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

K. van Thienen-Visser[a,*], J.A. Roholl[a], B.M.M. van Kempen[a], A.G. Muntendam-Bos[b]

[a] Geological Survey of the Netherlands, TNO, Princetonlaan 6, Utrecht, The Netherlands
[b] State Supervision of Mines, Henri Faasdreef 312, Den Haag, The Netherlands

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

* Corresponding author.
E-mail address: karin.vanthienen@tno.nl (K. van Thienen-Visser).

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
0013-7952/

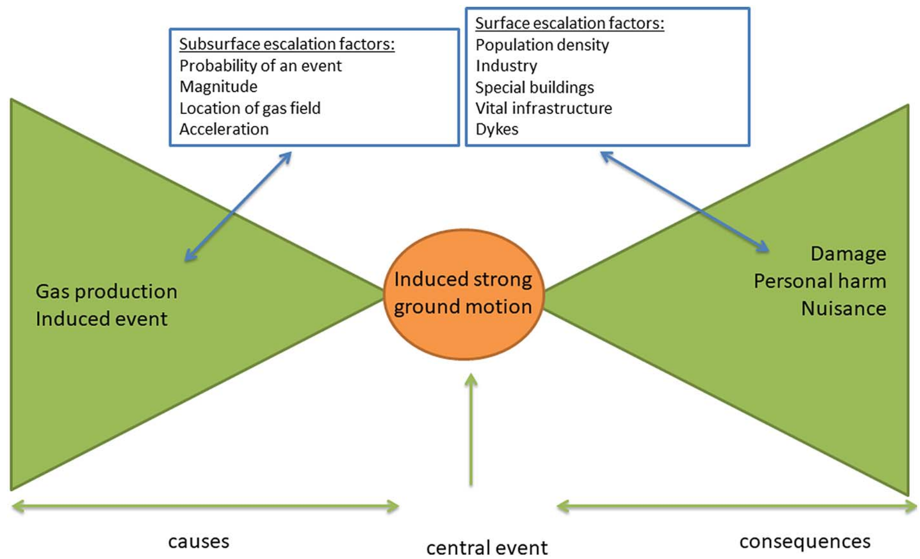

Fig. 1. Bow-tie with induced strong ground motion as central event. On the left hand side the single cause of human induced seismicity taken into consideration in this paper is indicated and on the right hand side the consequences. The escalation factors subsurface and surface play a role on escalating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