Seismic hazard due to small-magnitude, shallow-source, induced earthquakes in The Netherlands

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Abstract

The Netherlands has large on-land gas reservoirs, which are being exploited since 1960. Small-magnitude ($M_L \leq 3.5$), shallow (depth < 4 km) events induced by this gas exploitation cause light damage and much concern to the regional population. As one of the consequences the Dutch law requires since 2003 seismic hazard and risk estimates for each mining concession. Up to now only general quantitative hazard estimates, maximum possible earthquake and maximum possible intensity were available. Here we provide more specific quantitative hazard estimates. A long-term monitoring program shows a stationary rate of seismicity since 1992, probably coupled to a stationary production rate. Based on this we present a first order site-specific hazard estimate using a Probablistic Seismic Hazard Analysis (PSHA). We predict, and observe, relatively high Peak Ground Accelerations (PGA). PGA above 0.2g is not unusual, but damage has so far been restricted to non-structural damage, mainly cracks in masonry. Relevant hazard estimates for the local, mostly low-rise buildings are given in terms of Peak Ground Velocity (PGV) or the maximum in the 50% damped response spectra at 10 Hz. For example, above the largest Dutch gas field, the Groningen field, we expect that peak values of 20 and 30 mm/sec may be exceeded with a 10% probability in 1 and 10 years, respectively. Above some small (about 3-4 km^2) gas fields, Roswinkel and Bergermeer, we expect values around 35 and 60 mm/sec, respectively. These values, which exceed the Dutch building research (SBR) vibration guidelines, are obtained using simple model assumptions and are accompanied by an uncertainty analysis. The PSHA provides an important additional insight for the decision maker as to which relevant uncertainties may be decreased and which not. This information can be and is being used to set research and monitoring priorities.

Keywords: induced seismicity, small earthquakes, seismic hazard, Peak Ground Velocity, Peak Ground Acceleration, PSHA, The Netherlands, gas exploitation.

1. Introduction

Earthquakes in the north of The Netherlands induced by the exploitation of gas fields are small, but they occasionally cause non-structural damage (Dost and Haak, 1997; Haak et al., 2001). This is of concern to the regional population and the Dutch government. On the other hand, the Dutch gas reserves on land are of considerable national economic importance. Therefore both the exploitation companies and the Dutch government aim at a balanced policy to meet both concerns. Since January 1, 2003 the new Dutch mining legislation requires, among others, a hazard and risk analysis for each new exploitation license (Staatsblad, 2002). However, hazard and risk analysis are usually not developed in such detail for small and shallow earthquakes, whether natural or induced by exploitation of hydrocarbons. Therefore, all involved parties in The Netherlands (exploitation companies, government and research institutes) jointly worked out an acceptable long-term approach. It was agreed that this approach should reflect the state-of-the-art knowledge and should be consistent with available legislature and international practice with regard to hazard assessment. The group also believed it to be important that the approach helps decision makers in specifying which knowledge we still lack in order to reduce uncertainties and set monitoring priorities. When decision makers can identify the epistemic (Toro et al., 1997) uncertainties they desire to eliminate or reduce, it becomes easier to set joint research priorities.

In this paper we concentrate on the hazard analysis, defining hazard as the severity or frequency of ground motion due to earthquakes. Risk analysis, which we define as a product of hazard, exposure, vulnerability and cost, is only partly considered. For example, intensities, defined according to the Modified Mercalli scale or the European EMS scale (Grünthal et al., 1998) incorporate an aspect of risk. Earlier analysis in The Netherlands (De Crook et al., 1995, 1998; Haak and De Crook, 1993) aimed at a general analysis: estimating the maximum possible earthquake and the maximum probable intensity. Our main goal is a quantitative approach in terms of estimated strong ground-motion, but we refer to intensities as well.

2. Induced seismicity in The Netherlands

Seismicity of tectonic origin in and around The Netherlands is related to the Roer Valley graben and mostly observed in the southeast of the country (Figure 1). Seismicity induced by gas exploitation is mostly observed in the north of The Netherlands.

The seismicity in The Netherlands is monitored by a digital seismometer network, which currently consists of 19 permanent and 2 mobile stations. Eleven of these stations are borehole seismometers in the north of The Netherlands. We also operate 17 accelerometers to complement our data and measure specifically near-source strong ground-motion. This network has been improved and successively enlarged with time. The current borehole network in the north of the country, most important for the induced seismicity, exists in its present configuration since 1995. Consequently, observations of induced seismicity since 1995 are consistent. The Dutch network is currently capable of detecting and locating events with $M_L > 1.5$ in all of The Netherlands with the exception of the southwestern part, the province of Zeeland (Dost and Haak, 2006).

We recorded the first known event ($M_L = 2.8$) in the north of The Netherlands near Assen, a town in the northeast. The hypocenter of this event was found to be shallow (about 1 km) in the vicinity of a gas reservoir in production and has been explained as an induced event. Since 1992 (installation of the first borehole seismometer) the seismicity in the north of The Netherlands has been displaying a steady rate (Figure 2). Up until the end of 2003 the KNMI monitoring network observed more than 340 induced events within a magnitude range $-0.8 < M_L < 3.5$. Approximately 60 of those events have been felt. Only nine of those events had magnitudes $M_L \geq 3.0$. The observed frequency-magnitude distribution for all these events combined fits well a general truncated exponential distribution ($M_{max} = 3.5$), although local variations can be identified (Figure 3). No events with $M_L > 3.5$ and no EMS intensities larger than VI have been observed so far.

In our study we present results for three special gas fields: the Groningen field, one of the largest known gas reservoirs in the world, and two smaller fields, Roswinkel and Bergermeer. A more detailed discussion on these specific gas fields provides also a quick overview of the current knowledge we have about gas-induced seismicity in The Netherlands.

Groningen field

The Groningen reservoir (Figure 4) is situated in the sandstones of the Upper-Rotliegend (lower Permian) at varying depths ranging from about 3150 to 2600 meters (RGD, 1995). It is also around this depth that we observe the induced seismicity. The first event occurred in 1991, 28 years after the gas production started. From 1991 to 2003 we identified 179 events with magnitudes in the range –0.2 ≤ M ≤ 3.0. Many of the events seem to occur along NW-SE trending faults at reservoir level in the northwestern part of the gas field (Mulders, 2003; Dost and Haak, 2006). As yet we have not been able to corroborate the hypothesis that the seismicity is related to specific fault zones. The field still has approximately 50% of its original reserves (Van der Weerd, 2004).

The Roswinkel and Bergermeer fields

Two relatively small gas fields in The Netherlands have initiated, through their activity, much of the discussion on induced seismicity; the Roswinkel field in the north-east and the Bergermeer field in the north-west (Figure 1 and 4). Both gas fields have released a total seismic energy corresponding to approximately one event of M_L = 3.7 (Table 1). Both gas fields had similar size largest event, M_L = 3.4 and M_L = 3.5 respectively. However, the reservoirs are significantly different. The Roswinkel reservoir is situated in the sandstones of the Bontzandsteen (Trias) in an anticlinal structure due to salt tectonics at a depth varying from 2000 to about 2400 meters. The seismicity occurs most probably just above the reservoir in the anticlinal structure. The Bergermeer reservoir is situated in the sandstones of the Rotliegend (lower Permian) at a depth of about 2100 meters. Existing normal faults form significant reservoir boundaries. The seismicity that occurred so far has been associated with the re-activation of one major normal fault. In both fields relatively few small events occurred, in this aspect they are different from the others. For both fields several detailed systematic studies (Rijkers et al., 1999; Haak et al., 2001; Logan et al., 1997) have tried to find a relation between exploitation variations and the seismicity, but none has been found. Both fields, Bergermeer and Roswinkel, are approaching the end of their production cycle. The Bergermeer field has so far only generated four events ($3.0 \leq M_L \leq 3.5$) (Haak 1994a,b; Haak et al.,2001), the Roswinkel field more than 36 events ($1.0 \leq M_L \leq 3.4$). A truncated exponential frequency-magnitude model with $M_{max} = 3.5$ has been derived for the Roswinkel field (Figure 5).

Seismicity, exploitation and tectonics.

For the period prior to the 1986 Assen event we have no hard evidence of any tectonic events in the North of the country (Houtgast, 1992). Further, all current seismicity in the north of The Netherlands (Figure 1 and 4) recorded with instrumentation installed after 1986 occurred at a 'shallow' depth. Most events have been located around a depth of 2.5 km ± 0.5 km, corresponding to the average depth of the reservoir. No events occurred at depths larger than 4 km and all events have so far been located in or around exploited gasfields. Consequently, it was concluded that the seismicity is induced due to gas exploitation (BOA, 1993). That this is not an isolated case of induced seismicity due to exploitation is clear from evidence at other gas reservoirs (Wetmiller, 1986; Grasso, 1992; Grasso et al., 1994; Segall and Fitzgerald, 1998) and other hydrocarbon reservoirs (Rutledge et al., 1998; Zoback and Zinke, 2002).

