ± 9°
SNE	19° ± 5°	20° ± 8°

Except for the station MLZ the intervals of incidence angles of earthquakes and blasts are overlapping. A rather great difference in incidence angles at the station MLZ is caused by small epicentral distances (cca 10 km) of selected earthquakes as compared with the distances to other stations (20-30 km). This is not a principal problem owing to the fact that many of other earthquakes come from different epicentral regions. As a result of this test an assumption can be made that the conversion coefficients of various events at a particular station do not differ much and their differences may be neglected. The absolute value of the coefficients will be included in the site amplification factors.

Attenuation, site response: To get an idea of the Q-factor and the site amplification factors, an optimization of energy ratios between pairs of stations was made. The inverse problem was defined by the ratio of energies of the *i*-th event computed from recordings at the *j*-th station and at the reference *k*-th station:

$$\frac{E_{ij}}{E_{ik}} = R_j \left(\frac{r_{ik}}{r_{ij}}\right)^2 \exp\left(-\frac{2\pi f}{\alpha\, Q}\left(r_{ij} - r_{ik}\right)\right) \tag{3}$$

where E_{ij} is the energy of the *i*-th event determined at the *j*-th station, not corrected for attenuation, nor for geometrical spreading and site response, R_j is the site response of the *j*-th station related to the site response of the reference station and r_{ij} is the epicentral distance of the *j*-th station.

Energies of 12 events determined at four most triggering stations were selected for the inversion. For the purpose of azimuthal independence of the task only blasts were among selected events. The number of unknown parameters was only four (Q, $R_1 .. R_3$), which ensured a good stability of the problem. The fixed parameters were f = 6Hz and α = 6000 m/s. The problem was solved by the simplex method, the covariance matrix C^x of the solution was obtained from the data covariance matrix C^y following Matsu'ura and Hasegawa (1987) as

$$C^{x} = \left(D^{T} \, (C^{y})^{-1} \, D \right)^{-1} \tag{4}$$

where $D_{ij} = \partial y_i / \partial x_j$. The results of the inversion are shown in Table 3.

TABLE 3

Q-factor and site responses related to JAC

Q	Relative site response R_j for station: KVM	MLZ	SNE	JAC
200 ± 40	6.9 ± 1.2	16.8 ± 1.1	19.0 ± 1.2	1.0

The value Q = 200 represents an acceptable value for a sedimentary basin. The differences in site response magnitudes among the stations are a consequence of different local conditions of the stations (JAC is located in an old ore mine 500 metres below the surface) and shows the necessity of the site response study. Naturally, this method which used the stations of one network only, could not give absolute values of the station amplification factors, and so the absolute value of energies obtained may differ in the range of one order.

3. RESULTS

Using (1) and the parameter values and simplifications described in the preceding section the energy of all events including local earthquakes and blasts was determined as an average from the single-station determinations. The energy of blasts was in the range of 10^3 - 10^7 J, while the energy of earthquakes ranged from 10^4 to 10^8 J. For each event the variance of energy average was determined. In order to get a typical energy of both types of events, a mean value of energy and its variance of determination were computed for both blasts and earthquakes. The results are presented in Table 4.

TABLE 4

Average energy and average variance of it's determination

Type of event	Number of events	Mean energy	Mean variance
Blast	793	6.7E+5 J	63%
Earthquake	44	4.0E+7 J	74%

As expected the typical seismic energy of earthquakes was much higher than that of quarry blasts. With regard to the simplifications used in the method the big mean error of energy determination is not surprising. Probably the biggest portion of this error is a consequence of neglecting the radiation pattern. This is seen from the smaller variance of energy of blasts whose radiation pattern should be spherical.

