

## A seismic zoning map conforming to Eurocode 8, and practical earthquake parameter relations for the Netherlands

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### Abstract

A zoning map for earthquake intensities and a relation between intensity and design ground acceleration are presented, conforming to Eurocode 8, the European earthquake building code. For the southeast of the Netherlands, reduced or simplified seismic design procedures may be used. For the remainder of the country, where expected intensities are very low, the provisions of Eurocode 8 need not be observed. From the Netherlands data set, the linear frequency–magnitude relation for the tectonic earthquakes is re-calculated. A correlation between intensity and magnitude is determined and compared with similar relations in California and Germany. The radius of perceptibility estimated from the local magnitude is more accurate than that estimated from the maximum observed epicentral intensity. This radius is substantially greater in the Netherlands than in California for the same epicentral intensity. The maximum expected earthquake for the Netherlands is estimated at about  $6\frac{1}{4}$  local magnitude.

### Introduction

All earthquakes, which occurred in the Netherlands, and the earthquakes outside the country, which were felt within its borders, were described chronologically in a catalogue by Houtgast (1991). This catalogue lists all known seismic data for each event i.e. origin time, epicentre location, depth, local magnitude ( $M_L$ ), maximum observed epicentral intensity ( $I_o$ ), radius of perceptibility ( $R_{max}$ ), isoseismal maps and focal mechanisms. It also contains an epicentre map, an isoseismal map of maximum observed intensities for the Netherlands and an isoseismal map of maximum expected intensities for the Netherlands and surroundings.

From the complete part of this catalogue, De Crook (1994) calculated the frequency–intensity and the frequency–magnitude relation for the Netherlands. With these relations, he determined the mean return periods for intensities and magnitudes.

The earthquake hazard for any site in the Netherlands can be estimated with a probabilistic method, described earlier (De Crook 1993). Applying this

method, De Crook (1993) obtained seismic hazard intensity maps for the annual probabilities of occurrence 0.02, 0.01, 0.005, 0.001, 0.0004 and 0.0001.

This study presents a new zoning map for intensities, and establishes a relation between intensity and design ground acceleration according to the rules of the Eurocode 8 earthquake building code.

Furthermore, this study also derives some practical relations for earthquake engineers from the earthquake data for the Netherlands, viz. a re-calculated frequency–magnitude relation, re-determined mean return periods for different magnitudes, a magnitude–intensity relation, and  $R_{max}$  as a function of  $I_o$ , and of  $M_L$ . The magnitude–intensity relation is compared with similar relations in California and Germany. Finally, the maximum expected earthquake magnitude is estimated according to several methods.

## Tectonics and seismicity

The Netherlands is situated in the northwest of the Rhine graben system. This rift structure consists of several branches: the Upper Rhine Graben, the Roer Valley Graben, the Hessian Graben and the Belgian zone. The Hessian Graben displayed little neotectonic activity, while the other three regions are clearly active seismically (De Crook 1993).

The major Cenozoic faults in the Netherlands are the Peel Boundary Fault and the Feldbiss, the bordering faults of the Roer Valley Graben. This graben extends into the Rhenish Massif in Germany. The tectonic earthquakes in the Netherlands have been observed mainly in the southeast. The seismicity decreases to the northwest (Houtgast 1991). The largest observed earthquakes occurred at Uden in 1932 ( $M_L = 5.0$ ) and at Roermond in 1992 ( $M_L = 5.8$  to 5.9). The magnitudes of all other observed earthquakes were smaller than 4.5. The maximum observed epicentral intensity was VII. The focal depth estimates of the earthquakes varied between about 2 and 25 km, with an average of 13 km (De Crook 1994).

