Engineering Geology 237 (2018) 198–207

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Categorizing seismic risk for the onshore gas fields in the Netherlands

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ARTICLE INFO

Keywords:
Induced earthquakes
Groningen gas field
Geostatistics
Netherlands
Seismic risk

ABSTRACT

In recent years public concern about earthquakes induced by gas production has increased in the Netherlands. This has mainly been caused by numerous seismic events related to gas depletion in the Groningen gas field, the largest gas field in Western Europe. Induced seismicity has also been observed in 31 smaller gas fields located on land (onshore) or in the area close to the Dutch coast. Earthquakes with magnitudes as high as M_L = 3.5 have occurred in Roswinkel and Bergermeer causing damage to buildings.

In 2016 State Supervision of Mines (SSM), with input from the geological survey of the Netherlands (TNO) and the onshore operators, proposed a guideline for a qualitative seismic risk analysis for depletion induced seismicity arising from gas production in the small fields in the Netherlands. The guideline follows international practices for risk assessment using a risk matrix approach. This paper elaborates the seismic risk guideline and reports on the application of the guideline to the gas fields in the Netherlands.

Risk is a combination of hazard and consequences. The result of the seismic risk analysis is qualitative and gives a relative scoring of the producing gas fields in the Netherlands in terms of risk. In order to obtain more information on the quantitative assessment of the risk, more detailed studies are needed. The Groningen gas field clearly poses a much larger seismic risk than that obtained for the other, smaller gas fields, most of which fall into the lowest risk category. Because of the large difference in risk between the Groningen field and the other smaller gas fields, the guideline of SodM deems it sufficient to carry out a qualitative risk analysis for the other gas fields in the Netherlands, as performed in this paper. Based on the combination of the hazards and consequences, the risk can be further interpreted and, if necessary, appropriate measures can be implemented.

1. Introduction

In recent years public concern about seismic events induced by gas production has increased in the Netherlands, largely because numerous events have occurred due to gas depletion of the Groningen gas field. The Groningen field is the largest gas field in Western Europe, with originally close to 3000 billion cubic meters (bcm) gas in place (Van Thienen-Visser and Breunese, 2015). In 2013, an investigation by the Dutch State Supervision of Mines (SSM) showed that the occurrence probability of earthquakes with larger magnitudes in the Groningen gas field was higher than previously expected (Muntendam-Bos and de Waal, 2013). Since 2013, several investigations have analyzed the seismicity of the Groningen field and its relation to gas production. Based upon these the Dutch minister of Economic Affairs imposed measures to reduce production since January 2014, to limit the seismicity of the Groningen gas field. These measures have proved effective: between 2014 and 2017 the seismicity rate and magnitude of the events have declined considerably (Nepveu et al., 2016). Although, recently, one larger magnitude event has occurred (M = 3.4, January 8th 2018).

Induced seismicity has also been observed in 31 smaller gas fields located on land (onshore) or in the area close to the Dutch coast. Earthquakes with magnitudes as large as M_L = 3.5 have occurred in the Roswinkel and Bergermeer fields (Van Eck et al., 2006) and have resulted in building damages (Roos et al., 2009; Van Kanten-Roos et al., 2011). The level of seismic activity in the small gas fields varies significantly. Most fields have experienced only a few events. Some fields are, however, more active such as the Annerveen, Eleveld, and Roswinkel gas fields.

In 2016, using input from the geological survey of the Netherlands (TNO) and the onshore operators, SSM formulated a guideline (Muntendam-Bos et al., 2015) for a qualitative seismic risk analysis for the small fields in the Netherlands consisting of three steps. The guideline addresses the risk matrix approach of the second step, which follows international practice, however it provides no details. This paper focuses specifically on these details in the methodology, which

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https://doi.org/10.1016/j.enggeo.2018.02.004
Received 24 March 2017; Received in revised form 26 January 2018; Accepted 8 February 2018
Available online 20 February 2018

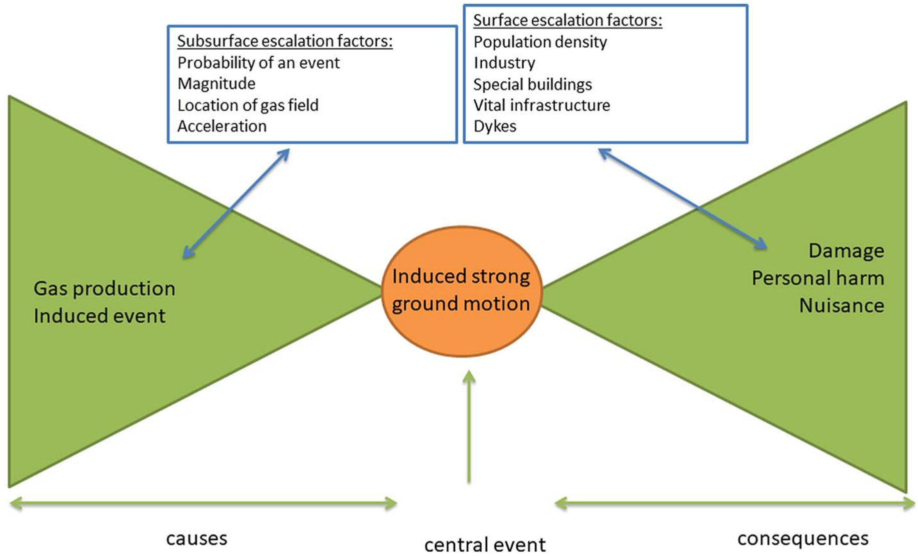

Fig. 1. Bow-tie with induced strong ground motion as central event. On the left hand side the single cause of human induced seismicity taken into consideration in this paper is indicated and on the right hand side the consequences. The escalation factors subsurface and surface play a role on escalating the cause toward the central event and the consequences respectively.

have since been developed and shows the application of this second step. Step one and three are specified in the guideline which is beyond the scope of this paper.

