

Probabilistic seismic hazard assessment for The Netherlands

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Abstract

This probabilistic seismic hazard analysis for The Netherlands is based on the catalogue of European earthquakes published by the Commission of the European Communities. The seismic hazard is assessed by applying a modified version of the McGuire program. This method uses for each seismotectonic zone a linear frequency-intensity relation, an upper bound of intensity, an average depth for large earthquakes and an azimuth-dependent attenuation. It assumes a Poisson process for large earthquakes. The annual probability versus intensity is calculated for sites at gridpoints with 7 km spacing. Hazard intensity maps are presented for the annual probabilities of occurrence 0.02, 0.01, 0.005, 0.001, 0.0004 and 0.0001. A rough estimate of the error is approximately one half of an intensity unit for all probabilities. The highest seismic hazard in The Netherlands is found in the south-east with intensity VIII for a 0.0001 annual probability and is decreasing to the north-west in line with the seismicity.

Introduction

Seismic hazard assessment in The Netherlands is an important aspect in the safety analysis of nuclear power plants, but even for buildings the interest in seismic hazard is increasing. Earthquake aspects are considered in both the nuclear power plants regulation and the building code of The Netherlands. Both are under revision regularly. The regulation for nuclear power plants is based on the International Atomic Energy Agency publications, IAEA safety series 50-C-S, 50-SG-S1 and 50-SG-S2. The existing building code includes only recommendations on earthquake-resistant buildings in an appendix and is based on an early draft of the Eurocode no. 8 by the European Communities (Bossenmayer et al. 1984). Both the nuclear power plants regulation and the building code are also based on an earthquake zoning map of Northwest-Germany,

Belgium, Luxemburg and The Netherlands (Ahornner et al. 1976).

This study presents a probabilistic seismic hazard analysis for The Netherlands within the framework of Eurocode 8 (Bossenmayer et al. 1989) following De Crook (1989), but is different in that we apply a different catalogue (Van Gils & Leydecker 1991) and a larger region, and calculate the seismic hazard for The Netherlands only. The advantage of the catalogue of Van Gils & Leydecker (1991) is that it includes earthquakes both in and around The Netherlands and applies consistently the same intensity scale (MSK, 1964). As each site in The Netherlands may potentially be affected by earthquakes within a radius of about 200 km, our region of interest is defined as 0–10° E, 49–55.5° N.

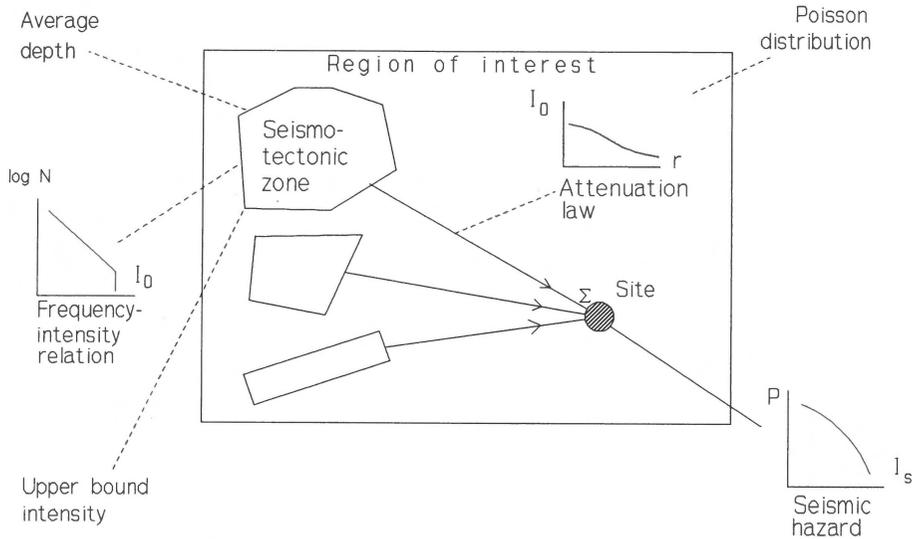


Fig. 1. Probabilistic seismic hazard model.

Probabilistic seismic hazard analysis

This study used the probabilistic seismic hazard analysis method as presented by Cornell (1968) and implemented in a FORTRAN program by McGuire (1976), modified by Mayer-Rosa & Merz (1976). This section presents a brief description of the method. For more details the reader is referred to Cornell (1968). Figure 1 shows the different steps in the model used for the probabilistic seismic hazard analysis in a schematic way.

Firstly, the seismotectonic zones are specified in a region of interest.

Secondly, the seismicity in each zone is specified by a linear log frequency-maximum intensity (I_0) relation. This method was preferred to the usual frequency-magnitude relation approach, because the available data lacks a homogeneous magnitude for the whole observation time. For each zone the seismicity is further characterized by an upper bound in the maximum intensity, reflecting the expected maximum possible earthquake, and an average hypocentral depth, while a Poisson process characterizing the occurrence of large earthquakes, i.e. independence between succeeding events and a constant rate of occurrence, is assumed for the whole region of interest. Although the Poisson process assumption contradicts the processes of accumulation and stress release (Mayer-Rosa & Merz

1976), we can show that for our region of interest a Poisson process describes the data adequately for natural earthquakes with I_0 equal to V or larger.

Thirdly, the attenuation is specified by the Sponheuer relation (Sponheuer 1958) with different parameters for each seismotectonic zone.

Finally, we obtain as output the annual probabilities of occurrence versus intensity for the site of interest, due to the combined contribution of all seismic zones. These curves indicate the probability that a specific intensity at the site of interest will be exceeded due to an earthquake in any of the seismotectonic zones, or alternatively, the mean return period (the reciprocal of this probability) for a specified intensity at the site of interest.

