February 2015 Report: EP201502207168

NAM

Nederlandse Aardolie Maatschappij

Threat assessment for induced seismicity in the Twente water disposal fields

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Nederlandse Publiekssamenvatting

In dit rapport wordt het risico voor bodembewegingen/-trillingen als gevolg van waterinjectie in de oude (leeggeproduceerde) gasvelden van Twente beschreven. Deze lege gasvelden worden op dit moment gebruikt door NAM voor het in de diepe ondergrond injecteren van het productiewater afkomstig uit het Schoonebeek olieveld.

In de MER is uitvoerig aandacht besteed aan de effecten van bodembewegingen (daling en trillingen) indien water geïnjecteerd wordt. De MER concludeert dat de beoogde injectiereservoirs in Twente niet eerder seismisch actief zijn geweest en dat, indien de oorspronkelijke reservoirdruk niet wordt overschreden, er dan ook geen trillingen als gevolg van waterinjectie worden verwacht.

Het feit dat 4 jaar waterinjectie in Twente niet tot bodembewegingen heeft geleid is in overeenstemming met de conclusies uit de MER. Echter om hierover aanvullende inzichten te verkrijgen is op verzoek van Staatstoezicht op de Mijnen besloten een aanvullende risico-analyse uit te voeren.

Dit rapport beschrijft deze risico-analyse en gaat in op de belangrijkste factoren in de ondergrond die mogelijkerwijs zouden kunnen leiden tot het optreden van bodemtrillingen (aardbevingen) als gevolg van waterinjectie. Daarna wordt de relevantie van deze factoren getoetst aan de ondergrondse condities zoals bekend in Twente.

Op basis van een systematische kwalitatieve inschatting van factoren die het optreden van aardbevingen zouden kunnen beïnvloeden en de conditie van de ondergrond in Twente, bevestigt deze nadere analyse de conclusie van de MER dat het zeer onwaarschijnlijk is dat aardbevingen zich in Twente in de toekomst zullen voordoen. In het huidige rapport wordt deze conclusie onderbouwd aan de hand van de volgende inzichten:

- Om een aardbeving te genereren moet een breukvlak in de diepe ondergrond in een kritieke spanningstoestand komen. Echter gedurende de 55 jaar van gasproductie en de eerste 4 jaar van waterinjectie zijn er geen trillingen geregistreerd in de regio Twente. Daaruit wordt geconcludeerd dat er geen breuken zijn in de ondergrond die zich in een kritische spanningsstaat bevinden.
- De natuurlijke spanningstoestand in de injectiereservoirs is nagenoeg isotroop. Dat betekent dat er geen groot verschil bestaat tussen de horizontale en verticale spanningen. Dit inzicht is gebaseerd op basis van spanningsmetingen in de reservoirs en betekent dat er een onverwacht grote verandering van de spanningstoestand op zou moeten treden om een breuk in het reservoir in een kritieke spanningstoestand te brengen.
- Wereldwijd is gebleken dat waterinjectie slechts in incidentele gevallen aardbevingen veroorzaakt. Uit een door TNO uitgevoerde vergelijking van velden waar door injectie wel bodemtrillingen zijn voorgekomen, blijkt dat in nagenoeg al deze gevallen de druk in het reservoir gedurende de injectie was toegenomen tot niveaus die boven de oorspronkelijke druk van het veld liggen. Bij de waterinjectie in Nederland (en dus ook Twente) schrijven de verleende vergunningen voor dat de reservoirdruk onder de oorspronkelijke reservoirdruk dient te blijven.

De bovengenoemde resultaten bevestigen dat er een zeer geringe kans is op bodemtrillingen in Twente als gevolg van waterinjectie, echter dit volledig uitsluiten is niet mogelijk omdat:

a. De ondergrondse condities in elk injectiereservoir altijd elementen bevatten die uniek zijn.
b. Bijna alle voorspellende aardbevingsmodellen gekalibreerd zijn aan opgetreden bevingen. Aangezien er tot op heden geen bodemtrillingen in Twente geregistreerd zijn kunnen dergelijke modellen voor dit gebied niet worden ontwikkeld. Geomechanische modellen, zoals voor een deel ook in dit rapport gebruikt, zijn indicatief maar derhalve ontoereikend om op een volledig betrouwbare manier aardbevingen te kunnen voorspellen

Hoewel er tot op heden in Twente geen enkele bodemtrilling/aardbeving geregistreerd is, worden op basis van dit rapport de volgende aanbevelingen gemaakt:

1. Uitbreiding van het KNMI geofoonnetwerk in Twente, om zodoende de mogelijkheid eventuele aardbevingen (ook die met zeer geringe sterkte) beter te kunnen detecteren en er de plaats van te kunnen bepalen. Hiermee wordt de mogelijkheid om dit te doen op hetzelfde niveau gebracht als in de rest van Noord-Nederland.
2. Aanleggen van een zogenaamd accelerometernetwerk om grondversnellingen als gevolg van bodemtrillingen te kunnen meten. De reden voor deze aanbeveling is de relatief ondiepe ligging van de injectievelden in Twente. Zelfs indien er een trilling met een lage sterkte op zou treden, kan deze mogelijkerwijs resulteren in een iets grotere beweging van de bodem in vergelijking met andere velden elders in Nerderland, die over het algemeen dieper gelegen zijn.
3. Definiëren en implementeren van een seismisch risico- en responsplan, dat de acties beschrijft die genomen moeten worden indien zich onverhoopt toch een beving voordoet.

Inmiddels heeft NAM al deze aanbevelingen overgenomen. De geofoon- en accelerometer netwerken worden in 2015 geplaatst en het seismisch risico- en responsplan zal opgenomen worden als addendum in NAM’s Waterinjectie Management Plan voor de waterinjectie in Twente. Dit addendum zal eind februari 2015 worden voorgelegd aan Staatstoezicht op de Mijnen.

Summary

Four depleted gas fields in the Twente area are utilised for the disposal of produced water from the Schoonebeek oil field. The risk for induced seismicity associated with this project was assessed as very low in the original Environmental Impact Assessment. This was based on the fact that in the past no seismic events have been detected and that during the injection period the reservoir pressures will not exceed to original pressures.

In the global literature (e.g. National Research Council, 2012) several cases are described of seismicity related to the injection of fluids and gas. Whilst these seismically active fields only represent a small set of all the injection fields, this has led some people to suggest that seismicity may also occur in the Twente injection fields. To address these concerns the Dutch regulator (State Supervision of Mines) requested NAM to do a further and more detailed study into the seismic risk in the Twente area.

This report provides a summary of the main mechanisms that could lead to induced seismicity as observed in other fields that are subjected to injection. Next, the applicability and relevance of these mechanisms is assessed for the Twente situation. It leads to an inventory of possible threats and a qualitative assessment of its consequences for the seismic hazard.

