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Seismic Hazard Assessment Based on Historical Data and Seismic Measurements

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Abstract

Iceland is situated on the mid-Atlantic Ridge and the seismic activity there is mainly related to the ridge. Most of the destructive earthquakes in Iceland occur in the South Iceland Lowland and off the north coast. This paper is restricted to the South Iceland Lowland.
Historical and measured data are used to calculate the probability of occurrence of earthquake of magnitude 6 or more in the South Iceland seismic zone. The maximum expected magnitude in the zone is also estimated. The seismic hazard is discussed in respect to destruction zones due to catastrophic earthquakes since 1700. Calculations of earthquake hazard are also made. They show the largest expected intensity during a 100 years period. All calculations are based on the third Gumbel's distribution of extreme values.

The data

Historical events

The first documented earthquake in the South Iceland Lowland occured in 1164. The time periods from 1200 to 1430 and from about 1560 are covered with contemporary sources. It is assumed that we have an overview of almost all catastrophic earthquakes during this time. From 1431 no contemporary sources exist at all for more than a century. After mid-sixteenth century writing of annals was resumed in Iceland. From about 1560 we have continuous contemporary sources. The oldest document includes reliable information on earhquakes back to 1500. Fig. 1 shows the increase in the number of sources from 1560 to 1700. After 1700 the number of sources i.e. both annals and official documents increases considerably. Since 1700 these sources are believed to be reliable enough to estimate magnitudes of earthquakes larger than 6.

The estimation of magnitudes of historical earthquakes

From the settlement of Iceland in the 9th and 10th century and until the first decades of this century most houses were made of turf and stone. The structure of these constructions was similar through the centuries. If the area of the destruction zone is known it is possible to use it to estimate the relative size of an earthquake. Near the end of the turf building period we have one instrumentally measured earthquake. It occurred on May 6, 1912. The magnitude of this earthquake was 7.0 based on 18 stations (Kárník, 1969). This earthquake is used as a key to calculate the magnitudes of earthquakes in the South Iceland Lowland that have known destruction zones. To estimate the magnitudes of historical earthquakes it is also neccessary to make use of equations (4) and (5).

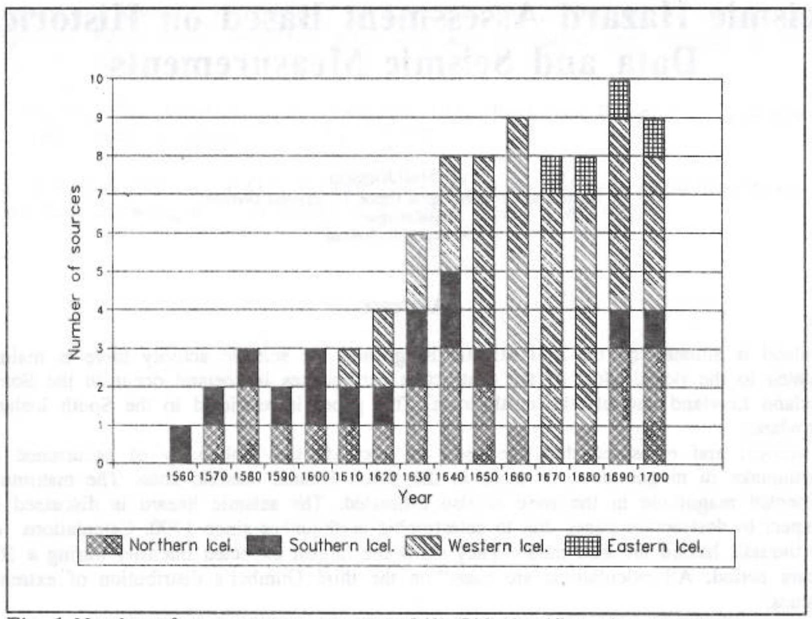

Fig. 1 Number of contemporary sources 1560-1700 classified after its origins

Instrumental data

From the first decades of this century data from only few seismic stations in Europe are available (Kárník, 1969). These stations could detect Icelandic earthquakes down to magnitude 5.5. In the period 1909-1914 a seismometer of Mainka type was operated in Reykjavík. The data from this period are incomplete but the seismometer could detect events down to 4.0 from the South Iceland Lowland.