The frequency-magnitude distribution of all seismicity together (~340 events) and that of the large Groningen field (~180 events) fits well a truncated exponential distribution model with $M_{max} = 3.5$ (Figure 3) similar to natural seismicity. This corresponds with observations of others (Grasso and Sornette, 1998; Lahaie and Grasso, 1999). Although some fields, like the Bergermeer field, show distinctly different seismicity behaviour, it seems reasonable to assume that induced seismicity in the north of The Netherlands behaves in general like chaotic phenomena. As in natural seismicity we have a stress driving mechanism. However, the driving mechanism of induced seismicity in hydrocarbon reservoirs is obviously related to (induced) poroelastic stress changes (Segall et al., 1994; Segall and Fitzgerald, 1998; Zoback and Zinke, 2002) and therefore most probably to production rates (Lahaie and Grasso, 1999). On a large scale we do see during the last 10 years an overall steady production rate and a stationary seismicity rate (Figure 2).

Unfortunately, so far we have been unable to quantify such relations on a smaller scale, i.e. individual fields or compartments (Ruthledge et al., 1998).

In estimating the seismic hazard we also considered the option that exploitation might trigger existing tectonic fault instabilities. However, we believe this to be highly unlikely, as a) there is no historical evidence of tectonic earthquakes in north of The Netherlands (Houtgast, 1992), b) no faults in the north of The Netherlands seem connected to distant faults on which natural seismicity has been observed and c) as presented above, so far, observed earthquakes in the region occurred at the top of the seismogenic zone of the crust. It is unlikely that such shallow events would trigger larger events rupturing deeper and stronger parts of the seismogenic zone (Scholtz, 2002). Consequently, in our hazard estimates we did not include the option that exploitation will trigger existing tectonic fault instabilities and thus large earthquakes.

Maximum probable magnitude.

Induced events that are not triggering active tectonic faults most probably do not exceed a maximum size, which is related to the maximum relative compaction due to extraction of hydrocarbons. Using this argumentation, Logan et al. (1997) found a maximum M_w = 3.8 or, with less conservative assumptions, both De Crook et al. (1995) and Logan et al. (1997) found M_w = 3.6 for the Bergermeer field. Haak (1994b) and Haak et al. (2001) have shown that the M_L magnitudes, as estimated by the KNMI, correspond to M_w within the magnitude range concerned. Following De Crook et al. (1995; 1998) M_{max} has been re-estimated using two statistical interpretations of the observed seismicity:

a) If we assume stationary energy release, the upper and lower bound of the cumulative energy release curve may be used to estimate the M_{max} (Makropoulos and Burton, 1983). We used here the regional magnitude-energy relation of Ahorner and Pelzing (1985):

$$\log E_s(Joule) = 3.81 + 1.64 M_L \quad \text{Eq 1}$$

For this we find an estimate M_{max} = 3.8 (Figure 2).

b) A Bayesian approach to estimate M_{max} from the observed seismicity and a truncated exponential distribution model for the frequency-magnitude relation (De Crook et al., 1998). In a Monte Carlo procedure M_{max} was repeatedly estimated from a truncated exponential distribution assuming errors in the magnitude estimates (normal distribution) and the average number of events for a certain magnitude (Poisson distribution). The *a priory* constraint was that in the magnitude range 1.5 < M_L < 2.7 the distribution fits

$$log\ N = 2.16 \pm 0.15 - 0.80 \pm 0.08\ M \qquad \text{Eq.2}$$

as obtained from the 1986-2003 observations. We thus obtained a mean, M_{max} = 3.7, and a mean plus one standard deviation, M_{max} = 3.9 estimate (Table 2). Comparison between 1998 (De Crook et al., 1998) and 2004 in Table 2 shows that the estimate remained fairly stable.

From the two approaches above we conclude that the size of an induced event in the north of The Netherlands is unlikely to exceed M_L = 3.9. So far the largest observed event in the north of The Netherlands, M_L = 3.5, occurred in the Bergermeer field 9/9/2001 in the northwestern Dutch province of North-Holland.

3. Ground-motion prediction relations for shallow small earthquakes

Peak ground acceleration and velocity

Ground-motion prediction equations or attenuation relations are usually empirical relations and show a large variability due to many factors like focal mechanism, rupture process, site response and unknown details of the 3D crustal structure. A review can be found, among others, in Campbell (2003). None of these attenuation relations are calibrated for small, shallow earthquakes for which we intend to use it. Therefore, we calibrated and tested in Dost et al. (2004) our local observations against a number of extrapolated ground-motion prediction equations based on different sets of data (Campbell, 1989, 1997, 2000, 2001; Ambraseys, 1995; Sabetta and Pugliese, 1987; Campbell and Bozorgnia, 2003). We found in Dost et al. (2004) that the relation proposed by Campbell (1997) predict our observed Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) for M_L > 2.7 reasonably well:

$$\ln A_h = -3.512 + 0.904M - 1.328 \ln \sqrt{r^2 + (0.149 e^{0.647M})^2} \qquad \text{Eq 3}$$

Here A_h (in units of g) is the average horizontal PGA, M is $M_w = M_L$ and r (km) is the source-to-site distance, which, for small events, is effectively the hypocentral distance. The lognormal variation, σ, varies between 0.55 and 0.39 (Campbell, 1997). Campbell (1997) also presented an associated PGV prediction equation.

Induced seismicity, Intensities and observed peak ground motions.

Induced, shallow and small events may cause relatively large PGA at close distances (McGarr, 1984). On February 19, 1997, for example, we recorded a short (0.1 sec) acceleration pulse with PGA of 0.31g (PGV = 5.5 cm/sec) for a M_L = 3.4 event at around 3 km hypocentral distance from the source in the Roswinkel exploitation field in northeastern Netherlands. Large PGAs due to small, shallow earthquakes are not unusual, they are also observed elsewhere (Fletcher et al., 1983; McGarr and Bicknell, 1990; Ahorner, 1997 personal communication; Wu et al., 2003). However, the strong accelerations are usually short, often only one cycle, and the PGV is in these cases often a more robust damage indicator. The PGV therefore also shows better correlation with intensities ≥ V (Schenk et al., 1990; Van Staalduinen and Geurts, 1998; Wu et al., 2003).

For smaller intensities, mainly people's perception, not damage, determines the intensity. So far little work has been done to correlate peak ground motion with intensities < V. However, it is those small intensities that indicate the annoyance factor for each induced event and are therefore, in our case, significant. Only the intensity II (felt) can be coupled to observations, i.e. approximately 0.4 mm/sec or 0.5 – 2.5 cm/sec^2 (ISO 2631-2, 1989), or 1-2 cm/sec^2 (Wald et al., 1999). An exponential interpolation for velocity between intensity II and V, as proposed by Wald et al. (1999), does not seem to fit our data (Table 3). In Figure 6 we show averaged observed intensities (Dost and Haak, 1997) for the February 19, 1997 M_L = 3.4 induced event near Roswinkel compared with the predicted PGA and PGV values for this event using Campbell (1997) and Dost et al. (2004). The "observed" intensities presented in Figure 6 are based on averaged values and approximately circular macroseismic isolines in Dost and Haak (1997). The estimated PGA and PGV values have been derived using attenuation relations that have been verified with local data (Dost et al., 2004). In practise we find small local variations due to site response differences, but still fairly reasonable circular macroseismic isolines. Currently we have too few sites with common ground-motion and intensity measurements to develop an adequate intensity ground-motion relation for small intensities.

Response spectra and response spectral peaks

We also considered another hazard parameter, the horizontal velocity amplitude of the response spectra (Gupta, 1990) at a specific frequency and damping. Van Staalduinen and Geurts (1998) proposed to adapt the type 2 response spectra as presented in the Eurocode 8 (CEN, 2003) to the situation in the north of The Netherlands, based on observed accelerograms. Moreover, they showed that for the typical low-rise housing construction in the northern part of The Netherlands a 50% damping may be assumed for the whole building and propose a normalized averaged response spectra for 50% damping:

$SA_{50}(f) = 1.2 \cdot A_h$ for $f > 10$ Hz , and $SA_{50}(f) = 0.0895 \cdot A_h \cdot f^{1.0516}$ for $f < 10$ Hz. Eq 4

In this equation $SA_{50}(f)$ is the amplitude of the 50% damping acceleration response spectrum at frequency f . From 19 horizontal acceleration records at six sites we observed for earthquakes with $M_L < 3.9$ clear peaks in the velocity response spectra, SV_{max}, around 10 Hz (Figure 7). Synthetic response studies of the known shallow subsurface profile predicts only small variations in the site response on those six sites (see also Wassing et al. 2004a, b). Preliminary analysis of our data also indicates that a factor f^2 instead of $f^{1.05}$ in equation 3 may probably be more appropriate. However, this needs to be corroborated with more observational data. As $SV_{\max}$ (at 10 Hz) provides a reasonable characteristic of the 50% damped response spectra, we propose SV_{max} as a simple relevant parameter for seismic hazard analysis.

