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MODEL TESTING OF THE RELIABILITY OF SEISMIC HAZARD ASSESSMENT BASED ON SEISMOSTATISTICAL AND SEISMOTECTONIC METHODS

Jiří BUBEN and Vladimír RUDAJEV

Institute of Geotechnics, Czechoslovak Academy of Sciences, V Holešovičkách 41, 182 09 Prague 8, Czechoslovakia

Abstract: By means of numerical modelling of earthquake occurrence it was found that the seismostatistical method of assessing the maximum possible earthquake has quite insufficient reliability in the case of low intraplate seismicity which takes place in the central part of the Bohemian Massif.

The two following small-scale seismic models were also applied: (1) Rockbursts occurring in a deep coal mine and (2) seismoacoustic impulses due to thermal fracturing or to stick-slipping of rock samples in the laboratory. The experiments confirmed (a) the dependence of maximum possible seismic focal energy on the maximum possible volume of the source zone, and (b) the dependence of interoccurrence time of the strongest events on the slipping rate or on the power of the internal heater (source of thermal stress). All experiments confirmed the result of numerical modelling, namely that short (about 100) series of seismic input data (catalogue) cannot yield any reliable assessment of seismic hazard.

Key words: seismic hazard assessment; seismicity; numerical and small-scale models

1. INTRODUCTION

The assessment of the seismic hazard to localities situated in the territory of the Bohemian Massif consists in evaluating weak intraplate seismicity. Such evaluation is made by means both of the seismostatistical and seismotectonic methods (Šimůnek, 1983).

In the case of weak seismicity, the seismostatistical method relies on statistical evaluation of macroseismic intensities $I°$ MSK of historical earthquakes in the region under consideration. In the central part of the Bohemian Massif only shallow

($5 < h < 15$ km) foci are encountered with small epicentral intensities $I_0 < 6°$.

According to Kárník *et al.* (1981), the following empirical relation holds for the time period of the last 400 years, when the set of macroseismic data is homogeneous for $I_0 > 4$

$$\log N_1 (I_0) = a - b\, I_0, \qquad (1)$$

$$a = 2.62, \quad b = 0.89$$

where N_1 is the mean number of events per year.

The seismostatistical method is based on the assumption that empirical function (1) also holds for a rather longer time period than 400 years. In the case of prescribing the safe shut-down earthquake (SSE) for the building site of a nuclear power plant (NPP) the time period under consideration must be 10,000 years. According to the NPP Safety Rules (CSCAE, 1979), valid in our country, intensity I_{SSE} of SSE must be prescribed so that probability p of its occurrence once per time period T = 1 year is $p = 1 \cdot 10^{-4}$. The antiseismic design of NPP respecting the so determined value of I_{SSE} must enable the reactor to be shut down without uncontrolled radiation escape.

In principle, the statistical prediction of the value of I_{SSE} extends the validity of a and b (determined for the "short" period of 400 years) to the whole stipulated period of 10,000 = = 400 × 25 years. The value of intensity I_{max} with its annual frequency N_1 = 0.0001 is given by the relations

$$\log N_1 (I_{max}) = -4 = a - b \cdot I_{max} \qquad (2)$$

$$I_{max} = (4 + a)/b$$

Such determination is evidently not correct, owing to the necessary assumption of stationarity of earthquake occurrence during the whole "long" period of 10,000 years, which is 25 times longer than the period of observation (Buben and Rudajev, 1991).

For testing the reliability of this extrapolation we used a numerical model of the occurrence of earthquakes considered as a purely random and stochastic process (Buben and Rudajev, 1973).

2. NUMERICAL MODEL

Let us have a generator (polling urn) of independent random integer numbers $1 < I < 5$. Let probability $p(I)$ of the occurrence of value I be

$$p(I) = (1 - 10^{-b}) \cdot 10^{-bI}, \qquad (3)$$

the b value being constant.

Let the urn contain a large number of events (in our case it was 1,000 events). From these events let us take out only 1,000 : 25 = 40 (random and independent) events in one test. In this way we modelled the ratio between the periods of 10,000 years and 400 years.

If all 1,000 events were taken out, we could determine frequencies $N(I_i)$, $i = 1, 2, 3, 4, 5$. The regression line of function $\log N(I_i) = f(i)$ would be of the (1) shape, having the parameter b_t at zero dispersion, which is the manifestation of the deterministically introduced ("true") content of the urn.