In line with the original EIA, it is concluded that induced or triggered seismicity is not expected to occur in the Twente fields because:

- No seismic activity with $M_L \geq 1.5$ (the detection limit of the existing seismic network and the lower limit of magnitudes that can be felt at surface) have been detected or recorded during the 55 years of depletion or during the first four years of injection. Therefore it can be concluded that the faults were not critically stressed during this period.
- The ambient stress state is close to isotropic for most of the injection reservoirs meaning that significant induced stress changes are required to destabilize faults
- Observations in injection fields elsewhere in the world reveal that in the few cases where seismic activity was observed, the reservoir pressure during injection was nearly always increased to levels higher than the original pore pressure. Reservoir pressures in the Twente fields will remain below the virgin reservoir pressure (as stipulated by the Water Management Plan).

The above key observations support the assessment that the chance for induced earthquakes to occur in the Twente injection fields is very low, however the risk cannot be excluded completely because:

- Every field has unique elements which makes that using fields elsewhere in the world as a direct analogue has to be done with care.
- Almost all predictive seismological models are based on statistics of historical earthquake data, which is not available for the Twente fields. Current deterministic tools lack detailed knowledge of both the physical processes and the variability and uncertainty in the available data.

Whilst no earthquakes have been recorded in the area, the uncertainties are such that it is recommended to expand the monitoring capability in the area. Specifically the following 3 recommendations are suggested:

- Expand the existing KNMI passive seismic network in Twente such that, in the unlikely case that an earthquake would occur, the location detection limit is at least equivalent to the rest on the North Netherlands.
- With the expansion of the geophone network also install an accelerometer network to measure associated ground movement velocities and accelerations. This would allow comparing these to other regions.
- Put a seismic risk management protocol in place (e.g. Zoback, 2012).

Introduction

This document describes the potential threats related to seismicity induced or triggered by the injection of produced water from the Schoonebeek oil field into depleted gas reservoirs in the Twente area.

In the global literature (e.g. National Research Council, 2012) several cases are described of seismicity related to the injection of fluids and gas. Whilst these seismically active fields only represent a very small fraction of the total number of injection wells (Zoback, 2012), this has led some people to suggest that seismicity may also occur in the Twente injection fields. To date, however, no tremors or earthquakes have been recorded in Twente, despite the fact that the fields have been subjected to 55 years of gas production and already 4 years of water injection. The seismic risk was also addressed in the original MER (Environmental Impact Assessment; http://www.nam.nl/nl/our-activities/water-injection-in-twente.html) and was assessed as very low.

Nevertheless, the Dutch regulator (State Supervision of Mines) requested to do a further and more detailed study into the seismic risk. This report provides a summary of the main mechanisms that could lead to induced seismicity as observed in other fields that are subjected to injection. Next the applicability and relevance of these mechanisms is assessed for the Twente situation. It leads to an inventory of possible threats and allows a qualitative assessment of its consequences for the seismic hazard. Moreover an assessment is made of a theoretical maximum magnitude event that could occur based on fault areas and mechanical properties.

Three fields in the Twente area (Figure 1) were selected for produced water disposal that started in 2011:

- Tubbergen-Mander: Zechstein (ZEZ) Carbonates reservoirs
- Tubbergen: Zechstein (ZEZ) Carbonates reservoirs
- Rossum-Weerselo: Zechstein (ZEZ) Carbonates and Carboniferous (DC)sandstone reservoirs

Figure 1 selected fields in the Twente area for produced water disposal. The blue lines in the map indicate the position of the water pipeline

Mechanisms

Induced seismicity results from sudden slip or rupture of pre-existing faults, fractures or bedding planes due to stress changes caused by human activities in the (sub)surface, like mining and production/injection of fluids and gas. These stress changes interact with the ambient tectonic stress on these surfaces (e.g. TNO, 2014). Conceptually, faults can slip when the shear stress on the fault exceeds the strength of the fault. A compressive failure criterion like the Mohr-Coulomb failure criterion shows that increasing the shear stress, reducing the normal stress, increasing the pore pressure and/or reducing the friction coefficient or cohesion of the fault can bring a fault to the onset of failure. This concept is a simplification and does not honour the complexity involved in these processes in nature. Therefore the concept can be used in a qualitative sense but cannot be used for the prediction of earthquakes. The complexity arises from a currently insufficient definition and understanding of fault mechanical properties, fault geometry and stress variability on and along the fault plain. The concept can be used however to increase the understanding of the mechanism and perhaps to identify areas in the reservoir that are more likely to be prone for reactivation. Thus far no examples of a successful study where this concept succeeded in predicting earthquakes accurately are reported in literature.

The main mechanisms that can cause induced or triggered earthquakes are (TNO, 2014):

1. Poro-elastic stress effects as a result of the production or injection of a substitute in the subsurface
2. Pore pressure increase in a (sub) critically stressed fault
3. Chemical reactions reducing the strength of a fault
4. Thermal changes effecting stresses
5. Mass changes
6. Stress transfer from nearby earthquakes

The first four mechanisms from this list could also be relevant for the Twente water injection case and will be described in more detail in the subsequent paragraphs with an application to the injection fields. The last two mechanisms are only relevant for areas with critically stressed large faults and natural earthquakes. This is not the case in the Twente area.

Triggered versus induced earthquakes

People distinguish triggered from induced earthquakes where the main discriminator is defined by the magnitude of the man induced stress change with respect to criticality of the stress situation in the subsurface. A definition for both terms is provided by McGarr et al. (2002): “The adjective "induced" describes seismicity resulting from an activity that causes a stress change that is comparable in magnitude to the ambient shear stress acting on a fault to cause slip, whereas "triggered" is used if the stress change is only a small fraction of the ambient level”. In the case of the Twente disposal fields it is likely that a relatively high stress change is required and therefore the adjective “induced” is used in the rest of the document.

Mechanism 1: Poro-elastic stress effects as a result of the production or injection of a substitute in the subsurface

The main mechanism that induces fault reactivation is thought to be the change of effective stresses as a result of pore pressure decrease (production) or increase (injection). This can have an effect on the stresses in the reservoir as well as a possible effect on the stresses in the rock surrounding the reservoir.

The latter case is illustrated by Segall (1989) where he refers to a mechanism where critically stressed faults located around a reservoir may be triggered by effective stress changes (Figure 2) as a result of a shrinking or compacting reservoir.

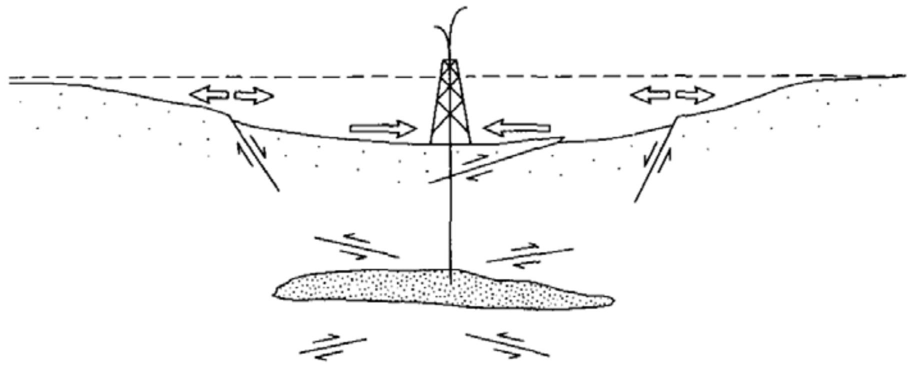


Figure 2 Highly schematic representation of surface deformation (subsidence) and fault reactivation in the subsurface that could occur in response to fluid extraction (Segall, 1989).

