

## Review TBO rapportage onderzoek 5

Technische Begeleidingscommissie Ondergrond (TBO),  
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# Technische Begeleidingscommissie Ondergrond

## 1. Inleiding

In deze notitie beschrijft de Technische Begeleidingscommissie Ondergrond (TBO) de resultaten van het reviewproces voor de rapportage van NAM over onderzoek 5, getiteld “Report on Subsurface Aspects of Induced Earthquakes in the Groningen Field”.

### *Vraagstelling en scope*

Onderzoek 5 maakt onderdeel uit van de 11 onderzoeken die de Minister van Economische Zaken heeft aangekondigd in zijn brief aan de Tweede Kamer van 11 februari 2013. In die brief spreekt de minister over een “onderzoek naar de (nieuwe) maximum sterkte van bevingen voor het Groningen gasveld”. NAM heeft de scope van het onderzoek verbreed tot en met het ‘seismisch hazard’ dat gepaard gaat met de bevingen in Groningen. In deze rapportage wordt het begrip (seismische) hazard gebruikt, waar het gaat om de kans op de overschrijding van een bepaalde bodembeweging. Als het woord risico wordt gebruikt, wordt bedoeld op die kans (hazard) maal de gevolgen (in termen van schade).

Aan de rapportage van NAM ligt een aantal (deel)studies ten grondslag, op het gebied van geomechanische modellering, statistische analyse en petroleum engineering. (Zie bijlage 2 voor een schematisch overzicht van het “Earthquake Study and Data Acquisition Program” van NAM.)

De rapportage van NAM is opgebouwd uit de volgende elementen:

- Een beschrijving van de geologie van het Groningen veld en van de historisch waargenomen seismiciteit in het veld.
- Een korte beschrijving van gegevens en relevante literatuur over geïnduceerde aardbevingen.
- De effecten van gasproductie op de compactie van het gasveld.
- Het vrijkomen van in het veld door compactie opgebouwde energie door aardbevingen.
- De berekening van de beweging aan het oppervlak die daarvan het gevolg is.
- Op basis van de voorgaande elementen is de ‘seismische hazard’ berekend, met de daarbij behorende grondbewegingen en contouren. Hiervoor wordt een probabilistische analyse gemaakt, met behulp van een Monte Carlo simulatie.
- Een hoofdstuk is gewijd aan geomechanische modellering en met name aan de rol van breuken.
- Een laatste onderdeel gaat over het verzamelen van aanvullende gegevens, waarvoor NAM een meet- en monitoring programma zal opstellen.

### *Proces*

De TBO is sinds mei 2013 periodiek geïnformeerd over de voortgang en de (tussentijdse) resultaten. Er zijn drie grote workshops georganiseerd, waarop deelstudies zijn gepresenteerd en bediscussieerd. Daarnaast zijn er voor experts technische bijeenkomsten georganiseerd over specifieke onderwerpen, gericht op begrip en verdieping. De TBO heeft in al deze discussies vooral gestuurd op het binnen de beschikbare tijd verkrijgen van de best mogelijke antwoorden op de vragen van de minister.

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## *Inhoudsopgave*

In de volgende paragraaf worden de bevindingen van NAM kort samengevat. Daarna wordt in paragraaf 3 een beoordeling gegeven van de resultaten. In paragraaf 4 en 5 volgen ten slotte de conclusies en aanbevelingen van de TBO aan de Stuurgroep. In bijlage 1 volgt een schematisch overzicht van de belangrijkste conclusies van de NAM rapportage, waarin de TBO zijn gedetailleerde commentaar heeft opgenomen, de mogelijke consequenties schetst en aanbevelingen geeft voor vervolg activiteiten.

Bijlage 2 geeft, zoals gezegd, een schematisch overzicht van de door NAM uitgevoerde (deel)studies. In de bijlagen 3 en 4 worden afzonderlijke meer gedetailleerde reviews gegeven van de belangrijkste van die(deel)studies. Het betreft in de eerste plaats een review van de hazard analyse die is gemaakt. In de tweede plaats volgt een review van het aanvullende geomechanische werk, toegespitst op het gedrag van breuken in Groningen.

## **2. Bevindingen van NAM**

De rapportage bevat de resultaten van onderzoek naar geïnduceerde seismiciteit in het Groningen veld, dat door NAM in 2013 is uitgevoerd. NAM benadrukt dat er weliswaar veel vooruitgang is geboekt in het begrip van de seismiciteit in het Groningen veld, maar dat de onzekerheden in de daarop gebaseerde voorspellingen voor de toekomstige seismiciteit aanzienlijk zijn. Er is een grondige statistische analyse uitgevoerd op de gegevens van alle 187 bevingen in Groningen met een magnitude van 1,5 en hoger, geregistreerd in de periode april 1995 tot oktober 2012. De grote mate van onzekerheid is o.a. gevolg van het beperkte aantal bevingen in deze periode, vooral in de hogere magnitude klassen. De onzekerheid neemt toe naarmate verder in de toekomst wordt gekeken. NAM stelt dat de resultaten van de seismische hazard analyse conservatief zijn en kondigt een programma aan om aanvullende gegevens over het veld te verzamelen en nader onderzoek uit te voeren om de onzekerheden, waar mogelijk, te reduceren.

Beschreven wordt dat de productie uit het gasveld leidt tot verlaging van de druk in het reservoir, die resulteert in compactie van het reservoirgesteente, waardoor spanning wordt opgebouwd in de ondergrond. De seismiciteit in het veld, zo wordt verondersteld, ontstaat als een gedeelte van deze spanning (of opgeslagen mechanische energie) zich ontladst als het gesteente gaat schuiven langs een natuurlijke breuk in het veld. In de onderliggende studies van Bourne en Oates (zie bijlage 3) stelt NAM dat er een relatie bestaat tussen de toenemende compactie van het gasreservoir en de in de loop der jaren toegenomen seismiciteit.

Als de seismiciteit in de toekomst de trend volgt die in het verleden is waargenomen, is er - op basis van de huidige statistische analyse op de 187 historische bevingen met een magnitude van 1,5 en hoger - in de komende tien jaar (periode 2013-2023) een kans van 50% op een beving met een magnitude (M) groter dan 4,2 op de schaal van Richter, een 10% kans op  $M > 4,9$  en een 1% kans op  $M > 5,4$ . Het betreft hier de kans over de genoemde periode van 10 jaar. De jaarlijkse kans neemt toe in de tijd.

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Het voorspellen van de frequentie en magnitude van toekomstige bevingen kent een grote onzekerheid. Wanneer vervolgens in de hazard analyse het effect van een bepaalde beving in termen van grondbewegingen wordt berekend, worden additionele grote onzekerheden geïntroduceerd, die inherent zijn aan de daarvoor gebruikte empirisch bepaalde Ground Motion Prediction Equations (GMPEs).

Voor de grondbeweging wordt op basis van een probabilistische seismische “hazard” analyse voor de komende tien jaar een jaarlijkse overschrijdingskans van 0,2% voorspeld op een maximale grondversnelling (PGA) groter dan 0,57 g, boven het gebied met de grootste reservoir-compactie. In diezelfde periode is er een jaarlijkse overschrijdingskans van 1% op een PGA groter dan 0,26 g.

De belangrijkste bijdrage aan de onzekerheid in de berekende hazard is volgens NAM de zogenaamde partiticoëfficiënt. Dit is een empirische factor die beschrijft welke fractie van de totale - vanwege compactie - in een gegeven periode opgeslagen energie vrijkomt in de vorm van bevingen. Om deze onzekerheid te reduceren dient meer fysisch begrip van de partiticoëfficiënt verkregen te worden en vervolgens in de analyses te worden ingebracht. NAM werkt o.a. aan meer gedetailleerde geomechanische modellering, maar die wordt bemoeilijkt door het gebrek aan relevante gegevens van het veld. Een programma om aanvullende gegevens te verkrijgen is gestart. Daarmee kan potentieel de bestaande onzekerheid worden gereduceerd, stelt NAM.

### 3. Beoordeling

De TBO is onder de indruk van de kwaliteit en de omvang van het werk dat wordt gepresenteerd, in het licht van de beperkte hoeveelheid gegevens en de korte tijd die voor het onderzoek beschikbaar was. Een gedegen statistische en seismologische analyse van de beschikbare data leidt tot een voorspelling van de seismische hazard, meer in het bijzonder van de frequentie van bevingen als functie van tijd en plaats en van de grondbeweging aan het oppervlak die gepaard gaat met een aardbeving.