Model input parameters

Earthquake catalogue

The present seismic hazard assessment for The Netherlands is based on data from the European earthquake catalogue of Van Gils & Leydecker (1991). Our selection for the region 0–10°E, 49–55.5°N includes only earthquakes with $I_0 \geq IV$ for the period AD 330–1983. Obvious errors were corrected after inspection of the original source material and incomplete data for 1982 and 1983 were

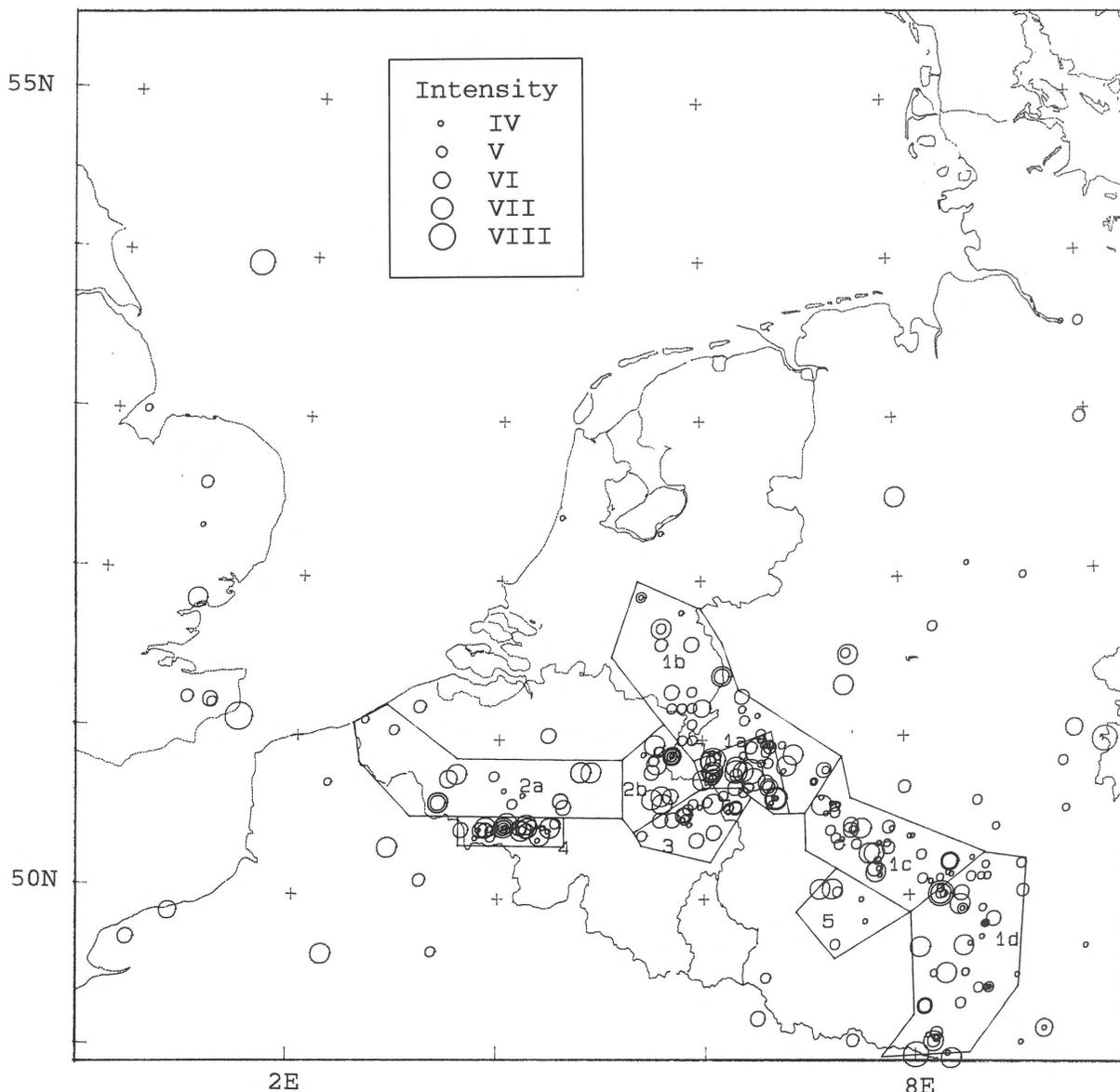


Fig. 2. Earthquake epicentres and seismotectonic zones. All 312 events with intensity \geq IV from 330–1983 are plotted. The maximum intensity is VIII–IX. For numbers of (sub)zones see text ‘Seismotectonic zonation’.

completed. For each event the catalogue information, if known at all, consists of epicentre location (latitude, longitude, country and region or town), origin time (date, time), depth, magnitude, I_0 (MSK-scale) and radius of perceptibility (R_p). The focal depth of the earthquakes varies between a few and about 30 km. The maximum observed intensity I_0 is VIII–IX.

For the seismic hazard analysis, described in the previous section, a number of events have been excluded for various reasons. Firstly, earthquakes with $I_0 < IV$ are excluded as they do not contribute to the seismic hazard. Secondly, obvious induced seismicity (i.e. rockbursts, mining events) and identified explosions are excluded. None of these events caused intensities larger than IV in The Nether-

