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Fracture risk estimation for Swedish earthquakes

Markus Båth

Seismological Institute, Uppsala, October 5, 1979

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SUMMARY

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Markus Båth

PREFACE

Swedish earthquakes are no doubt tectonic, i.e. of the same nature as the large earthquakes around the earth. This means that our earthquakes are sudden ruptures along fracture planes. The fractures propagating from an earthquake source imply certain risks to underground storages of radioactive waste. Partly there is a certain possibility of canisters being broken, partly and probably even more important is the risk of enhanced water circulation due to new or increased fracturing. These and related problems were discussed at a conference in the KBS' Stockholm offices on June 14, 1979, attended by Messrs Lars Bertil Nilsson, Nils Rydell, Otto Brotzen, Anders Bergström, Tönis Papp, and the present author. It was felt off-hand among the participants in the conference that Swedish earthquakes would not constitute any serious risk factor for underground storage facilities. However, it was also emphasized that it would be very important to replace this feeling by numerical risk estimations. As the present author had already been involved for the past 2-3 years in research of the seismicity of Sweden and as the necessary instrumental data were at hand, I was stimulated by this conference to undertake such a study. The results are presented in this report. Among other things, it is found that the fracture risk in a carefully selected site is only about 10^{-6}.

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Letter Section

Fracture risk estimation for Swedish earthquakes

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ABSTRACT

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For Swedish earthquakes, the average magnitude increases gently with the focal depth, whereas the seismic wave energy exhibits significant maxima at 15, 23 and 28 km depth. The earthquake fracture risk is estimated to be about 10^{-6} for an underground storage facility in a carefully selected site.

INTRODUCTION

A reliable estimation of the fracture risk due to earthquake faulting is important for the location and design of underground storage facilities of various kinds. An accurate and detailed knowledge of the frequency and distribution of the seismicity, both horizontally and vertically, is indispensable for risk estimations. On the basis of instrumental data for Swedish earthquakes in the period 1951—1976, the geographical distribution has been derived in earlier papers (Båth, 1978a,c, 1979b). As to the vertical distribution, only the frequency—depth relation has been clarified in an earlier paper (Båth, 1979a).

In the present paper, we deduce relations of magnitude and seismic wave energy to focal depth. A generally valid method for the fracture risk estimation is applied to the storage of radioactive waste material at about 500 m depth in good bedrock (Kärnbränslesäkerhet, 1977, 1978, see Ref.). Formation of fractures could entail a certain risk, both by breaking the canisters and by enhancing the ground water circulation. On the other hand, vibrations alone are not considered to be damaging.

Besides its practical significance, the seismicity—depth dependence is of considerable tectonophysical interest. Global depth distributions of strain release, frequency, magnitude and seismic wave energy have for example been presented by Båth and Duda (1963) and Båth (1979c, p. 167).

NOTATION

D	average rupture on the fault plane, cm
E	seismic wave energy, ergs
ΣE	energy summed over all events per km depth, ergs
F	total horizontal area of fracture zones, km^2 (Båth, 1978c)
h	focal depth, km
i	fracture zone index
L	length of fracture zone, km
M_L	regional Richter magnitude (Båth et al., 1976)
M_0	seismic moment, dynes.cm
n	number of observations
N	frequency of events per km depth
ΣN	cumulative frequency = number of events $\geqslant M_L$ per year in the total observation area Y
r	radius of active fault plane area, assumed circular, cm, m, km
R	radius of circular fracture zone in the province of Västergötland = 40 km (Båth, 1978c)
R_1	fracture risk for a site outside fracture zones, i.e., at a minimum distance of $(W + r)$ from nearest fracture zone, year^{-1}
R_2	fracture risk for a site inside any fracture zone, year^{-1}
S	active fault plane area, cm^2
T	recurrence period, years
W	width of fracture zone, km
Y	total observation area = land area of Sweden (449,900 km^2) + part of the Bothnian Bay (33,600 km^2) = 483,500 km^2
μ	modulus of rigidity, dynes/cm^2
τ	reference period = 1 year

DEPTH DEPENDENCE

Our material consists of $n = 106$ observations of h and M_L of Swedish earthquakes in the period 1951—1976 (Båth, 1979b). All depth values are instrumental, i.e., calculated from differences between arrival times of recorded crustal waves. Thus, h is based exclusively on kinematic properties, while M_L is based on dynamic properties only. This eliminates any inherent relation between h and M_L, which could not be excluded for the corresponding macroseismic quantities. Moreover, our material can be considered to be representative and unbiased.