2. Method

In the seismic risk guideline (Muntendam-Bos et al., 2015) central to the assessment of seismic risk is the bow-tie assessment methodology. In a bow-tie analysis, the causes and consequences of a central event are examined. To the left of the central event the causes are inventoried and to the right, the consequences. In the case of induced seismicity the central event is strong ground motion. The strong ground motion induced is related to a seismic event occurring due to human activities. In our case we specifically focus on induced events occurring due to production of gas from a gas field. Hence, only a single cause is represented in the bow-tie of Fig. 1. The consequences of the induced strong ground motion could be damage to houses, industry and dykes, and personal injury and nuisance.

Beside the cause (gas production), there are various factors which influence the likelihood for a seismic event to occur and whether the event induces a damaging ground motion. These are all related to the subsurface. At the same time, the extent of the consequences at the surface is also affected by circumstances. In the bow-tie methodology, these factors are known as escalation factors. For both the hazards and the consequences, escalation factors have been defined. They are chosen using expert judgment and information in published studies on induced seismicity due to gas production in the Netherlands. In the risk matrix method these escalation factors are combined with a scoring scheme for the degree to which they increase the probability of the main event or a consequence in order to assess the seismic risk.

Observations in the Netherlands indicate that a minimum pressure depletion may be required in order to induce a seismic event during gas production. A threshold value of 90 bar was derived (Eijs et al., 2004; Van Eijs et al., 2006). In a later reanalysis the threshold was adjusted to 28% of the initial gas pressure in the reservoir (Van Thienen-Visser et al., 2012). This may indicate that the old, tectonically inactive faults in and bounding the gas fields have a larger cohesion and are, therefore, not critically stressed. However, some care should be taken as the analysis has been performed on all recorded seismicity, independent of the magnitude of the events, while the detection and location thresholds over the Dutch gas fields varies and events below these thresholds may have occurred in the gas fields but remained undetected.

In addition to the level of depletion, it has been shown empirically that several geological characteristics of the fields are discriminative for whether or not seismicity is induced (Eijs et al., 2004; Van Eijs et al., 2006; Van Thienen-Visser et al., 2012). They include the fault density, which is determined using the length of the faults in the reservoir and the bulk volume of the reservoir, and the relative stiffness captured in a contrast between the Young's modulus of the reservoir and seal. In (Eijs et al., 2004; Van Eijs et al., 2006; Van Thienen-Visser et al., 2012) these geological characteristics were combined in a statistical study to determine the historical probability that a gas reservoir had experienced earthquakes during gas production. For the seismic risk analysis, we consider this probability as one of the input parameters.

If an event occurs, the magnitude of the event, the hypocentral depth, and the site response of the local shallow subsurface determine the extent of the ground motion. The risk over the lifetime of the gas field largely depends on which magnitudes occur frequently. Since the frequency of these magnitudes are related log-linearly to the largest magnitude event which could realistically occur, using a Gutenberg-Richter relation (Gutenberg and Richter, 1956), the maximum magnitude has been adopted as one of the escalation factors. Local site amplification is another important parameter that influences the extent of the ground motion as very soft soils can significantly amplify ground motions. Hence, it has also been adopted as one of the escalation factors.

The guideline presented by Muntendam-Bos et al. (2015) identified the need to include the public sensitivity and tolerance to seismicity, and the construction standards of the buildings in the exposed area. As an escalation factor an estimate of the possible extent of damage to infrastructure and buildings and an estimate of the social, financial, and reputational impact of a seismic event was suggested. However, to assess the escalation factors, the method needs to focus on public information which is relatively easily accessible and irrefutable. Building vulnerability is an important factor, but information on this factor is usually not available. We found that population density, and the presence of industrial facilities, dykes, important buildings (hospitals, schools, etc.) and vital infrastructure are factors which escalate the extent of the consequences on which information is indisputably available. In the next paragraphs each escalation factor is discussed in more detail.

Tables 1 and 2 show the scoring of the escalation factors of the subsurface and surface respectively, which was absent in Muntendam-Bos et al. (2015). Based upon the characteristics of each gas field, the

Table 1
Scoring of the subsurface escalation factors.

Points	Probability and occurrence of induced events	Magnitude	Location of gas field	Acceleration
5		Both methods $M_L > 4.5$		
4	> 5 $M_L \geq 1.5$ events occurring each year	1 method $M_L > 4.5$ and/or both methods $4.1 \leq M_L \leq 4.5$		
3	< 5 $M_L \geq 1{,}5$ events occurring each year	1 method $4.1 \leq M_L \leq 4.5$ and/or both methods $3.6 \leq M_L \leq 4.0$		$> 60\%$ weak soil ($V_{s,30} \leq 200$ m/s) and/or $> 30\%$ susceptible soil[a]
2	P = 42% or Events $M_L < 1.5$ occurring	1 method $3.6 \leq M_L \leq 4.0$ and/or both methods $3.1 \leq M_L \leq 3.5$	North of the line Amsterdam - Arnhem	30–60% weak soil ($V_{s,30} \leq 200$ m/s) and/or 15–30% susceptible soil[a]
1	P = 19%	1 method $3.1 \leq M_L \leq 3.5$ and/or both methods $2.6 \leq M_L \leq 3.0$		10–30% weak soil ($V_{s,30} \leq 200$ m/s) and/or 5–15% susceptible soil[a].
0		1 method $2.6 \leq M \leq 3.0$ and/or both methods $M_L \leq 2.5$	South of the line Amsterdam – Arnhem	$< 10\%$ weak soil ($V_{s,30} \leq 200$ m/s) and/or $< 5\%$ susceptible soil[a]

[a] Soil that is extra susceptible to amplification, such as peat layers that are thicker than 3 m and peat layers with a thickness between 1 and 3 m on top of a relatively stiff soil.

gas field's individual score is calculated. The points are then normalized by the maximum possible number of points to achieve the normalized of the subsurface and the surface escalation score. The combination of points for the normalized subsurface and surface escalation scores (subsurface × surface) gives the qualitative seismic risk for the given field.

The result of the seismic risk analysis depends on the escalation factors chosen and on the number of points attributed to each of the factors. The method weights the subsurface and the surface factors equally by first normalizing both and then determining the normalized risk.