Geomechanical analysis (e.g. Mulders, 2003) shows that the stress changes around a reservoir are actually small, implying that faults should be critically stressed in order to slip. Van Eijs et al. (2006) indicated that for the producing gas field in the Netherlands a certain critical pressure drop (around 10MPa) was required before the first induced earthquake was recorded. This observation indicates that a significant stress change needs to occur before faults can be reactivated. Therefore the general observation is that the faults in the subsurface of the middle and northern part of the Netherlands are not critically stressed (van Wees et al, 2014).

The concept of fault reactivation due to changes in the effective stress is shown in Figure 3 by a Mohr-circle. The blue circle 1 represents the virgin stress condition where maximum effective principal stress S_1 in the Dutch subsurface is likely to be close to the value of the vertical effective stress. Depletion causes an increase in shear stress (green circle 2) but in this example the shortest distance to the failure line slightly increases with depletion implying a more stable situation. Poro-elastic changes therefore provide an explanation for induced seismicity observed above some of the Dutch gas fields during production but geomechanical models fail to explain why some of the Dutch fields show seismicity and others don't. This is likely caused by other factors but the available measurements and knowledge do not allow refining this.

Mechanism 2: Pore pressure increase in a (sub) critically stressed fault

In the previous paragraph it was shown how effective stresses in and around a reservoir may change to a possible state that could lead to faults reactivation. Direct injection into a fault is an additional scenario that could lead to fault reactivation. The concept is also shown in Figure 3. Injection in the porous reservoir normally causes a decrease of the shear stress. In the case of linear elastic behaviour with a poroelastic constant, defined by $\gamma = \frac{DS_3}{DP}$ or the change in total minimum principal stress divided by the change of pore pressure, having the same value as during the depletion phase, the stress state would return to its original position (from the green circle 2 back to the blue circle 1).

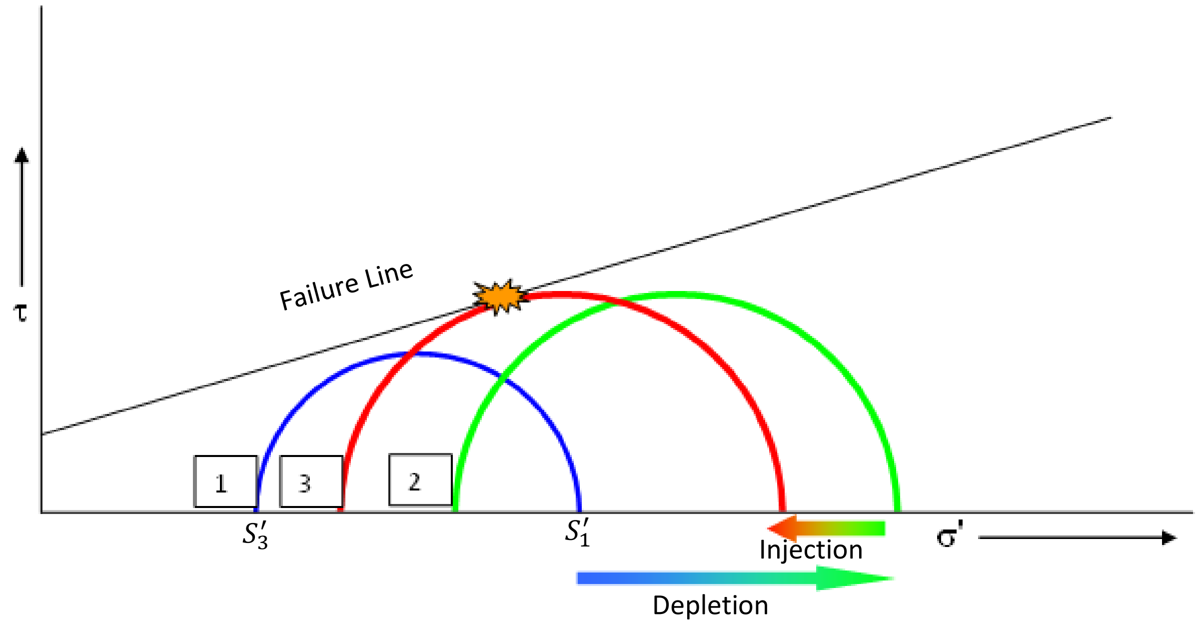


Figure 3 Mohr-Coulomb stress representation of the effective normal stresses (σ') on the horizontal axis versus the shear stress (τ) on the vertical axis

During injection it might be possible that the water is injected directly into a relatively high (when compared to the host rock) conductive fault. In this case both principal effective stresses will decrease with the same amount as the pore pressure increase (from the green circle 2 to the red circle 3, Figure 3). Following this scenario, the maximum shear stress may exceed the frictional resistance of a fault causing it to slip.

The Zechstein carbonate reservoirs in the Twente area are characterised by conductive faults and fractures in a relative low permeable host rock. Therefore this scenario could be more applicable to these reservoirs than to the deeper Carboniferous sandstone reservoir.

Application of the mechanisms related to pore pressure changes to the Twente injection fields

There are no records of observed seismicity during the gas production from the Twente gas fields (1951 to 2006). Before 1995 this could be attributed simply to the fact that the KNMI geophone network wasn't installed yet. However, since 1995 any seismic event with a local magnitude $M_L \geq 1.5$ would have been detected and recorded by the KNMI network. Since the start of the water disposal in the Twente fields in early 2011 no earthquakes were recorded in the region either. These observations confirm that faults in the area are not critically stressed and indicate that to date faults are not in an unstable condition. This observation, however, does not provide a guarantee that they will remain stable until the end of the project. The uncertainty and variability of fault stress paths and strength of the faults remains too large to perform a reliable quantitative assessment. A basic analysis on the available stress data is performed that could provide qualitative guidance on the probability of fault reactivation. Stress paths on faults are however dependent on a wide variety of parameters like reservoir configuration, rock and fault heterogeneity, rock compaction and of course rock mechanical parameters, not captured in this analysis.

Expected pressures and volumes in the injection fields

The expected pressures and volumes per injection well are listed in Table 1. The last three columns provide the pressure information to construct Mohr circles to visualise stress development.

