Introduction

In the Netherlands there has been an intense public debate on induced seismicity related to mining activities, especially gas production. This can be attributed to the induced seismicity of the Groningen field which has led to damage on a large scale and has a great impact on part of the inhabitants. Since the start of the century the number of earthquakes and also the magnitudes of the earthquakes in the Groningen field have increased. The magnitude 3.6 earthquake near the village of Huizinge in 2012 triggered a series of research projects on the subject, and lead to the understanding that earthquakes cannot only be seen as leading to (widespread) damage to buildings but also to material personal risk levels. Since, a number of cuts have been imposed on the production of the field between 2014 and 2017. Following the magnitude 3.4 earthquakes near the village of Zeerijp in 2018 and the village of Westerwijtwerd in 2019 it was decided to cease gas production from the Groningen gas field as soon as possible.

The developments in the Groningen gas field have had a strong influence on how the Dutch society perceives induced seismicity. The long time it took before government started to take the adverse consequences serious as well as its subsequent struggle to mitigate the adverse consequences effectively, has made not just Groningen but the rest of the country weary of gas production and its possible adverse consequences. As a result, even a small probability of an earthquake evokes strong emotions. The mining law has been adjusted to take the risk of induced seismicity into account in a better way. The gas production companies are confronted with more strict regulations. The sensibility for induced seismicity has also lead to more scrutiny in other mining activities such as salt solution mining and geothermal activities.

The regulator in the Netherlands (Staatstoezicht op de Mijnen, SodM) has a twofold role. One role is advising the Ministry of Economic Affairs and Climate Policy on production plans and permits, and the other role is supervising if the production is done in a safe manner. Induced seismicity is an important aspect in both roles. This paper describes the risk management approach of the regulator in the Netherlands.

How is the induced seismicity risk assessed in the Netherlands?

From a regulator perspective the ideal world would allow the quantification of risk for a certain (subsurface) activity, and compare this risk with a norm as it is defined by the law. If the risk is higher, then the activity is not allowed. If it is lower, then the activity is allowed to proceed. However, in the real world it is not possible to determine the risk of subsurface activities with a high level of confidence. This is caused by the high level of uncertainty in the (subsurface) data used, and the limited amount of data to calibrate the models which calculate the risk.

In most cases even determining the hazard is very challenging, and can realistically only be performed in a qualitative way and not in a quantitative way. Without a quantitative hazard, it is impossible to determine a quantitative risk. Without an established risk, it cannot be compared with a norm. However, even a qualitative risk can be used to determine measures to control the risk.

In the Netherlands guidelines for the assessment of seismic risk have been developed (Muntendam-Bos et al. 2015; IF and Qcon, 2017). These guidelines adopt the approach that all systems are different and context dependent and thus require different approaches for risk assessment. The guidelines use a qualitative risk scoring approach for categorizing the gas fields or geothermal projects, respectively. This approach is consistent with international state-of-art frameworks for risk assessment of induced seismicity (e.g. Majer et al. 2013; Wiemer et al. 2017). Depending on the scores and the resulting category, the risk management requirements are determined. In many instances, risk governance is very simple and largely limited to monitoring. In other contexts, it can require much more involvement.

Seismic Risk Assessment for Gas fields

The seismic hazard assessment guideline for gas fields uses qualitative scores that are derived from indicators that describe seismic hazard and risk (in terms of secondary hazards and exposure).
For the seismic hazard concern three subsurface indicators are considered: the probability of an induced earthquake (of any magnitude) during the operation of the field, the realistic maximum magnitude of an earthquake, and the effect of the earthquake on the ground motion. The probability of an induced earthquake (of any magnitude) during the operation of the field is determined using the DHAIS method (van Thienen-Visser et al. 2012). The realistic maximum magnitude of an earthquake is calculated in two ways. One calculation uses the fault geometry, the other uses an energy balance. The effect of the earthquake on the ground motion is taken into account by assessing the soil stiffness in the area as soft soil amplifies ground motions.