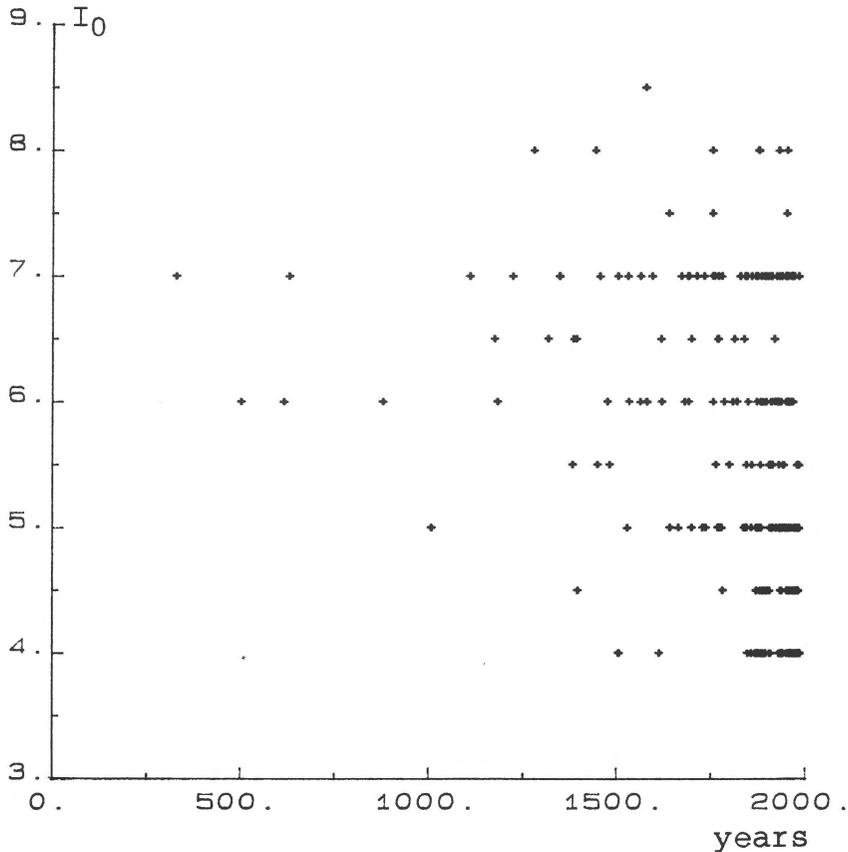


Fig. 3. Maximum intensities I_0 of 312 earthquakes versus time.

lands. Moreover, these events occur generally at a shallow depth, implying significantly smaller R_p than for normal earthquakes, and outside the borders of The Netherlands. Consequently, they can be neglected in our analysis. Thirdly, in order to obtain a catalogue of time-independent events, i.e. to justify the use of the Poisson process, fore- and aftershocks are excluded applying a subjective space-time window. With the above modifications we arrive at a catalogue of 312 earthquakes (Fig. 2) for the probabilistic analysis.

In the next step the catalogue completeness is checked. From Fig. 3, which shows the observed intensities I_0 with time, it is obvious that for intensity IV, for example, the catalogue is incomplete, i.e. the first ± 1400 years provide no reports with this intensity, while the last 100 years include more than 50 observations. For larger intensities, for example VII, the catalogue is complete for a longer period.

Following Schenk (1983) we demonstrate in Figs 4a–e that the completeness in the catalogue for the intensity classes IV, V, VI, VII and VIII is acceptable for respectively 1930–1983 (minus the world-war years 1940–1945), 1905–1983 (minus the world-war years 1914–1918 and 1940–1945), 1875–1983, 1800–1983 and 1600–1983. Within these periods we still find fluctuations in the activity. Remarkable is the period 1950–1983 with increased activity, clearly visible for the intensities VII and VIII (Figs 4d, e). A closer scrutiny of the data set explains this observation. The events that occurred in the region Hainaut in Belgium are probably in most cases nontectonic events (Ahorner 1983a). The 1953 event in the Werra Potash district, Germany, with intensity VIII is mining-induced (Leydecker 1986). Excluding these events removes most of the mentioned fluctuations in seismicity.

Unfortunately, for the individual seismotectonic

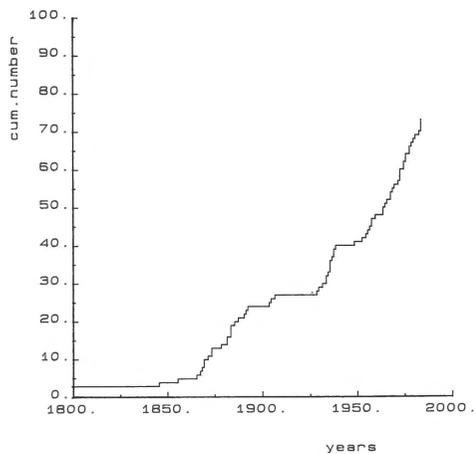


Fig. 4a. Class 3.6–4.4.

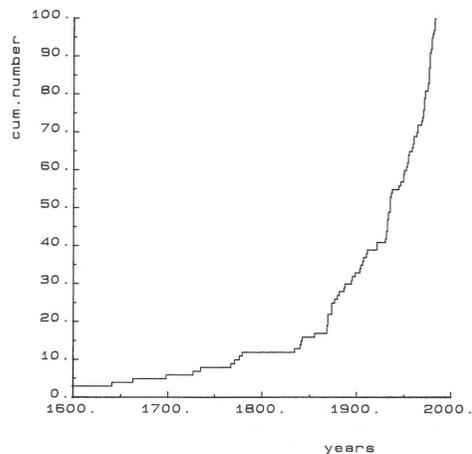


Fig. 4b. Class 4.5–5.4.

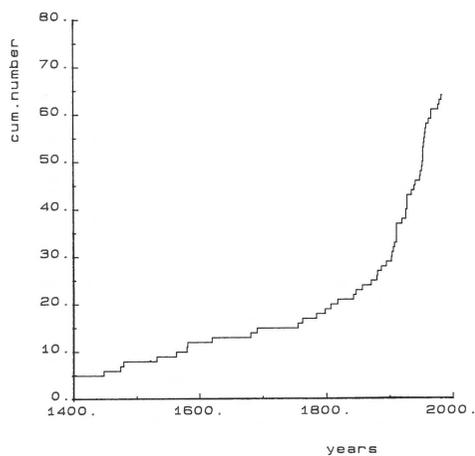


Fig. 4c. Class 5.5–6.4.