## A zoning map conforming to Eurocode 8

### Intensity zoning map

For the purpose of Eurocode 8 (ENV 1998-1-1 1994), an earthquake building code for Europe, the Netherlands will here be subdivided into seismic zones, which depend on the local hazard corresponding to a reference return period of 475 years. This return period, stipulated in Eurocode 8, corresponds to a probability of 0.0021 or an exceedance probability of 10% in 50 years. This probability is also used for the building code in the USA. For the Netherlands, a seismic hazard map for intensities (MSK scale) with a return period of 475 years is calculated with the procedure of De Crook (1993) and plotted in Figure 1. This map is the basis for the zoning map of Figure 2. The intensity intervals  $< 4.5$ ,  $4.5-5.5$ ,  $5.5-6.5$  and  $6.5-7.5$  (Table 1) are defined as seismic zones A, B, C and D, respectively. Within these zones the hazard is assumed to be constant (rule of Eurocode 8). For zone A there is no relevant seismic hazard, because no damage to buildings is expected. For zone B, the hazard is very low, because the damage to buildings is negligible to slight, and not structural, for intensities  $< 5.5$  (Grünthal 1993). The zones C and D have a low to moderate hazard level.

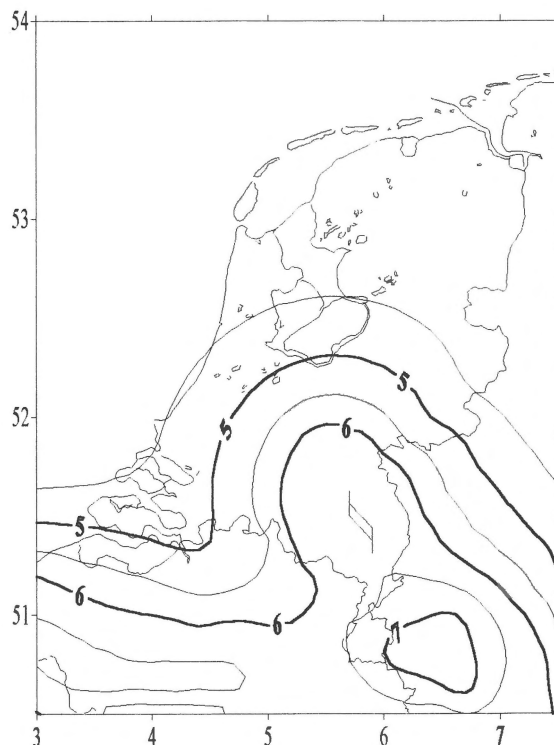


Figure 1. Seismic hazard intensity map for the Netherlands with a return period of 475 years. The isolines with numbers indicate the macroseismic intensity (MSK scale).

### Definition of the design ground acceleration

For most applications of Eurocode 8, the hazard for each seismic zone is described in terms of a single parameter, i.e. the design ground acceleration, which is defined as the effective peak ground acceleration  $a_{eff}$  in rock or firm soil. The use of this  $a_{eff}$  is an attempt to compensate for the inadequacy of the actual peak ground acceleration to describe the damaging potential of the ground motion. In the  $a_{eff}$ , the frequency content and the duration of the seismic strong ground motion are taken into account. A definition for  $a_{eff}$  is described in Van Eck (1990):

$$a_{eff} = \sqrt{(2 \ln(2.8 f T))} a_{RMS} \quad (1)$$

where

$f$  = predominant frequency,

$T$  = duration of strong motion, and

$a_{RMS}$  = root mean square acceleration.