Well	Disposal Reservoir	Seal	Seal thickness	max planned Q	max expected THP	Pres,or	Pres,now	Pres,final
			m	m3/d	bar	bar	bar	bar
TUM1	Z3	Bsst	128	346	27	190	17	37
TUM2	Z2&Z3	Bsst	145	100	56	190	65	69
TUM3	Z2&Z4	Bsst	137	100	50	190	51	59
ROW2	Z2&Z3	ZEZ halite	36	2000	75	150	8	17
ROW3	DC	ZEZ halite	328	1500	106	199	77	188
ROW4	Z2&Z3	ZEZ halite	50	2500	85	150	15	105
ROW5	Z2&Z3	ZEZ halite	30	2500	51	150	7	10
ROW7	Z2&Z3	ZEZ halite	50	1800	45	150	12	79
ROW9	Z2&Z3	ZEZ halite	49	1350	106	150	15	148
TUB7	Z2	ZEZ halite	94	2250	48	211	7	113
TUB10	Z2&Z3	ZEZ halite	46	2000	86	211	15	131

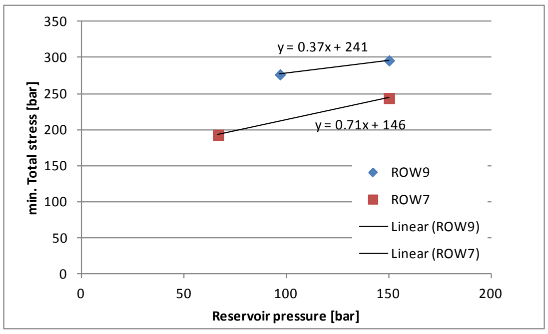
Table 1 Overview of the injection wells, expected top hole pressures (THP) and final reservoir pressures

Stresses and stress path in the injection fields

The instantaneous shut in pressure (ISIP) can be regarded as an upper bound value for the minimum principal total stress (S_3) (Zoback, 2010). Four values for the ISIP were retrieved from injection tests in Rossum-Weerselo and one in Tubbergen-Mander. The tests in the ZE carbonates yield a high value for the ISIP of around 2.1 bar/10m. This value represents the initial (undepleted) condition. Only two valid tests are available for the deeper Carboniferous (DC) sandstones, taken at the time while the field was already depleted. Because of the sparse data in this area, additional data was collected from the nearby Coevorden Carboniferous field (van Eijs, 2012). The ISIP values reported for this field are presented in Table 2 and show also high values for S_3. The values that were measured in the Zechstein carbonates at virgin pressure were close to the vertical stress. Values for ISIP's inform the DC reservoirs tend to be, on an average, somewhat lower. Particularly, the stress state in the Zechstein reservoir points to a near isotropic stress condition (S1 almost equal to S3) that is unfavourable for fault reactivation as explained below.

A uniaxial (infinite layer cake reservoir, no fault offsets) Mohr-Coulomb analysis is conducted using the ROW data shown in Table 2. The maximum principal stress is assumed to be vertical with a gradient of 2.2 bar/10m, in line with density data measured in wells. The initial minimum stress gradient of 2.13 bar/10m (from the ISIP value) is almost identical, pointing to the near isotropic stress state. A depletion constant was estimated based on data from two wells in which the ISIP was measured while the field was partially depleted. In this analysis the initial values for the S_3 was assumed to be 2.13 bar/10m. The slope (0.37 and 0.71) of the two lines in the left figure in Figure 4 represents the depletion constant. The two values indicate that the effect of the depletion on the development of the stress is highly variable.

The gradient in ROW7 shows the highest value, which is used to draw the Mohr circle (Figure 4). The stress circles are compared to a linear failure line having no cohesion and coefficient of internal friction of 0.6 (Byerlee, 1978). The ambient (original) stress state is represented by the red dot while the depleted situation is represented by the purple circle. The dashed circle represents the worst case stress scenario after direct injection into a fault using an average end pressure of 60 bar. The anticipated final pore pressures in the fields at the end of the injection period are in all cases lower than the original pressures. The figure points out that an isotropic stress state requires a longer and/or steeper stress path during depletion before it will reach the failure line when compared to a situation with ambient shear stress. It is expected therefore that a field with an initial isotropic stress state (such as the Twente Zechstein fields) is less prone to earthquakes than a field with ambient shear stresses.



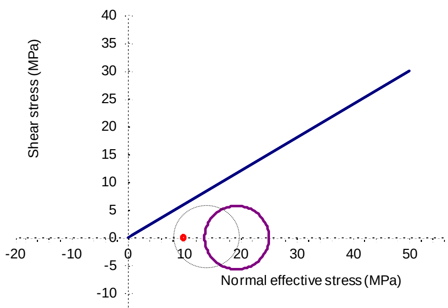


Figure 4 left: stress path for the S3 in the ROW wells, right: Mohr-Coulomb stresses for the ROW7 wells at the current situation (purple) and initial situation (red). Direct injection into a fault would lead to the situation represented by the black dashed circle.

Table 2 ISIP values for ZE carbonates and DC sandstones recorded in ROW, TUM and COV wells

well	date of job	Reported ISIP bar/10m	depletion (bar) (estimated from P/Z plot ARPR2012)	average depth perf (TVD)	formation
ROW-9	21/2/1983	1.99	95	1200	ZEZ2C
ROW-7	30/10/1986	1.68	105	1150	ZEZ3C
ROW-3	2009	1.32	135	1800	DC
ROW-6	2009	1.62	110	1800	DC
TUM-2	29/11/1979	2.13	0	1200	ZEZ2C
COV-2	27/01/1984	2	200	2720	ZEZ2C
COV-24	11/09/1984	2.2	0		ZEZ2C
COV-35	29/05/1986	2	200	2800	ZEZ2C
COV-21	10/01/1984	2.3	0		ZEZ2C
COV-21	28/09/1983	2.15	0		DCCTH
COV-22	30/06/1984	2.14	0	2820	DCCTO (shale)
COV-22	30/06/1984	1.87	0	2820	DCCTH (sand)
COV-22	30/06/1984	2.03	0	2830	DCCTH (shale)
COV-22	30/06/1984	1.85	0	2830	DCCTH (sand)
COV-20	05/04/1984	2.03	60	2950	DCCTH
COV-20	15/10/1981	2.15	0		DCCTH
COV-34	09/04/1984	1.75	80	2780	DCCTK
COV-49	12/07/1988	1.85	0		DC zandsteen
COV-13	20/05/1980	1.94	40	2900	DCCTD (shaly)
COV-13	12/06/1980	1.87	40	2900	DCCTD (shaly)
COV-13	16/06/1980	1.94	40	2850	DCCTD (sandy)
COV-13	17/06/1980	1.92	40	2850	DCCTD (sandy)
COV-13	22/06/1980	1.96	40	2800	DCCTD (sandy)
COV-13	23/06/1980	2.2	40	2800	DCCTD (sandy)

Limburg (DC) reservoirs

There is only limited data available for the Carboniferous (DC) reservoirs in the Twente fields (Table 2) and the data show a high variation in values for the ISIP gradient in the nearby Coevorden area. The virgin stress in the area shows values for the S_3 that are lower (1.85-1.95 bar/10m) than the vertical gradient of 2.2 bar/10m. In 2009, when the field was at maximum depletion, 12 injection tests were executed of which only 2 tests (ROW-3 and ROW-6) yielded reliable values for the S_3 (Rijkeboer, 2009). The available results are visualized in a Mohr-Coulomb diagram for the test in ROW-3 and ROW-6 assuming a virgin S_3 gradient of 1.85 bar/10m at a depth of 1800 m (Figure 5). The left figure indicates that direct injection into a fault could result in fault slip. This scenario is less likely for the DC reservoir because it consists of sandstone and not of a fractured carbonate rock as is the case for the Zechstein reservoirs.