The following least squares regressions between M_L and h are calculated, including their standard deviations.

(1) Regression of M_L on h ($n = 106$; FF in Fig. 1):

$$M_L = (0.017\,h + 2.49) \pm 0.43 \tag{1}$$

(2) Regression of M_L on h with M_L averaged over depth intervals of 5 km each ($n = 6$, assumed of equal weight; large dots in Fig. 1):

$$M_L = (0.018\,h + 2.48) \pm 0.07 \tag{2}$$

(3) Regression of h on M_L ($n = 106$; GG in Fig. 1; cf., Båth, 1978c):

$$h = (5.65\,M_L - 0.06) \pm 7.71 \tag{3}$$

(4) Orthogonal regression (n = 106; HH in Fig. 1):

$$M_L = (0.023\,h + 2.40) \pm 0.43 \tag{4}$$

Equation 1 represents hardly a significant variation of M_L with h. A major reason for the large scatter is the uncertainty of the h values. Nevertheless, a significant correlation coefficient of +0.31 ± 0.09 holds good between M_L and h (n = 106). Moreover, eq. 2, which agrees closely with eq. 1, represents a significant variation of M_L with h. While eq. 3 can be used

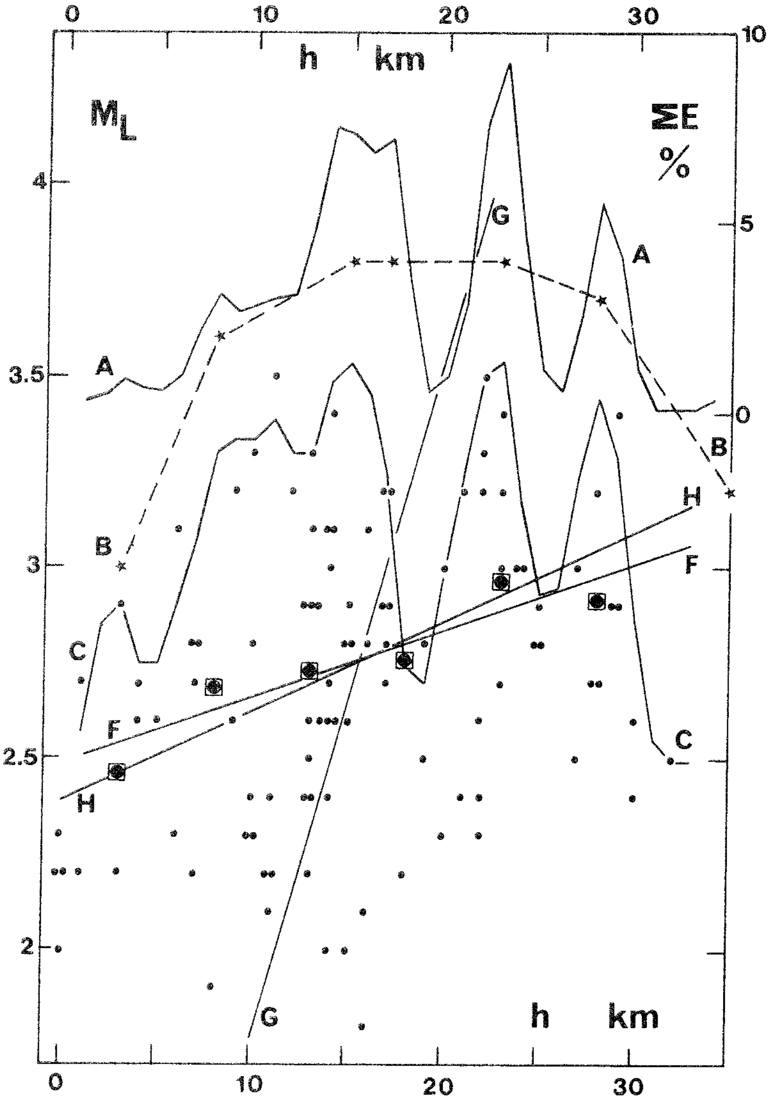

Fig. 1. Variation of magnitude (M_L) and seismic wave energy (ΣE) with focal depth (h). Small dots = individual observations of M_L and h; large dots = average M_L per 5 km depth; stars = absolute M_L maxima per 5 km depth; AA = ΣE; BB = absolute M_L maxima per 5 km depth; CC = smoothed M_L maxima per km depth; FF = regression of M_L on h (eqs. 1 and 2); GG = regression of h on M_L (eq. 3); HH = orthogonal regression M_L-h (eq. 4).

for calculating the average h for a given M_L, eqs. 1 and 2 can be used to calculate the average M_L for a given h. None of the equations 1—4 should be extrapolated beyond the point cloud.

Due to the relatively large scatter of our data, nothing but linear relations between M_L and h is suggested. Finer details can neither be revealed by the individual data (eqs. 1 and 3), nor by the average magnitudes (eq. 2). However, plotting maximum magnitude versus depth modifies the picture. The curve *CC* in Fig. 1 is calculated by consecutive smoothing of