$a_{eff}$  corresponds to a 50% probability of not exceeding the value  $a_{eff}/a_{RMS}$ , and is equal to the median

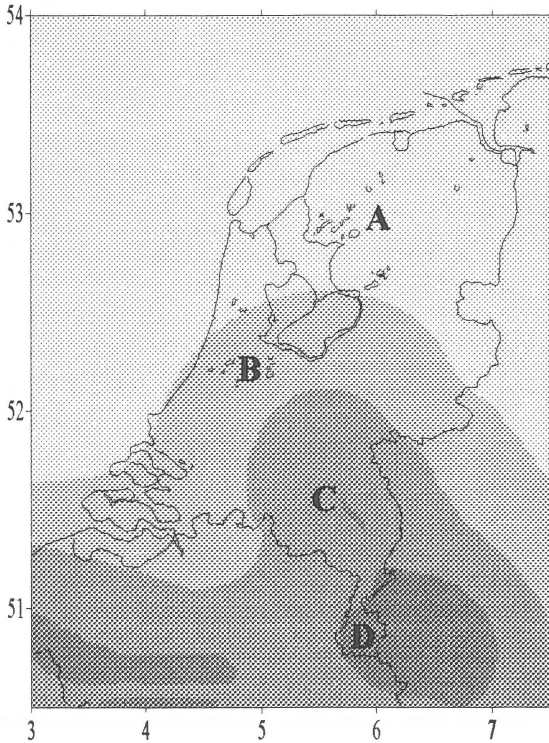


Figure 2. Proposed seismic zonation map for the Netherlands, derived from Figure 1. The design ground accelerations for the zones A, B, C and D are 10, 22, 50 and 100 cm/sec<sup>2</sup>, respectively.

peak ground acceleration. The difference of  $a_{eff}$  with another ground acceleration defined by Van Eck (1990) is small:

$$\hat{a}_{max} = \sqrt{(2 \ln(2 f T))} a_{RMS} \quad (2)$$

$\hat{a}_{max}$  corresponds to a 37% probability of not exceeding the value  $\hat{a}_{max}/a_{RMS}$  and is equal to the mean peak ground acceleration. Consequently,  $a_{eff}$  will provide a slightly more conservative estimate for the design ground acceleration than  $\hat{a}_{max}$ . Both definitions are based on the theory of stationary time series and are valid for sufficiently long time series. Thus, for the far field, the design ground acceleration is approximately equal to the mean peak ground acceleration.

For short time series, i.e. in the near field at short distances to the earthquakes, the approximations of  $a_{eff}$  and  $\hat{a}_{max}$  fail. However, according to Krinitzky et al. (1993), the mean peak ground acceleration is about twice greater in the near field than in the far field, but  $a_{eff}$  is up to 40% reduced. We assume that the design ground acceleration for the near field is approx-

Table 1. Macro seismic intensity (MSK scale), horizontal mean peak ground acceleration  $a_h$ , and design ground acceleration (dga) in seismic zones A to D of Figure 2.

Zone	Intensity interval	$a_h$ cm/sec <sup>2</sup>	dga cm/sec <sup>2</sup>
A	<4.5		<10
B	4.5–5.5	22	22
C	5.5–6.5	50	50
D	6.5–7.5	100	100

imately the mean peak ground acceleration in the far field. This definition for the design ground acceleration established above is in accordance with the definition in Eurocode 8.

#### Relation between intensity and acceleration

In the Netherlands, no locally recorded accelerograms are available. Therefore, an empirical relation between macro seismic intensity (MSK scale) and horizontal mean peak ground acceleration, currently in use in the anti-seismic design practice of nuclear power plants in Germany (Ahorner 1983), is chosen for application in the Netherlands (Table 1). This relation is valid on well-consolidated soil and is mainly based on measurements in the far field. In France, about the same correlation is used (Ahorner 1983). These accelerations are lower than those derived from data of southern Europe, Japan and the USA (Ahorner 1983; Krinitzky et al. 1993; Margottini et al. 1992).