Het bovenstaande neemt niet weg dat er zeker kanttekeningen bij de resultaten kunnen worden geplaatst, zoals NAM dat zelf in een aantal opzichten ook nadrukkelijk doet. Een eerste kanttekening van NAM is dat ten aanzien van de resultaten een grote - en met het aantal jaren waarmee vooruit gekeken wordt snel toenemende - onzekerheid bestaat. De verwachting is dat een deel van die onzekerheden in de komende jaren kan worden gereduceerd, als meer gegevens beschikbaar komen en aanvullend onderzoek wordt gedaan. De TBO deelt de mening van NAM over de grote onzekerheid in de berekende seismische hazard. Voor een deel is die onzekerheid inherent aan de gekozen (statistische) benadering, en de beperkte hoeveelheid gegevens die voor de analyse beschikbaar is. Voor een ander deel heeft de onzekerheid te maken met de beperkte fysica in het model waardoor de seismiciteit nu uitsluitend is gekoppeld aan de compactie van het veld.

Grote onzekerheid bestaat er over zowel de grootte (nu geschat op 0,1%) als de ontwikkeling in de tijd van de partiticoëfficiënt. Extrapolatie van deze factor op basis van de huidige gegevens is niet eenduidig en wordt nog niet ondersteund door een geomechanische duiding.

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Zoals NAM opmerkt, is het onzeker of de op basis van de historische gegevens afgeleide (exponentiële) ontwikkeling van die coëfficiënt zich in de toekomst zal voortzetten.

Uit de rapportage blijkt niet of voldoende is onderzocht op welke wijze en in welke mate de partiticoëfficiënt ook afhangt van andere factoren dan de cumulatieve compactie. Daarbij valt te denken aan, bijvoorbeeld, niet lineaire tijdsafhankelijke effecten door vervormingsgedrag van steenzout van de Zechstein formatie, afhankelijkheid van de breukdichtheid en van de snelheid waarmee de productie en dus de daaruit volgende compactie plaatsvindt. Dat laatste is van belang gegeven de discussie over het verlagen van de productiesnelheid als mitigerende maatregel. Het sneller of langzamer produceren van het veld heeft in het huidige NAM model hetzelfde gevolg als het sneller of langzamer afspelen van een film: dezelfde geschiedenis speelt zich af in een kortere of langere tijd. Het totale aantal bevingen en de verdeling naar magnitude van die bevingen blijft daarbij gelijk.

Ook ten aanzien van de in de toekomst te verwachten compactie zelf (die het aandrijvend mechanisme vormt) bestaat aanzienlijke onzekerheid. De drie verschillende compactiemodellen die NAM heeft beschouwd leiden in de eerste vijf jaar tot beperkte verschillen (minder dan 5 cm), maar daarna nemen die verschillen fors toe. Dit draagt in belangrijke mate bij aan de toenemende onzekerheid op de langere termijn. Daarbij moet worden aangetekend dat NAM in de statistische analyse tot nu toe heeft gewerkt met een zogenaamd (bi)lineair compactiemodel. Inmiddels gaat NAM voor de 'base case' bodemdalingsberekening uit van het *time decay* compactiemodel, dat tot een iets grotere compactie leidt. Het berekenen van de seismische hazard met dat compactiemodel moet nog worden uitgevoerd. Ook een derde compactiemodel, het zogenaamde *isotach* model, is nog niet doorgerekend. Toepassen van het *isotach* model zou tot een nog grotere compactie leiden in vergelijking met het *time decay* model.

Een tweede kanttekening van NAM zelf is dat de resultaten als conservatief beschouwd moeten worden. De TBO neemt aan dat met 'conservatief' in dit verband bedoeld wordt, dat resultaten worden gepresenteerd die *worst case* scenario's representeren, die m.a.w. aan de bovenkant van (maar binnen) de onzekerheidsmarges vallen. In de ogen van de TBO kan worden gesteld dat de hazard analyse voor de komende vijf jaar in die zin conservatief is, omdat de gepresenteerde hazard een gemiddelde kans over de komende tien jaar betreft, terwijl het model uitgaat van een jaarlijkse toename van die kans (omdat de partiticoëfficiënt exponentieel toeneemt). Als gevolg wordt de kans in de eerste jaren van de periode van 2013 tot 2023 overschat en in de laatste jaren van dezelfde periode onderschat.

Een ander element dat als conservatief ingeschat kan worden beschouwd, is de afschatting van de bovengrens voor de fysisch maximaal mogelijke magnitude. De TBO is het eens met NAM dat de gepresenteerde methoden om die bovengrens op basis van fysische overwegingen te bepalen van weinig nut zijn, ook al omdat ze geen invloed hebben op de berekende seismische hazard.

Gelet op de grote onzekerheden is een antwoord op de vraag of de resultaten conservatief zijn in zijn algemeenheid thans niet (wetenschappelijk) te onderbouwen. In de ogen van de TBO

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maken die onzekerheden het meer in zijn algemeenheid zeer risicovol om nu definitieve conclusies te trekken, zeker voor de langere termijn.

De TBO deelt de mening van NAM dat meer gegevens en verder onderzoek (bv. de verdere geomechanische studies en het uitvoeren van het voorgenumen monitoringsplan) nodig zijn om de onzekerheden in de toekomst mogelijk te kunnen reduceren.

Een meer gedetailleerde beschrijving en beoordeling van de conclusies van de rapportage van NAM is gegeven in paragraaf 4 en in meer detail opgenomen in bijlage 1. Hier worden de belangrijkste opmerkingen uit die bijlage kort genoemd:

- NAM gaat in de onderliggende onderzoeken uit van het bestaande productieprofiel van Groningen. De belangrijke vraag, wat de impact zou zijn van een aangepast productieprofiel (bv. productiebeperking) op de seismische hazard, wordt in de rapportage niet beantwoord. NAM heeft toegezegd deze vraag mee te nemen in de rapportage over onderzoek 6. Het antwoord op deze vraag lijkt zeer relevant om nut en noodzaak van een eventuele productiebeperking te kunnen beoordelen.
- De empirische “Ground Motion Prediction Equations” die worden gebruikt, zijn gebaseerd op tektonische aardbevingen in Europe en het Midden Oosten, maar aangepast om te fitten aan de waarnemingen in Groningen. Het is de vraag of deze GMPEs ook gelden voor grotere magnitudes dan tot nu toe zijn waargenomen in Groningen. Ook is niet aangetoond dat sterkere geïnduceerde bevingen vergelijkbaar zijn met tektonische aardbevingen met een vergelijkbare magnitude. De gemeten duur van de bevingen in Groningen is, bij gelijke sterkte, langer dan bij andere gasvelden in Nederland (o.a. Roswinkel) en de vraag is hoe deze duur zich verhoudt tot tektonische bevingen. Deze kanttekening neemt niet weg dat op dit moment geen betere GMPEs voorhanden zijn.
- Voor de groundbeweging voorspelt NAM op basis van een probabilistische seismische hazard analyse voor de komende tien jaar een jaarlijkse overschrijdingskans van 0,2% op een grondversnelling (PGA) groter dan 0,57 g, boven het gebied met de grootste reservoir compactie. In diezelfde periode wordt een jaarlijkse overschrijdingskans van 1% op een PGA groter dan 0,26 g voorspeld. De TBO tekent hierbij aan dat dit een gemiddelde kans is over de komende tien jaar. De jaarlijkse kans zal kleiner zijn in 2013 en groter in 2022, gezien de veronderstelde exponentiële toename van de partiticoëfficiënt.
- De centrale vraag van de minister voor onderzoek 5 betrof de (nieuwe) maximale sterkte van bevingen voor het Groningen gasveld. Voorheen werd rekening gehouden met een maximum van  $M = 3,9$ , maar de ontwikkeling van de seismiciteit in de afgelopen jaren maakte het nodig dit cijfer te herzien.

Deze vraag wordt in de rapportage van NAM niet beantwoord. Er wordt weliswaar een *fysisch* maximaal mogelijke magnitude gepresenteerd, maar die is niet vergelijkbaar met de *waarschijnlijke* maximale magnitude, waarvan bij de  $M = 3,9$  sprake was. De TBO betwijfelt of de gehanteerde methodieken om tot een afschatting van de bovengrens van  $M_{max}$  te komen wel toepasbaar zijn in het geval van Groningen en of de gekozen parameters wel realistisch zijn. De TBO is verder van oordeel dat een vergelijkbare

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waarschijnlijke maximale magnitude ( $M_{max}$ ) voor de kortere termijn wel afgeleid zou kunnen worden uit de gepresenteerde berekeningen, bijvoorbeeld door de  $P_{90}$  te nemen voor de komende tien jaar. In dat geval zou de  $M_{max}$  uitkomen op  $M = 4,9$  met een overschrijdingskans van 10%. Daarbij moet aangetekend worden dat in de door NAM gepresenteerde hazard analyse  $M_{max}$  geen rol speelt en vervangen wordt door het totaal beschikbare seismische moment.

Prof. Main (University of Edinburgh), die de onderhavige rapportage van NAM heeft gereviewd, complimenteert de auteurs en onderzoekers met het veelomvattende en professionele werk dat in zo korte tijd is verricht. Hij concludeert dat “all of the major conclusions and caveats listed in chapter 11 (*dat de conclusies samenvat - TBO*) are reasonable in the light of current knowledge [...], as are the plans in going forward with outstanding work to reduce the remaining uncertainties further”. Main komt wat dat laatste betreft met suggesties voor de richting van het geomechanische werk (bv. onderzoek naar de partiticoëfficiënt of de feitelijke aspect ratio).