3. Influence factors for the subsurface

3.1. The probability of an induced event

The probability of an induced event occurring due to gas production in the Netherlands has been investigated previously in Van Eijs et al. (2006). In that study a correlation between hydrocarbon reservoir properties and induced seismicity in the Netherlands was investigated. It was found that pressure depletion, fault density and relative stiffness of the reservoir compared to the overburden were properties that can discriminate seismic active from inactive fields in the Netherlands. In an update in 2012 (Van Thienen-Visser et al., 2012), the results were further refined by observations of induced seismicity between 2004 and 2010. In the update, the occurrence probability of induced earthquakes was classified at different levels ranging from negligible, 19%, 42% and 100%, with 100% being assigned when induced earthquakes have already occurred.

If a specific gas field has a negligible probability of an event being induced by gas depletion, the field is discarded from the current risk matrix analysis. This is in accordance with the guideline's first step analysis (Muntendam-Bos et al., 2015). The justification is the fact that if the central event (strong ground motion) does not occur, the risk will not occur either.

3.2. Maximum magnitude

In the context of the present study, the maximum magnitude is defined as the strongest magnitude of an event which could realistically occur in a gas field. The occurrence probability of the maximum magnitude event is low but not negligible. The maximum magnitude is determined using two methods reflecting both the geological and operational limiting aspects that influence the maximum magnitude that could occur in a gas field.

In the first method the dimension of the largest fault in the gas field is used to estimate an upper bound of the possible slip area of an earthquake. The slip area can be used to estimate the maximum magnitude of a possible event. The method was previously applied to determine the maximum magnitude for the Bergermeer gas storage (Muntendam-Bos et al., 2008).

The relation between the seismic moment (M_0) and the slip surface, assuming a dip-slip rectangular fault, is given by Stein (2006):

$$M_0 = \frac{3\pi}{8}\Delta\sigma\,(w^2L)$$

In this equation $\Delta\sigma$ is the stress drop, w is the height, and L the length of a rectangular fault. The stress drop is defined as the difference in stress over a fault before and after an event. The seismic moment can be transformed into a moment magnitude using (Hanks and Kanamori, 1979) and converting to SI units,

$$M_w = ({}^{10}\log(M_0) - 9.1)/1.5$$

For naturally occurring events the stress drop typically varies between 1 MPa (10 bar) and 10 MPa (100 bar) (Abercrombie, 1995). For most observed induced events in the Netherlands, stress drops have not

Table 2
Scoring of the surface escalation factors.

Points	Population density (number of people per km^2)	Industry	Special buildings and vital infrastructure	Dykes
4	> 2500	Multiple directly above the field	Multiple hospitals and/or energy suppliers above the field	Primary dykes above the field
3	1000–2500 and/or 500–1000 including vulnerable flats within 5 km of the gas field	1 above the field and/or multiple within 5 km of the field	1 hospital and/or energy supplier above the field or multiple within 5 km of the field. Multiple schools and/or public buildings above the field	Primary dykes within 5 km of the field and/or secondary dykes above the field
2	500–1000 and/or 250–500 including vulnerable flats within 5 km of the gas field	1 within 5 km of the field	1 school and/or public building above the field or multiple within 5 km of the field	Secondary dykes within 5 km of the field
1	250–500 and/or < 250 including vulnerable flats within 5 km of the gas field		1 school and/or public building within 5 km of the field	
0	< 250	None within 5 km of the field	None within 5 km of the field	None within 5 km of the field

exceeded 5 MPa (50 bar Dost, 2018). We have chosen a stress drop of 5 MPa as a conservative estimate for determining the maximum magnitude. If a stress drop of 1 MPa is chosen, the calculated maximum magnitudes will be 0.5 magnitude units (M_w) lower. If a stress drop of 10 MPa is chosen, calculated maximum magnitudes will be 0.2 magnitude units (M_w) higher.

In our analysis it is assumed that movement of faults is limited to the reservoir itself. Geomechanical modeling (Wees et al., 2014) shows that depletion induces increasing stresses on faults inside the reservoir and just above and below it. The assumption that movement is limited to the reservoir where depletion occurs is reasonable if tectonic stresses are such that movement of faults will not propagate much beyond the boundaries of the reservoir. This assumption seems reasonable, given that induced events in the Netherlands have only occurred after at least a significant pressure depletion in the gas reservoirs (Van Thienen-Visser et al., 2012; Wees et al., 2014). However, it may lead to an underestimation of the maximum magnitude if faults below the reservoir are critically stressed.

Fault orientation in the local stress field plays an important role for the occurrence of induced seismicity. The local stress field, however, is largely unknown, which is why fault orientation is not explicitly taken into account. Implicitly, however, the initial stress field is taken into account as only gas fields with a depletion of > 28% are considered for the seismic risk analysis (Eijs et al., 2004; Van Eijs et al., 2006; Van Thienen-Visser et al., 2012), since they may have a non-negligible probability of causing an event in the Netherlands. The observation that induced seismicity does not seem to occur in gas fields with a depletion < 28% implies that optimally orientated fault patches may become critically stressed and slip only after a depletion of 28%. Many gas fields in the Netherlands are produced to a depletion level of 90% or more. At this level, even fault patches that are not optimally orientated in the stress field may become critically stressed and may slip as well. Therefore, fault orientation may not be that important for depleted gas fields in the Netherlands.

Since the largest fault in the reservoir is used to calculate a maximum magnitude, irrespective of its orientation, this could lead to an overestimation. Relative to the thickness of the reservoir the fault length may be such that it is quite unlikely that the entire fault will slip. Both taking the entire length of the fault in the reservoir as well as not taking account of fault orientation tend to lead to overestimation of the maximum magnitude that could occur.