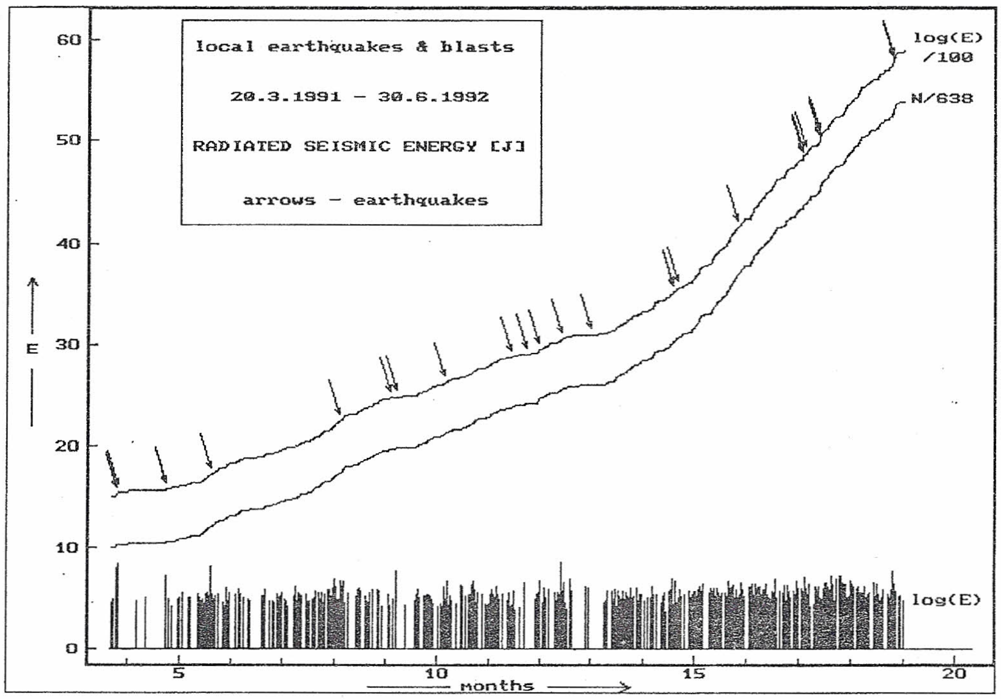

Fig. 2. Time dependence of radiated seismic energy. Months are numbered from the beginning of 1991. Bottom: logarithm of energy. Centre: Number of events registered, scaled to the upper curve, shifted vertically by a factor of 10. Top: Cummulative sum of the bottom plot, vertical shift of 15.

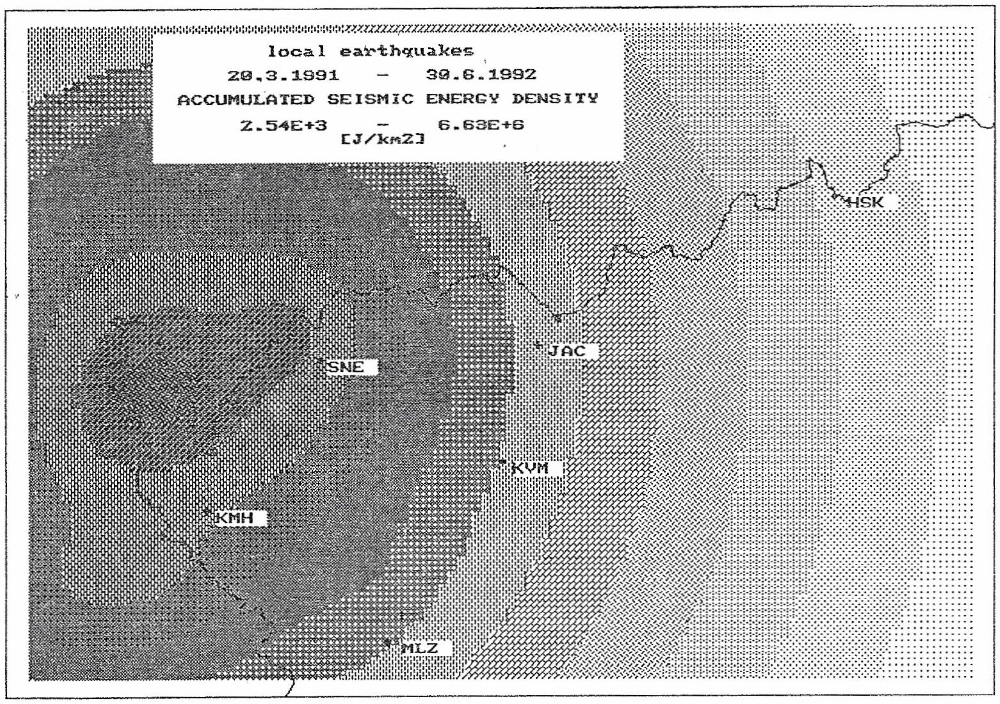

Fig. 3. Spatial dependence of cumulated energy density of earthquakes. Adjacent shades of gray denote a double change in energy density.

In order to get a notion of seismic exposition of the area two plots were constructed; one in the time domain and one in the space domain. Fig. 2 shows the time domain dependence. The bottom plot shows an almost constant level of radiated seismic energy. Randomly distributed extreme values of energy correspond to earthquakes (arrows to the upper curve). Excepting the beginning of the year (months 12 to 13 in the graph) the gaps in the energy radiation are mostly caused by a non-uniformity of the network function. After the Christmas gap the number of events registered strongly increased (see the bottom and centre plots) which was caused by including the station HSK (Fig. 1) in the network processing. The cumulative curves of energy and of number of events are closer to each other in this period due to the higher sensitivity of the network which registered weaker blasts than in 1991.