In the year 1925 measurements with the Mainka seismometer were resumed and it was operated until 1951. Since 1951 Sprengnether seismometers have been used in Reykjavík. In the fifties and sixties more seismic stations were installed in other parts of the country. After 1973 a new step was taken in the development of a seismic network covering the country and the number of stations grew rapidly during the following years. In 1986 4 seismic stations were situated in the South Iceland Lowland and 10 other within 50 km distance from it. Since March 1991 the SIL-system has been operated regularly.

Since 1926 there is complete catalogue available of all earthquakes above 4 in the South Iceland Lowland and since 1951 all events above 2.2 are documented and we can make a complete catalogue for the last decade at least down to magnitude 2.0. The SIL-system can completely detect earthquakes from the zone down to magnitude 0.

Earthquake probability in the South Iceland Lowland based on historical and measured data from 1700.

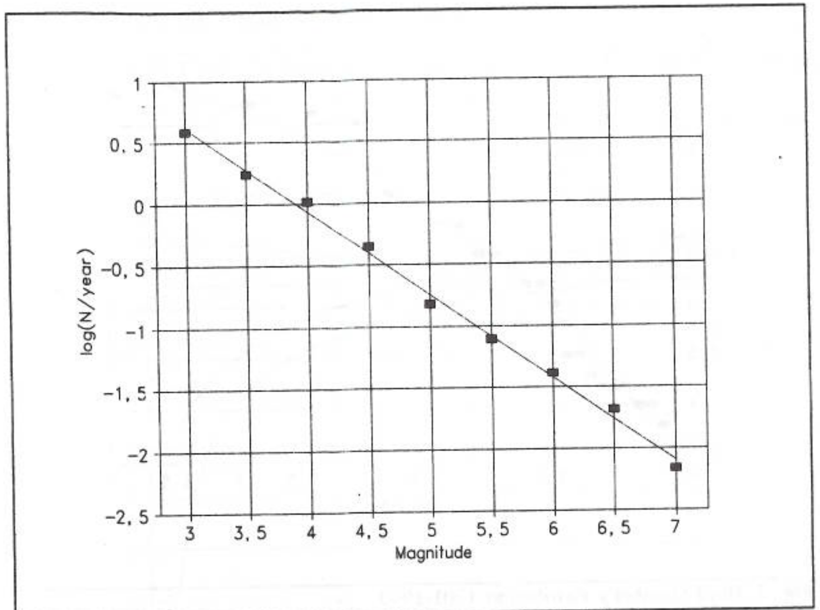

Fig. 2 Data since 1700 fitted with the Gutenberg-Richter relation

The Gutenberg-Richter relation

To estimate the probability of earthquakes in the South Iceland Lowland two methods are used here. The first makes use of the well-known recurrence relationship of Gutenberg and Richter:

$$\log(N) = a - bM \qquad (1)$$

where N is the annual number of earthquakes $\geq$ M. The constant a = $\log(N_o)$ where N_o is the number of earthquakes $\geq$ 0. To find the constants in (1) data from 1954-1980 were used to estimate the annual frequency in the interval $3.0 \leq M < 4.5$, data from 1926-1980 for the interval $4.5 \leq M < 6.0$ and historical data from 1700 to estimate the frequency of magnitudes 6 and above.

The results are shown in Fig. 2. The b-value is 0.678 and a = 2.65 which means that we can expect about 450 earthquakes a year of magnitude 0 and above. The linear relationship (1) does not attempt to describe the curvature observed at both low and high magnitude ranges. The equation has no upper limits and therefore it forecasts higher values of M for long time intervals as realistic. International experience shows that for M larger than 7 the observed recurrence pattern falls below the linear relationship. For the lower part it is obvious from SIL-measurments which have lasted more than a year that we can expect over 1000 earthquakes a year with magnitude 0 and larger when swarms are not included.