The design ground accelerations for the zones B, C and D are approximately equal to the horizontal mean peak ground accelerations for the intensity intervals 4.5–5.5, 5.5–6.5 and 6.5–7.5 (Table 1). For zone A, the design ground acceleration is estimated at < 10 cm/sec<sup>2</sup>. In seismic zones with a design ground acceleration not greater than 40 cm/sec<sup>2</sup>, no special provisions need to be observed (rule of Eurocode 8). This rule is valid in zones A and B. Seismic zones with a design ground acceleration not greater than 100 cm/sec<sup>2</sup>, like zones C and D, are low-seismicity zones, for which reduced or simplified seismic design procedures may be used for certain types or categories of structures, as specified by the national authorities (rule of Eurocode 8). Zones with a design ground acceleration greater than 100 cm/sec<sup>2</sup>, in which the rules of Eurocode 8 need to be applied, do not exist in the Netherlands.

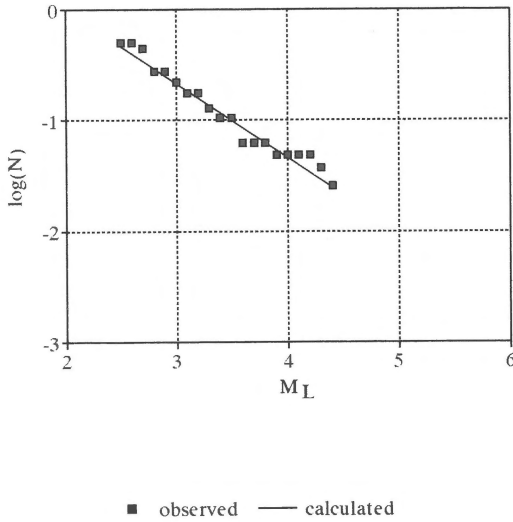


Figure 3. Frequency–magnitude relation for the Netherlands.  $N$  = the cumulative annual number of events;  $M_L$  = local magnitude.

### Practical earthquake parameter relations

The relations derived in the next sections from the observed tectonic earthquakes in the Netherlands (Houtgast 1991), are in principle valid for the south-east of the country, where most of these earthquakes occurred. The southeast of the Netherlands belongs to the seismotectonic zone of the Roer Valley Graben and constitutes a seismotectonic subzone, of which the national borders are artificial limits. The derived relations are important for earthquake engineering in the Netherlands.

#### Frequency–magnitude and frequency–intensity relations

The frequency–magnitude relation for the Netherlands given in De Crook (1994) was based on only five points. The present re-calculation uses all points in Figure 3. These points have a correlation coefficient 0.98. This slightly modified relation is:

$$\log(N) \pm 0.07 = (1.34 \pm 0.10) - (0.67 \pm 0.03)M_L \quad (3a)$$

where  $N$  = the cumulative annual number of events.

The mean return periods ( $1/N$ ) determined with Equation 3a for  $M_L = 2, 3, 4$  and  $5$ , are 1, 5, 22 and 102 years, respectively.

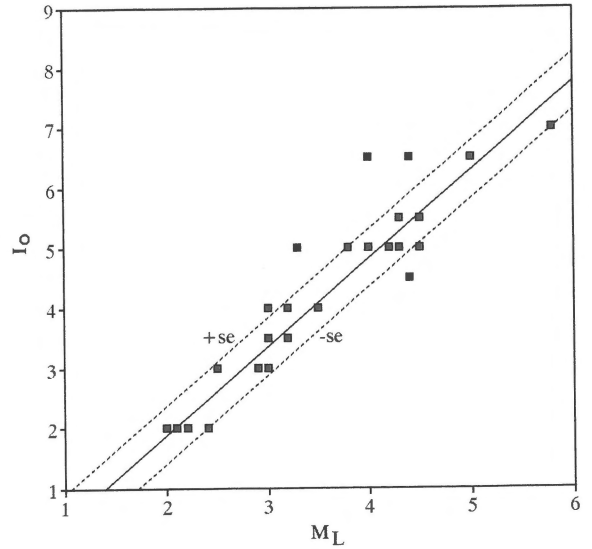


Figure 4. Intensity–magnitude relation for the Netherlands.  $I_o$  = maximum observed epicentral intensity;  $se$  = standard error.