Production from Dutch gas fields results in reservoir compaction and stress changes on reservoir faults (Roest and Kuilman, 1994; Mulders, 2003; TNO, 2013). The second method for calculating the maximum magnitude is based on the available energy in the reservoir which could be released in a single seismic event, assuming none has already been released prior to this event. This method has been described in Bourne et al. (2014), where reservoir compaction is linked to induced seismicity occurring in the Groningen field. Compaction in the reservoir can be calculated using different compaction models, e.g. a linear relation between depletion and compaction/strain, a time decay relation introducing a delay between depletion and compaction/strain (Mossop, 2012), or a rate type compaction model where compaction/strain depends both on depletion and depletion rate (De Waal, 1986; Pruiksma et al., 2015). For the Groningen gas field the rate type compaction model is found to best predict the temporal behavior of the observed subsidence (Fokker and van Thienen-Visser, 2016; NAM, 2016). In our analysis, the rate type compaction model (RTiCM Pruiksma et al., 2015) is used instead of a linear compaction model if the geology for the reservoir and seal is similar to the Groningen gas field. Since the RTiCM model was calibrated on laboratory measurements of cores from the Groningen field as well as on the subsidence for the Groningen field and not for the other gas fields, this more sophisticated compaction model can be used only for gas fields similar to the Groningen gas field.

From the volume of compaction, a reservoir moment (in Nm) is calculated as (Bourne et al., 2014).

$$RM = 2^{*}G^{*}Vc$$

where G is the shear modulus of the reservoir rock and Vc the bulk compaction volume. The resulting maximum magnitude (M_w) is calculated using

$$M_w = ({}^{10}\log(\alpha^{*}RM/2) - 9.1)/1.5$$

Following TNO (2013) a strain partitioning coefficient α is introduced to account for the fact that not all available energy is released seismically. Part of the energy will be dissipated in aseismic movement, elastic strain, heat, etc. In the Groningen gas field, which has the largest number of observed induced events, 0.5% of the total energy has been released seismically (Bourne et al., 2014). This translates into a strain partitioning coefficient of $\alpha = 0.005$. Using a conservative approach, a strain partition coefficient of 0.01 (1% maximum release of seismic energy) is assumed, which is higher than that observed in all gas fields in the Netherlands. As such, this assumption adopts an upper bound to the strain partitioning coefficient and tends to overestimate the maximum magnitude. Increasing or decreasing the strain partition coefficient by a factor of 10 increase or decrease the strongest magnitude by 0.7 magnitude units (M_w). If the linear compaction model is used instead of the RTiCM, magnitudes increase by 0.2 magnitude units (M_w).

3.3. Location of gas field

In the Netherlands no induced seismicity due to gas production has been recorded south of the line Amsterdam–Arnhem, despite gas production in several fields (see Fig. 5). Tectonic events have been observed in the southern provinces of Limburg and Noord Brabant indicating that tectonic stresses are likely to be higher in these regions. There is no record of tectonic or induced events in the area of Rotterdam/The Hague. Considering the detection threshold in this area, this means that no seismicity with magnitudes exceeding $M_L = 1.8$ have occurred. It is yet unexplained why gas production in this area does not lead to (detectable) seismic events. Possible explanations are differences in local stresses, different orientations of faults, local geology, or the absence of the thick Zechstein salt layer in this area that is present in the north of the Netherlands. It has been shown that gas fields with a thick Zechstein salt layer as seal have a statistically higher probability of causing induced seismicity while gas is being produced (Van Eijs et al., 2006). Geomechanical analysis (Orlic and Wassing, 2012) indicates that salt has a major influence on the occurrence of seismicity resulting from gas depletion. Salt at 3 km depth (which is the depth of most of the gas fields in the Netherlands), behaves ductile and will flow to relieve imposed stresses. The relaxation of the stresses in salt leads to additional stresses being added to the top of the reservoir.

3.4. Amplification

Combining the magnitude of an induced event with focal depth gives a first order estimation of the peak ground acceleration (PGA) that will be induced at the surface. The near-surface geology can have a significant impact on signal amplification, e.g. more damage is observed for houses on weak soils such as peat or clay than for houses on strong soils such as sand (Kruiver et al., 2015). The map of shallow soils given in Wassing and Dost (2012) is used to determine the percentage of available soils (weak soils, peat) within the contour of the gas field and a 5 km periphery around the gas field. The percentages of soils available in this area determine the score for amplification.

The scoring adopted for the subsurface escalation factors is different for each individual factor and is based on expert judgment. The possible strongest magnitude and the probability of inducing an event are assigned the highest weights, whereas the weights for the location and acceleration are lower because they are expected to contribute less to the cause of ground motion than the first two factors. The degree of ground motion will largely be determined by the probability that an event will occur and the magnitude of the event.