De TBO deelt de observatie van professor Main dat het belangrijk is om de onzekerheden verder te reduceren. De belangrijkste onzekerheden betreffen het compactiemodel, de ontwikkeling van de partiticoëfficiënt (en de onderliggende fysieke processen) en de GMPE.

## 4. Conclusies

1. De TBO is van mening dat NAM in korte tijd grote stappen heeft gezet in het verkrijgen van meer begrip van de seismiciteit in het Groningen veld. Het onderzoek is met voldoende onafhankelijkheid opgezet en uitgevoerd en doorstaat - zoals blijkt uit verschillende onafhankelijke reviews - de toets der wetenschappelijke kritiek.
2. De grondige statistische analyse op de set gegevens van de 187 historische aardbevingen heeft geleid tot meer inzichten en vormt een goede basis voor de hazard berekening. O.a. vanwege de beperkte hoeveelheid gegevens bestaan er echter nog grote onzekerheden.
3. De TBO concludeert dat er consensus is over het eerste orde fysisch mechanisme dat de bevingen veroorzaakt. Het drijvend mechanisme wordt gevormd door de door gasproductie veroorzaakte afnemende reservoirdruk. Deze leidt tot compactie van het reservoirgesteente. Vervolgens komt een gedeelte van de hierdoor opgebouwde spanning vrij als seismische energie.
4. Er is consensus over de conclusie dat verdergaande depletie van het reservoir (verdere drukdaling) zal leiden tot meer aardbevingen en daarmee tot een grotere kans op sterkere bevingen en dat het niveau van de jaarlijkse gasproductie in eerste orde bepaalt hoe frequent de aardbevingen zich zullen voordoen.
5. Er is nog geen consensus over het fysisch model dat de afhankelijkheid van de compactie van de drukdaling in de tijd het beste beschrijft (het ‘compactiemodel’). Hiervoor bestaan verschillende hypothesen die op basis van de huidige bodemdalingmetingen alle valide kunnen zijn. De diverse modellen zullen naar



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verwachting voor 2018 leiden tot verschillen in de bodemdalingsvoorspellingen die toetsing beter mogelijk maken.

6. Er is een reële mogelijkheid dat op de iets langere termijn (> 5 à 7 jaar) een tweede effect in het fysisch mechanisme - nl. een afhankelijkheid van compactie van de snelheid van productie - een belangrijke rol zal blijken te spelen. Hierover bestaat op dit moment geen consensus. De invloed van de productiesnelheid op de seismiciteit is daardoor een onzekere factor, waarnaar NAM in de ogen van de TBO nog onvoldoende onderzoek heeft gedaan.
7. De grootte van de partiticoëfficiënt en de ontwikkeling ervan in de tijd zijn belangrijk en in belangrijke mate bepalend voor de toename van de seismiciteit in de komende jaren. De TBO deelt de conclusie van NAM dat de huidige statistische analyse laat zien dat het waarschijnlijk is dat deze coëfficiënt toeneemt. De mate waarin dit het geval zal zijn is echter zeer onzeker omdat goed fysisch begrip van de betekenis van de empirisch bepaalde partiticoëfficiënt ontbreekt.
8. Het is gewenst om verder onderzoek te doen naar de afhankelijkheid van de partiticoëfficiënt van andere factoren dan de compactie zoals de breukdichtheid en de compactiesnelheid.
9. De TBO betwijfelt of de gehanteerde methodieken om tot een afschatting van de bovengrens van  $M_{max}$  te komen wel toepasbaar zijn in het geval van Groningen. Bovendien is de *fysisch* maximaal mogelijke magnitude die gepresenteerd wordt, niet vergelijkbaar met de *waarschijnlijke* maximale magnitude.
10. De TBO vindt de alternatieve weg die in het onderzoek is gekozen, nl. het uitvoeren van een seismisch hazard analyse m.b.v. een Monte Carlo simulatie, een goede aanpak.
11. De TBO onderschrijft de conclusies van NAM dat er meer gegevens en aanvullend onderzoek nodig zijn om verdere stappen in de komende jaren te kunnen zetten.

## 5. Aanbevelingen

Hoewel onderzoek 5 (in combinatie met onderzoek 6) naar het zich laat aanzien voldoende basis vormt voor besluitvorming op dit moment, is de onzekerheid op de wat langere termijn zo groot, dat aanvullende onderzoek en data acquisitie noodzakelijk wordt geacht met als doel om die onzekerheden binnen beheersbare grenzen te houden. De TBO vindt het met het oog op het reduceren van de onzekerheden gewenst dat NAM de noodzakelijke verdere stappen verder concretiseert en daarvoor ook een planning maakt. In de ogen van de TBO zullen daarin ten minste de volgende onderdelen een plaats moeten krijgen.

- Maatregelen om de noodzakelijke extra gegevens te verkrijgen. Daarbij gaat het in elk geval om gegevens die een betere bepaling van de historische bodemdaling en calibratie van het compactiemodel mogelijk maken, extra gegevens over de seismiciteit (nauwkeuriger plaatsbepaling, dieptebepaling en duur van de beving) en over de resulterende grondbeweging (PGAs en PGVs).



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- Op basis van deze extra gegevens kan de monitoring verbeterd worden en kan regelmatig een nieuwe beoordeling van de seismische hazard worden gemaakt. Dit vormt de basis van een seismisch risico management systeem, met inbegrip van de bovengrondse aspecten.
- Het compactiemodel moet nader worden bezien. De verschillende gesuggereerde modellen dienen op hun validiteit en toepasbaarheid getoetst te worden, zowel aan de hand van nieuwe meetgegevens in Groningen in de komende jaren, als door wetenschappelijk onderzoek.
- Het porositeitsmodel dat medebepalend is voor voorspelling van compactie dient kritisch te worden gevalideerd en te worden geactualiseerd naarmate meer gegevens binnen komen.
- Er moet meer fysica worden gebracht in de seismische hazard analyse en in het bijzonder in de afleiding van de partiticoëfficiënt en de GMPEs. Door geomechanische modellen te integreren in de statistische analyse kan de rol van breuken en van de compactie-snelheid worden ingebracht. *Full waveform* modellering kan de onzekerheden in de GMPEs verlagen.
- Er is 3D geomechanische modellering nodig om bv. de effecten van de oorspronkelijke spanningstoestand in de ondergrond (*stress state*), de dichtheid, geometrie en afmetingen van breuken te bestuderen.

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## Bijlage 1

### Review by the TBO of the conclusions of NAM's draft report on 'Subsurface Aspects of Induced Earthquakes in the Groningen Field'

4. Historical compaction / subsidence and future trends			
Conclusions NAM	TBO comments	Consequences	Follow-up
Three compaction models were calibrated against field data and applied to assess the uncertainty in future compaction and subsidence. All models fulfill the condition that they match the historical dataset.	Different compaction models have different consequences for the future behaviour of compaction with production. Indeed, all models are matched to the subsidence so far.	At this point, no conclusions about the compaction model can be drawn yet.	The compaction model and time delay behaviour of compaction need to be studied using future subsidence measurements of levelling and, ideally, permanent GPS stations.
At present, the base case compaction model is the time-decay model that describes compaction following depletion with a fixed time-decay constant. The bi-linear model reacts instantaneously on the depletion and of the three models predicts the least amount of subsidence and compaction in the future. The third model, the isotach model proposed by TNO, where loading rate plays an important role in the calculated compaction, predicts significantly more compaction in future and is regarded as the high compaction case.	The previously used bi-linear model is considered to be less plausible, also by NAM. This reduces the number of choices for the models, effectively: the time-decay or the isotach compaction model.	Using the time-decay model (preferred by NAM at this moment) results in lower future compaction compared to using the isotach model. The difference becomes significant between 7 – 10 years from now.	See above
A prognosis for the next ten years shows only little difference between the four compaction models. Results for the period beyond are seen to diverge.	Three compaction models were considered instead of four. For the next 10 years the compaction between the different models seems to diverge only by 5 cm. After this period, the differences in compaction for the different models increase.	Due to this uncertainty (which model is best) a prognoses for compaction at the end of field life (up to 2080) is uncertain. As a result a reliable prognosis can only be made for shorter time periods.	Monitoring of the development of subsidence in view of these different compaction models.
A conservative assumption in the hazard	There are examples of foreign gas	A calculated figure for	Introduce more physics in the