The standard errors in the frequency–intensity relation for the Netherlands given in De Crook (1994) are incorrect; the correct relation is:

$$\log(N) \pm 0.15 = (0.82 \pm 0.31) - (0.42 \pm 0.07)I_o \quad (3b)$$

The  $\log(N)$  and  $I_o$  values have a correlation coefficient 0.98. The coefficients of Equations 3a and 3b are estimated, using the least-squares method, and assuming that the errors in the magnitude and intensity values are negligible in relation to those of the  $\log(N)$  values. This assumption is uncertain. However, the correlation coefficients are nearly 1, and then each type of least-squares method has approximately the same result (Morgan 1960; Guest 1961).

#### Relations between magnitude and intensity

The intensity–magnitude relation for the Netherlands determined from 42 observed tectonic earthquakes is:

$$I_o \pm 0.48 = (-1.05 \pm 0.28) + (1.47 \pm 0.08)M_L \quad (4)$$

The correlation coefficient of the data is 0.94. This relation (Figure 4) is valid for  $1 < M_L < 6$  and an average focal depth of 13 km. Equation 4 differs slightly from the relation obtained in De Crook (1994), where

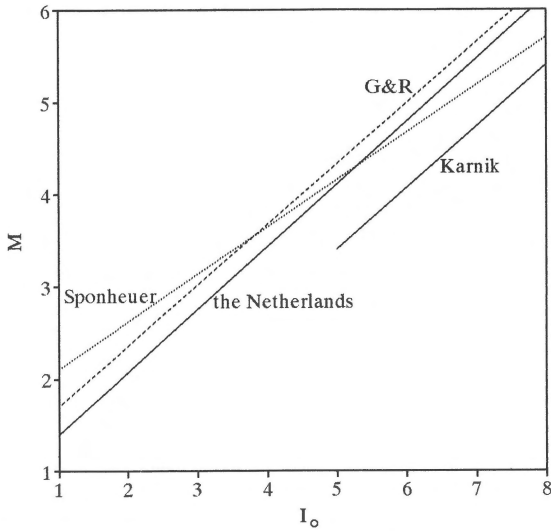


Figure 5. Magnitude-intensity relations.  $M = M_L$  for the Netherlands,  $M = M$  for Gutenberg & Richter (G & R) and for Sponheuer ( $h = 10$  km and  $\alpha = 0.01$ ) and  $M = M_s$  for Karnik.

the  $M_L$  of the Roermond earthquake 1992 was estimated to be 5.5 instead of 5.8 (Camelbeeck et al. 1994). The coefficients of Equation 4 are estimated with the least-squares method, assuming that the errors in the magnitude values are negligible in relation to those of the intensity values. The uncertainty in the magnitude determination is substantially smaller than that in the intensity determination, but not negligible. However, the correlation coefficient of the data is high (0.94) and therefore Equation 4 is an accurate approximation for the relation between the intensities and the magnitudes (Morgan 1960; Guest 1961).

The magnitude-intensity relation for the Netherlands determined with Equation 4 is:

$$M_L = 0.71 + 0.68I_o \quad (5)$$

The well-known Gutenberg & Richter relation (1956) for crustal earthquakes in California is  $M = 1 + \frac{2}{3} I_o$ , with  $M$  defined as earthquake magnitude. For  $2 < M < 6$ , the observed  $I_o$  is about  $\frac{1}{4}$  intensity unit higher in the Netherlands than in California (Figure 5).

According to the relation  $M = 0.52 I_o + 1.56 \log h + 0.7 \alpha h$ , where  $h$  = average depth and  $\alpha$  = attenuation coefficient (Sponheuer 1962), lower intensities are found in Germany than in the Netherlands for  $2 < M < 4$ , with  $h = 10$  km and  $\alpha = 0.01$ . For  $M > 5$  the intensities are higher.