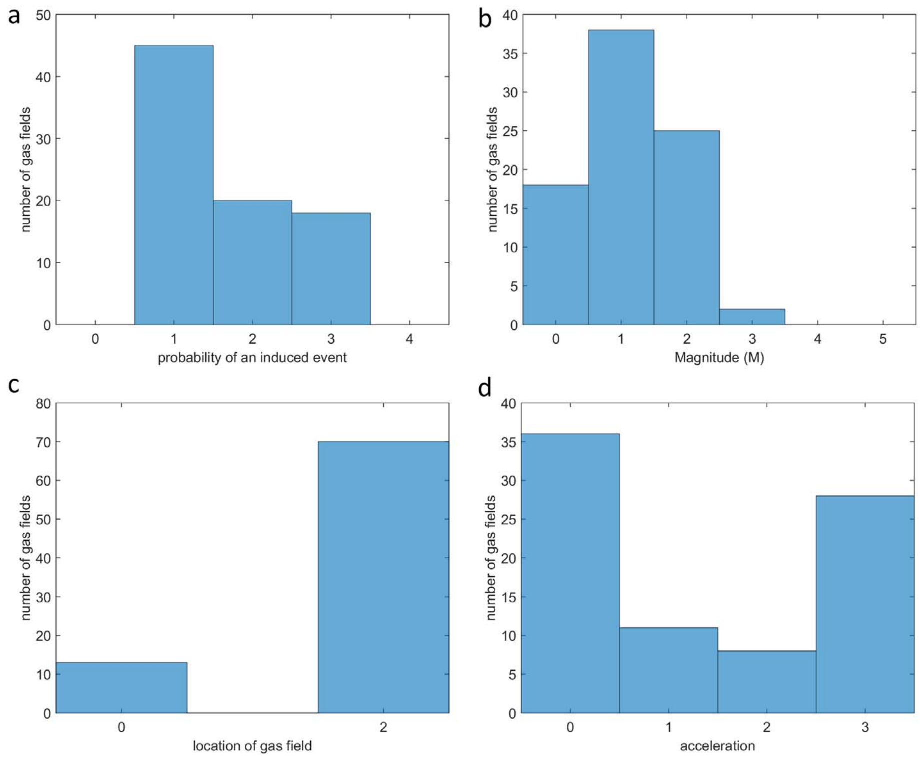

Fig. 2. Histograms of the subsurface escalation factors: probability of an induced event (a), Magnitude (M) (b), location of gas field (c) and acceleration (d).

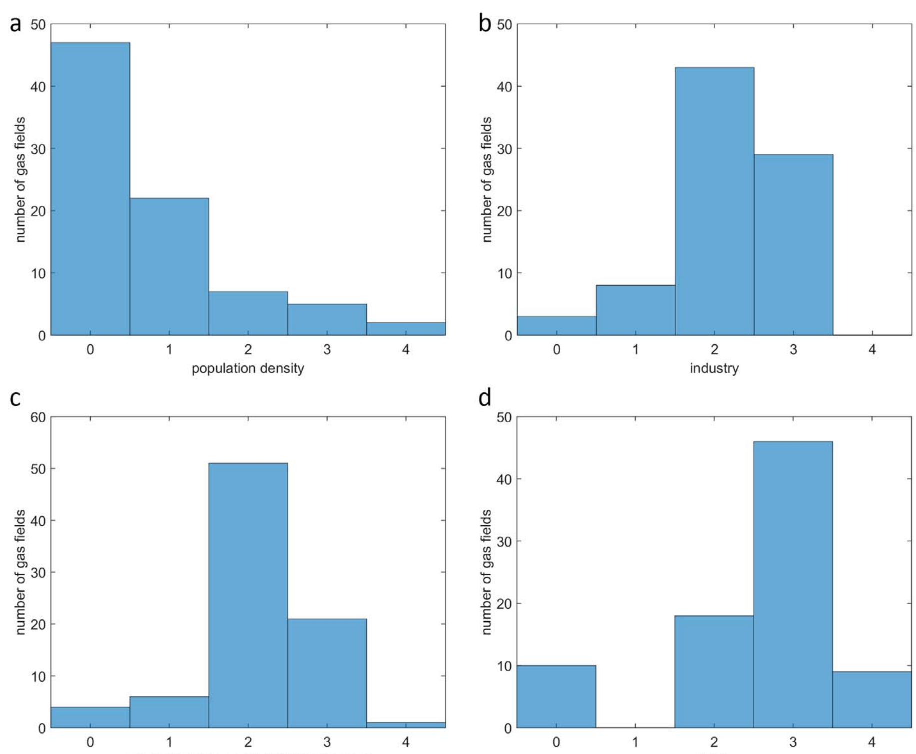

Fig. 3. Histograms of the surface escalation factors: population density (a), industry (b), special buildings and vital infrastructure (c) and dykes (d).

4. Influence factors for the surface

4.1. Population density

Ground motion due to an induced event may cause building damage which affects the population in the vicinity of the event. The extent of damage to infrastructure and buildings and the amount of people affected are directly related to the risk posed. The population density is a measure of the amount of people and buildings that could be affected by an induced event in a specific field. It is determined as the number of people per km^2 within the contour of the gas field, including a buffer zone of 5 km around the contour. Most damages due to relatively small

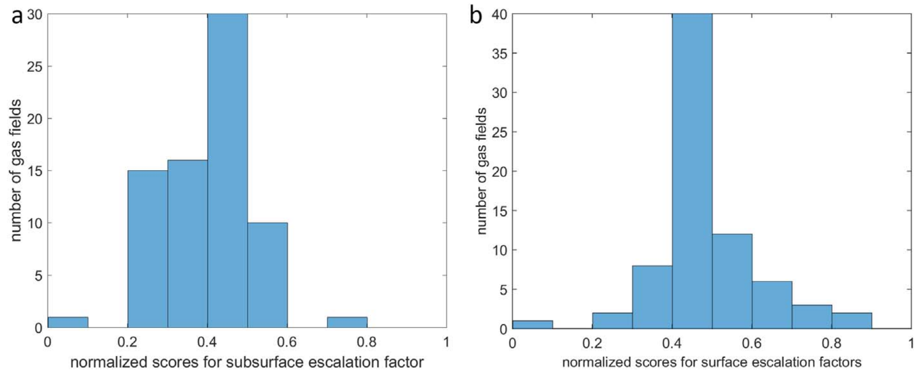

Fig. 4. Histogram of the normalized scores for the subsurface(a) and surface (b) escalation factors.