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calculation is that all modeled compaction volumes are recoverable strain volumes, available as stored strain energy for release as seismic energy.	fields, geothermal systems and water disposal systems where the amount of stored energy in the system does not equal the amount of released seismic energy.	total stored energy cannot be used to derive a realistic value for Mmax.	derivation of the partitioning coefficient. Investigate if the use of information available elsewhere would make it possible to substantiate a smaller partitioning coefficient.
<b>5. Induced seismicity due to gas production</b>			
Albeit rare, the open literature contains several comprehensive listings summarizing the known cases of induced seismicity following gas production.	The fact that open literature only describes a few examples does not mean that seismicity itself is rare. Few gas fields elsewhere have the dense monitoring system that Groningen has. It is likely that micro seismicity always takes place.	Micro seismicity can, probably, be observed for all producing gas fields.	
In most cases induced earthquakes are of small or intermediate magnitudes but there are documented cases of larger, damaging earthquakes being apparently induced or triggered by extraction of fluids from the subsurface. Magnitudes tend to fall in the range of $M=1 - 5$ (see advice KNMI 2012).	Larger magnitude events have generally occurred in active tectonic regions making them likely to be triggered instead of induced. In the literature this distinction is not always made e.g. in Klose (2013).	Triggering of larger magnitude events cannot be excluded in active tectonic regions. Conclusions from literature should be handled with care	
The Rotenburg $M=4.4$ earthquake is potentially a good analogue for Groningen (both Rotliegend reservoirs).	The report does not substantiate this. More information on e.g. the size of the field, the dimension of the fault(s), the amount of production/pressure drop and the geology would be needed in order to support this statement.	Rotenburg cannot be taken as an analogue for Groningen without further research.	Potential analogues for Groningen need to be analysed.
The Yibal example shows that events induced by reservoir compaction can be located outside (above or below) the reservoir.	It is not clear how Groningen compares to Yibal, in terms of e.g. geology, geomechanical parameters.	Events induced by reservoir compaction cannot be excluded to occur below or above the reservoir itself.	Improved monitoring in wells should provide this information.
<b>6. Release of energy by Earthquakes</b>			

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<p>According to current model-based predictions for the areal distribution of reservoir compaction at the end of field life, an induced earthquake of <math>M &gt; 6.5</math> is physically impossible. This limit, however, provides no information about the likelihood of an induced <math>M \leq 6.5</math> earthquake.</p>	<p>The assumption made here is that all compaction strain is released in a single seismic event. This is a very conservative assumption.</p>	<p>The maximum <i>physically possible</i> magnitude is large (<math>M=6.5</math>), albeit impossible to occur, and cannot be compared to the historical maximum <i>probable</i> magnitude of <math>M=3.9</math>.</p>	
<p>The location, frequency and magnitude of observed earthquakes in the Groningen field are consistent with bulk reservoir volume changes (compaction), being the main source of seismicity.</p>	<p>This implies that (increase in) compaction drives the induced seismicity. Other aspects such as initial stress state, differential compaction and presence of faults may also be relevant, but are not included in the present empirical seismicity model. These could also explain the observed variations over the field.</p>	<p>Prediction of future behaviour for areas with hitherto low seismicity is difficult as uncertainties are large and other factors have not been taken into account.</p>	<p>Improved monitoring and regular re-assessment based on new data.</p>
<p>The fraction of bulk reservoir volume changes accommodated by seismogenic fault slip is about 0.1%. If this fraction were invariant with production, the maximum magnitude of a future event is expected to be <math>M=4.5</math> with a 95% upper bound of <math>M=5.5</math>.</p>	<p>This comes from comparison between the estimated total seismic moment and moment realized.</p>		
<p>There is evidence that the release of seismic moment per unit production escalated with increasing production volume. If this trend continues with future production, an increasingly large fraction of the induced strain may be accommodated by seismogenic fault slip.</p>	<p>This implies that the strain partitioning factor (now estimated at 0.1%) could increase in the future as compaction will increase further.</p>	<p>The dependence of the strain partitioning coefficient on total compaction could change considerably.</p>	<p>Further investigate the sensitivity of the strain partitioning factor for increasing compaction and for different compaction models.</p>

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<p>The fraction of induced strain accommodated by earthquakes is likely increasing with increasing reservoir compaction. This explains the observed temporal and areal distribution of earthquakes.</p>	<p>The extent to which the strain partitioning factor will increase in future is very uncertain.</p>	<p>Only, if the present trend continues, the annual number of earthquakes and the risk of larger magnitudes will increase significantly over the coming ten years.</p>	<p>It is important to keep on following the development of the strain partitioning factor in the next years.</p>
<p>If this escalation trend continues with future production the footprint of earthquakes is expected to continue extending from the center towards the edges of the field, but the relative abundance of earthquakes will continue to be localized within the regions of largest reservoir compaction in the center of the field.</p>	<p>In general this is a valid and plausible expectation. However, considering specific locations over the field, the presence or absence of (larger) faults is also important, since they are required to initiate earthquakes.</p>	<p>Local fault density is likely to influence the location of future earthquakes, in particular for larger magnitudes. The criticality of the faults will determine whether the shear stresses on the faults are sufficient to induce earthquakes. Prediction of future behaviour for areas with hitherto low seismicity is uncertain.</p>	<p>An attempt should be made in to integrate the statistical approach to seismicity with geomechanical modelling.</p>
<p>If future seismicity follows the same trend of increasing fault strain partitioning observed in the historic earthquake catalogue, then based on the current analysis there is a 1 in 2 chance of <math>M &gt; 4.2</math>, a 1 in 10 chance of <math>M &gt; 4.9</math>, and a 1 in 100 chance of <math>M &gt; 5.4</math> before the end of 2023. These estimates include known uncertainties associated with the trend of seismogenic fault slip accommodating an increasing fraction of the induced strain but currently exclude the possible trend of the b-value decreasing with compaction that may increase the likelihoods stated. These estimates also exclude</p>	<p>Uncertainties in these numbers are large and grow fast at later times. The chances given here would increase if future compaction would prove to follow the isotach model rather than the bi-linear model.</p>	<p>These findings imply the need for a measurement and control loop based seismic risk management system for Groningen.</p>	<p>These findings imply the need for a measurement and control loop based seismic risk management system for Groningen.</p>

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the possibility of triggered earthquakes that may increase these likelihoods.			
<b>7. Movement at surface</b>			
Recorded peak ground accelerations (PGA) and velocities (PGV) from induced earthquakes in the Groningen field show remarkably low amplitudes, even compared to recordings from earthquakes of similar magnitude in the Roswinkel field.	These observed lower amplitudes might be related to the observed longer signal duration	Extrapolation to larger magnitudes is uncertain.	It is important to improve monitoring of PGA/PGV across the field and to use the observations to update the empirical ground-motion prediction equations that are being used to estimate PGA and PGV.
The most likely explanation for these low amplitudes is the effect of the high-velocity, high-density basal anhydrite layer in the Zechstein formation immediately above the Groningen gas reservoir, since this creates a strong negative impedance contrast.	This is a likely explanation. Other possible explanations should not be excluded at this point.	The presence of the anhydrite layer may prevent higher amplitudes of ground motion for magnitudes up to M=3.5.	Waveform modeling should be performed to investigate this. Other possible explanations should be investigated as well.
The beneficial effect of the basal anhydrite is not assumed to hold for motions from larger earthquakes (M>4) until verified by other investigations, and for the initial hazard analysis it is assumed that ground-motion amplitudes will be comparable to those recorded in tectonic earthquakes.	For larger events, the thick Zechstein layer also plays a role as high velocity layer, similar to the anhydrite layer.		
On this basis, ground-motion prediction equations (GMPEs) derived from recordings of tectonic earthquakes in Europe and the Middle East have been adopted for the prediction of PGA and PGV. The equations were selected on the basis of using hypocentral distance, which is consistent with the way earthquakes are modeled in the hazard analysis, and including a term for site amplification effects that is able to model the influence of the soft near-surface conditions	The adapted GMPEs used are for general tectonic events in Europe and Middle East. It remains to be seen whether the GMPEs hold for larger magnitudes, Also it remains to be proven that larger induced events are comparable to tectonic events of similar magnitude. However, this is at the moment the best model.	Hazard analysis strongly depends on the GMPE used. All GMPEs are associated with high uncertainties.	Improved monitoring of PGA/PGV and regular reassessment of GMPE in the case of higher magnitudes occurring.

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encountered in much of the Groningen field.			
The equations have been adopted in their original form for larger earthquakes, but adjusted below a threshold magnitude (4.2 for PGA, 3.8 for PGV) in order to provide a good fit to the Groningen data at smaller magnitude levels.	The adjusted part of the GMPE fits the observed Groningen PGA/PGV data.	The uncertainty of the GMPE in the smaller magnitude range ( $M < 4$ ) is (relatively to $M > 4$ ) small as it was fit to the observed Groningen data.	
Additional work is required to refine the local applicability of the selected GMPEs to the Groningen field and also to estimate the associated levels of epistemic uncertainty.	The Groningen database is small and has a limited magnitude range. Evaluation of epistemic uncertainty (rising from incomplete knowledge) is essential		A suitable model for the range of epistemic uncertainty should be developed.
Since currently only PGA and PGV are being predicted in the hazard analysis, it is important to take account of the fact that for most of the earthquakes considered in the hazard analysis, the duration of shaking will be short as a result of the small magnitude of these earthquakes.	Whether the duration of larger magnitude events is also short remains to be seen. Duration of Groningen events is already much larger than for Roswinkel events.	It cannot be excluded that the duration of shaking for larger events is larger than so far observed.	Monitoring of the duration of shaking and comparison with duration models based on other data to improve future seismic hazard estimates. The duration of shaking should become part of the seismic hazard assessment.
<b>8. The Hazard</b>			
A Monte-Carlo approach to Probabilistic Seismic Hazard Assessment (PSHA) was identified as being best suited to the analysis of the Groningen field's induced seismicity.	For a statistical analysis, a Monte Carlo approach is indeed best suited.	In a Monte Carlo approach all uncertainties can be taken into account giving an accurate uncertainty range of the resulting analysis.	
Independent PSHA implementations in Python and C gave the opportunity for valuable cross checking of hazard estimates.	Cross-checking is important as the hazard estimates have a high impact.	An independent check on the implementation of a new algorithm minimizes unwanted errors.	