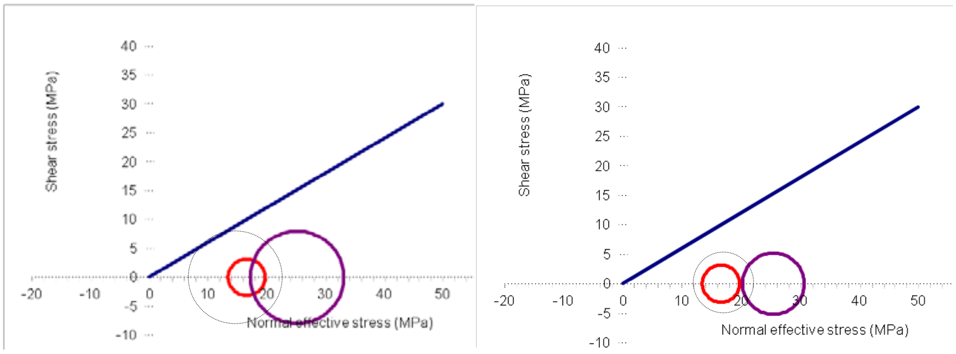


Figure 5 Mohr-Coulomb diagram for ROW-3 (left) and ROW-6 (right)

Some remarks on the usefulness of the M-C analysis

The Mohr-Coulomb analyses shown above are a highly simplified representation of reality and are dependent on the choice of the failure line parameters: the cohesion and the coefficient of friction, which is unknown for the faults.

Mechanism 3: Chemical reactions

It might be possible that chemical reactions that arise from injection of fluids into a fault change the frictional properties of that fault. Suckale (2009) indicated that stress-dependent corrosion reactions could affect both failure strength and the rate of crack growth. This mechanism is suggested as a cause for induced seismicity in the Fashing Field, Texas, US (TNO, 2014). Bois et al. (2013) describe the case of an induced earthquake in Friesland close to a water injection well that is injecting water at a very low rate. Based on a geomechanical analysis they claim that it is unlikely that direct stress changes from the injection process (both pressure increase and cooling) itself have caused the earthquake. They conclude that it is more likely that a water weakening effect, like for instance a chemo-physical effect on the capillary pressure, could have decreased the cohesion of an existing fault thus leading to the earthquake. Water weakening effects could also occur in the Twente injection reservoirs but the observation that in the first four years of injection no earthquakes are registered clearly speak against this. Assuming that, certainly in the near well regions, the fractures in the reservoir have been exposed to water, it is to be expected that such dramatic water weakening effects, as inferred for the Friesland case, will not occur in the Twente fields.

Mechanism 4: Thermal changes

Injection of fluids or gas colder than the reservoir rock will cool down the rock surrounding the injection wells. Thermal stresses in the near well area will affect the local stress and strain conditions. Thermal contraction can reduce normal stresses and increase shear stresses on a fault (Figure 6), hence promoting fault reactivation and induced seismicity (TNO, 2014). The change of the normal effective stress depends on the volumetric thermal expansion/contraction, the rock bulk modulus and the change in temperature.

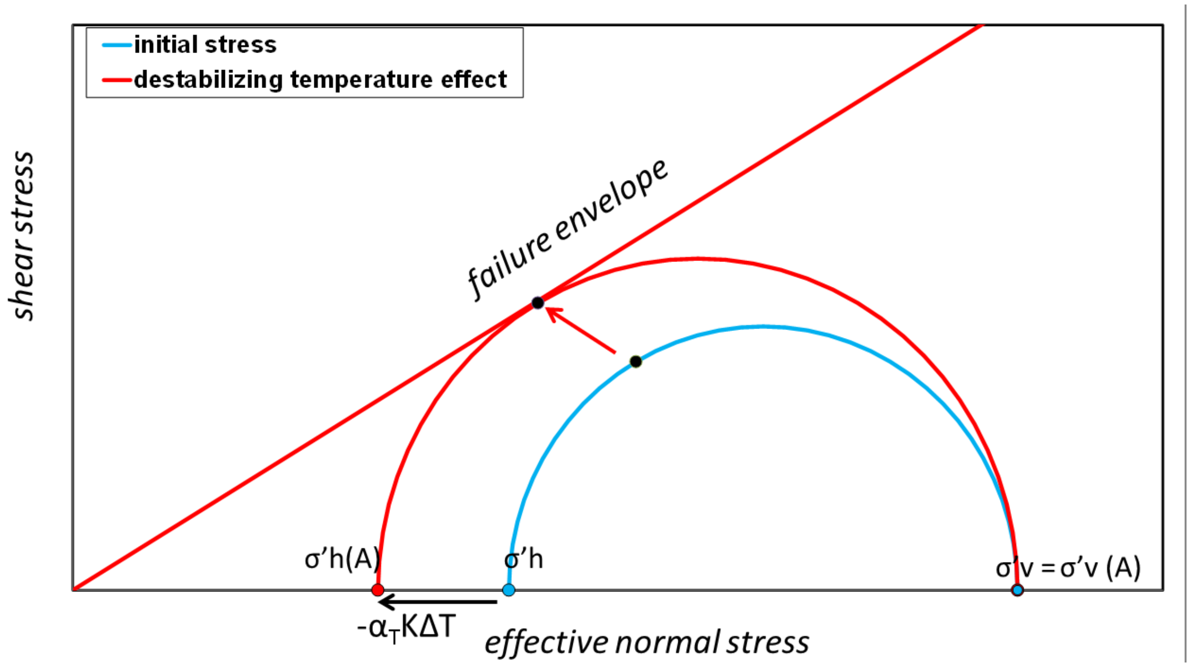


Figure 6 Example of a hypothetical tress path due to cooling of the reservoir rocks. α_T is volumetric thermal expansion coefficient, K is rock bulk modulus, ΔT is temperature change (TNO, 2014).

The impact of thermal stress on possible fault reactivation depends on a number of factors, e.g. the thermal properties of the injected fluids and rocks, temperature differences between injected fluids and reservoir rocks, flow characteristics, injection rates and volumes and the type of fluid or gas injected (heat capacity, thermal conductivity).

Temperatures in the injection fields

Based on temperature logs in the Twente injection wells, it is clear that the temperature differences between the reservoir rock (around 50 °C) and injected water (around 20 °C)is relative small (Figure 7). This will significantly limit the potential of this mechanism. The 30 °C temperature differences between the formation and the injection water is highest close to the well and will reduce rapidly with distance away from the injection point into the reservoir. In the first years of injection no seismic event was recorded and therefore it is not expected that this mechanism plays a role of significance in destabilizing faults in the field.