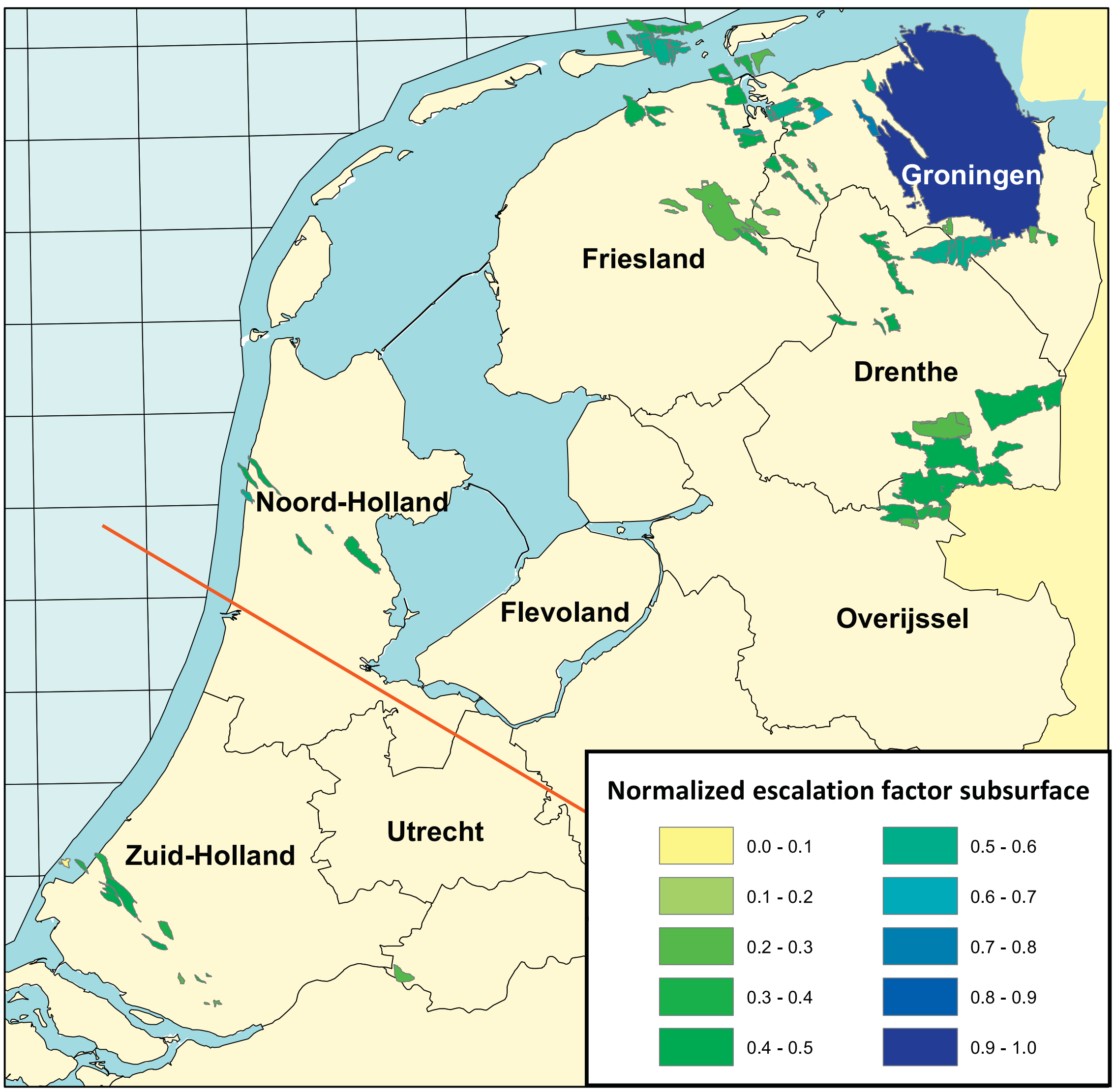

Fig. 5. Geographic distribution of the normalized scores for subsurface escalation factors for the producing gas fields in the Netherlands. The south of the Netherlands is not shown as there are no gas fields here. Non-producing and negligible risk fields are not indicated. The red line gives the line Amsterdam-Arnhem used for the subsurface escalation factors.

magnitude events occurs within a zone of 5 km of the earthquake (Roos et al., 2009). According to Roos et al. (2009), the probability of a house being damaged is < 5% for houses at distances > 5 km from the induced event. The conclusions of Roos et al. (2009) are based on events with a maximum observed magnitude of 3.5 that have occurred in the Netherlands. Even though the maximum magnitude, for some fields, may be somewhat larger (up to a magnitude of 4.0), the 5-km buffer zone seems realistic given that events can occur within the entire contour of the gas field. The population density is taken from CBS statistics (Statistics Netherlands electronic databank StatLine, 2018).

As mentioned in the previous section, damage to buildings is also related to building vulnerability. There is no publicly accessible

Fig. 6. Geographic distribution of the normalized score for the escalation factor for the producing gas fields in the Netherlands. The south of the Netherlands is not shown as there are no gas fields here. Non-producing and negligible risk fields are not indicated.

information on types of houses (detached, semi-detached, terrace, quality of the foundation, building style) per location in the Netherlands or on the vulnerability of buildings. However, studies of the building stock above the Groningen gas field (Crowley et al., 2018) have shown four-story apartment buildings to be especially vulnerable. This is mainly due to the use of brick masonry, their long frontage and the fact the ground floor is often occupied by retail premises (decreasing the amount of load-bearing structure on the ground floor). In addition, damage to these buildings exposes a large number of people. We therefore added one malus point for areas where flats of this type are common (Table 2).

4.2. Industrial areas

Industrial premises are common in the Netherlands. Given that the country is densely populated, loss of containment at an industrial facility as a result of damage incurred by an earthquake could have far-reaching consequences for public safety. Hence, this is an important escalation factor in the risk analysis. For this escalation factor, the information on the Dutch risk map is used (www.risicokaart.nl). All industrial areas within the contour of the gas field or within 5 km of the contour are identified. Each industrial area counts individually.

4.3. Special buildings and vital infrastructure

Damage to special buildings such as hospitals, schools, libraries, and to other municipal and public buildings due to strong ground motion exposes large groups of people. Such buildings also serve an important communal function in the event of a disaster. Vital infrastructure such as electricity plants and nuclear plants need to be extra secure to avoid major consequences. The number of special buildings and vital infrastructure is therefore added as a separate escalation factor. This information can also be derived from the Dutch risk map.

4.4. Dykes

Dykes are numerous in the Netherlands because so much of the country lies below sea level and because of the risk of flooding from the many rivers crossing the Netherlands. Larger ground motions may cause ground liquefaction (Deltares, 2014) underneath the dykes. The dykes that separate the land from the sea are called primary dykes. Those that separate the river from the land are called secondary dykes. As the collapse of primary dykes has greater repercussions than the collapse of secondary dykes, the method distinguishes between primary dykes, secondary dykes and the absence of dykes (Table 2).