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<p>Eurocode 8 has been adopted as a standard framework for the assessment of the seismic capacity of buildings in the Groningen field area. Consideration of PGA and PGV values corresponding to the 475-year return period specified in Eurocode 8 requires that a specific production period is chosen for calculating the annualized hazard due to the planned production and expected compaction.</p>	<p>Eurocode 8 is a standard framework and appropriate for assessment of seismic hazard in the Groningen area.</p>	<p>The annual hazard has to be calculated for a given production period.</p>	
<p>Predicted maximum ground motions with an average annual 0.2% chance of exceedance, for the 10 years of production from 2013 to 2023, are 22 cm/s (PGV) and 57% of g (PGA), located above the region of greatest reservoir compaction. These values were obtained using the modified form of the Akkar et al (2013) GMPE and by integrating over magnitudes from 1.5 to 6.5.</p>	<p>These values are average for the period 2013-2023. Annual hazard will be lower in 2013 and higher in 2023 if the assumption of an exponential increase in strain partitioning factor is correct.</p>	<p>Annual hazard is in particular sensitive to the behavior of partitioning coefficient.</p>	
<p>Direct comparisons with published 475-year hazard maps can be very problematic because such standard hazard maps generally impose a lower minimum magnitude limit than the <math>M=1.5</math> used here, such as <math>M=5</math> in California and <math>M=4.5</math> in Europe.</p>	<p>Seismic hazard maps for induced seismicity, so far, hardly exist for other fields than Groningen. 'Lower' should be replaced by 'higher'</p>	<p>Seismic hazard due to tectonic or due to induced events is difficult to compare.</p>	<p>Investigate the difference between seismic hazard due to tectonic and due to induced events.</p>
<p>Disaggregation of the hazard showed that the seismic hazard is dominated by events of intermediate magnitudes (<math>M = 4 - 5</math>). This contrasts with the maximum possible magnitude, <math>M = 6.5</math>, implied by the compaction-based seismicity model, showing that the induced seismic hazard is not well characterized by <math>M_{max}</math>.</p>	<p>The <i>physically</i> possible maximum magnitude <math>M=6.5</math> cannot occur. It is not used in the hazard analysis. The maximum <i>probable</i> magnitude, however, will have an impact on the seismic hazard.</p>	<p>Intermediate magnitudes will dominate the seismic hazard due to their probability of occurrence and the used GMPEs. The effect of a maximum <i>probable</i> magnitude event will be more extensive at least in affected area.</p>	<p>Examine the maximum <i>probable</i> magnitude and derive its impact in terms of seismic hazard.</p>

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The most important uncertainty affecting the calculated hazard is the very large uncertainty in the coupling coefficient relating seismic moment budget to the volumetric strain due to compaction.	Note : by 'coupling coefficient' is meant 'strain partitioning coefficient'	The future behavior of the partitioning coefficient is uncertain	Focus further research on the physical basis of the partitioning coefficient
Sensitivity tests showed that the selection of a suitable ground motion prediction equation (GMPE) and the future production period chosen for calculating the annualized hazard had a strong influence on the resulting hazard estimates. Changes to the b-value however had limited impact on the calculated results.	GMPE and annual production will have a large impact on the annual seismic hazard.		
<b>9. The role of faults</b>			
The minimum horizontal stress is poorly constrained. No reliable data is available from the time before production started, while limited data is available under depleted reservoir conditions. Stress anisotropy is expected between different formations, but is not well established (except for the Zechstein formation). Both initial value and stress development as a consequence of depletion should be measured when having the opportunity (drilling of new wells, work overs).	Minimum horizontal stress is often poorly constrained.	This introduces more uncertainty on the criticality of the faults.	Relevant for new gas fields: try to measure initial stress and the development stress in gas fields at the start of production as well as several times during production.
Reservoir pore pressure in the Rotliegend reservoir is well established from production and observation wells, but there are areas in the field with poor well coverage. The main area of uncertainty is the pressure field over time in the underlying aquifer and in the overlying Ten Boer Claystone. Data acquisition is needed to reduce these uncertainties.	Pressure drop uncertainties in the underlying aquifer and the overlying Ten Boer Claystone introduce uncertainties in the compaction of the Groningen field and thereby in the estimation of seismic hazard.	Additional uncertainty in the total compaction of the field which gives additional uncertainty in the estimation of seismic hazard.	Pressure data acquisition in the over- and underburden is necessary.
Pore pressure evolution within faults is not known and cannot be measured in the subsurface. However, the impact of this process can be	2D geomechanical modelling will provide more insight into specific geomechanical issues such as pore		The results should be incorporated into the seismic hazard analyses where

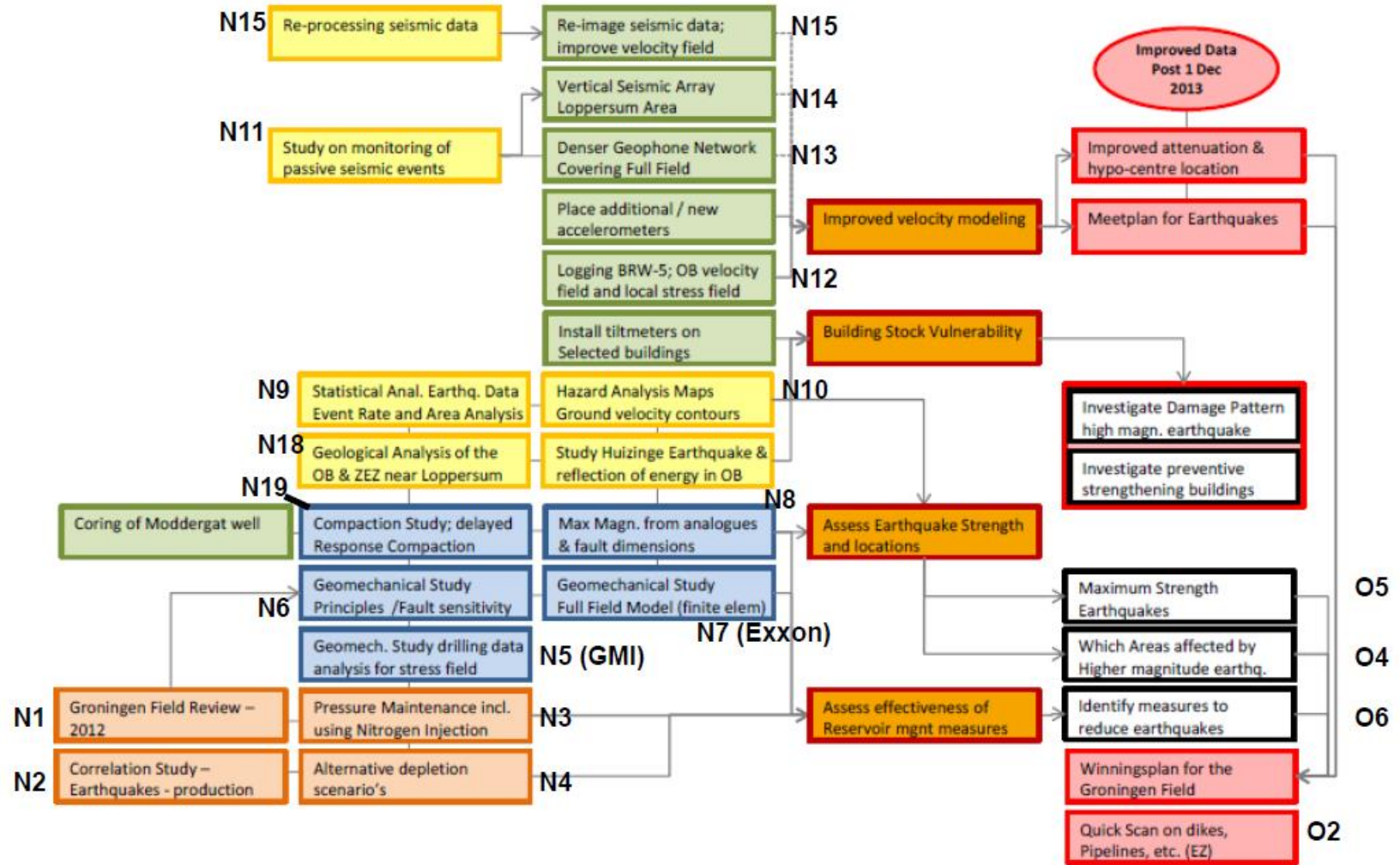
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evaluated through modeling. This is the objective of the ongoing vibration analysis study (2D evaluations).	pressure evolution within faults, but also constitutive behavior, behavior of the salt etc.		applicable.
The accuracy of determining hypocenter locations needs to be improved to differentiate between possible failure mechanisms. Both the installation of down hole geophones and additional shallow geophones fulfill this objective.	The improvement in hypocenter location accuracy will also help to determine the actual depths of the events as well as locations on existing faults	If the failure mechanism is known more accurate prediction may be possible in future.	Down hole geophones and additional shallow geophones should be installed.
Time-delayed compaction and other irreversible deformations that could delay or reduce fault slippage is the subject of ongoing research (KNAW, 2013).	Compaction has a much larger impact on seismic hazard than previously recognized.	Compaction is important for the determination of seismic hazard. Improved understanding of compaction theory will lead to improvement of assessment of seismic hazard.	The compaction model and time delay behaviour of compaction need to be studied using future subsidence measurements of levelling and, ideally, permanent GPS stations in order to correctly predict the future compaction and subsidence. New findings resulting from academic research should be incorporated as soon as possible in the future work related to the Groningen field.
Advanced 3D geomechanical modeling is carried out to investigate the stress evolution in and around the producing Groningen field and its relation to the reactivation of faults. The models also serve to evaluate the effects of different production scenarios in the framework of TBO research topic 6.	It is noted that this work will not be ready before the end of 2013. In future 3D geomechanical modeling is expected to give insight into these issues. However, uncertainties and simplifications in 3D modeling are such that conclusions have to be drawn carefully.		3D geomechanical modeling should be performed. The results should be incorporated into the seismic hazard analyses where applicable.