However, taking out only 40 values (by the so-called "short" realisation) we establish only one estimate b_e of "true" value b_t. In order to evaluate the reliability of this estimate, we make, e.g., 100 such independent experiments from which we determine a set of b_e values. To do this, the following two methods were used: (1) linear regression, and (2) weighted means respecting various frequencies $N(I)$ of I.

Considerable differences between the "true" value b_t and its estimates b_e were established. Comparison of both methods used showed that the method of weighted means yielded better results.

The differences $(b_e - b_t)$ follow rather well the Gaussian distribution with the "true" value b_t as the mean. By evaluating a set of described experiments with the preset "true" value $b_t = 0.500$ it was found that the value of parameter b_s, being determined from only one experiment, will be lying within the interval $0.425 < b_s < 0.575$ with probability $P = 0.68$.

It results from this numerical model that the application of the seismostatistic method in the central part of the Bohemian Massif has insufficient reliability. This holds even if all other requirements of the statistical method (stationarity, mutual independence of rare and random values) were fulfilled.

3. SEISMOTECTONIC MODELS

The assessment of I_{max} must be improved by adding further input data, namely the characteristics of tectonic faults in the region, their geometry, tectonic activity, geomechanical parameters and stress distribution in the focal region. As a rule, these data regarding the region under study are difficult to obtain.

The lack of reliable seismotectonic data follows also from the mentioned considerable difference between the short period of geoscience surveying (human life length) and relatively long periods of SSE occurrence. The solution of the problem was therefore aimed at physical modelling.

The occurrence of rockbursts in deep mines is seen as a suitable model of earthquakes (Buben and Rudajev, 1977) from the following three viewpoints:

(1) A sufficiently extended data set may be acquired within an acceptably short time period.

(2) The shape and structure of rockburst-prone area are usually better known that those of earthquake area.

In the deep coal mine Kladno, the rockburst foci with seismic energies $K = \log E$ (Joule), $2 < K < 6.2$, have been monitored by the local seismic station during the last 30 years. The distribution function of rockbursts

$$\log N(K) = A - \gamma \cdot K \tag{4}$$

points to the fact that the occurrence of rockbursts can be used as a model of earthquake occurrence. The definition range of empirical function (4) ends at the value of maximum energy $K_{max} = 6.2$ (Buben and Rudajev, 1977).

3.1. Maximum possible energy K_{max}

Complex analyses of rockbursts resulted in the conclusion that value K_{max} primarily depends on the focus volume, which can be, in a first approximation, simulated by a sphere with radius R, e.g. using modification of the inverse Sharp model (Fučík and Rudajev, 1979a).

This dependence was described by the relation

$$\log R = C_1 K - C_2 \ . \tag{5}$$

Parameter C_1 depends on the geometrical shape of the focus. In the case of a sphere $C_1 = 1/3$. The value of C_2 depends on elastic modules, on the strength of rock and also on coefficient p describing the transition of deformation energy W to energy E_S of seismic waves, $E_S = p \cdot W$.

The values of C_2 for various estimates of transition coefficient p are given in the following table:

p %	10	1	0.1
C_2	1.54	1.2	0.87

For the geomechanical modules of rock mass in the Kladno coal mine diameter R of the focal volume sphere for $K_{max} = 6.3$ should have the value $2R = 54$ m. Assuming a focus volume of eliptical shape with axes $a = b = 3\,c$, then for maximum rockburst energy $K = 6.2$ it results from (5) that a = b = 39 m.

The superstrata of the coal seam are formed by cretaceous layers (claystones and sandstones). On locating the rockburst foci it has been found that they mostly occur in a brittle, relatively strong sandstone layer (Rudajev and Přibyl, 1969). The thickness of this layer is about 40 m. This seems to be in excellent agreement with the values determined from (5).

3.2. Interoccurrence time intervals

Assessments of rockburst and seismic hazard are based on certain analogies: The most probable interoccurrence intervals of strong rockbursts inside an active zone in the mine working depend on the rate of excavation. The shallow tectonic earthquakes in the central part of the Bohemian Massif are most probably generated as brittle slipping along pre-existing faults, and the length of interoccurrence intervals should depend on the slip rate.

In order to study these relations, we started a series of laboratory experiments recording seismoacoustic emission due to stick-slipping and to brittle fracturing of rock samples.