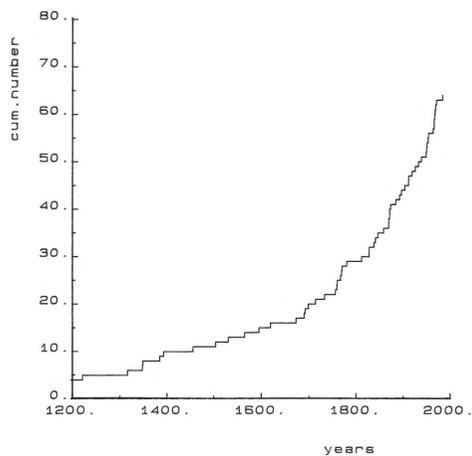


Fig. 4d. Class 6.5–7.4.

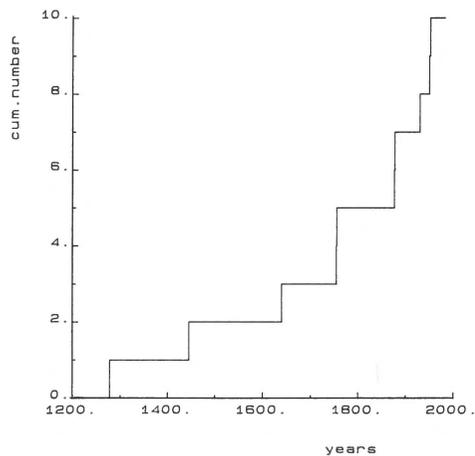


Fig. 4e. Class 7.5–8.4.

Figs 4a–e. Cumulative number of earthquakes (312 in total) versus time for intensity classes IV–VIII (class 3.6–4.4= class IV; 4.5–5.4= V, 5.5–6.4= VI, 6.5–7.4= VII and 7.5–8.4= VIII).

zones the period of complete data sets may vary; this has been considered below for each zone separately.

Seismotectonic zonation

A seismotectonic zone is defined by its observed seismicity (earthquakes and its static and dynamic parameters), its geophysical, geological and tectonic characteristics and its place within a larger tectonic framework. The dominant tectonic feature in the region of interest is the Rhine graben system, a rift structure with several branches: the Upper Rhine Graben, the Lower Rhine Graben, the Hessian Graben and the Belgian Strike-Slip region (Ahorner 1983b, 1985). Of these four regions the Hessian Graben displayed little neotectonic activity, while the other three regions are clearly seismically active and therefore form the backbone of the seismotectonic zonation used in this study. The observed stress patterns agree with an overall NW-SE compression of Western Europe (Han-Shou Liu 1985, Ahorner 1985). The following detailed division in

zones and subzones (Fig. 2) is further based on articles in Pavoni & Green (1975), Fuchs et al. (1983), Ritsema & Gürpınar (1983), Melchior (1985), and Bonjer et al. (1984):

- 1) The Lower Rhine Graben (LRG) and the northern part of the Upper Rhine Graben (URG), which are a neotectonic fracture zone NW-SE with dominantly normal fault (dip slip) earthquakes and a maximum horizontal compressional stress approximately NW-SE. This zone is divided in the following subzones:
 - a) the LRG area with higher seismicity,
 - b) the LRG area with lower seismicity,
 - c) the Middle Rhine zone across the Rhenish Massif with low stress-drop earthquakes, and
 - d) the northern part of the URG.
- 2) The Belgian zone (BZ), which follows the border line between the Caledonian Brabant Massif in the north and the Hercynian Rhenish Massif in the south. It is subdivided in two subzones:
 - (a) the BZ-west and middle part with strike slip earthquake mechanisms, and

Table 1. Seismotectonic zone parameters

(Sub)zone No.	Area km ²	Intensity		Depth h	Activity			Attenuation		
		min.	max.		R	R _c	b	α _a	α _b	γ
1a	2064	V	IX	8	0.141	0.683	-0.43	0.01	0.01	0
1b	9206	V	VIII	13	0.110	0.119	-0.43	0.01	0.001	35
1c	5781	V	VIII	7	0.105	0.182	-0.43	0.02	0.02	0
1d	8943	V	IX	6	0.129	0.144	-0.43	0.03	0.03	0
2a	8376	V	VIII	18	0.072	0.086	-0.38	0.01	0.004	90
2b	2582	V	VIII	6	0.098	0.380	-0.38	0.01	0.01	0
3	2443	V	VII	11	0.182	0.745	-0.38	0.01	0.01	0
4	1475	V	VIII	4	0.339	2.298	-0.20	0.15	0.15	0
5	2524	V	VIII	6	0.027	0.107	-0.43	0.02	0.02	0
6	10000	V	VII	11	0.0008	0.0008	-0.38	0.01	0.01	0

For numbers of (sub)zones see text section 'Seismotectonic zonation';

min. intensity = lower bound;

max. intensity = upper bound (MSK scale);

h = average depth in km;

R = annual number of events with intensity ≥ V;

R_c = annual rate per 10.000 km²;

b = coefficient of frequency-intensity relation;

α_a = maximum attenuation; α_b = minimum attenuation (perpendicular to α_a);

γ = azimuth (in degrees) of α_a-axis of attenuation ellipse counter-clockwise from east.

- (b) the BZ-east part with both strike slip and dip slip earthquake mechanisms and a higher seismicity than in subzone 2a.
- 3) The Stavelot-Venn zone (Hohes Venn), which is a SW-NE Hercynian anticline on the Rhenish Massif with a large uplift (1.6mm/year) and old thrust faults.
 - 4) The Hainaut zone at the border of the Rhenish Massif. It is situated partly on the thrust fault of the Faille du Midi and characterized by earthquakes with extremely shallow focuses with strike slip mechanisms. These events are probably related to Paleozoic evaporites.
 - 5) The Hunsrück zone, which is the southern border region of the Rhenish Massif with normal faults nearly SW-NE.
 - 6) The background seismicity zone with relatively low seismicity, which is the region outside zones 1–5.