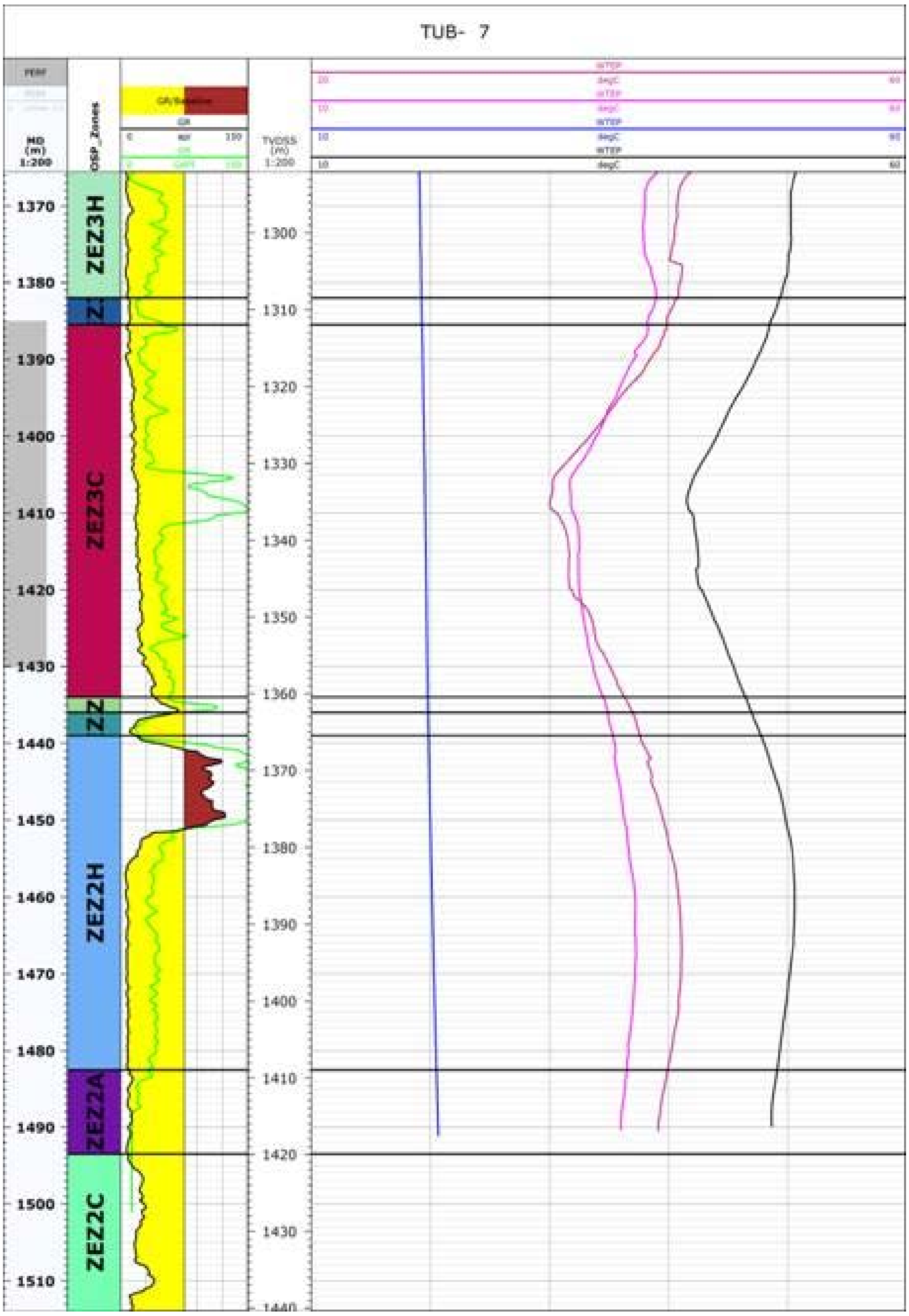


Figure 7 Measured temperature in the Tubbergen-7 well. The temperature scales are from 10 to 60 °C.

Observations from other fields

On a global scale induced seismicity is only prevalent in a small set of all the injection fields (e.g. National Research Council, 2012; Zoback 2012). TNO has conducted a literature review of injection-related seismicity observed in fields outside of the Netherlands. The main findings of the study (TNO, 2014) also relevant for the Twente water injection project are summarized below:

- In almost all field studies reviewed by TNO (2014) seismicity was observed when the pore pressure during injection was higher than the original reservoir pressure. Important is the fact that none of the Twente fields will exhibit higher than ambient pore pressure and the end of the injection time.
- The most important mechanism leading to induced seismicity was the increase of pore pressure in faults resulting in a significant reduction of normal effective stress in the fault making them more prone to fault slip.
- Delay between the onset of injection and the triggering of earthquakes has been observed. In some cases seismicity has been observed to continue well after shutting-in wells. This means that the absence of earthquakes in the first years of production does not provide a guarantee that earthquakes will not occur in the future.
- If faults are critically stressed a small pore pressure increase may cause fault reactivation. Given that no seismicity has been observed during the depletion phase of the Twente fields and the first years of injection indicate that faults in the Twente fields are not critically stressed.

An estimate of the maximum possible induced event using fault surface calculations

In the previous sections it is demonstrated that the key conditions that could result in faults becoming critically stressed and therefore prone for causing induced seismicity are not expected to be present in Twente.

This section explores what, in the unlikely scenario that an induced earthquake would occur, the absolute worst case magnitude would be. In parallel with the method applied below, TNO is currently conducting a similar assessment on small gas fields in the onshore Netherlands ("Quick scan Mmax of small onshore gas fields", TNO in prep). In this context, the below results are to be treated as very preliminary. As and when the TNO approach is shared, methods and outcomes will be compared, with the intent to arrive at a common and consistent approach.

The method used here aims to estimates the potential maximum seismic moment that could be released if a fault plain of a certain size slips in its entirety. The seismic moment can be used in a subsequent step to calculate a possible maximum magnitude. This method was first proposed by Aki (1966) and describes the relationship between the seismic moment (M_0) and the product of fault area (*S*), shear modulus (*G*) and possible displacement (*D*).

$$M_0 = G \cdot D \cdot S$$

The maximum displacement for faults in reservoirs will be dependent on the maximum expansion of the reservoir subjected to injection. According to Table 1, final pressure increase resulting from injection will only be a fraction of the total pressure depletion of the fields and at present it is unknown what part of the reservoir compaction will be reversible. The assumption of full elastic rebound will lead to conservative values for the expansion. Uniaxial compaction experiments were done on core material from ZEZ2C taken from the nearby Coevorden field. The average compaction value (Cm) obtained from these experiments is around 0.5E-5 bar^{-1}. Based on this compaction or, in this case, expansion value and a Poisson's ratio of 0.25, a shear modulus is estimated to be around 7 GPa.