the maximum M_L for each km of h by the rule $(a + 2b + c)/4$. The curve exhibits clear maxima at 15, 23 and 28 km depth, in very good agreement with the frequency—depth (N—h) curve of Båth (1979a). The correlation coefficient between maximum M_L and log N is $+0.86 \pm 0.05$ ($n = 29$), which is highly significant (cf. eq. 9 in Båth, 1978b). It is important to note that in using maximum magnitudes we really do not depend on the scatter of the individual data. The average magnitude shows a certain parallelism with the maximum magnitude but with considerably suppressed variations (cf. eq. 2 in Båth, 1978d).

The depth variation of M_L reflects the response of the rock to the tectonic motions, and most likely the maxima correspond to low-velocity layers in the crust (Båth, 1979a). The crustal discontinuities (Conrad at 19 km and Moho at 38 km depth) are welded contacts with lower seismic activity. Moreover, the brittle, low-quality nature of the uppermost 1.4 km (Båth, 1978e) is well manifested. For example, in the top kilometer nothing larger than $M_L = 2.3$ is found (excluding rockbursts), while $M_L = 3.0$ is found at around 3 km depth.

The depth variation of the released seismic wave energy is calculated by combining the frequency—depth relation with the E-M_L relation (Båth et al., 1976):

$$\log E = 12.30 + 1.27\, M_L \qquad (5)$$

The percentage depth variation of energy (*AA* in Fig. 1) is obtained by summing E for each km of h, then smoothing these E values consecutively over h by the rule $(a + 2b + c)/4$. The energy curve has maxima at 15, 23 and 28 km depth and shows a great similarity with the maximum magnitude curve (*CC* in Fig. 1) and with the frequency—depth curve (Båth, 1979a). This is natural as the energy curve incorporates both these curves which have a high internal correlation. In a similar way, depth variations can be easily derived for any other parameter with a clear relation to the magnitude M_L, e.g., for maximum intensity and ground acceleration (Båth, 1980).