In this study the lower limits of (1) are not of interest. Another disadvantages in the

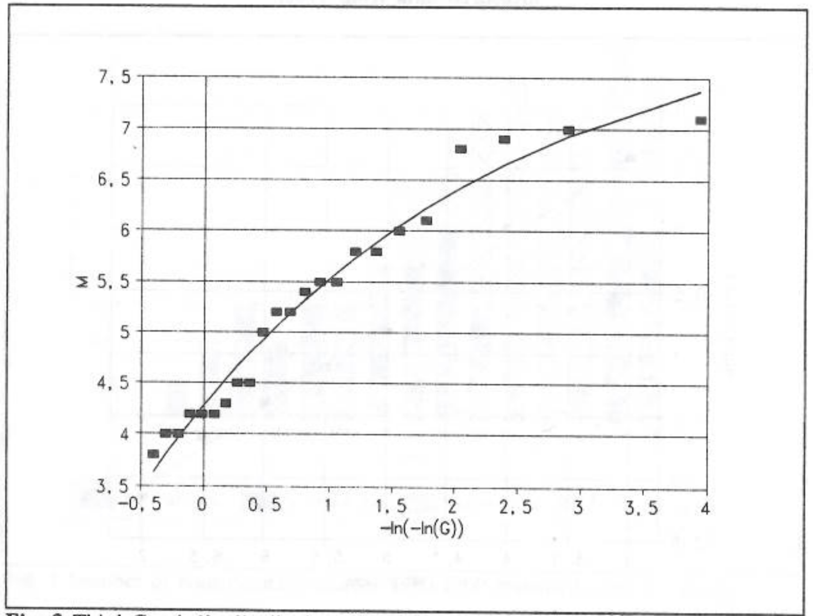

Fig. 3 Third Gumbel's distribution 1701-1990

calculations of the constants in (1) is that they are not based on complete dataset from 1700 but on a combination of three datasets.

The maximum magnitude

The earthquake of August 14, 1784 is the greatest event in the South Iceland Lowland since 1700 (Fig. 8). Sources which are reliable back to 1500 show that no greater event has occurred there at least since 1500. Older sources do not indicate larger earthquake in the region. The magnitude of the 1784 earthquake has been estimated 7.1 with the above-mentioned method. Therefore it is assumed that the maximum magnitude in the South Iceland seismic zone is slightly above 7.1.

Gumbel's third distribution

To overcome the disadvantages of the Gutenberg-Richter relation the Gumbel's third distribution of extreme values is used (Burton, 1979). The time period since 1700 has been divided into 29 intervals each of ten years. Only the extreme value of M in each interval is used. This distribution takes the form:

$$G^{III}(M) = \exp(-((w-M)/(w-u))^{k}) \quad (2)$$

This distribution has an upper bound. The equation may be transposed to give M, using probability P(M) to replace $G^{III}(M)$ as:

$$M = w-(w-u)[-\ln(P(M))]^{(1/k)} \quad (3)$$

The third Gumbel's distribution is shown in Fig. 3.

In Fig. 4 the third Gumbel's distribution of extreme values and the Gutenberg-Richter