Core experiments were also performed on the Carboniferous sandstone of the Coevorden field. These experiments yield higher Cm values and therefore lower shear modulus values (2.7E-5 bar^{-1} and 1.2 GPa respectively). The average displacement on a typical fault was calculated from the maximum vertical expansion (E) divided by 2. This number is divided by $\cos 30°$ to obtain the maximum displacement (D) along a dipping fault plain with an inclination of 60 degrees. The maximum area of slip (S) is calculated by multiplying the estimated length (l) of a fault (as derived from the top of reservoir maps) by the average reservoir thickness (T), again, divided by $\cos 30°$ to correct for the inclination (Figure 8).

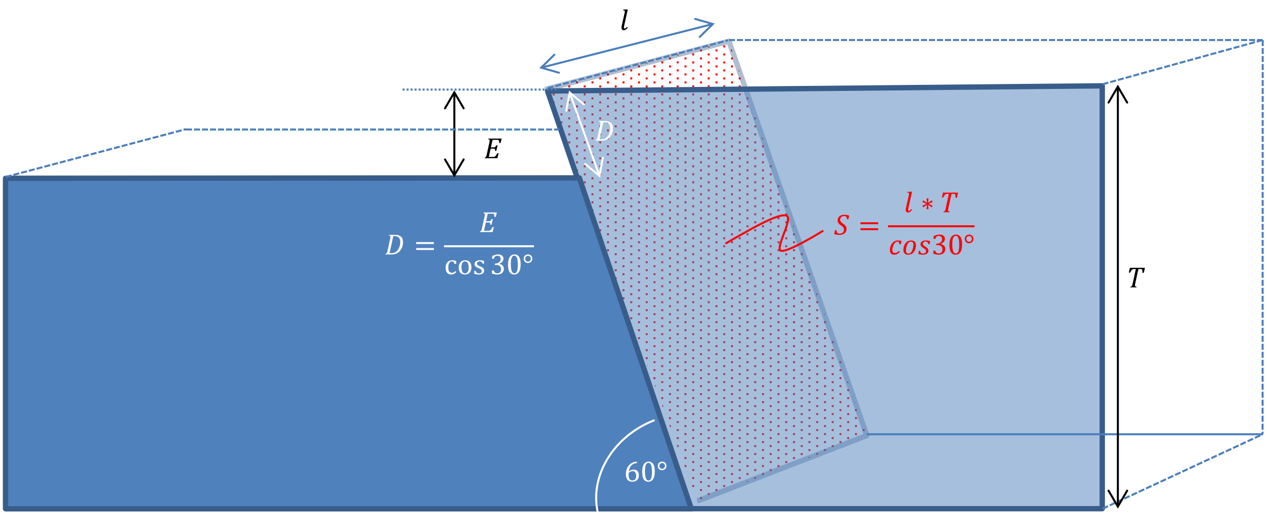


Figure 8 Definition of the geometry properties used in the calculations

The average thickness of the individual reservoir units is used here because it is unlikely that a possible rupture that starts in one of the reservoir units will connect to faults in another unit. This is based on the fact that [1] there is always a layer of viscous salt between two reservoirs units blocking brittle deformation (NAM report EP201310201845) and that [2] there is a stress contrast between the reservoir rock and the salt because of the reservoir pressure depletion. Both situations are unfavourable for fault rupture outside the reservoir.

For each field the faults with the largest lengths were selected for the calculations with the assumption that the fault will rupture in one go to its largest extent and using maximum values for expansion. This implies that the results represent the absolute maximum possible values for the magnitude and should be considered as very conservative. Also this analysis assumes that a fault will actually become critically stressed, something that based on other observations is estimated to be highly unlikely.

Figure 9 shows the top of reservoir structure maps with the selected faults highlighted in red. The numbers next to the faults match with the fault nr in Table 3. The possible maximum magnitude is calculated using the following relationship between seismic moment and moment magnitude (Hanks and Kanamori, 1979):

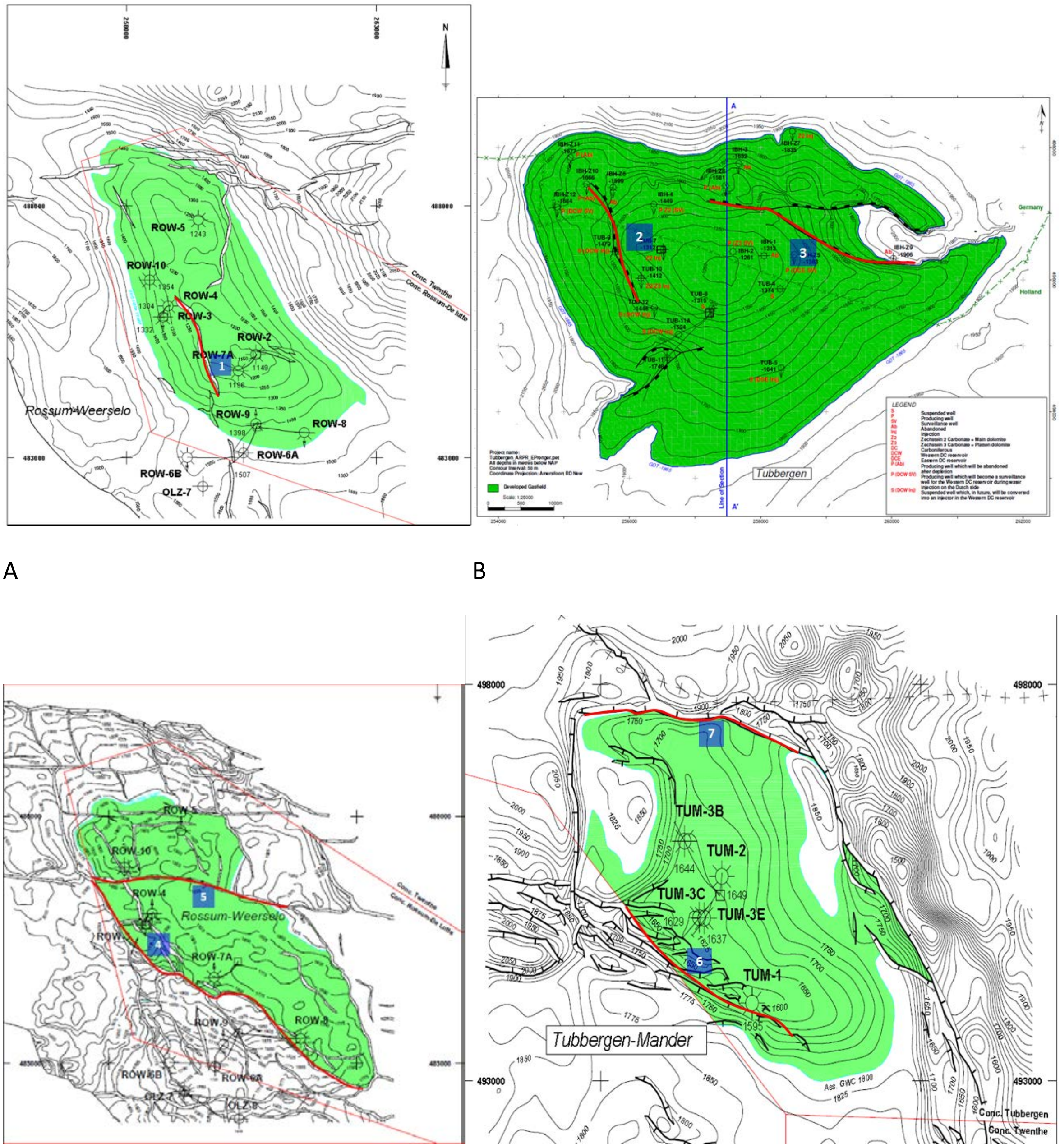
$$M_w = \frac{2}{3}\log \mathrm{M}_0 - 10.7333$$