Response spectral peak, PGA and PGV

Given the PGA, its short duration of approximately one or two cycles, and the dominant frequency of around 10 Hz, one can obtain a simple relation between PGA and $SV_{\max}$. The amplitude decrease for a steady state oscillation going through a single-degree-of-freedom damped system (system response in the response spectral approach) is a factor $(1 - e^{N_c d 2\pi})$ for N_c cycles and damping d. Assuming that in our cases strong ground-velocity is short (N_c = 1) one can approximate $SV_{\max}$ with:

$$SV_{\max}(f) = A_h \cdot (2\pi f)^{-1} \cdot (1 - e^{-d2\pi}) \qquad \text{Eq 5}$$

Here A_h is the horizontal PGA, d is the damping coefficient used in the response spectrum. In our case d = 0.5 for 50% damping. Consequently we have a simple conversion relation between PGA and $SV_{\max}$.

Given d = 0.5 and f = 10 Hz we also find that V_{max} as obtained with the above relation for 50% damping corresponds with the PGV as shown by Van Staalduinen (1995) for f ≤ 10 Hz and confirmed when compared with the PGV estimates using Campbell (1997). Consequently, PGV and $SV_{\max}$ are practically interchangeable.

Site response

In Dost et al. (2004), where we also compared surface observations with borehole observations, we found that the Campbell (1997) PGA and PGV relations predict well our observations including an average (soil) site amplification factor of around two. Wassing et al. (2004a,b) confirmed that this is a reasonable first approximation. They performed a specific study combining our results with a number of soil classes relevant for The Netherlands, but also modelled a large number of typical site response cases.

4. Hazard analysis

In the above sections we provided a summary of the current knowledge we have about the induced seismicity in the north of The Netherlands and proposed some seismicity models and parameters. We believe that we can provide reasonable generalized statistical models of the seismicity, which in turn would enable us to do a probabilistic hazard analysis, providing ground motion estimates. Therefore, based on our observations as described above we pursue a PSHA with the following basic assumptions:

a. Seismicity in the north of The Netherlands as observed since 1986 can be classified as induced seismicity due to gas exploitation and is not related to tectonic movements.

b. The induced seismicity occurs only within or in the direct vicinity of the gas reservoir being exploited.
c. The induced seismicity behaves like natural seismicity, i.e. most probably as chaotic phenomena and stationary as long as the gas exploitation continues at a long-term steady rate (Grasso and Sornette, 1998; Main, 1996).
d. Currently, we are not able to include in our hazard analysis a quantitative (physical) model for the causal relation between exploitation (rate) and seismicity except the simple on/off model, i.e. exploitation or no exploitation.

Our motivation for the first three assumptions has been presented in the previous section on seismicity.

The last assumption deserves some more explanation. Induced seismicity, as observed in The Netherlands, is extensively studied in order to find one or more causal relations between exploitation and the occurrence of seismicity. Consequently a number of hypotheses relating to specific fields have been presented (Logan and Rudnicki, 1994; Logan et al., 1997; Roest and Mulders, 2000; Roest and Kuilman, 1993,1994; Van Eijs, 1999; Nagelhout and Roest, 1997). In some cases differential stress across existing faults caused by compaction due to exploitation has been identified as an important factor (Mulders, 2003). So far, however, we have not been able to find a general quantitative model predicting the occurrence or non-occurrence of seismic events in a gas field, given specific physical conditions like reservoir pressure, pressure gradients, major faults, etc. Segall et al. (1994) and others suggest that it may be possible to produce such a model. They show a correlation between the predicted seismicity and the observed seismicity using a poroelastic stressing model for the Lacq gas field in France. Recently, Van Eijs et al. (2006) systematically compared a large amount of detailed exploitation data from many fields with the occurrence or non-occurrence of seismicity. They found plausible statistical relations between exploitation and induced seismicity for some cases, which we are currently investigating to include in the PSHA.

Methodology

Ground motion estimates at a site help engineers and regulators to analyse possible risk and/or implications from a regulators perspective. Consequently, site-specific hazard in terms of estimated ground motion is the hazard parameter we choose.

Then, from a range of possible methodologies to estimate the ground motion (Reiter, 1990) we have chosen a probabilistic seismic hazard analysis to estimate the site-specific ground motion. Here we present only a short description of the method, details can be found, for example, in Thenhaus and Campbell (2003) and McGuire (2004).

The generalized probabilistic approach was originally proposed by Cornell (1968) and developed in Cornell and Merz (1975) into what is currently known as the Probabilistic Seismic Hazard Analysis (PSHA). A ground-motion prediction equation (P[A>a]) depends on the size of the earthquake and the source-site distance, *r*. In Cornell's approach the ground motion at a site is estimated from all possible magnitude and distance combinations. In other words, we integrate over the ground motion estimate conditional to a combined magnitude probability and distance probability. The probability that a ground acceleration *a* will be exceeded at a specific site can be written as a conditional probability:

$$P[A > a] = \lambda \int_R \int_M P(A > a \mid m, r) \cdot f(m) \cdot g(r) \cdot dm\, dr \qquad \text{Eq 6}$$

Here, *f(m)* is the frequency-magnitude density distribution and *g(r)* an source-site density distribution, characterizing the probability that an event occurs at a distance *r* from the site. *λ* is a scaling factor representing the mean seismicity rate, and *m* the local magnitude.

Consequently, a general PSHA requires one or more ground-motion prediction equations, one or more frequency-magnitude distributions and implicitly a seismicity distribution in space. We prefer to keep our model as simple as possible. More complexity, as for example proposed by Lasocki (2005) also assumes we have more information to differentiate between models. This is not available in our case.

Return periods and exploitation

The seismic hazard can be, and is here, defined as the probability that a ground motion at a specific site will be exceeded during a time period, i.e. return period, T (years). Alternatively, it is the probability that a ground motion will be exceeded with an annual frequency of 1/T. In general, seismic hazard due to natural earthquakes is, rather haphazardly, presented as the probability that a PGA will be exceeded in T = 475 years (Bommer and Pinho, 2006; GSHAP, 1999). An alternative interpretation is a 10% probability that this PGA will be exceeded in 50 years.

The gas production in a field, however, continues usually during only one or several decades, i.e. much less than 475 or even 50 years. Therefore, instead we have chosen T = 100 years and T = 10 years, or 10% probability of exceedance in ten years and 10% probability of exceedance in one year respectively. For these return periods, comparable to the 'production life' of a field, we obtained the hazard for two parameters: PGA and SV_{max} with 50% damping.

Hazard estimates.

The hazard is estimated only for the duration of the production phase of three relevant gas fields, Roswinkel and Bergermeer fields (Figures 1 and 4), two small seismically active fields, and the Groningen field (Figure 4), the largest gas field in The Netherlands. Additional examples are presented in Van Eck et al. (2004). For all seismic hazard estimates we assume Campbell's PGA and PGV attenuation relation as described above with σ = 0.4 (for the lognormal distribution) as a low first approximation, and an exponential frequency-magnitude distribution based on the observed relations with M_{max} = 3.5 and M_{min} = 1.5. Models with M_{max} > 3.5 had little influence on the seismic hazard estimates. Further, we assume that the seismicity is uniformly distributed over the surface projection of the gas field and that it has a stationary rate during the production phase.

The hazard for a specific site is estimated by a numerical integration of (Eq. (6)). A number of programs have been developed over time to do this. EQRISK (McGuire, 1976), FRISK (McGuire, 1978) and SEISRISK (Bender and Perkins, 1987) are some examples. Our calculations have been done with a modified version of EQRISK. A detailed description of the methodology and its algorithm can be found in Cornell (1968) and McGuire (1976).

We estimated the hazard for the surface area above and in the direct vicinity of the gas field. For simplicity, we present the results as a specific cross-section of the area near the border of the gas field, as explained in Figure 8. Such hazard sections are in general valid as long as we do not have drastic contour variations on a kilometer scale in the gas field. The results are presented in Figure 9.

Parameter and model uncertainties

For the Roswinkel case we have performed a limited logic-tree approach to get an idea of the uncertainties involved (Figure 10 and Table 4). The results show that within a limited range of model parameters the hazard estimates may vary by a factor of two, mostly determined by the variability of the ground-motion prediction equation, σ. This sensitivity to σ is easy to explain and has been pointed out in many other studies (for example Van Eck and Stoyanov, 1996). Unfortunately, σ is largely determined by inherent unpredictable physical variations of the ground motion propagation and therefore difficult to reduce. Toro et al. (1997) also call this type of uncertainty aleatory uncertainty.