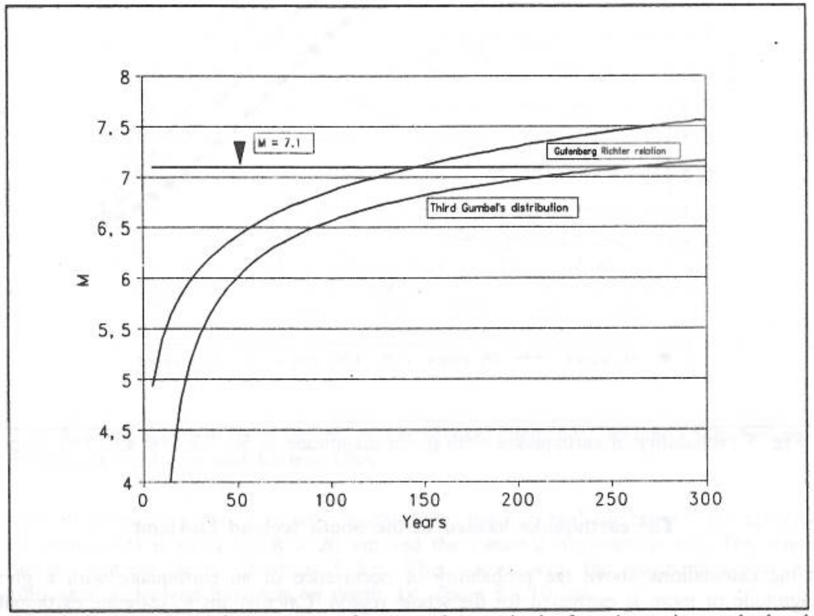

Fig. 4 Comparision of the value of expected magnitude for given time calculated after the third Gumbel's distribution and Gutenberg-Richter relation

relation are compared. The figure shows the largest earthquake magnitude expected for various time intervals calculated with these two methods. The Gutenberg-Richter relation always forecasts higher magnitudes than the third Gumbel's distribution. For periods longer than 150 years it gives unrealistic values compared to the expected maximum magnitude in the South Iceland seismic zone.

Earthquake probability in the South Iceland Lowland

The calculations of earthquake probability are based on the third Gumbel's distribution. The results are shown in Fig. 5. The last large earthquake in the South Iceland Lowland was on May 6, 1912. The magnitude was 7 and since then no event of magnitude ≥ 6 has occurred in the region. In other words there are 80 years since earthquake of magnitude ≥ 6 has occurred in the region. The calculations show probabilities as follows for earthquakes in the South Iceland Lowland during the next 20 years: P(M ≥ 6.0) = 0.87, P(M ≥ 6.5) = 0.67 and P(M ≥ 7.0) = 0.38.

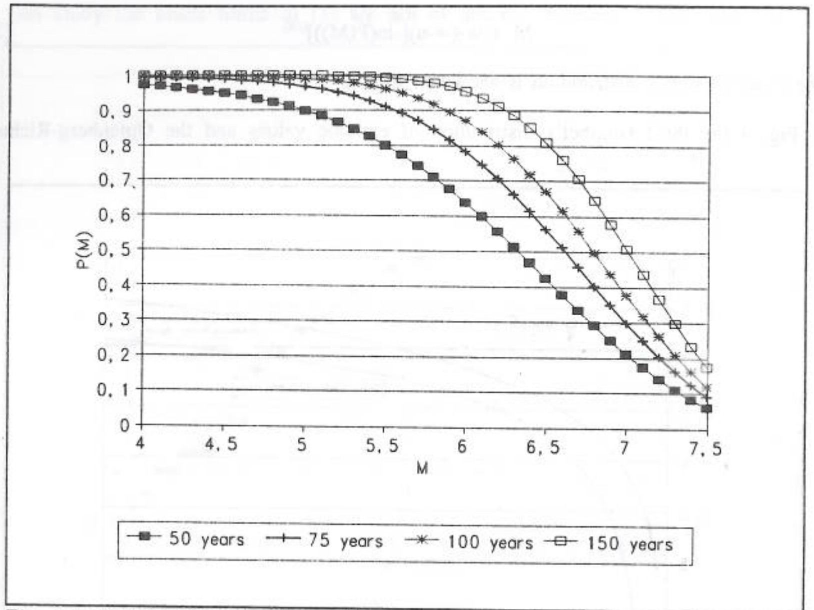

Fig. 5 Probability of earthquakes with given magnitude in 50, 75, 100 and 150 years

The earthquake hazard in the South Iceland Lowland

In the calculations above the probability of occurrence of an earthquake with a given magnitude or more is estimated for the whole region. Calculations to estimate earthquake hazard shows on the other hand the probability of a given effect (intensity, acceleration, etc.) of an earthquake at a given site. In this paper the earthquake intensity, MSK scale, is used. To study the intensity of an earthquake with known magnitude and origin at certain place it is neccessary to know the attenuation of intensity.