Fault nr.	Reservoir	Average pressure increase [bar]	Reservoir layer thickness [m]	Cm [10^{-5} bar^{-1}]	Max D [m]	G [pa]	Fault length [km]	Fault area [m^2]	Mo [dyne cm]	Mw
1	ROW ZE	61	45	0.5	7.9E-03	7.0E+09	2	1.0E+05	5.7E+19	2.5
2	TUB ZE	111	54	0.5	1.7E-02	7.0E+09	2	1.2E+05	1.5E+20	2.8
3	TUB ZE	111	54	0.5	1.7E-02	7.0E+09	3	1.9E+05	2.2E+20	2.9
4	ROW DC	111	65	2.7	1.1E-01	1.2E+09	7	5.2E+05	7.0E+20	3.2
5	ROW DC	111	65	2.7	1.1E-01	1.2E+09	4	3.0E+05	4.0E+20	3.0
6	TUM ZE	11	45	0.5	1.4E-03	7.0E+09	3	1.6E+05	1.5E+19	2.1
7	TUM ZE	11	45	0.5	1.4E-03	7.0E+09	3	1.6E+05	1.5E+19	2.1

Table 3 fault properties for the faults mapped in Figure 9

Based on the values and assumptions mentioned the maximum possible magnitude varies in the range of 2 < Mw < 3.2. Values for Rossum-Weerselo Carboniferous are the highest because of a higher pressure differential, end pressure in the reservoirs and a larger fault area. As stated above, these results are preliminary and will be compared to the work currently being conducted by TNO ("Quick scan Mmax of small onshore gas fields", TNO in prep).

Even if an induced event would occur, which is not likely, it is to be expected that only a small segment of the large fault plain would slip, thus vastly reducing the slip area and hence the associated magnitude.



A B

C D

Figure 9 Top of structure maps for: A; Rossum-Weerselo Zechstein2C, B; Tubbergen Zechstein2C, C; Rossum-Weerselo Carboniferous, D; Tubbergen-Mander Zechstein3C

Possible peak ground accelerations as a result of induced seismicity

In the case of seismicity occurring during the injection period, it is important to understand the relation between the magnitude of an earthquake and the ground acceleration that is relevant for the potential impact it could have on the built environment. Accelerometers can be used to produce accelerographs, which register the acceleration as a function of time. The most common parameter that is deduced from the accelerograph is the maximum amplitude of the recorded waves or the Peak Ground Acceleration (PGA). Equations that relate magnitude to acceleration and distance from the location of the hypocentre are known as Ground-Motion Prediction Equation or GMPEs. Dost et al. (2004) published an equation that is based on measurements of the nearby Roswinkel field. NAM (2013) describes alternative functions for the Groningen field where lower PGA's have been recorded for similar magnitudes. Because there has never been an earthquake recorded in the Twente area there are no measurements of both magnitude and PGA. Therefore only a general statement can be made of the potential impact of an earthquake if it were to occur at relative shallow depth in the injection reservoirs (from 1100 to 2400 m). Both the Roswinkel and Groningen field are located deeper and therefore an event with a similar magnitude could produce higher PGA's at the surface above the Twente fields. Because of this uncertainty it is recommended to install accelerometers in the area to investigate the GMPE in case of possible events in the future.

Conclusions

This document describes possible threats that could lead to induced or triggered seismicity and how these relate to the conditions as observed in the Twente fields. Table 4 shows a list of the assessed mechanisms and consequences and a qualitative assessment of the possible impact on the seismic hazard. This assessment ranges from ++ a very low impact to - - a very high impact.

Mechanism or consequence	Qualitative Assessment	Reasoning
Poro-elastic stresses	+	+ Low ambient shear stress + Limited pressure increase + No seismicity during depletion – DC reservoir more prone to fault reactivation
Pressure increase in faults	+ -	+ Low ambient shear stress + Limited pressure increase – Zechstein carbonate reservoir are known to be fractured reservoirs
Chemical reactions	+ -	+ No seismicity observed during four years of injection – One small earthquake occurred in a Dutch Zechstein reservoir at low injection pressures. Chemical changes were proposed as the main driver in that case.
Thermal changes	+	+ Temperatures differences are limited
Maximum magnitude	+	+ Assessment of possible maximum magnitudes shows values up to a magnitude of 3.2. This a lower maximum than the general reported value of 3.9 by the KNMI
PGA	-	– Shallow depth of the fields could result in relative high PGA's at the location of the epicenters

Table 4 Qualitative assessment of the threats and consequences on the seismic hazard

Table 4 is a subjective evaluation of the threats. It can be used for further discussion with stakeholders and for recommendation on monitoring requirements. In the absence of observed and recorded earthquakes in the Twente area it is not possible to make any quantitative statements on the risk and hazard.

In general the following conclusion can be drawn:

- Induced or triggered seismicity is not expected to occur in the Twente fields because:
    - No seismic activity with $M_L \geq 1.5$ occurred during the 55 years of depletion or during the first four years of injection. Therefore it can be concluded that the faults were not critically stressed during this period.
    - The ambient stress state is likely to be close to isotropic for most of the injection reservoirs meaning that a significant induced stress change is required to reactive faults
    - Observations in fields elsewhere in the world reveal that in almost all cases where seismic activity was observed, the reservoir pressure during injection was higher

than the original pore pressure. Reservoir pressures in the Twente fields will remain below the virgin reservoir pressure (as stipulated by the Water Management Plan).

The above observations support the assessment that the chance for induced earthquakes to occur in the Twente injection fields is very low, however the risk cannot be excluded completely because:

- Every field has unique elements which makes that using fields elsewhere in the world as a direct analogue has to be done with care.
- Almost all predictive seismological models are based on statistics of historical earthquake data, which is not available for the Twente fields. Current deterministic tools lack detailed knowledge of both the physical processes and the variability and uncertainty in the available data.

Whilst no earthquakes have been recorded in the area, the uncertainties are such that it is recommended to expand the monitoring capability in the area. Specifically the following 3 recommendations are suggested:

- Expand the existing KNMI passive seismic network in Twente such that, in the unlikely case that an earthquake would occur, the location detection limit is at least equivalent to the rest on the North Netherlands.
- With the expansion of the geophone network also install an accelerometer network to measure associated ground movement velocities and accelerations. This would allow comparing these to other regions.
- It should be considered to put a seismic risk management protocol in place (e.g. Zoback, 2012).

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