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## Bijlage 2

### Earthquake Study and Data Acquisition Program – Dependency and Overview



## **Bijlage3: TBO Review of the NAM studies into the Seismic Hazard in the Groningen gas field**

### **Summary**

At the request of the Steering Group, the TBO (Technische Begeleidingscommissie Ondergrond) has reviewed the results of the studies carried out by NAM in 2013 into the seismic hazard caused by gas production from the Groningen field. The reviewers appreciate the quality and quantity of the work presented, also in view of the limited time period and the limited amount of data available for its execution. NAM has managed to pull together, at short notice, expertise available inside and outside of the NAM and Shell organisations. A novel seismology model has been developed relating induced seismicity in Groningen to the reservoir compaction resulting from the gas production.

The TBO notes the empirical nature of the presented findings and their reflection in the NAM seismicity model. The underlying physics is limited and needs to be extended by further studies and data. The introduction of a partitioning coefficient allows for the fact that only part of the accumulated strain energy is partitioned onto faults and released as seismic energy. This partitioning coefficient is an empirical parameter that can absorb or hide other physical processes not yet included in the model. The limited physical substantiation of the partitioning coefficient and the uncertainties in the limited data on which it is based, create considerable uncertainties on its further development. And hence on the development of seismicity for periods beyond a few years into the future. Some of these uncertainties may reduce over the coming years as new data and results from additional studies become available. Others will remain, as they are a consequence of the unpredictability of the occurrence of earthquakes.

In the opinion of the TBO it is shown by NAM that the observed phenomenon of increasing seismicity with increasing production is likely to continue for the coming years. And that, even when considering the large uncertainties, PGAs and PGVs may occur at a level and frequency that cause serious concern. The TBO agrees with NAM that the annual number of earthquakes and hence the annual hazard scales with the annual gas production. The TBO notes that the number of earthquakes during the total field life might reduce with lower production rates if time dependent relaxation mechanisms play a role. This aspect has not been investigated in depth.

A solid statistical and seismological analysis is made of the data from the Groningen field based on all registrations until October 2012. Based on its results, a workflow has been implemented that can be used to determine seismic hazard as a function of location and time under different Groningen gas production scenarios. First results are presented. Proper analysis and recognition of the large uncertainties in the obtained results are provided. The TBO is of the opinion that the analysis results in an empirical description of induced seismicity and the related seismic hazard to be expected in Groningen. It is made plausible that for the data analysed (until October 2012), the released seismic moment increases more or less exponentially with reservoir compaction. The TBO agrees with NAM that if this trend continues, the released seismic moment, the annual number of induced earthquakes and subsequently the probability of higher magnitude earthquakes in Groningen will increase. Under the assumption of a continued exponential increase, a PGA of above 0.57g is calculated

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for an annual average 0.2% chance of exceedance between 2013 and 2023. The uncertainties in these predictions are very large and grow fast with time, in particular for predictions beyond a few years from now.

The TBO notes that the annual hazard will not be constant during the next 10 years. Initially the hazard will be lower, rising to higher values towards the end of the period. The TBO agrees that longer term (beyond ca. 2030) and depending on the future development of reservoir compaction, the hazard could gradually decrease again. The latter is a net result of the competing effects of increasing total compaction and decreasing annual production.

With respect to attempts to determine a maximum earthquake magnitude for Groningen it is noted that none of the three different methodologies as applied by NAM results in values below 5.5. However, the TBO doubts whether the methods used to arrive at an estimate of an upper limit to  $M_{max}$  are applicable to the case of Groningen. Furthermore, the presented values for *physically maximum possible* magnitudes cannot be compared to values of *probable* maximum magnitude. In any case,  $M_{max}$  is not relevant for the calculation of seismic hazard.

The main hazard (probability of a PGA above a given value) will result from earthquakes with magnitudes between 4.5 and 5.5 at hypocentral distances up to 10 km. Higher magnitudes contribute less to the hazard, mainly due to their lower probability combined with a saturation of ground motion amplitudes at these higher magnitudes.

The report does not show if and how it was examined to what extent the strain partitioning factor also depends on parameters other than compaction, such as e.g. the density of faulting, the production rate, or non-linear, time-dependent deformation behavior of rock salt of the Zechstein formation.

The TBO agrees with NAM that the reported findings imply the need for a strongly increased study and monitoring effort in combination with regular (annual) hazard assessment updates to feed a measurement and control loop as part of the seismic risk management system.

*Table 1: Summary of key uncertainties of the seismic hazard analysis identified by the TBO and proposed follow-up*

Key Uncertainty	Character	Consequence	Proposed follow-up
Development of strain partitioning coefficient	Lack of data  Lack of understanding of underlying physical mechanisms	Large uncertainty in future seismicity levels and in the PGA value corresponding to a 0.2% annual chance of exceedance	Test against different geomechanical models Study and include effects of initial stress state, fault density, fault orientation, deformation rate etc. though 3D geomechanical modelling. Improved monitoring of earthquakes (surface seismometers, accelerometers, borehole seismometers) Measurement and control loop
GMPE	Lack of data	Large uncertainty	Calibration with future data Full waveform modelling



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Key Uncertainty	Character	Consequence	Proposed follow-up
Reservoir moment	Lack of data Lack of detailed studies Lack of accurate calibration	Large uncertainty in future seismicity levels and in the PGA value corresponding to an 0.2% annual chance of exceedance	Better determination of historical subsidence. Test alternative geomechanical models and compaction scenarios against the observed subsidence. Test impact of porosity model uncertainty
Impact of initial stress state, faults	Lack of data	Localisation of future events	3D geomechanical studies Better monitoring
Event density map	Limited data Uncertainty in porosity model	Localisation of future events	Monitor development over time Improve porosity model Incorporate effect of fault density on localisation
Impact of production and compaction rate on seismicity	Lack of data Lack of study	Unknown impact of production rate	Literature study on relaxation mechanisms, production/compaction rate dependence etc. (e.g. laboratory studies, field studies) Seek independent advice and review

## 1. Introduction

At the request of the Steering Group, the TBO (Technische Begeleidingscommissie Ondergrond) has reviewed the studies carried out by NAM in 2013 into the number and strength of earthquakes induced by gas production from the Groningen field. The work reviewed in this report is related to Research Question 5 and (to a limited extent) Research Question 6 raised by the Minister of Economic Affairs (Ref 1).

- Investigation 5: Maximum magnitude of earthquakes in the Groningen gas field  
Investigation 6: Alternative production technologies to reduce the number and magnitude of the earthquakes (including the effects of production reduction)

Most of the results related to investigation 6 will be documented by NAM in a separate report to be reviewed by the TBO at a later stage. In the context of investigation 5, NAM commissioned a study by Bourne and Oates, from the Shell Technology Center in Rijswijk, into the seismic hazard for the Groningen Field. This review deals with this study, that has been documented in three preliminary reports made available to the TBO (Ref 2,3,4).