An intensity - distance relation for Iceland

To calculate the attenuation of intensities in Iceland isoseismal maps from 8 earthquakes have been analyzed. Their epicenters are distributed over all seismic zones in the country and their magnitudes range from 5.2 to 7.0. The method of Chandra et al. (1979) was used to estimate the average attenuation in Iceland. From these 8 earthquakes attenuations of 25 epicentral distances from 20 to 204 km were used for the analysis. The result was:

$$I - I_o = 0.8767 - 0.0123R - 1.5691\log R \qquad (4)$$

For these earthquakes the relation between I_o and magnitude was found to be:

$$I_o = 0.33 + 1.24 \qquad (5)$$

R is the epicentral distance and I is the intensity at R. Here I_o stands for the **calculated** epicentral intensity which is usually much lower than the **real** intensity at the epicenter. The relation (4) is valid for R > 20 km and the standard deviation is 0.2. The relation indicates a mean depth of about 5 km. This agrees with the assumption that most earthquakes in Iceland have similar depth, i.e. about 5 - 10 km.

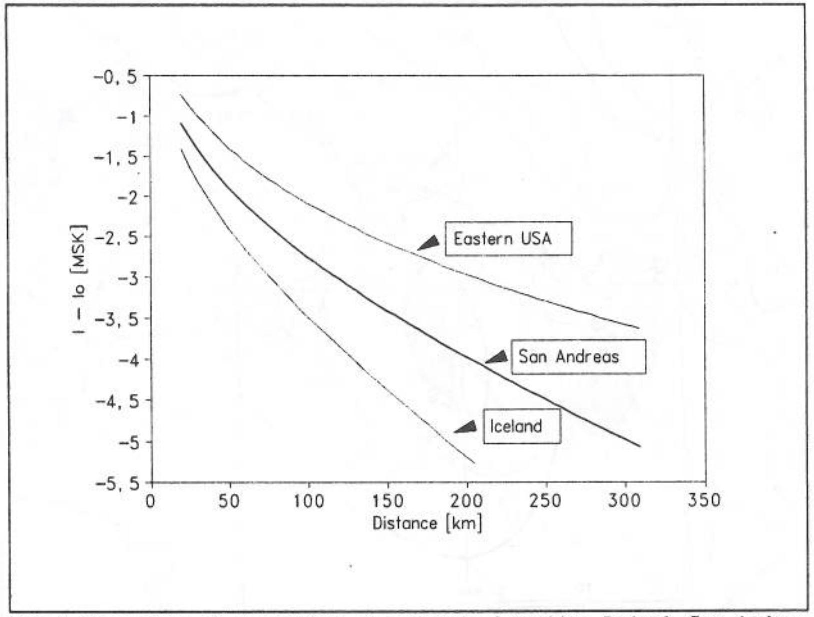

Fig. 6 Comparison of attenuations of earthquake intensities: Iceland, San Andreas Region in California and Eastern USA

The attenuation of intensities in Iceland appears to be higher than in Europe and North-America. Fig. 6 shows the attenuation for Iceland compared with the attenuation in the San Andreas Region in California and Eastern USA (Chandra, 1979).

The 1912 earthquake and the characteristic of catastrophic earthquakes in southern Iceland

As mentioned before the 1912 earthquake is a key to estimate magnitudes of historical earthquakes. The sizes of the destruction zones of this earthquake and other catastrophic earthquakes since 1700 are shown in Fig. 8. This figure also shows that the destructive zone for most of these earthquakes, as for the 1912 one, is elongated in N-S direction (Einarsson et. al., 1981; Einarsson, 1991). At the surface the origin is characterized with an 8 km long N-S fault system. The damage area can be divided into two parts, the fault zone and the area outside it. Inside the fault zone we can get intensities up to 10 or 11 but outside it the intensities decrease rapidly down to 7-8.