The concern about secondary hazards and exposure considers four indicators: population density, the presence of (important) dykes, critical infrastructure such as hospitals, and hazardous industry.

The scores are evaluated by summing and plotting the indicators of seismic hazard versus concern about secondary hazards and exposure. Using the qualitative scores three categories of gas fields in terms of concern about induced seismic hazard and risk are defined:

Category I: induced seismic hazard and risk concerns are low and normally no further actions are required;

Category II: induced seismicity is possible and damaging events cannot be excluded. For these fields it is expected that the monitoring is improved, and a seismic response protocol is in place. A quantitative, probabilistic analysis is not required as the seismic catalogue for these fields is far too small to perform a quantitative analysis with a reasonable amount of certainty.

Category III: induced seismicity is a major concern. For this category a quantitative risk assessment is necessary. Currently only the Groningen gas field scores belong to this category.

**Figure 1:** Seismic Risk Assessment scoring method currently used in the Netherlands for qualitatively determining the seismic risk potential of small gas fields

**Hazard and Risk Analysis for the Groningen field**

The operator of the Groningen field has developed a full probabilistic hazard and risk assessment (Van Elk et al. 2019). This method consists of a series of 8 models (Figure 2). The first 5 models calculate the seismic hazard, the last three models the seismic risk. Because of the many uncertainties, the model incorporates the aleatoric uncertainties using Monte Carlo simulations and the epistemic uncertainties as different branches on a logic tree. The modelled mean risk can be compared to the acceptable risk level as defined in the law. A more thorough explanation can be found in Van Elk et al. 2019).

**Figure 2** The Hazard and Risk Assessment methodology as described by Van Elk et al. 2019. The yellow boxes are the input, the orange boxes are the models, the blue boxes are the results.

**Seismic Risk Assessment geothermal operations**

The risk of induced seismicity due to geothermal activities, especially for hydrothermal projects, is much less recognized by the general public than the risk due to gas production. In some cases even operators claimed that induced seismicity in their system was impossible because the same amount which is produced is injected back into the same formation and therefore can’t cause pressure differences. Experience in Belgium and Germany (e.g. Mol, Landau) has shown that even a balanced system can induce seismicity. Also in the Netherlands low magnitude earthquakes are observed near geothermal systems. It is recognized that also for balanced geothermal systems a seismic risk assessment is necessary. Especially areas which also know tectonic seismicity are at higher risk.
The sector has developed a method which currently is approved by the regulator for determining the seismic risk category for geothermal projects (IF and Qcon, 2017). The method a priori categorizes systems in a high risk area (based on the location of the system in an area with natural seismicity) and systems near the Groningen gas field with its induced seismicity as systems of higher concern. All other systems use the scoring tool to derive the level of concern. The scoring tool only focusses on the seismic hazard concern and takes both site specific subsurface information into account (e.g. fault orientation), but also production specific factors (e.g. injection pressure). If the scoring tool shows that the system is not in the lowest category, then a location specific SRA has to performed.

How well do the seismic risk assessments perform?

SRA for gas fields
The SRA for the small gas fields works reasonably well. The onshore operators use the methodology to categorize the seismic risk for their onshore fields as part of their production plans as required by law. From the experience of using this SRA a couple of possible improvements have been identified.

The first improvement which is identified is updating the DHAIS study. In this study the seismic catalogue in the Netherlands is interpreted as complete, and the locations of the earthquakes in the catalogue as absolute. However, the seismic monitoring in the southwestern part of the Netherlands has been relatively poor in comparison to the northern part of the Netherlands. Subsequently, there is a major difference in the magnitude of completeness over the Netherlands. It can’t be excluded that the fields in the southwestern part have been seismically active in the past with low magnitude events (M<2.5) which could not be registered, while events of this magnitude (0.5<M<2.5) have been registered in the north. This influences the statistics of the study significantly. Recent investigations on further improvements of the SRA (Vörös and Baisch., 2019) also identified that the location uncertainty in the seismic catalogue makes it difficult to tie some events to a certain gas field. It is unclear how the DHAIS study has handled this uncertainty.