The work can be subdivided into the following main components:

1. An in depth statistical analysis of induced seismicity data registered in Groningen until October 2012
2. The development of a seismicity model linking released seismicity (total released seismic moment, location, magnitude and number of tremors) to the production induced volume changes resulting from compaction of the Groningen reservoir rock
3. Various attempts to derive a maximum possible magnitude for the induced earthquakes in Groningen



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4. The calculation of the future seismic hazard by combining the above seismicity model with the predicted (amount and distribution of) future reservoir compaction and a Ground Motion Prediction equation (GMPE). Monte Carlo simulations are used to calculate probabilities of future peak ground velocities (PGV) and peak ground accelerations (PGA) associated with induced earthquakes of a given magnitude at a given location using the GMPE. From this PGV and PGA exceedance maps are generated

Main results of the TBO review are discussed in section 2. Details are provided in Appendix A, Table A1. An overall assessment of the consequences of the results according to the TBO is given section 3.

## 2. Review of NAM's technical work

In the opinion of the reviewers, a commendable effort has been made to document findings and results “on the go” as work progressed. It resulted in the availability of three evolving draft reports within a period of less than a year. In general a high quality of progress reporting was maintained, supplemented with regular opportunities for verbal clarification and in depth technical challenge.

The TBO review of the work related to each of the above mentioned four main components is detailed in Table A1. The first column summarises the main results presented by NAM. In the next two columns, TBO comments and potential consequences are listed. The fourth column lists the recommendations for follow-up where appropriate.

The TBO appreciates the quality and quantity of the work presented. Even more so when considering the limited time period and the limited data available for its execution. The authors have managed to pull together, at short notice, expertise available inside and outside of the NAM and Shell organisations. They have developed a novel seismology model relating induced seismicity in Groningen to the reservoir compaction resulting from the gas production.

A solid statistical and seismological analysis is made of the data of induced earthquakes registered until October 2012, resulting in a workflow that can be used to determine seismic hazard as a function of location and time under different production scenarios. This workflow has been implemented for application to the Groningen field. First results are presented. Analysis and recognition of the large uncertainties in the obtained results is provided.

The case is convincingly made that the engine behind the induced seismicity is closely related to reservoir (differential) compaction caused by gas production.

With respect to attempts to determine a maximum earthquake magnitude for Groningen it is noted that none of the different methodologies as applied by NAM results in values below 5.5. However, the TBO doubts whether the methods used to arrive at an estimate of an upper limit to  $M_{max}$  are applicable to the case of Groningen. As an example, unrealistic values for the aspect ratio of available fault dimensions were assumed in the finite fault size limit method. Reduction to more accepted values reduces the maximum magnitude estimates to 4.5. Furthermore, the presented values for the *physically maximum possible* magnitude cannot be compared to values of *probable* maximum magnitude.

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In any case,  $M_{max}$  is not relevant for the calculation of seismic hazard. The authors did not use maximum magnitude as a hazard parameter in their analysis. This was replaced by the total available seismic moment in the Monte Carlo calculations. It is made plausible that maximum magnitude is not a suitable hazard indicator as the main hazard (probability of exceeding a given PGA) will come from earthquakes with magnitudes between 4.5 and 5.5 at hypocentral distances of up to 10 km. Higher magnitudes contribute less to the hazard, mainly due to their lower probability of occurrence combined with a saturation of ground motion amplitudes at these higher magnitudes.

The report does not show if and how it was examined to what extent the strain partitioning factor also depends on parameters other than compaction, such as e.g. the density of faulting, the production rate, or non-linear, time-dependent deformation behavior of rock salt of the Zechstein formation.

### 3. Assessment of consequences

The TBO notes the empirical nature of the presented findings and their reflection in the NAM seismicity model. The underlying physics is limited and needs to be extended by further studies and data analysis. For instance initial stress state, presence of (large) faults, fault density and compressibility contrasts between reservoir and overburden are currently not accounted for in the NAM seismicity model. The introduction of a partitioning coefficient allows for the possibility that only part of the accumulated strain energy is partitioned onto faults and released as seismic energy. The partitioning coefficient is an empirical parameter that can absorb or hide other physical processes not yet included in the model, e.g. those mentioned above or an intrinsic dependence on compaction rate. The exponential dependence on compaction can be the result of inadequate porosity and/or compaction models. The limited physical substantiation of the partitioning coefficient and the uncertainties in the modest amount of data on which it is based, create considerable uncertainties on its further development and hence on the development of seismicity for periods beyond a few years into the future as recognised by NAM. Some of these uncertainties are expected to reduce over the coming years as new data and results from additional studies become available. Others will remain as they are a consequence of the statistical nature of earthquake occurrence.

Nevertheless, the phenomenon of increasing seismicity with increasing production is likely to continue for the coming years. Even when considering the large uncertainties, reported PGAs and PGVs and their probabilities are at a level that causes serious concern. The TBO agrees with NAM that this justifies a strongly increased study and monitoring effort in combination with regular (annual) risk assessment updates to feed a measurement and control loop as part of the seismic risk management system.

The TBO is of the opinion that the study carried out by NAM results in an empirical description of induced seismicity and related risks to be expected in Groningen. Given the assumed linear relation between gas production, reservoir compaction and released seismic moment, the annual number of earthquakes and therefore also the annual hazard of larger earthquakes scales with annual gas production. A twofold increase in annual production would result in a doubling of the annual number of earthquakes. Equally, halving the production rate would halve the annual number of earthquakes. The TBO notes that the number of earthquakes during the total field life might reduce with lower production rates if time dependent relaxation mechanisms play a role, e.g. if the seismic partitioning coefficient also depends on compaction rate. The TBO considers this a shortcoming to be addressed

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urgently given the discussions on the use of the gas production rate for mitigation of the seismic hazard.

It is made plausible that, for the data analysed (until October 2012), the released seismic moment increases more or less exponentially with the available moment due to reservoir compaction. The TBO agrees with NAM that if this trend continues the released seismic moment, the annual number of induced earthquakes and the probability of higher magnitude earthquakes and high PGAs in Groningen will increase significantly over the next 20 years. Under the same assumption of a continued exponential increase, a PGA of above 0.57g is calculated for an average annual 0.2% chance of exceedance between 2013 and 2023.

The TBO notes that the annual hazard of exceedance will not be constant during the next 10 years. Initially the hazard will be lower, rising to higher values towards the end of the period. The TBO agrees that longer term (beyond ca. 2030) and depending on the future development of reservoir compaction, the hazard could gradually decrease again. The latter is a net result of the competing effects of increasing total compaction and decreasing annual production.

The TBO agrees with NAM that the quantitative uncertainties in all these predictions are large and that these uncertainties grow fast for predictions beyond a few years.

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## 4. Critical issues and uncertainties in NAM's workflow

The following workflow is used by NAM to calculate the seismic risk for Groningen. It can be applied to different production scenarios:

- 1 Calculate reservoir compaction as a function of location and time for a given production interval.
- 2 Calculate the total reservoir moment available at a given time using the Kostrov equation and the calculated reservoir compaction field.
- 3 Calculate the total seismic moment using a single random independent sample from the total seismic moment distribution (defined by the distribution of the strain partitioning coefficient) for the given production interval.
- 4 Calculate the seismic event density map given the reservoir compaction for a given area and production interval as well as the statistical distribution of the strain partitioning coefficient. Select event locations taking into account the event density map under 4)
- 5 Draw a magnitude for each event using an appropriate Bounded Gutenberg Richter relationship. The upper bound is given by the maximum available seismic moment from 3)
- 6 Continue with steps 4 and 5 until the seismic moment calculated under 3) has been (almost) consumed
- 7 Calculate PGVs and PGAs for all resulting events at each observation point, using a random draw of GMPE equation parameters within their uncertainty.
- 8 Count the number of times a given PGV of PGA is exceeded for a range of thresholds.
- 9 Repeat all of the above steps until the stochastic error in the results becomes acceptable.

The above steps are discussed in more detail below, together with the key assumptions, recognised uncertainties and recommendations for follow-up, as seen by the TBO.