We assume a uniform distribution of the seismicity as our source zonation model. However, as suggested in Figure 4, seismicity may well be concentrated on specific faults or fault zones. This implies an uncertainty that may have a significant influence on the seismic hazard estimates as depicted, for example, in Figure 11 for different source models of the Groningen field. This type of uncertainty may well be possible to reduce as we obtain more concrete evidence of seismicity restricted to faults or fault zones. Toro et al. (1997) call this type of uncertainty, which is due to incomplete knowledge, epistemic uncertainty. Better instrumental coverage combined with specific analysis techniques aiming at improved location of the relevant events are pragmatic actions currently being implemented.

5. Discussion

Seismic hazard due to small magnitude induced events, albeit due to gas and/or oil exploitation, geothermal energy production or waste disposal through water injection, poses increasing social and legal problems (Cypser and Davis, 1998). Little has been published in the open literature on how to monitor and quantify this hazard adequately to address such problems. In this and an accompanying paper by Bommer et al. (2006) we present different approaches that have been implemented to deal with seismic hazard due to small-magnitude induced events.

The above hazard approach has been used for a first-order estimate of the seismic hazard due to induced seismicity in the framework of the 2003 Dutch mining legislation. We provide site-specific ground motion estimates and probabilities of occurrence instead of general maximum possible earthquake or maximum intensity. The obtained hazard estimates, PGA and response spectral characteristics, can be directly related to existing codes and regulations, for example Eurocode 8 (CEN 2003), provided a local modification of the response spectra is introduced. It appears that in The Netherlands building requirements to withstand other external forces, like wind, are sufficient to withstand the possible earthquake forces to warrant Eurocode 8 building regulations (van Staalduinen and Geurts, 1998). Estimated PGV values can be compared with existing Dutch vibration guidelines (SBR richtlijnen, 2002), which are similar to the German DIN 4120 norms. Their implications, however, remain unclear. For example, we show that there is a clear probability that the guidelines will be exceeded; it has been observed (PGV > 2 cm/sec for 10 Hz; see also Van Eck et al. 2004 and Dost et al, 2006) and we predict it will happen again. Currently it is still under discussion how to handle this. The fact that international guidelines show a significant difference of level of tolerance from country to country (Van Staalduinen and Geurts, 1998) does not make these discussions easier.

We have opted for the simplest possible seismicity model as we lack sufficient evidence to verify more complex models. Here we discuss where we may find future improvements. We assumed a randomly distributed stationary seismicity model for gas fields with on-going production and observed seismicity. The general statistical seismicity model (Figure 3) is consistent with stress driven, chaotic models as mostly observed in natural seismicity (Grasso and Sornette, 1998; Zoback and Zinke, 2002), but we do observe variations in, for example, the Bergermeer field. Figure 2 and Table 5 further suggest that in fields with induced seismicity it may take up to around 20 years before we observe the first felt induced event, but it may also occur within four years. Unfortunately, so far all efforts to relate the occurrence of seismicity to the production rate or level (see Mulders, 2003 for an overview) have not provided an alternative consistent model. On the other hand we have indications that induced seismicity does not occur randomly within the gas field but is correlated with existing faults, as shown by Haak et al. (2001) for the Bergermeer field, Van Eck et al. (2004) for the Roswinkel field and Mulders (2003) for the Groningen field.

However, systematically associating small earthquakes to specific faults requires a dense, preferably 3D, monitoring network. Improvement of the monitoring network, however, remains subject to a cost-benefit discussion in which the exploitation companies are involved. Some small and short-term (weeks) borehole microearthquake experiments (Jupe et al., 2001) have been performed near some smaller fields and provide encouraging, but so far inconclusive, results.

Our hazard model is not applicable to gas fields where no seismicity has been observed. Fortunately, the new Dutch mining law of 2003 obliges the exploitation companies to submit detailed production information to the Dutch authorities. Although these data remain confidential it enabled Van Eijs et al. (2006) to relate composite production parameters with seismicity and predict the probability of the occurrence of seismicity in fields where so far no induced seismicity has been observed.

Accurate strong ground-motion estimates for small and shallow earthquakes are important to verify observations and experiences of the local population, but are also a significant component in the hazard analysis. In our analysis we have used an existing ground motion prediction equation calibrated against our limited set of ground-motion measurements (Dost et al., 2004). The obtained local prediction equations (Dost et al., 2004), however, still include large variations, as we are unable to remove known factors with the limited set of local observations. Therefore, to improve the equation and reduce this variability, we continue in collaboration with the exploitation companies to deploy more accelerometers within the relevant areas. This is combined with a web-based initiative to make automatic EMS intensity maps (Grünthal, 1998). This combined effort should help us obtain more accurate relations between ground motion, specifically PGV, and intensities in the range II to VI. The currently proposed relations (Wald et al., 1999) deviate significantly from our observations and model (Figure 6).

6 Conclusions

Long-term detailed monitoring in the north of The Netherlands has provided a unique and fairly good general statistical description of induced seismicity due to hydrocarbon exploration in this region. On the basis of this data we provide a pragmatic first order (quantitative) seismic hazard estimate for 'seismically active' gas fields to fulfill the requirements of the new Dutch mining legislation and relate to existing European and national guidelines and codes. We find that the general quantitative conclusions of De Crook et al. (1998) and Van Staalduinen and Geurts (1998) remain valid and did not change significantly after five additional years of observation: that the maximum earthquake is unlikely to exceed $M_L = 3.9$ and that not more than light, non-structural damage is to be expected. The PSHA provides a first-order hazard estimate, which can be associated with engineering interpretations and further risk analysis, but it also reveals many uncertainties. Some uncertainties are inherent, such as the non-deterministic character of seismicity and the wave propagation (aleatory variability). Other uncertainties are clearly due to our lack of knowledge of the seismicity and specific fault interactions, and understanding of the coupling between the production parameters and the mechanisms driving the seismicity (epistemic uncertainty). Our hazard analysis approach identified clearly to relevant decision makers which specific uncertainties are still unresolved and if, and how, these may be diminished. It enabled them to set future priorities for monitoring and research on induced seismicity. Unfortunately, the presented hazard concept requires a significant effort to explain to the general public, which is not a new problem (Wang et al., 2003)

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Figure captions

Figure 1. General overview over the seismicity in The Netherlands and its immediate surroundings since 1900. Red circles indicate natural tectonic earthquakes. Blue circles indicate earthquakes caused by man-made activities, classified by the KNMI, usually mining or gas exploitation. The earthquakes are scaled according to magnitude. Dark green solid lines indicate mapped faults in the upper-north-sea formation according to the NITG. A more detailed map (inset) for the northern part of The Netherlands is shown in Figure 4.

Figure 2. Cumulative of the square root of the seismic energy (E) in Gjoule (light grey curve) of all earthquakes with $M_L \geq 1.5$ as a function of time. The black straight lines indicate the upper and lower energy boundaries, providing an estimate of $M_{max} = 3.8$ assuming that the energy release is and remains stationary. The inlay figure compares the cumulative seismic energy release (light grey curve) with cumulative gas production on land (black curve). Gas production numbers are kindly supplied by the NITG.

Figure 3. Cumulative annual frequency-magnitude relation obtained for all induced seismicity in the north of The Netherlands for the period 1986 - 2003 (black curve) and observations (black crosses). Also is shown the same frequency-magnitude relation for all earthquakes in the Groningen field. However, for this selection we have shown the relation excluding (grey broken curve) and including (grey curve) three events $2.7 < M < 3.0$ that occurred October-November 2003. This shows that the slope (b-value) of the frequency-magnitude relation for a subset of 179 events has a tendency to approach the b-value of the frequency-magnitude relation for all earthquakes (340 events).

Figure 4. A schematic figure of the hydrocarbon (gas) exploitation fields (grey), the major fault structures (source: NITG), the seismometer station WIT (inverted triangle), borehole seismometers (triangles) and the seismicity (solid circles) in the north-eastern part of The Netherlands (inset of Figure 1). Some of the gas fields discussed in this report are indicated: RF - Roswinkel Field; GF – Groningen Field, EF – Eleveld Field, AF – Annerveen Field. After Dost and Haak (2006).

Figure 5. Annual cumulative frequency-magnitude relation for all events associated with the Roswinkel gas field during the period 1992 – November 2003 and the best fit seismicity model for all available data.

Figure 6. Ground motion model (PGA and PGV) of Dost et al. (2004) and averaged intensity observations for the M=3.4 Roswinkel earthquake of 19 February 1997 (Dost and Haak, 1997). Also shown are the intensity values as related to the PGV by Wald et al. (1999).

Figure 7. Frequency at which the peak of the velocity response spectra occurs as a function of earthquake magnitude (M_L). The peak frequencies are measured at the horizontal components of acceleration recordings of 19 events in the Netherlands; 12 shallow induced events (blue) in the northern part of The Netherlands and 7 natural seismic events (red) in the southern part of The Netherlands. All sites are characterized as stiff soil.