FRACTURE RISK

We start from the following relation between M_0 and M_L (Wyss and Brune, 1968):

$$\log M_0 = 15.1 + 1.7\, M_L \qquad (6)$$

$$3 < M_L < 6$$

Lacking a corresponding relation for Swedish earthquakes, we adopt this one, derived for earthquakes in the western U.S.A. The seismic moment is defined as follows:

$$M_0 = \mu\, D\, S \tag{7}$$

With $\mu = 0.6 \cdot 10^{12}$ dynes/cm^2 and a circular fault plane area with the radius r (cm):

$$S = \pi\, r^2 \tag{8}$$

we finally get from eq. 6:

$$\log r = 1.4 + 0.85\, M_L - 0.5 \log D \tag{9}$$

Equation 9 is evaluated in Table I, where a range of values of M_L and D is covered. The rupture approximates $2D$ at the center of the fault plane and approaches zero at its periphery.

With r obtained by eq. 9 and ΣN from Båth (1978b), two risk estimates are calculated by the following formulas:

$$\left.\begin{aligned} R_1 &= 0.05\, \Sigma N (1 + 2r)^2/(Y - F) \\ R_2 &= 0.95\, \Sigma N (1 + 2r)^2/F \end{aligned}\right| \tag{10}$$

Equations 10 express the fracture risk as the number of events to be expected per year within the respective areas. This formulation is in agreement with the expression for seismic risk (eq. 1 in Båth, 1979d):

$$R_{1,2} = 1 - \exp(-\tau/T) \tag{11}$$

In case of large T, as in the present case, eq. 11 simplifies to the following expression:

$$R_{1,2} = 1/T \tag{12}$$

For example, $R_{1,2} = 0.01$ would mean that one event is expected per 100 years in the specified area.

The coefficients 0.05 and 0.95 are due to the fact that 5% of our earthquakes are located outside the fracture zones and 95% inside, respectively (Båth, 1978c). The site area is = $(1 + 2r)^2$ km^2, which includes a storage area of 1 km^2 (cf., Kärnbränslesäkerhet, 1977, 1978). The total fracture zone area F is calculated by the following formula:

$$F = \sum_i 2(W + r)L + \sum_i \pi(W + r)^2 + \pi(R + r)^2 \tag{13}$$

where $\sum_i$ means summation over the 26 fracture zones, the first term is the main contribution, the second term gives the end effects of the linear fracture zones and the third term refers to a circular area in the province of Västergötland.

The data of Fig. 1 and Table I permit an estimation of the fracture propagation from any given event. Average conditions can be derived by eq. 2,

TABLE I

Radius r (m) of fault plane area for given magnitude M_L and given average rupture D (cm) from eq. 9

M_L	D											
	0.25	0.5	0.75	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
1.5	9	7	5	5	4	3	3	3	3	2	2	2
2.0	25	18	15	13	10	9	8	7	7	6	6	6
2.5	67	47	39	34	27	24	21	19	18	17	16	15
3.0	178*	126	102	89	73	63	56	51	48	45	42	40
3.5	473	335*	272	237	193	168	150	136	127	119	111	106
4.0	1260	891	725*	631	513	447	398	363	339	316	295	282
4.5	3350	2370	1930	1680	1360*	1190	1060	966	902	841	785	750
5.0	8910	6310	5130	4470	3630	3160	2820	2570	2400*	2240	2090	2000

*Most likely estimates.

but extreme conditions provide even more useful information. In Table II, examples 1—5 correspond to extreme combinations of h and M_L from Fig. 1. The h values are not used in the calculation. We find that $R_1 \simeq 10^{-7}$—10^{-6} and $R_2 \simeq 10^{-5}$—10^{-4}. Due to a partial compensation of ΣN and r, both R_1 and R_2 are practically constant for $M_L \geqslant 3.5$, whereas they increase towards lower magnitudes. In general, $R_2 \simeq 50\, R_1$.