The zones 1–5 coincide largely with the areas of relatively high seismicity and correspond therefore also with the zones specified by Ahorner & Rosenhauer (1975).

Seismic zone parameters

In modelling the seismic hazard using McGuire's modified program, we need to specify for each seismic zone or subzone the following parameters: the lower and upper bound intensity, the average hypocentral depth, the rate of seismicity R , the b -value in the frequency-intensity relation, and the attenuation coefficient α (Table 1).

Intensities lower than V are not important in seismic hazard assessment; therefore the lower bound intensity is taken to be V for each zone and subzone. For the upper bound or maximum possible intensity for each (sub)zone we assume the maximum observed intensity plus one. This is a generally accepted practice (IAEA safety series 50-SG-S1).

For the subzones situated partly in The Netherlands, i.e. 1a, 1b and 2b, the hypocentral depth is assumed to be the average depth of all earthquakes with I_0 larger than V . For the zones and subzones outside The Netherlands the hypocentral depth is chosen as the average depth of the earthquakes

with the largest I_0 within each zone or subzone, as only those larger events contribute significantly to the seismic hazard in The Netherlands.

Our hazard analysis model allows for two different frequency-intensity relations to describe the seismic activity: a linear or a quadratic frequency-intensity relation. Both alternatives are extensively compared in Merz & Cornell (1973). The limited amount of data, however, does not motivate the use of the more complex quadratic relation, i.e. three parameters to characterize the seismicity as compared to two parameters in the linear relation:

$$\log N = a + bI_0 \quad (1)$$

where

N = annual cumulative number of events, and
 I_0 = epicentral intensity.

This relation has the added advantage that the b -value may be related to geological characteristics of the region. Firstly, for each observed intensity, IV to $VIII$, the value N is obtained for the period for which the data is shown to be complete (section 'Earthquake catalogue'). Secondly, we determine the b -value, assumed constant within each zone, and thirdly the a -value, which differs for each subzone. Finally, the rate of seismicity, R , defined as the annual cumulative number of events for intensity V , is calculated from equation (1):

$$R = 10^{a+bV} \quad (2)$$

Using the least-squares method, two b -values are calculated respectively for zones 1 and 5 together, and for zone 4 from the seismicity in these regions. The b -value for 2, 3 and 6 is estimated from the seismicity in the whole region of interest. For zone 4 only data for the complete period 1930–1983 have been used, resulting in a remarkably low b -value, i.e. $b = -0.2$, probably because the seismicity is limited to the uppermost crust. In the next step the a -values are calculated using the least-squares method for each (sub)zone with the b -values fixed. For the zones 2 and 3 the data for intensity IV are omitted, because they are incomplete. In the final step, R is estimated from the obtained values of a and b for the zones 1–5. For the background seismicity, zone

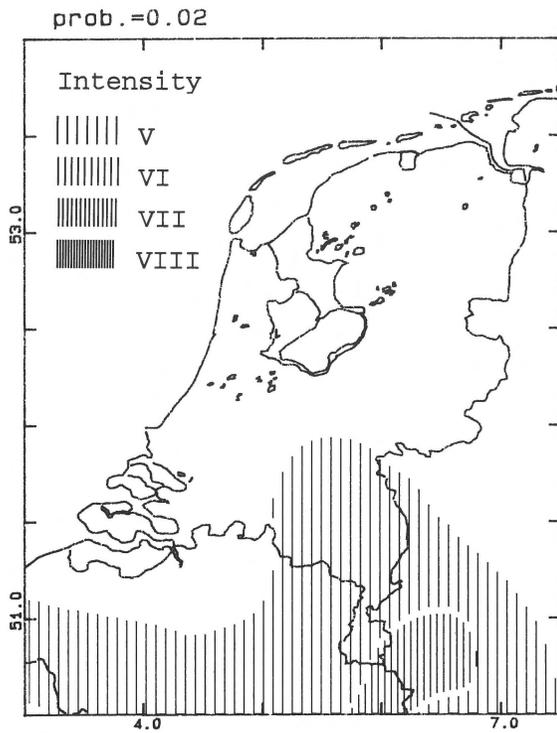


Fig. 5a. Probability 0.02.

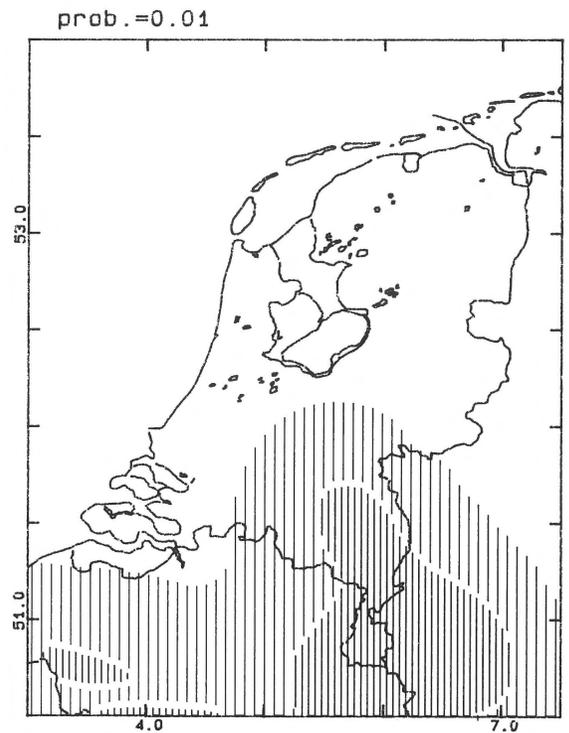


Fig. 5b. Probability 0.01.