Figure 8. Estimated hazard at and around the Roswinkel field. The hazard has been estimated for two return periods, i.e. T=10 years (left) and T=100 years (right). The hazard indicates a 10% probability that the peak values as indicated can be exceeded within 1 year (T=10) and within 10 years (T=100) respectively. Alternatively, the figures indicate an annual probability of 10% (T=10) and 1% (T=100) that the indicated peak values will be exceeded. In the following figures the hazard is only shown as a section indicated, for example, in this upper left figure. The x- and y-axis indicate distance in kilometers.

Figure 9. Seismic hazard as a function of distance from the surface projection of the exploitation field. Three examples are shown: The Groningen, the Bergermeer and the Roswinkel field. The top two figures show the PGA for two return periods, T=10 and T=100 years. The bottom two figures show the same for the V_{max} at 50% damping. These hazard-distance functions have been used in the pragmatic approach to obtain seismic risk estimates.

Figure 10. Sensitivity analysis for the seismic hazard in the vicinity of the Roswinkel field for different model and parameter values. Left figures: hazard estimates for T=10. Right figures: hazard estimates for T=100. From top to bottom: the PGA and

the peak spectral velocities 50% damping. Two extreme models (A and C) and one average model (B) are indicated in blue. Other models are indicated in green.
Hazard model A (upper curve): seismicity model 1, i.e. $N(M\geq 1.5)=8$, $b=0.8$, $M_{max} = 3.9$ and $\sigma = 0.4$.
Hazard model B (middle curve): seismicity model 2, i.e. $N(M\geq 1.5)=2$, $b=0.5$, $M_{max} = 3.5$ and $\sigma = 0.4$.
Hazard model C (lower curve): seismicity model 2, i.e. $N(M\geq 1.5)=2$, $b=0.5$, $M_{max} = 3.5$ and $\sigma = 0.2$.

Figure 11. Two source models used in a seismic hazard analysis for a schematic Groningen field and T=100. To the right the seismicity is assumed to be uniformly distributed over the whole exploitation field. To the left the seismicity is assumed to be distributed over four main faults (here modeled as straight lines). Observed seismicity suggests some linear correlations that may be related to fault zones.
This comparison gives an indication of the uncertainty due to the source modeling. In some areas the hazard increases in PGA from around 225 to 300-350 cm/sec^2. In other areas the hazard decreases in PGA from around 225 to about 100-125 cm/sec^2 and even lower. The x- and y-axis indicate distance in kilometers.

Table 1. *Roswinkel and Bergermeer field M ≥ 3.0 earthquakes and magnitude corresponding to the cumulative seismic energy release as observed up to 2003*

Date	**M_L**	**M_w**	**comments**
06-08-1994	3.0	-	Bergermeer
21-09-1994	3.2	3.2*)	Bergermeer
19-02-1997	3.4	-	Roswinkel
14-07-1998	3.3	-	Roswinkel
25-10-2000	3.2	-	Roswinkel
09-09-2001	3.5	3.5**)	Bergermeer
10-09-2001	3.2	3.1**)	Bergermeer
1986-2003 Roswinkel	**3.7**	-	Cumulative magnitude all recorded events
1986-2003 Bergermeer	**3.7**	-	Cumulative magnitude all recorded events

*) Haak (1994b);
**) Haak et al. (2001)

Table 2. *Estimated M_{max} using a Bayesian approach.*

mean	**median**	**84%**	**Comments**
3.5	3.5	3.8	Earthquake data 1986-1997 (De Crook et al, 1998)
3.7	3.6	3.9	Earthquake data 1986-2003 (This paper)

Table 3. *Intensity versus ground motion for natural events.*

Intensity	**I**	**II-III**	**IV**	**V**	**VI**	**VII**
PGA %g [a])	< 0.17	0.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34
PGV cm/sec [a])	<0.1	0.1-1.1	1.1-3.4	2.3-8.1	8.1-16	16-31
PGA cm/sec^2 [b])			<10	22	50	100
Pred PGV cm/sec [c])	< 0.5	0.2 – 1.2	0.5 – 4.5	1.0 – 7.0	1.5 –	
Pred PGV cm/sec [d])	< 0.5	0.2 – 1.2	0.5 – 2.4	1.0 – 3.4	1.5 –	

[a]) Wald et al. (1999) (used Modified Mercally scale)
[b]) De Crook (1996) seismic zoning map for The Netherlands conforming to Eurocode-8 (MSK-scale)
[c]) Predicted values using Dost (2004) for small induced events at around 2.5 km depth.
[d]) Predicted values using Campbell (1997) for small induced events at around 2.5 km depth.

Table 4. *Model parameters used for Roswinkel sensitivity study*

Seismicity models	1: N (M ≥ 1.5) = 8, b = 0.8
	2: N (M ≥ 1.5) = 2, b = 0.5
	3: N (M ≥ 1.5) = 2, b = 0.8
M_{max} parameter	3.5
	3.9
σ	0.2
	0.3
	0.4

Table 5. *Gasfields, their production start and the first observed seismic event.*

Gasfield	**Production start *)**	**First observed seismicity $M_L > 2.0$**	M_L	**Delay (years)**	**Comments**
Roswinkel	1980	11-06-1992	2.7	12	
Sleen	1981	-	-	-	Stopped production
Bergermeer	1972	06-08-1994	3.0	22	
Bergen	1978	10-10-2001	2.7	23	
Groningen	1963	05-12-1991	2.4	28	
Eleveld	1975	26-12-1986	2.8	11	First event uncertain location
Annerveen	1973	16-08-1994	2.3	21	
Roden	1976	02-09-1996	2.1	20	
Dalen (Zechstein**?**)	1974	17-11-1996	2.2	22	Event association uncertain
Norg	1983	-	-	-	
Appelscha	1999	16-06-2003	2.3	4	
Emmen (Zechstein)	1977	15-02-1991	2.0	14	
Waalwijk	1991	-	-	-	2003: 12 years
Middelie (Zechstein**?**)	1975	01-12-1989	2.7	14	association uncertain.
Lacq (France)	1957	1969	3.0	12	First felt induced event (Lahaie and Grasso, 1999)

*) source NITG/TNO

Figures

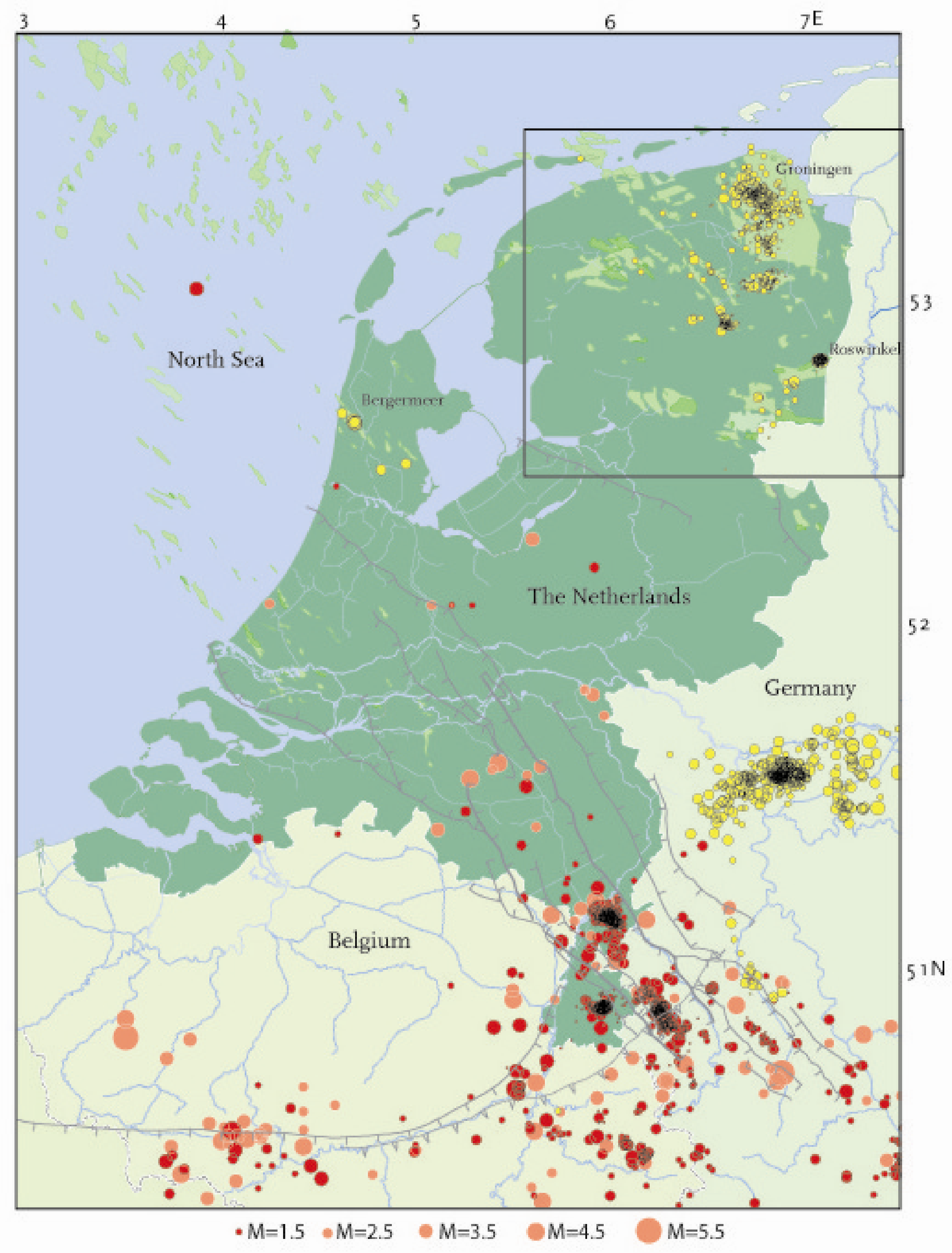


Figure 1.