A relation of Karnik (1969) for Germany, Belgium and the Netherlands is  $M_s = 0.67I_o + 0.07$ , where  $M_s$  is surface wave magnitude for  $I_o = V-VIII$  and  $h < 30$  km. With this relation, higher intensities are obtained, but normally  $M_s$  is smaller than  $M_L$  for  $M_L < 6$ .

### Radius of perceptibility

The radius of perceptibility ( $R_{max}$ ) depends on the maximum observed epicentral intensity ( $I_o$ ) and depth ( $h$ ) of an earthquake, and the attenuation ( $\alpha$ ) of intensity:

$$R_{max} = f(I_o, h, \alpha) \quad (6)$$

Taking for  $h$  and  $\alpha$  the average values for the Netherlands and supposing that  $R_{max}$  is proportional to  $I_o^3$  (according to Gutenberg & Richter 1956), then:

$$R_{max} = a + bI_o^3 \quad (7)$$

Similar for the local magnitude  $M_L$ :

$$R_{max} = a + bM_L^3 \quad (8)$$

Figures 6 and 7 show the observed  $R_{max}$  of the tectonic earthquakes in the Netherlands in relation to  $I_o$  and  $M_L$ , respectively. The respective correlation coefficients of the data are 0.85 and 0.98. The coefficients  $a$  and  $b$  in Equations 7 and 8 are calculated from 36 and 31 events, respectively, using the least-squares method:

$$R_{max} \pm 52 = -17.9 + 1.0I_o^3 \quad (9) \\ \text{for } III \leq I_o \leq VII$$

$$R_{max} \pm 23 = -61.9 + 2.7M_L^3 \quad (10) \\ \text{for } 3 \leq M_L \leq 6$$

The standard error of  $R_{max}$  in Equation 10 is approximately half of the error in Equation 9 and the correlation coefficient is substantially higher. To estimate the radius of perceptibility  $R_{max}$ ,  $M_L$  gives a more accurate result than  $I_o$ .

According to the relation of Gutenberg & Richter (1956), which reads  $R_{max} = 0.5I_o^3 - 1.7$  and which was derived from earthquakes in California,  $R_{max}$  is substantially smaller in California than in the Netherlands (Figure 6).

### Maximum expected earthquake magnitude

The largest observed earthquake in the Netherlands occurred at Roermond in 1992 with  $M_L = 5.8$ . Often,

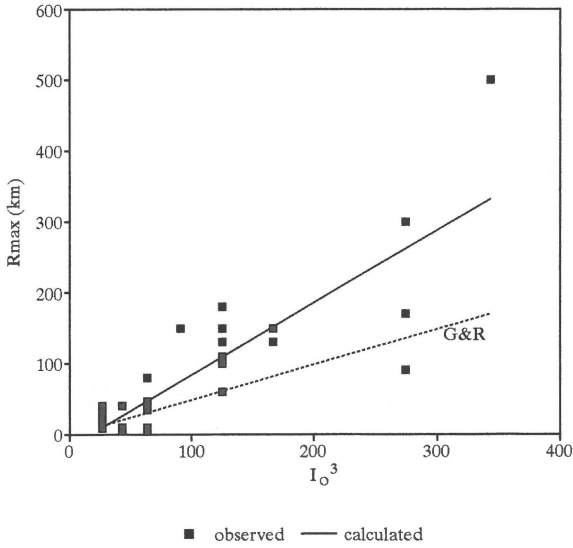


Figure 6. Radius of perceptibility  $R_{max}$  in relation to  $I_o$ . Solid line = Netherlands, dotted G & R line = California.