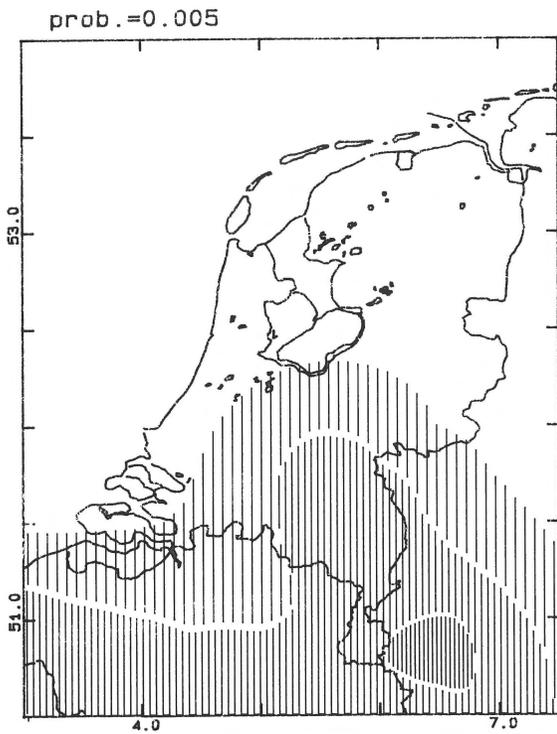


Fig. 5c. Probability 0.005.

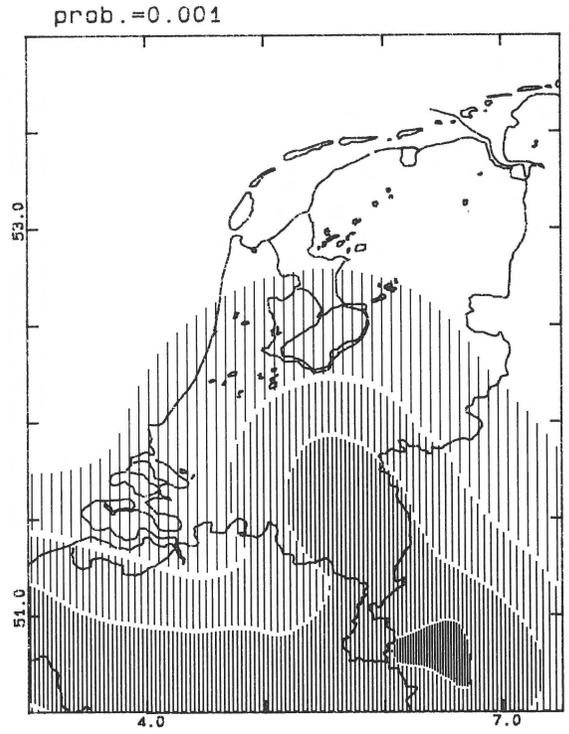


Fig. 5d. Probability 0.001.

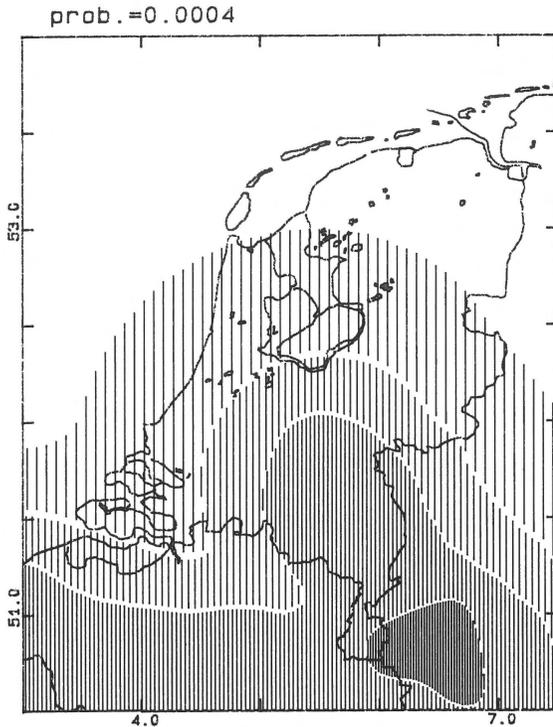


Fig. 5e. Probability 0.0004.

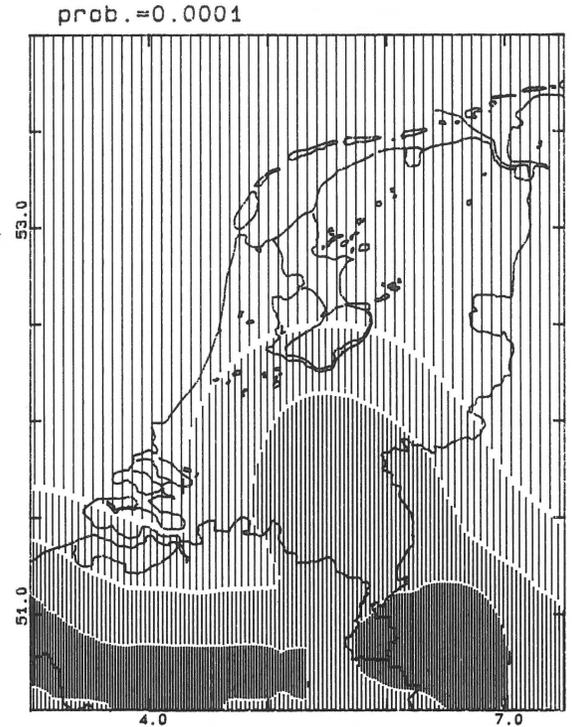


Fig. 5f. Probability 0.0001.