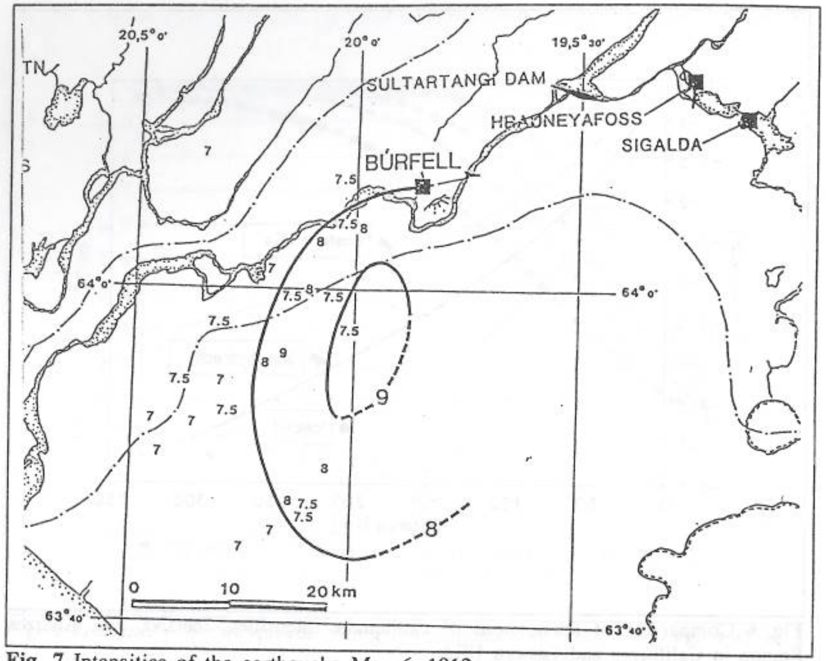

Fig. 7 Intensities of the earthquake May 6, 1912

In Fig. 7 reevaluated intensities[1] in the vicinity of the epicenter of the 1912 earthquake are shown. According to (5), $I_o = 9.0$. Fig. 7 shows that the isoseism 8 is in 15 km average distance from the origin. Although no isoseism less than 20 km away from epicenter were used to determinate the relation (5) it seems to hold for the average attenuation outside the fault zone for the earthquake 1912. In the following calculations it is therefore assumed that the attenuation relationship is valid outside the fault zone.

The seismic hazard in the South Iceland Lowland

In Fig. 8 the destruction zones of catastrophic earthquakes in the South Iceland Lowland since 1700 are shown. This map was compiled by Sveinbjörn Björnsson (Guðjón Petersen et. al., 1978). Within these destruction zones more than 50% of all houses at each farm were totally ruined. The boundary of the destruction zone is equivalent to the calculated intensity 7.8 according to the 1912 earthquake and (4) and (5). In the years 1725, 1726, 1766 and 1829 smaller quakes caused damages in limited areas at the eastern margin of the zone and 1752 and 1766 at the western margin.

The map from Sveinbjörn Björnsson is modified here to show how often damages have occurred at different sites in the area. The map shows that destructive earthquakes with

[1]) In thise paper the MSK intensity scale is used. The MSK scale is identical with the modified Mercalli scale of 1956 by Richter (Grünthal, 1989).