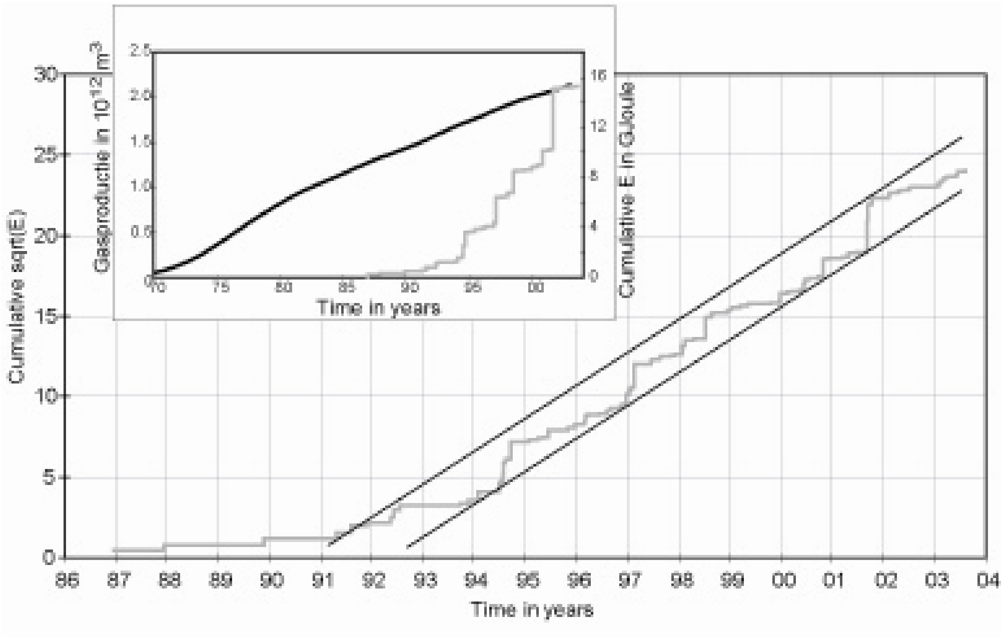


Figure 2.

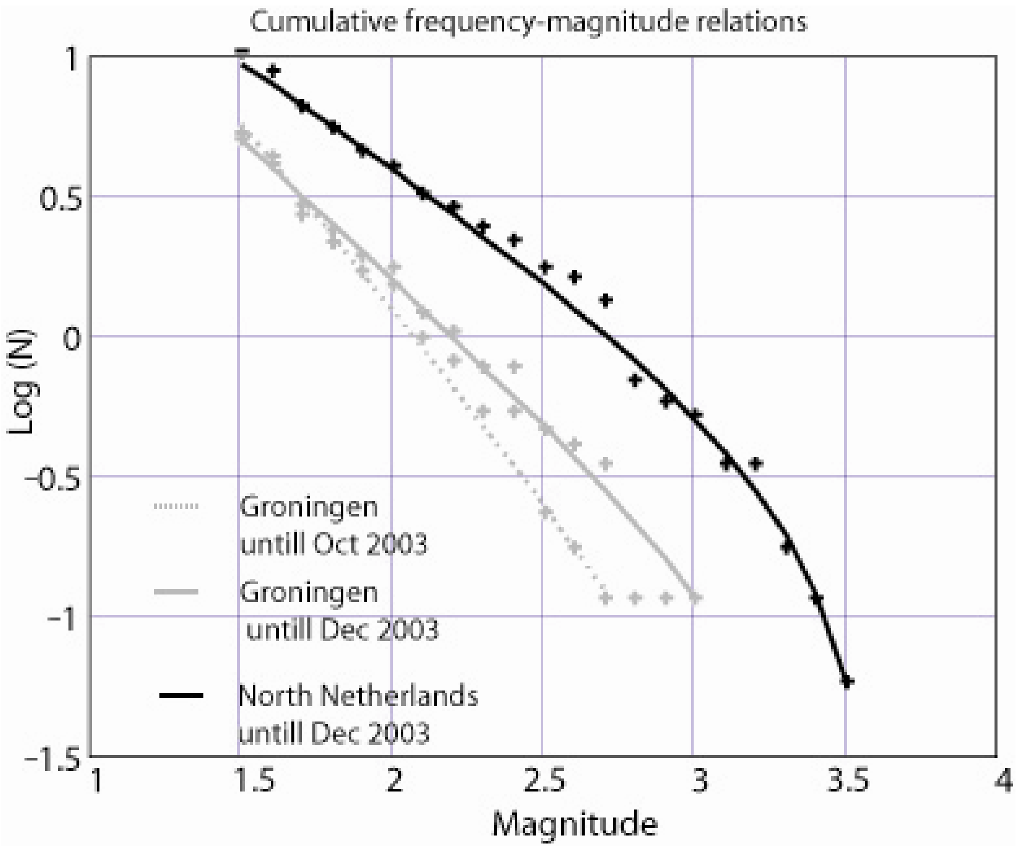


Figure 3.

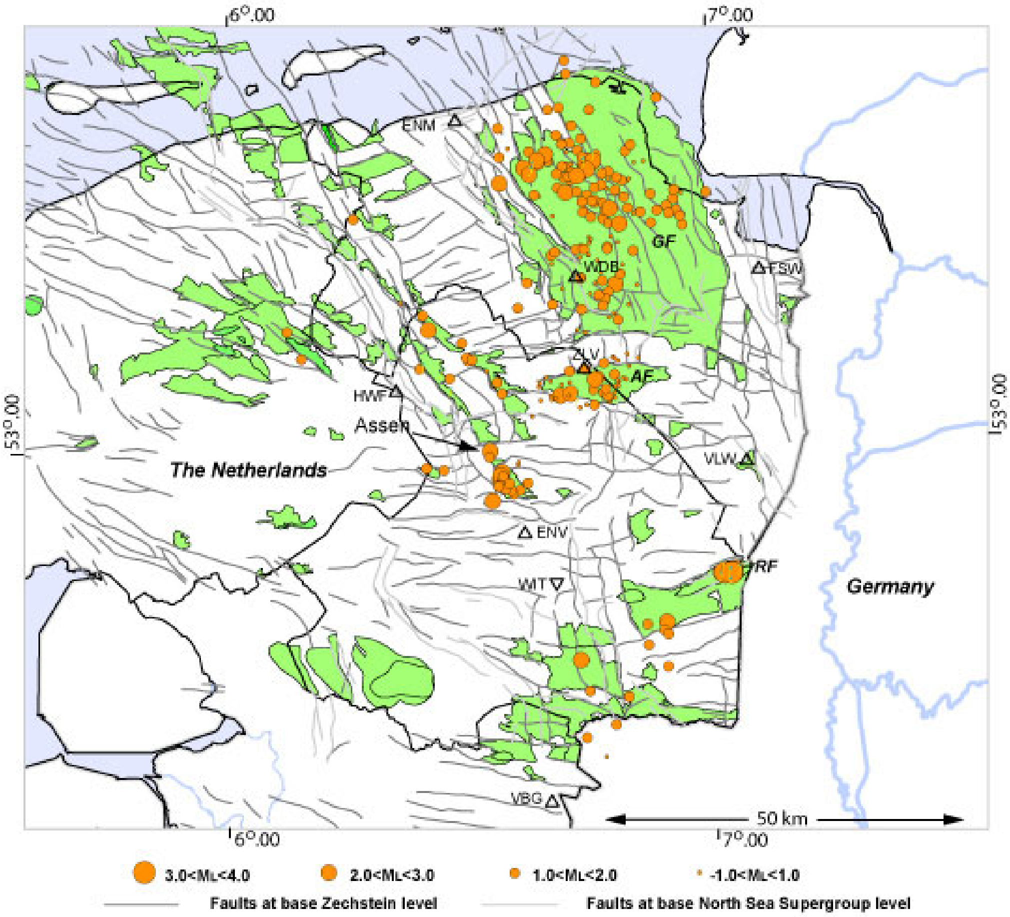


Figure 4.