Figs 5a-f. Hazard intensity maps for The Netherlands with annual probabilities 0.02, 0.01, 0.005, 0.001, 0.0004 and 0.0001.

6, the a -value is estimated only from the observed intensities in The Netherlands due to earthquakes outside zone 1-5.

For the attenuation we use in this study the relation of Sponheuer (1958):

$$I_r = I_0 - 3 \log(d/h) - 1.3 \alpha (d-h) \quad (3)$$

with

$$d = \sqrt{r^2 + h^2}$$

where

I_0 = epicentral intensity

I_r = intensity at epicentral distance r

h = focal depth

d = hypocentral distance and

α = attenuation coefficient.

With the exception of subzone 1d the average attenuation coefficient α for each (sub)zone is obtained from De Crook (1989). The α -value of subzone 1d is based on Sponheuer (1958). Most isoseismals are assumed to be circular (independent of the azi-

muth); however, for some events clearly elliptical isoseismals can be recognized. For the subzones 1b and 2a, consistent observations motivate the definition of two attenuation relations defined for both directions of the two elliptical axes α_a and α_b (Table 1). The parameters, which are determined for each (sub)zone, are summarized in Table 1.

Results

Seismic hazard intensity maps for The Netherlands were obtained by applying the modified version of McGuire's program (Mayer-Rosa & Merz 1976) to sites at gridpoints with 7 km spacing and with input parameters as specified in Table 1. Annual probabilities of 0.02, 0.01, 0.005, 0.001, 0.0004 and 0.0001 have been considered (Figs 5a-f). For probabilities lower than 10^{-5} the expected intensities reach the upper bound intensities. Moreover, such low probabilities assume unrealistic stability of the seismo-

tectonic regime and are therefore meaningless. The highest seismic hazard in The Netherlands is found at sites in the south-east of the country, where the intensities VII and VIII appear with an annual probability of 0.001 and 0.0001 respectively, while the seismic hazard for intensity VI, i.e. slight damage, has an annual probability of 0.01. The seismic hazard is decreasing to the north-west, in line with the seismicity shown in Fig. 2.

Recent earthquakes, like the Liège, Belgium, earthquake of Nov. 8, 1983 and the Roermond, The Netherlands, earthquake of April 13, 1992 have negligible influence on the obtained seismic hazard maps. The Liège earthquake is included in the analysis, while the Roermond earthquake does not change significantly the modelling parameters for zone 1b.

The small earthquakes with local magnitude $M_L < 3$, which are observed in the northern part of The Netherlands since 1986 did not cause damage and hence $I_0 \leq V$. These events may modify slightly the hazard maps for intensity V, but are negligible in seismic hazard assessment. The low number of these events does not motivate at present a separate seismic zone and should be considered to be included in the background seismicity. A multidisciplinary research project was started in October 1991 to investigate a possible relation between gas extraction and these earthquakes.

Uncertainties

The influence of the errors in five zone parameters (upper bound intensity, depth, rate R, b-value, attenuation) on the seismic hazard has been investigated by De Crook (1989) for the site Venlo, The Netherlands, with a procedure comparable to the one presented by Rabinowitz & Steinberg (1991). For the worst-case and the best-case scenario the intensity total standard error decreased from approximately one intensity unit for the annual probability of 0.01 to half an intensity unit for the annual probability of 10^{-6} . However, the probability that all parameters will fit the worst-case scenario, or the best-case scenario, will be very small, assuming no correlation between the parameters. If we further

assume a normal distribution of each of the N parameters around an average value, the standard error, e, in the seismic hazard estimate will be: $e = \text{total error} / \sqrt{N}$, provided that each parameter contributes equally to the error. For an annual probability of 0.01 this is indeed approximately correct and gives us accordingly an error of approximately one half of an intensity unit. For an annual probability of 10^{-6} only one parameter contributes to the seismic hazard, i.e. upper bound intensity, and the uncertainty remains half an intensity unit.

Consequently, a rough estimate of the error in our seismic hazard estimates is approximately one half of an intensity unit for all probabilities. It should be noted that the above approach does not replace a rigorous statistical analysis of the possible error. However, with the limited amount of available data we are unable to provide a realistic probabilistic description of the input parameters for such a rigorous statistical approach.

Two model assumptions within the above described seismic hazard analysis have not been considered in this error discussion. Firstly, the zone and subzone definitions and secondly, the Poisson process of the occurrence of large earthquakes.

The choice of the zones and subzones remains a trade-off between an increased accuracy of the model and an increased uncertainty in the source zone parameters. The zonation adopted in section 'Seismotectonic zonation' is judged to be an optimal choice.

The Poisson process for the occurrence of earthquakes has been tested for events within their respective complete periods (see section 'Earthquake catalogue') for $I_0 \geq VIII$, VII, VI and V. For the com-