The surface factors are weighted equally and therefore have identical influence on the outcome of the analysis.

5. Application to the Dutch gas fields

The current analysis focuses on the producing onshore gas fields in the Netherlands. It excludes temporarily and permanently non-producing fields, fields further than 3 miles (4.8 km) from the Dutch coast and fields with a negligible probability of experiencing an induced event. There were in January 2016 142 producing gas fields onshore or within the 3-mile (4.8 km) zone (EZ, 2014). Based on their geological and production characteristics, 58 fields are considered to have a negligible probability of inducing a seismic event due to gas depletion. By definition, these 58 fields also have a negligible seismic risk and have been discarded from the risk matrix assessment. For the remaining 84 producing gas fields, the seismic risk was assessed with the methodology outlined in the previous sections. Simple 3-D static reservoir models for each gas field were built to assess the reservoir volume. Assuming a maximum pressure drop in the reservoir based on the expected abandonment pressure (from the latest production plan), compaction was calculated and related to the magnitude which could occur given the operational constraints. For the second estimate of the maximum magnitude based on fault size, a top side view of the reservoir was used to measure the largest fault in the reservoir. The escalation factors were scored using the method explained in the previous section and Tables 1 and 2. The scores for 83 producing gas fields (excluding the Groningen gas field) for the individual escalation factors are shown in Fig. 2 for the subsurface and Fig. 3 for the surface. Fig. 4 shows the final normalized score for the escalation factors of both the subsurface and surface. There is a visible spread in both the subsurface and the surface factors, indicating that the escalation factors chosen allow for differentiation between the fields.

The geographic distribution of the normalized score for the escalation factors is shown in Fig. 5 for the subsurface and Fig. 6 for the surface. The gas fields in northeastern Netherlands (Groningen and Drenthe provinces) have a higher score for the subsurface escalation factors, which is consistent with the seismic activity recorded in this area. The gas fields in western Netherlands (Zuid-Holland province) score lower for the subsurface escalation factors consistent with the fact that no induced seismicity due to gas production has been recorded here. However, these fields score significantly higher for the surface factors, due to the high population density, significant industrial activity and associated increased number of special buildings and vital infrastructure. In addition, this area is close to the sea (high score for primary dykes).

The final normalized score for the escalation factors of the subsurface were combined with the final normalized score for the factors of the surface to obtain normalized risk (Fig. 7). Fig. 7 shows the spread of the gas fields within the normalized risk using this method. The Groningen gas field in the north of the Netherlands has by far the largest seismic risk associated with gas production. A quantitative seismic risk analysis has been done for the induced seismicity of the Groningen gas field (NAM, 2016). Because of the large difference in risk between the Groningen field and the other smaller gas fields, the guideline (Muntendam-Bos et al., 2015) deems it sufficient to carry out a qualitative risk analysis for the other gas fields in the Netherlands, as performed here. Fig. 8 shows the normalized seismic risk for the small Dutch gas fields in map view, with the color of the gas field indicating the seismic risk. Most of the producing gas fields with a normalized risk between 0.3 and 0.4 are in the provinces of Groningen, Drenthe, and Zuid-Holland (the northeast and west of the Netherlands). This is in line with the abovementioned increased scores for the subsurface escalation factors in Groningen and Drenthe and the surface escalation factors in Zuid-Holland. Most of the producing gas fields with a normalized risk between 0 and 0.1 are entirely or partly offshore, but within the 3-mile zone from the coast. This is primarily because of the lower score for the

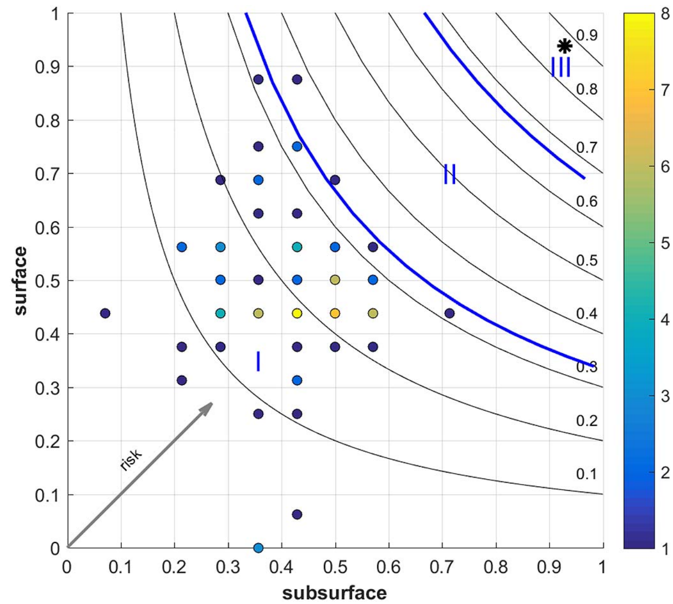

Fig. 7. Seismic risk matrix for all producing gas fields in the Netherlands. The color scale indicates the number of gas fields with the same score. The lines indicate equal risk. The black star indicates the risk for the Groningen gas field obtained using this method. Non-producing and negligible risk fields are not shown.

surface escalation factors (as there are no people living on top of these fields).

6. Discussion and conclusion

The seismic risk analysis yields qualitative results: relative scores for the producing gas fields in the Netherlands in terms of risk. The Groningen gas field is clearly an outlier with a much larger seismic risk than expected for the other, smaller, gas fields.

The decision to score the subsurface and surface escalation factors affects the result. As there is a large difference between the Groningen gas field and the small gas fields, a slight change in the scoring will not appreciably affect the results. The method has been set up specifically for the Netherlands, so applying it to a different region could entail choosing different escalation factors and a different scoring scheme.

The score for the seismic risk may also change over time. The score for the surface factors will change as the population density increases or decreases, often also leading to changes in industrial activity and vital infrastructure as well as the presence of special buildings. The probability of inducing an event will change if the first event is induced in a currently inactive field. The score for the magnitude could change if production plans are altered and production continues to lower reservoir pressures. This may cause additional compaction, thereby increasing the reservoir moment available for the release of seismic energy. However, since a different scoring in Table 1 for the maximum magnitude is obtained at a 0.5 magnitude units (M_w) difference, therefore it is not very likely that small changes of the maximum magnitude will lead to a different score for this escalation factor.