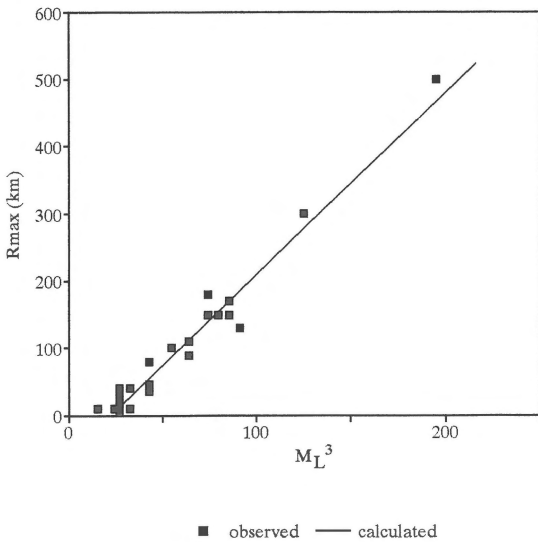


Figure 7.  $R_{max}$  in relation to  $M_L$  for the Netherlands.

0.5 magnitude unit is added to the largest observed historical earthquake as an estimate of the maximum magnitude for a region. Applying this rule to the Netherlands, the maximum magnitude is  $M_L = 6.3$ .

The relation derived by Ahorner & Pelzing (1985):

$$\log(E) = 10.81 + 1.64M_L \quad (11)$$

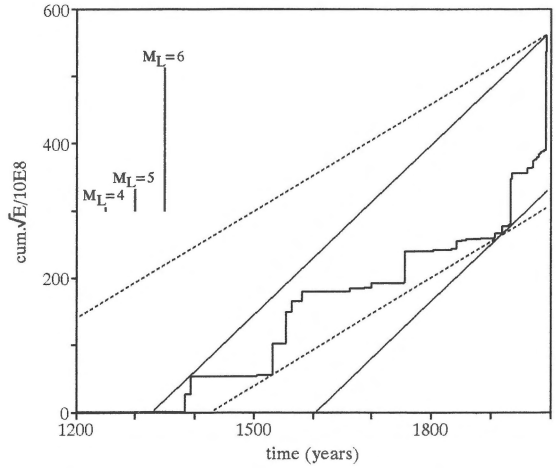


Figure 8. Cumulative  $\sqrt{E}$  versus time graph for the Netherlands, from which the maximum expected magnitude can be estimated. Two solutions are possible. The vertical distances between the two parallel, solid or dotted lines are a measure for the maximum expected magnitude. The bars indicate the  $\sqrt{E}$  values for  $M_L = 4, 5$  and  $6$ , respectively.

where  $E$  = seismic source energy release in ergs, is applied to calculate  $\sqrt{E}$  of the earthquakes in the Netherlands. When  $M_L$  is unknown, it is evaluated with Equation 4. The cumulative  $\sqrt{E}$  of earthquakes observed from 1395 to 1992 is plotted as a function of time in Figure 8. When the relative  $\sqrt{E}$  maxima and minima are connected by two parallel lines, the vertical distance between these lines is a measure for the maximum expected magnitude, assuming that the energy can be released by one single earthquake (Benioff 1951). In Figure 8, two solutions of parallel lines are possible. The maximum expected magnitude is in both cases  $M_L = 6.1$ . This method is based on the assumption that for the period of observation the total energy accumulation is about the same as the total energy release observed. The energy accumulation is relatively slow for the Netherlands, and during the period 1395 to 1992 this accumulation and probably also the energy release did not reach their maximum values. To apply this method, a complete data set with at least two cycles of increased earthquake activity is needed. The seismic data used for the Netherlands are not complete for this period (De Crook 1994) and probably not even one complete cycle is observed. Thus, the maximum expected magnitude will be larger than 6.1.

The extreme-value-theory approach (Gumbel 1958), using an incomplete and relatively small data set like that for the Netherlands, gives unacceptably large

errors in estimating the maximum possible earthquake (Knopoff & Kagan 1977).

As there exists a large uncertainty about the geometrical and seismic dimensions of individual faults in the Netherlands (Ritsema 1985), the estimation of the maximum magnitude from the lengths or fault plane areas of known faults is unreliable.