4. LABORATORY MODELLING OF SEISMIC EVENTS

We recorded the seismoacoustic emission appearing in both types of models. We used a piezo pick-up with preamplifier and logarithmic compressor of amplitude values, and an analogue hot pen recorder. The records cover a dynamic range of 60 dB and the frequency band from 10 kHz up to 60 kHz.

(1) In the first model, seismoacoustic emission was generated by an internal mechanical stress caused by an electrical heater inserted into a cylinder-shaped body made of cca 20,000 cm^3 of solidified resin. A piezo pick-up, type KD 35a, was glued on the resin surface.

(2) In the second model, seismoacoustic emission was generated by stick-slipping around rough surfaces of various rock samples. The pick-up was glued on one of the two pieces of rock, near the slipping surface. The slipping rate was about 0.01 mm/s.

Many thousands of seismoacoustic impulses (with duration time of about 3 ms) were recorded by both models. The impulses were evaluated by means of the empirical amplitude-occurrence relation of shape (1) and by means of time-dependent cumulative number $N(t)$ and cumulative maximum trace logarithmic amplitude $\log A(t)$. For evaluating the values of parameter b we preferred the method based on weighted averages.

The experiments have yielded the following preliminary results:

(1) In both cases, the impulses appear randomly in time. No foreshock- or aftershock-sequences were observed. The lengths of interoccurrence time intervals T_i are distributed according to the negative exponential law which holds for seismic events, too.

(2) The scatter of b values is considerable, and the variations of b at successive stages of seismogeneric processes have the character of random walking. It was not possible to distinguish between stress fracturing and stick-slipping on the basis of b values.

(3) In the case of stick-slip modelling, the value of b clearly depends on the roughness of slipping surfaces. It depends only very little on normal stress q in the range of $5\ \text{kPa} < q < 150\ \text{kPa}$. No dependence of the b value on the slip rate has been observed (perhaps because of too small interval of slip rates used).

(4) In the case of thermal stress modelling, the instantaneous value of b clearly does not depend on the instantaneous value of activity a, defined in Eq. (1). Let us demonstrate this on the following experiment:

In resin model No. 1 the fracturing process continued during 5,000 seconds. The total number of all registered impulses was 6,656. Consequently, the mean value of frequency was 1.33 impulse per second. The graph of cumulative number of events as a function of time shows that the whole seismogeneric process can be divided into two segments. In the first, 740 s long segment the mean frequency of events was four impulses per second. In the second segment the frequency suddenly sank to the value of one impulse per second. Despite the different values of "seismic activity" a (see Eq. 1), parameter b did not change its value.

(5) The great scatter of b values, determined from segments containing a small number of events (such as 100), is very similar to that obtained from numerical models.

5. RESULTS OBTAINED

On the basis of numerical modelling of the occurrence of earthquakes it was proved that the macroseismic seismostatistical method only had a low reliability, which was not sufficient for the seismic hazard assessment for nuclear power plants, if applied in the regions with weak intraplate seismicity.

Research into the seismicity of rockbursts as a model of seismicity of tectonic earthquakes yielded the following results:

(a) Maximum possible energy E_{max} of seismic events inside an active seismic source zone depends primarily on the dimensions (volume) of this seismogeneric structure (Fučík and Rudajev, 1979b).

(b) The autocorrelation function of the time series of interoccurrence intervals of rockbursts increases with increasing lower limit E_{min} of events included into the input data series. It follows that the strongest (extremal) events appear more regularly than the weak ones. This supports the hypothesis that the interoccurrence intervals of very strong (near maximum) events (called characteristic events) are nearly constant for the given individual source zone, provided the value of strain (stick-slip) velocity has a constant value (Schwartz, 1988).

(c) The multidisciplinary approach to the prediction of rockburst occurrence based on the statistical method of predictive filtering of multichannel input data yielded prediction errors which were much smaller than those arising in one-channel predictive filtering of the time series of seismic data only. As a supporting data series (the so-called "weak precursors") we consider the tectonic slipping rate (Rudajev and Fučík, 1982).

The laboratory models of fracturing as well as stick-slipping confirmed the considerable scatter of b values appearing in the cases of short-time data series. The interoccurrence time intervals of events depend primarily on the rate of deformation, i.e. on the power of the internal heater, or on the rate of stick-slipping.

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