In most of the escalation factors the area of the gas field plays a major role. This influence is logical and acceptable, given that a larger area implies a larger gas volume, more available energy, longer fault traces affected by the depletion and a larger possible effect from an induced event.

Existing information and research forms the basis of the seismic risk analysis presented here. In future, more information and knowledge will become available, which could lead to modifications to the seismic risk analysis method. For instance, other relevant factors might be taken into account, such as the in-situ stress, orientation of faults, types of building, and types of industry. These have not been considered here

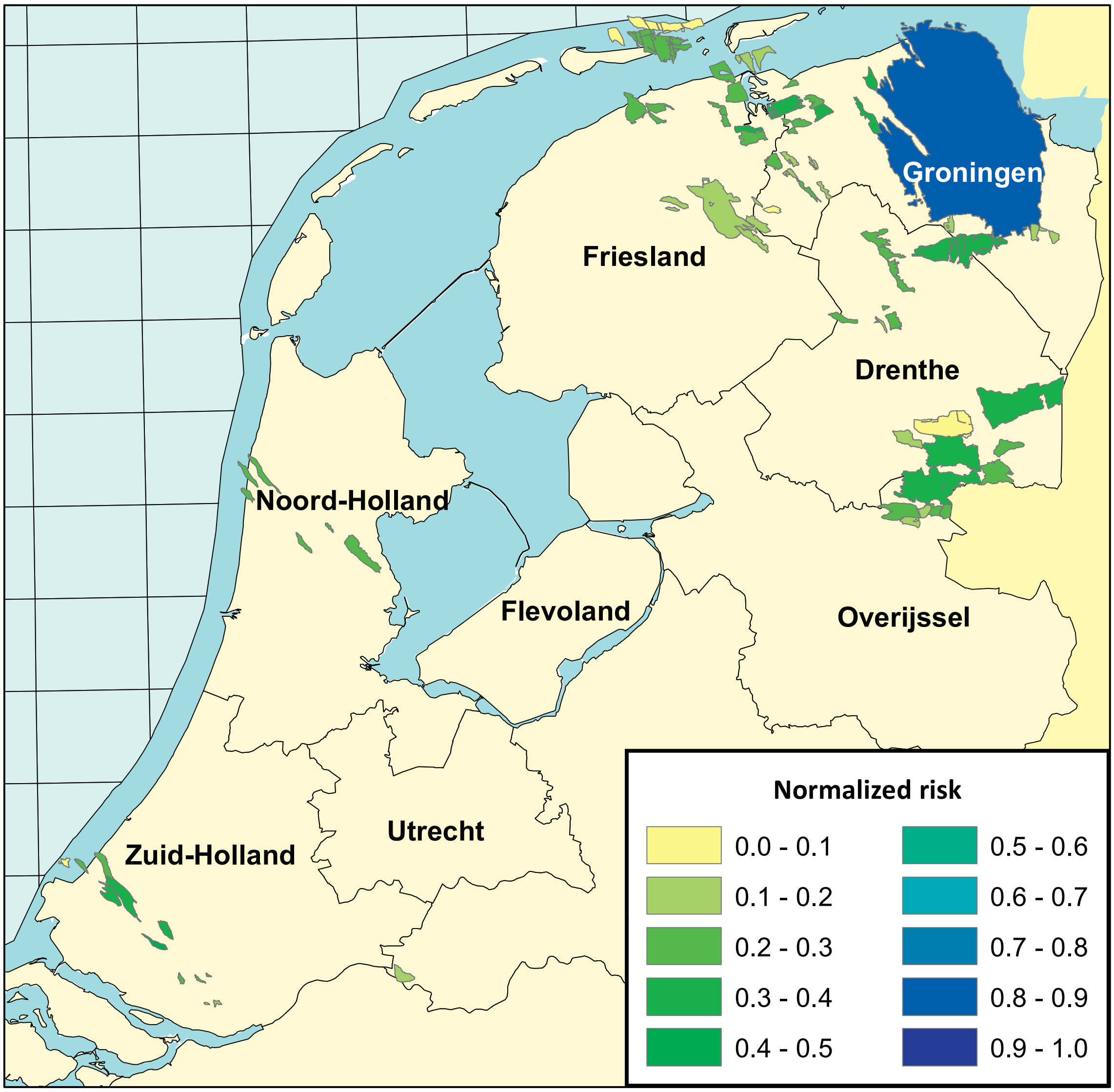

Fig. 8. Geographic distribution of the normalized risk for the producing gas fields in the Netherlands. The south of the Netherlands is not shown as there are no gas fields here. Non-producing and negligible risk fields are not indicated.

due to lack of data on these parameters. The choices made when setting up the seismic risk assessment should therefore be reviewed regularly as new data or knowledge becomes available.

Risk assessment is only the first step toward risk management. Several production-reducing measures have been imposed on the Groningen gas field, with the aim of reducing seismic activity. This aim has been achieved, at least for the short term (2014–2017). A recent earthquake (January 8th 2018, magnitude 3.4) may change this assessment. The attainability of managing seismic activity in the small gas fields (e.g. by a traffic light system) has yet to be demonstrated. Whether operational measures to limit the number and strength of induced events exist remains highly uncertain, especially for fields at the end of their lifecycle. This is currently being investigated.

Acknowledgments

We thank Jenny Hettelaar, Cees Geel, Geert de Bruin, Tom van Hooff of the Geological Survey of the Netherlands and Hans Roest of the Dutch State Supervision of Mines for their contribution to the study and the Dutch guideline, respectively. The Dutch guideline was drafted by the Dutch State Supervision of Mines at the request of the Ministry of Economic Affairs of The Netherlands. We also thank Stefan Baisch for his constructive comments which have improved this manuscript and Joy Burrough for advising on the English.

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