The space dependence of accumulated seismic energy of earthquakes is illustrated by Fig. 3, a similar dependence for all events is shown

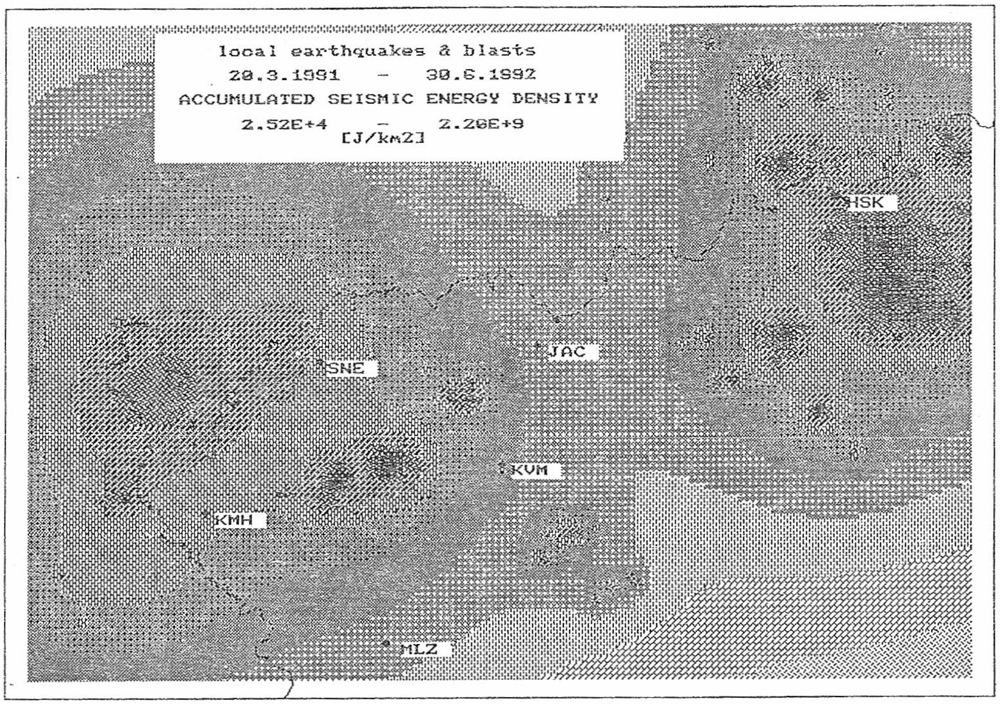

Fig.4. Spatial dependence of cumulated energy density of earthquakes and blasts. Adjacent shades of gray depict a double change in energy density.

in Fig. 4. These pictures were constructed by stacking the energy contributions from each event within elements of the Earth's surface. The energy contributions were computed using an isotropic model of wave propagation with the same attenuation characteristics as were used for determinating the source energies.

Comparing these two pictures one can see a difference in the shape of the energy field and also in its absolute values. A simple shape of the surface energy field of earthquakes is caused by their relatively deep hypocentres. Some weak earthquakes have no effect on the shape of the function at all (compare with their epicentres in Fig. 1). On the other hand, the surface position of blasts causes a dramatic shape and higher values of the energy field (see Fig. 4).

From this comparison one could conclude that the seismic exposition of the area, namely of the spa springs, is bigger due to industrial explosions than due to earthquakes. This would be a dangerous simplification. The positions of peak values of energy density are identical with the positions of the quarries and open-pit mines which lie on the Earth's surface and represent singular points. The energy density elsewhere is much smaller and is comparable with or smaller than that of earthquakes. For such conclusions the energy radiated from the source is more decisive, and this energy is higher for earthquakes. Moreover, the earthquake hypocentres lie in the shallow crust which is also a reservoir of mineral waters and may therefore affect each other.

4. CONCLUSIONS

In order to get comparable values of seismic energy of blasts and earthquakes a methodology of its determination was designed. The results show that the seismic energy of earthquakes is generally higher than that of blasts. On the other hand, the surface energy flow due to blasts is stronger in the vicinity of quarries than the energy flow of earthquakes. Nevertheless, this fact is not likely to affect the function of the mineral springs due to their distance from quarries. Another question is the suitability of seismic energy as a measure of seismic exposition of mineral springs. Hydrogeological structures are probably more sensitive to peak values of acceleration than to integral quantities such as energy.

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