TABLE II

Fracture risk estimation for selected examples

Example	h (km)	M_L	D (cm)	r (m)	ΣN per year		
					total observation area (Y)	site area	
						R_1	R_2
1	0.5	2.3	0.1*	72	10.9	$20.2 \cdot 10^{-7}$	$10.4 \cdot 10^{-5}$
			0.25	45		18.3	9.5
2	1	2.7	0.1*	157	5.0	12.3	6.3
			0.25	99		10.2	5.2
3	3	3.0	0.1	282	2.9	10.1	5.1
			0.25*	178		7.6	3.9
4	8	3.6	0.25	575	0.38	2.5	1.2
			0.5*	407		1.8	0.9
5	15	3.8	0.25	851	0.19	2.0	1.0
			0.7*	507		1.1	0.5
6	5	4.0	0.25	1260	0.10	1.8	0.8
			0.75*	725		0.9	0.4
7	10	5.0	0.25	8910	0.01	7.0	1.5
			3.5*	2400		$0.5 \cdot 10^{-7}$	$0.2 \cdot 10^{-5}$

*Most likely estimates.

① $R_1 = 0{,}05 \cdot 10{,}9 \cdot (1 + 2 \cdot 0{,}074)^2 / Y \cdot F = 20{,}2 \cdot 10^{-7}$ pa $F = 126\,869$ km^2 $F = 0{,}26\,Y$

③ $R_1 = 0{,}05 \cdot 2{,}9\ (1 + 2 \cdot 0{,}282)^2 / Y \cdot F = 10{,}1 \cdot 10^{-7}$ pa $F = 131\,828$ $F = 0{,}27\,Y$

Comments

(1) Different regions of the world and different methods have yielded a variety of relations between M_0 and M_L, of which eq. 6 is only one example. Repeating our calculations with several such relations (see Suteau and Whitcomb, 1979), we find that the risk values in Table II are at most increased by a factor of 2—3. Replacing the circular fault plane area by a rectangular area (length = 5 × width), we find an increase of the risk values by a factor of 1—4. Allowance for a modified eq. 6 and a modified shape of S could increase the risk values by a factor of about 10.

(2) The reliability of our risk estimates depends on the reliability and completeness of our basic data. These consist of instrumental earthquake statistics for Sweden for 1951—1976 (Båth, 1979b), and neither long-term variations of the activity, nor creep motions are included in the picture. In spite of the fact that even a ten-fold increase of the seismic activity would not increase R_1 beyond about 10^{-5}, it is recommended that recordings of local earthquakes are undertaken at any selected site (cf., Shapira and Båth, 1978). A chosen location should be remote from mining operations and other activities that could influence the stability of the rock.

(3) The obvious principle is to avoid seismically active zones, both in the horizontal and the vertical direction. In case of R_1, i.e., a location outside fracture zones, there is no need to consider vertical variations. But in case of R_2, i.e., a location inside any fracture zone, it will be necessary to include some depth statistics as well as more details about the fracture zone concerned (Båth, 1978c). Even under extreme conditions no fracture will propagate into a storage room at 500 m depth except from events in the proximity of the storage (Fig. 1, Table I). Fortunately, the energy contribution of the depth range h = 1—2 km amounts only to 1—2% of the total energy, and the corresponding frequency of events amounts to 4% (Fig. 1).

(4) As an alternative to the storage at 500 m depth, a storage below about 1400 m has been discussed. The markedly higher quality below 1400 m (Båth, 1978e) no doubt implies more homogeneous rock with fewer fractures, less risk of ice-load generated earthquakes and less risk of water circulation. A depth of 1400 m is still sufficiently removed from the maximum seismic activity, even in a fracture zone. As evidenced by the dispersion of the short-period Rayleigh wave Rg, the discontinuity at about 1400 m depth is a general property of the Swedish upper crust.

CONCLUSIONS

Instrumentally based statistics of Swedish earthquakes for the period 1951—1976 has led to the following conclusions:

(1) The average regional magnitude M_L increases with depth at the rate of 0.2 units per 10 km in the depth range of 0—35 km.

(2) The depth dependences of the largest M_L and of the total released

energy exhibit maxima at 15, 23 and 28 km depth, in excellent agreement with the frequency—depth dependence and probably corresponding to low-velocity layers.

(3) The risk of earthquake fracturing affecting a storage place at a depth of 500 m in the Swedish crust is estimated to be of the order of 10^{-6}, provided the place is carefully selected, i.e., in good rock outside established fracture zones.

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