Table 2. Parameters for Figs 6a-d

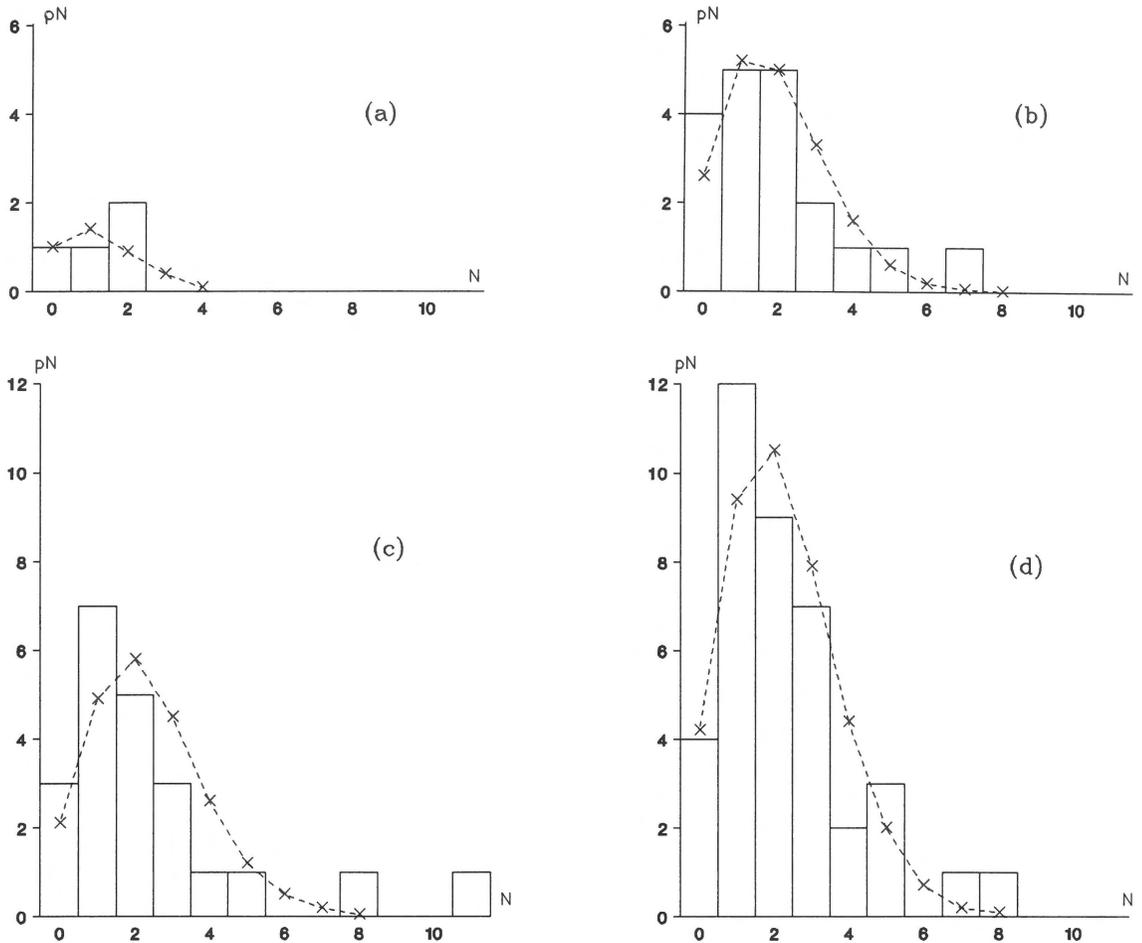
Figure	I_0	T	Δt	R
6a	VIII	384	100	0.013
6b	VII	184	10	0.195
6c	VI	109	5	0.468
6d	V	79	2	1.122

I_0 = intensity

T = complete period in years

Δt = time interval in years

R = annual cumulative number of events.



Figs 6a–d. Test of Poisson distribution for the complete part of the catalogue. Observed distribution (histogram) is the solid line and the Poisson function is the dashed line (in reality a smooth curve). a) $I_0 \geq VIII$ between 1600 and 1983; b) $I_0 \geq VII$ between 1800 and 1983; c) $I_0 \geq VI$ between 1875 and 1983; d) $I_0 \geq V$ between 1905 and 1983. N = number of events with intensities $\geq I_0$ in a time interval Δt (see Table 2). pN = number of time intervals with the same number N .

plete period T the number of events with intensity $\geq I_0$, N , has been counted for each time interval Δt (Table 2). In Figs 6a–d the number of time intervals pN with the same N is plotted as a function of N and compared with a theoretical Poisson function, i.e.:

$$pN(N) = \frac{T}{\Delta t} \cdot \frac{1}{N!} \cdot (R\Delta t)^N \cdot e^{-R\Delta t} \quad (4)$$

with rate R = annual cumulative number of events for intensity I_0 .

Table 2 lists the intensity I_0 , the complete period T , the time interval Δt and the rate R used to construct Figs 6a–d. These figures show a satisfactory agreement between the observed distribution and

the theoretical Poisson function for the complete periods. We conclude therefore, that the assumed Poisson process is valid for the intensities V, VI, VII and VIII.

Discussion and conclusions

This study presents improved seismic hazard intensity maps for The Netherlands based on the most recent tectonic and seismicity information available for a large region in and around The Netherlands.

The obtained hazard maps, which include an error estimate of half an intensity unit, may be used as

a basis for seismic zonation and building design codes. Clearly, the highest seismic hazard can be found in the south-eastern part of the country (Figs 5a–f).

This study also found that induced seismicity has a negligible importance on the seismic hazard maps of The Netherlands.

The seismic hazard maps do not include micro-zonation effects for which a detailed knowledge of the site conditions is required. Such micro-zoning effects may increase or decrease the local intensity by one unit as shown frequently in macroseismic maps.

Another hazard-increasing factor may be due to aftershocks. Large aftershocks can easily enlarge damage within the epicentral area. However, in this approach aftershocks have been excluded from the catalogue in order to fit the assumed Poisson process model. For The Netherlands the increased hazard effect due to aftershocks is probably negligible as the experience from the Uden (1932) and Roermond (1992) earthquakes shows.

De Crook & Schenk et al. (1989) en De Crook & Egozcue (1992) compared different methods to evaluate seismic hazard. They conclude that the input parameters are more important than the method used. Therefore, in this study the input parameters have been scrutinized. However, the upper bound or maximum possible intensity remains one of the most important uncertainty factors in the present seismic hazard estimates. Consequently, improving seismic hazard maps for The Netherlands requires improved estimates of the maximum possible intensities.

A more complete picture of the relative influence of the different input parameters may be found by applying some recently developed methods (Rabinowitz & Steinberg 1991, Coppersmith & Youngs 1990).

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