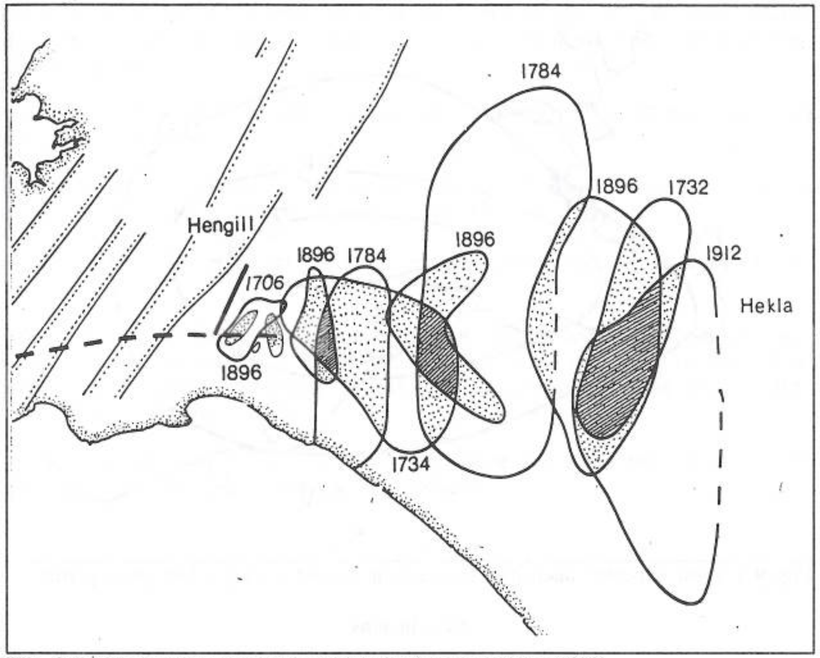

Fig. 8 Damage areas caused by major earthquakes since 1700

calculated intensity 7.8 or more have hit all sites in the region at least once since 1700. In an extensive part of the zone more than half of all houses at each farm fell twice during that period. It means that a destructive earthquake can be expected at each site in a considerable part of the zone every 150 years. Smaller areas have undergone destruction three times or more. It is concurrent whith the hypothesis that the earthquake cycle for a complete breakthrough lasts 140 years (Stefánsson and Halldórsson, 1988).

Calculated earthquake hazard

In Fig. 9 the calculated earthquake hazard in the South Iceland Lowland is showed (Halldórsson, 1987). The calculations are based on all known earthquakes $M \geq 5$ in the period from 1700 to 1980. The intensities of the earthquakes were calculated according to (4) and (5) for each point in a 0.2° x 0.1° (10 vs. 11 km) grid. The distribution of the intensities was analyzed at each point. The third Gumbel's distribution of extreme values was used. The period was divided into 28 intervals each lasting for 10 years and the largest event in each interval was used for the analysis.

As stated before we can expect magnitudes in this region up to magnitude 7.1 and from Fig. 9 we see that we can expect intensities over 7 covering about 900 km² area every 100 years.

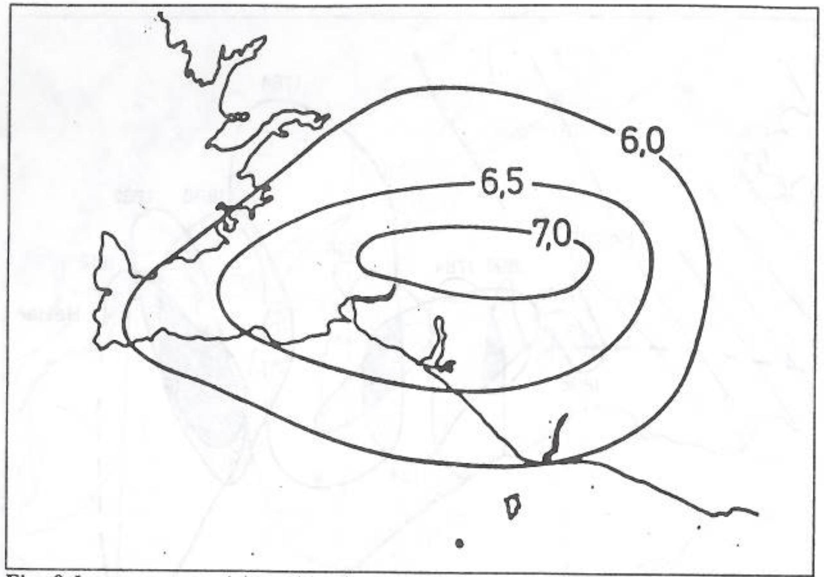

Fig. 9 Largest expected intensities in southern Iceland during a 100 years period

Conclusions

The maximum expected magnitude in the South Iceland seismic zone is slightly above 7.1. The probability of an earthquake of magnitude 6 or more somewhere in the South Iceland Lowland during the next 20 years is 87%.

Most of the South Iceland seismic zone has been hit twice by destructive earthquakes (intensity 7.8 or more) during the last 300 years. Every 100 years the intensity 7 or more can be expected covering a 900 km² area in the South Iceland seismic zone.

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