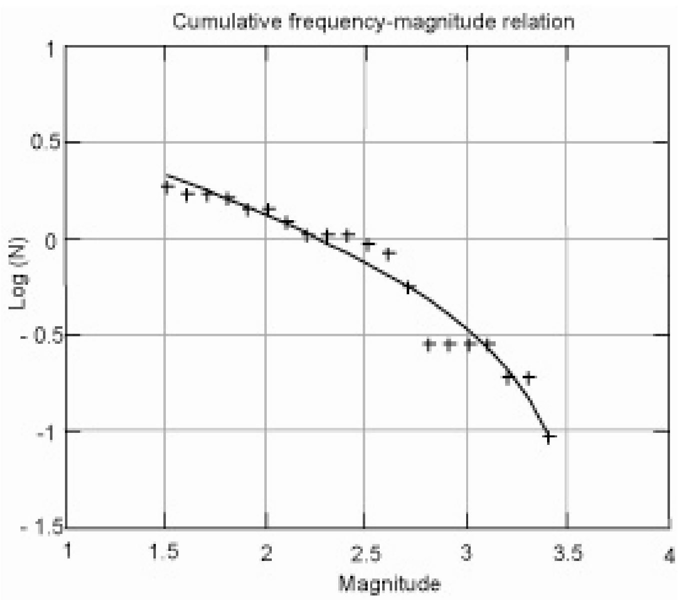


Figure 5.

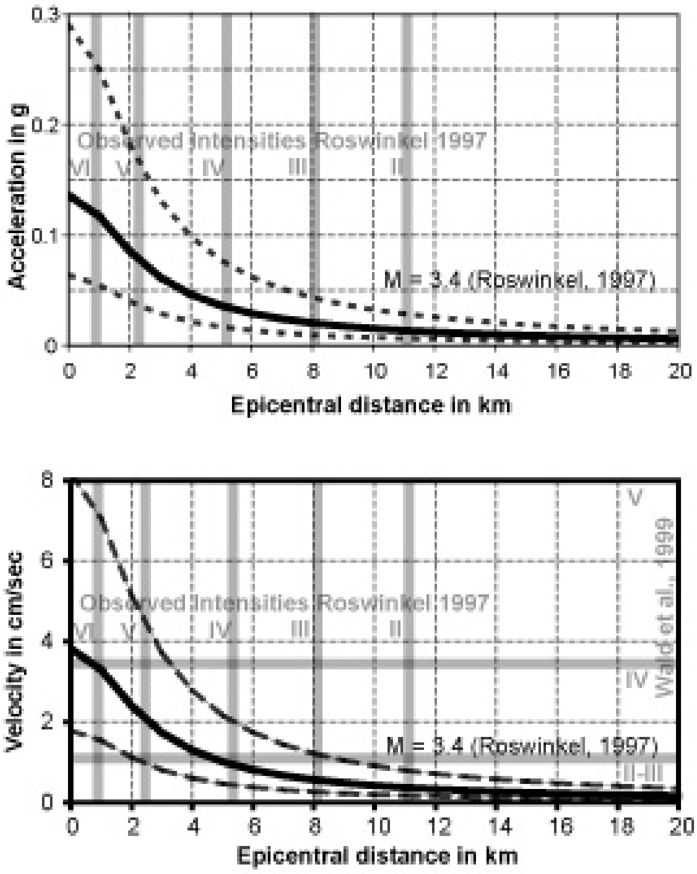


Figure 6.

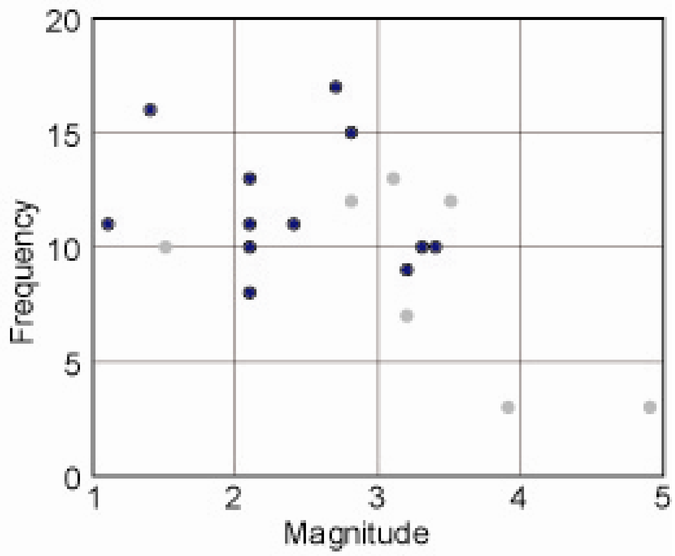
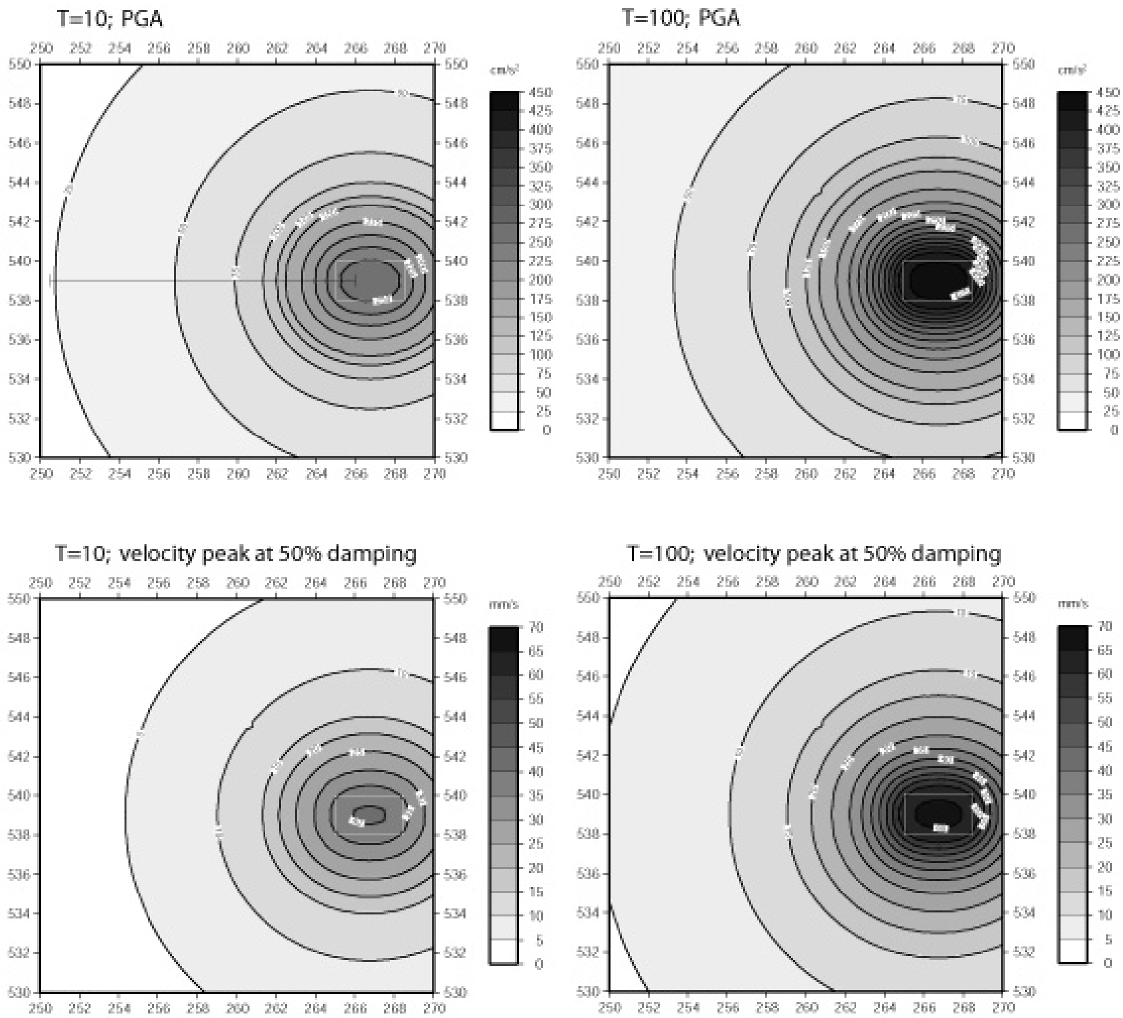


Figure 7.



T=10; PGA
T=100; PGA
cm/s²
T=10; velocity peak at 50% damping
T=100; velocity peak at 50% damping
mm/s

Figure 8.