For the Roer Valley Graben, excluding the area of the highest seismicity east of Aachen in Germany, the maximum expected magnitude was estimated at  $M_L = 6\frac{1}{4}$  (Rosenhauer & Ahorner 1994). The southeast of the Netherlands is situated in and around this graben and the estimate may be accepted for the entire Netherlands.

From the above-mentioned estimates ( $M_L = 6.3$ ,  $M_L > 6.1$  and  $M_L = 6\frac{1}{4}$ ), we may conclude that the maximum expected  $M_L$  for the Netherlands is about  $6\frac{1}{4}$ .

## Conclusions and discussion

According to the seismic zoning map for the Netherlands, the rules of Eurocode 8 need not be observed in the zones A and B (Figure 2). For zones C and D, simplified seismic design procedures may be specified by the national authorities.

In the probabilistic seismic hazard analysis, the seismic activity is assumed to be constant in the seismotectonic source zones (De Crook 1993). However, the earthquakes occur more frequently on the major faults in the southeast of the Netherlands, the Peel Boundary Fault and the Feldbiss. Thus, the seismic hazard near these faults is underestimated. Moreover, the maximum expected earthquake for the Netherlands is about  $M_L = 6\frac{1}{4}$ . According to Equation 5,  $I_o = 8^+$ . In De Crook (1993),  $I_o = 8$  is used for zone 1b, the 'Lower Rhine Graben area with lower seismicity'. So, the seismic hazard in the southeast of the Netherlands should be slightly higher.

The small earthquakes in the northeast of the Netherlands with  $M_L \leq 3.2$ , which were observed since 1986 (De Crook et al. 1995) and which were probably induced by gas extraction, may enhance slightly the hazard in zone A.

The damage caused by an earthquake depends strongly on the size of the earthquake, the duration, the frequency content and the soil conditions. The duration of the strong ground motion varies from a few seconds for small earthquakes to several tens of seconds for large events. It increases with magnitude and

hypocentral distance, and depends on soil conditions as well. The earthquake motion at a given point of the surface is generally represented by a horizontal and a vertical elastic ground acceleration response spectrum, depending on the design ground acceleration and the subsoil. These spectra are defined in Eurocode 8. The horizontal response spectrum is determined from acceleration recordings. Alternative representations of the earthquake motion, e.g. a power spectrum or a time history, may be used. It will be very difficult to determine the response spectrum or an alternative representation for different sites, because there are no ground acceleration data for the Netherlands. An alternative is to apply a standard response spectrum on rock or firm soil to the whole of the Netherlands, and to correct it for the soil conditions on site. This will be investigated in a later study.

The frequency–magnitude relation for the Netherlands given in De Crook (1994) is slightly modified. The mean return periods ( $1/N$ ) re-determined with this relation for  $2 \leq M_L \leq 5$  are practically the same.

The magnitude–intensity relation for the Netherlands is  $M_L = 0.71 + 0.68 I_o$  (Equation 5). In the Netherlands,  $I_o$  is normally about  $\frac{1}{4}$  intensity unit higher than in California. For  $M < 4$ , the  $I_o$  in the Netherlands is also higher than in Germany. For  $M > 5$ , however, it is lower.

The radius of perceptibility  $R_{max}$  estimated from  $M_L$  is more accurate than that estimated from  $I_o$  (Figures 6, 7). The respective standard errors of  $R_{max}$  are 23 and 52 km.  $R_{max}$  is larger in the Netherlands than in California (Figure 6).

The maximum expected local magnitude for the Netherlands is about  $M_L = 6\frac{1}{4}$ . This estimate is based on the incomplete earthquake data set of the Netherlands, which lacks a complete seismic cycle and which includes some unreliable historical events. The estimate is also based on the earthquakes that occurred in the wider Roer Valley Graben area, excluding the area of the graben's highest seismicity east of Aachen in Germany.

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