Secondly, in the communication of the SRA results there seems to be a tendency to play down the risk. Especially the operators feel that the calculated realistic maximum magnitude is too high, although this is based on widely accepted calculation techniques. Although there is a very low probability this magnitude will ever be experienced it shouldn’t be excluded as a possibility when defining safety measures. Nevertheless for a majority of the fields the correct monitoring and measures are in place to ensure safety.

HRA for the Groningen gas field
The HRA used for the Groningen gas field is of high quality and is considered as state of the art by international experts. However, close examination shows that several known and unknown uncertainties are not taken fully into account. In line with ISO 17776 Annex A when dealing with weak knowledge one should apply either stress scenario's or apply a safety factor. Therefor for defining the measures to ensure safety it was decided that a safety margin has to be taken into account. It was decided to base the scope of the strengthening program for buildings on the P90 risk derived from epistemic uncertainties in the logic tree. Although this decision sparked some discussion it has provided the necessary contingency in the housing strengthening program as the PSHRA models are improved and refined and the derived continuously resulting in fluctuations of the calculated risk. More elaborate discussion can be found in SodM (2018a, 2018b).

SRA for geothermal operations
The methodology is used by all operators to describe the seismic risk in the legally required production plans. In the implementation of this SRA there are two kind of interesting observations. First, it seems that operators tend to (unnecessary) avoid the location specific SRA required as a category II project, by adjusting the operation to a lower injection pressure and/or flow rate. The location specific SRA is interpreted by some operators as an indication of being a higher-risk geothermal operation. This is not the case, since the categorization is an indication of concern and the location specific SRA could show that the actual risk is low.

Secondly, use of the SRA shows that some of the parameters in the flow diagram are not very well quantified. One example is the distance to basement, since it is unknown in the Netherlands which formation should be considered as basement. Currently there is an effort to update the SRA to avoid these kinds of discussions.
In those cases where a location specific SRA was performed it is noticed that these are developed for the most likely case only. In these SRA’s the operator didn’t (or only poorly) consider other realistic scenario’s (within the range of uncertainty), even if these pose a much higher risk. This is not acceptable from a safety point of view.

Discussion
Looking at the implementation of the seismic risk assessment guidelines for the small gas fields and geothermal operations in the Netherlands it can be concluded that the scoring methods work reasonably well for determining the induced seismic risk as included in the legal required production plans.

However, it is noticed that in some cases there is a discrepancy between the interpretation of the operators and the interpretation of the regulator. Since it is very difficult or even impossible to calculate the risk probabilistically taking into account the full range of uncertainty, a lot of risk assessments are performed deterministically and are limited to the identification of the most likely scenario. However, from safety point of view, if the hazard can’t be calculated probabilistically, it is necessary to not only investigate the most likely scenario, but a range of possible scenarios that could lead to induced seismicity which reasonably span the range of uncertainty. It is necessary to identify and take into account all causes and consequences of induced seismicity as well as all related preventive and mitigating measures (for instance through a so-called bow-tie analysis). From a safety point of view the most likely scenario cannot serve as a basis for decisions. The decision which measures are necessary has to take into account all realistically possible scenarios since these can pose the highest risks.

Conclusions
In the Netherlands a couple of general guidelines based on well-established frameworks for risk assessment are used for determining the seismic risk for both small gas fields and geothermal projects. These methods work well for qualitatively scoring the risk in the legal required production plans. Improvements are identified, and currently worked on by several parties.

Various location specific risk assessments show the tendency of operators to concentrate to concentrate on the most likely scenario only instead of identifying multiple realistically possible scenarios which is a common practice in risk management.

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References