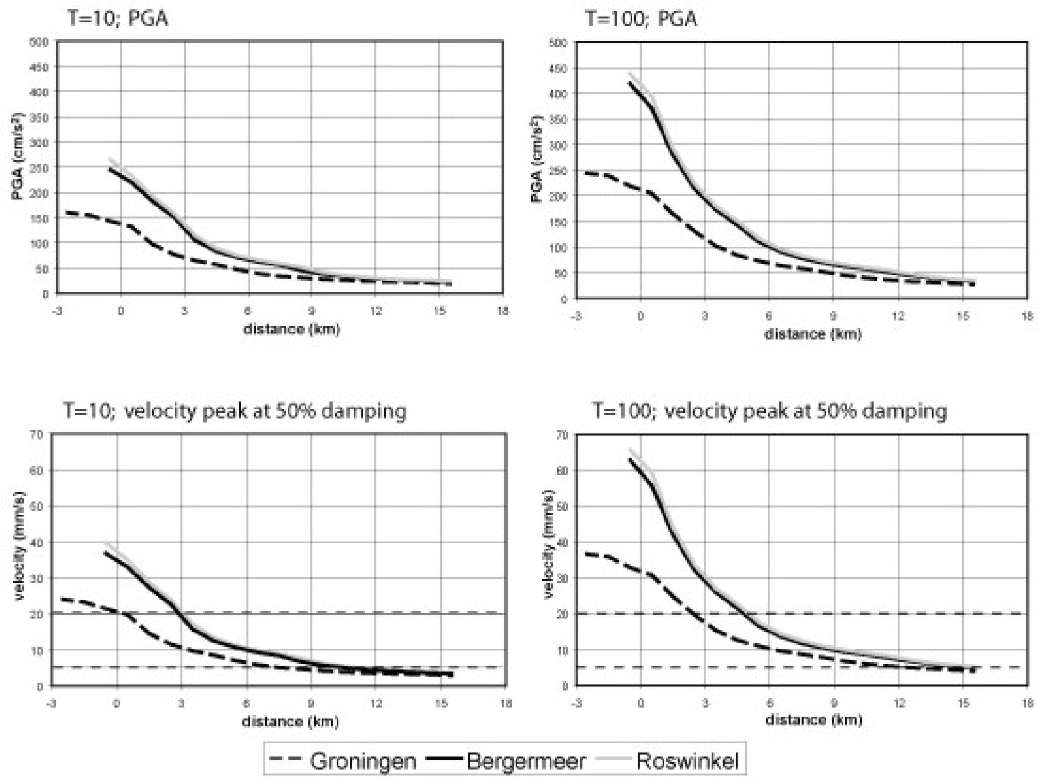


Figure 9.

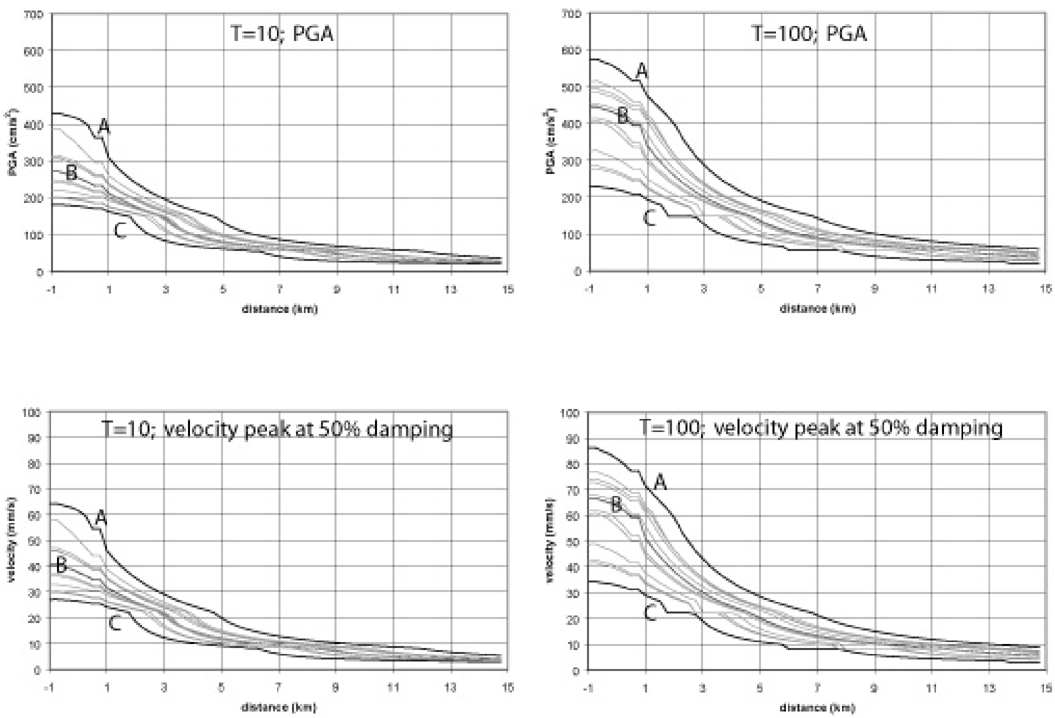


Figure 10.

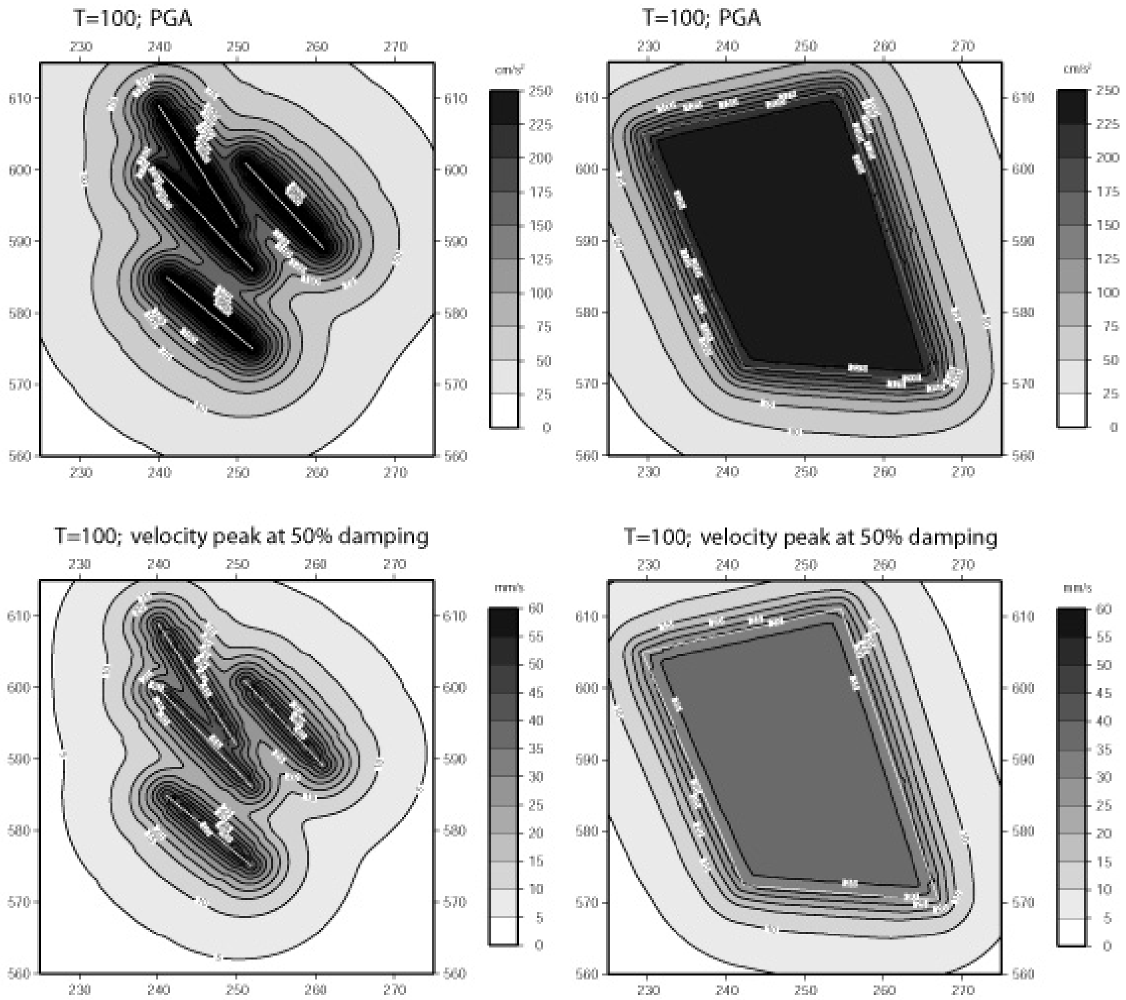

T=100; PGA
T=100; PGA
cm/s²
T=100; velocity peak at 50% damping
T=100; velocity peak at 50% damping
mm/s

Figure 11.