Step 1	Calculate reservoir compaction as a function of location and time for a given production interval (not part of the reviewed reports)
Description	Subsurface compaction is calculated by calibrating the geomechanical subsidence model against the observed surface subsidence between 1964 and 2013. For this, use is made of the static and dynamic reservoir models in combination with a geomechanical model calibrated against lab data and field history. This results in a subsurface compaction grid at reservoir level. Reservoir simulations are subsequently run to calculate future pressures under different production scenarios. These are then used to calculate reservoir compaction for each grid block as a function of location and time.
Key uncertainties	<p>1.1 The calculated reservoir compaction depends on the geomechanical model used. For the three models considered (the bi-linear, pressure decay and isotach/rate-type models) comparable fits with the historically measured subsidence can be achieved. A decision on which model to use cannot be made based on the fits obtained. The different models lead to significant differences in calculated future compaction, in particular for later times. Predicted subsidence during the field production period in the deepest point of the bowl varies between 42 and 65 cm depending on the compaction model chosen. Similar differences can be expected for the underlying compaction numbers. Impact on PGA exceedance risk maps will be large.</p> <p>1.2 The criteria used to decide which scenario gives the best fit to the measured “raw” geodetic levelling data (changes in height between individual benchmarks) has a significant impact on the parameter calibration for the geomechanical model and thereby on the calculated future compaction and subsidence</p> <p>1.3 The underlying static porosity model has a large impact on the underground lateral distribution of the reservoir compaction and therefore on the seismic risk maps. Uncertainties in the porosity distribution could be considerable as indicated by local misfits between measured and observed subsidence (e.g. around Delfzijl). The lateral variations in the porosity model seem rapid given the limited well control.</p>

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	<p>1.4 The subsidence data needs to be consistent. This means proper integrated analysis of all measurements of height differences for all time intervals in order to avoid artefacts of the processing. In addition, uncertainties in the measurements should be accounted for properly in the analyses. Given the long time span of Groningen measurements and the large areal extent this is not trivial, and can significantly impact the parameter calibration of the compaction model. Alternatively a methodology could be developed where only the directly measured changes in height differences between pairs of benchmarks are used to calibrate the geomechanical models (see 1.2).</p> <p>1.5 The impact of different production scenarios</p>
Consequences	Uncertainties 1.1, 1.2 and 1.4 result in large uncertainties in the predicted seismicity level at later times (more than a factor 10 in the annual number of earthquakes. Uncertainty 1.3 can have a significant impact on the predicted localisation of the calculated seismic risks. Uncertainty 1.5 will have a large influence on the time evolution of the seismic risk.
Recommendation	<ol style="list-style-type: none"> <li>1. Improved subsidence monitoring, including continuous 3D GPS.</li> <li>2. Development of improved technology to test competing geomechanical models against the evolution of benchmark height differences measured in the field.</li> <li>3. NAM to test validity and uncertainty range of the present porosity model.</li> <li>4. Re-processing of all available subsidence information in an integrated manner.</li> <li>5. Subsidence calculations under different production scenarios</li> <li>6. Development of low, expectation and high case compaction scenarios and calculation of the corresponding PGA exceedance risk maps</li> </ol>

<b>Step 2</b>	<b>Calculate the total reservoir moment available at a given time using the Kostrov equation and the calculated reservoir compaction field</b>
Description	The total reservoir moment is assumed to be a function of the strain at a given time. The total reservoir moment in a time span is given by the change in strain moment during this time span.
Key uncertainties	<ol style="list-style-type: none"> <li>2.1 The uncertainties in the calculated compaction equally apply here.</li> <li>2.2 Some questions can be raised on the applicability of the Kostrov equation. As faults and shear failure are likely to play an important role, it could well be that the partitioning coefficient increases with increasing shear strain, not with bulk strain (Kostrov).</li> </ol>
Consequences	As a result of uncertainties 2.1 and 2.2, the total reservoir moment could be up to two orders of magnitude higher or lower towards the end of the production period. The impact on seismic magnitudes will be limited given the logarithmic relation between magnitude and seismic moment. The probability of such higher magnitude events will increase or decrease proportionally with the change in total reservoir moment.
Recommendation	Continued monitoring and processing of subsidence (data) is necessary in order to assess the development of the total reservoir moment.

<b>Step 3</b>	<b>Calculate the total seismic moment using a single random independent sample from the total seismic moment distribution (defined by the distribution of the strain partitioning coefficient) for the given production interval.</b>
Description	The step determines the fraction of the total reservoir moment at the end of the production interval that will be realised through induced seismicity. The uncertainty in the strain partitioning is accounted for by drawing a sample from its derived distribution as a function of reservoir compaction.
Key uncertainties	3.1 The strain partitioning coefficient behaviour with increasing compaction is incorporated in this step. It is assumed that an extrapolation of the past behaviour is valid. Whether or not the resulting further exponential increase in the strain partitioning factor with increasing compaction will occur is uncertain.
Consequences	The exponential increase in the strain partitioning factor, with its large and increasing uncertainty band width, as currently implemented by NAM, results in an escalation of the predicted seismic moment with time, eventually approaching the total reservoir moment. Thus, the predicted seismic hazard escalates dramatically over time. And even more so if compaction increases beyond presently predicted values, which given the uncertainties in these, is possible.

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Recommendation	Check the relation between the partitioning coefficient and compaction under a range of compaction models and under different compaction scenario's Proper monitoring and regular (annual?) reassessment of the strain partitioning factor as part of a measurement and control management system.
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<b>Step 4</b>	<b>Calculate the seismic event density map given the reservoir compaction for a given production interval and the statistical distribution of the strain partitioning coefficient.</b>
Description	Calculate the seismic event density for a production interval using the reservoir compaction and the distribution of the partitioning coefficient which determines the amount of seismic energy released.
Key uncertainties	4.1 The event density may fluctuate with time due to aspects other than reservoir compaction., e.g. the impact of the triggering mechanism for which fault density, fault orientation within the stress field, etc. become important. These aspects are currently not included in the calculation of the event density map.
Consequences	The event density in certain areas may be over- or underpredicted. This influences the areal distribution of the ultimately derived PGAs and PGVs.
Recommendation	Proper monitoring of the areal distribution of the future seismic events and frequent reassessment of the event density distribution. More study into the significance of fault density, fault orientation and fault geometry as well as the subsurface stress regime.

<b>Step 5</b>	<b>Select event locations taking into account the event density map under 4)</b>
Description	For each event a location is randomly drawn on the basis of the event density map.
Key uncertainties	5.1 The event locations are drawn independent of the magnitude of the event (as these are derived in step 6). Hence large magnitude events could occur in locations with low event density. 5.2 The impact of initial stress state, fault density and compressibility contrasts is not taken into account in the derivation of the event density map.
Consequences	Large magnitude events may be predicted for areas with limited compaction, while they are unlikely to occur at those locations based on the underlying model which predicts seismicity onwards from compactations of 10-20 cm.
Recommendation	Adjust procedure to exclude the possibility of larger magnitude events occurring in low event density areas. Make an effort to incorporate effects of initial stress state, fault density, compressibility contrasts

<b>Step 6</b>	<b>Draw a magnitude for each event using an appropriate Bounded Gutenberg Richter relationship. The upper bound is given by the maximum available seismic moment from 1) and 3)</b>
Description	The Bounded Gutenberg-Richter relationship is used to derive a magnitude for each event. The upper bound in the relationship is the magnitude belonging to the total seismic moment resulting from steps 1 and 3 being released in a single event. The resulting energy distribution for a catalogue of events is a Pareto distribution.
Key uncertainties	6.1 The procedure assumes a stationary b-value of 1 in the Bounded Gutenberg-Richter relation. The possible non-stationary character of the b-value, which allows for more larger magnitude events to occur with time, relative to the total number of events, is not included. This may lead to a (limited) further escalation of the seismic hazard.
Consequences	Seismic risk may be underestimated with time.
Recommendation	Regular re-assessment of the non-stationary character of the b-value as part of a measurement and control management system.

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<b>Step 8</b>	<b>Calculation of PGVs and PGAs for all resulting events at each observation point</b>
Description	The adapted Akkar et al. relations are used to compute PGA and PGV for each of the events in the resulting catalogue of step 7 in each observation point.
Key uncertainties	8.1 This procedure assumes that the chosen GMPE is also valid for the larger magnitudes, while there is no calibration possible for Groningen since the larger magnitudes have not occurred in the area. This remains to be seen as the present shape of the relationship at higher magnitudes is based on data from tectonic rather than induced events
Consequences	GMPE for the higher magnitudes may be underestimated or overestimated for the specific area.
Recommendation	Regular re-assessment of the PGA/PGV relation calibrated for the Groningen area.



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## Conclusions

1. A solid and thorough statistical analysis is made of the Groningen earthquake data registered until October 2012, resulting in a workflow which can be used to determine seismic risk as a function of location and time under different production scenarios. This workflow has been implemented for application to the Groningen field. First results are presented. Proper analysis and recognition of the large uncertainties in the obtained results is provided.
2. The case is convincingly made that the engine behind the induced seismicity is closely related to reservoir compaction resulting from gas production.
3. It is made plausible that the phenomenon of increasing seismicity with increasing production is likely to continue for the coming years.
4. It is made plausible that for the data analysed (until October 2012) the released seismic moment increases more or less exponentially with the available moment due to reservoir compaction. If this trend continues released seismic moment, annual number of induced earthquakes and maximum observed magnitude will increase significantly over the next 20 years.
5. Even when considering the large uncertainties, reported PGAs and PGVs and their probabilities for the coming years are at a level that causes serious concern.
6. The TBO notes the empirical nature of the presented findings and their reflection in the NAM seismicity model.
7. The partitioning coefficient is an empirical parameter that can absorb or hide other physical processes such as intrinsic compaction rate dependence. The observed exponential dependence on compaction could be the result of inadequate porosity and/or compaction models. The TBO is of the opinion that this needs to be addressed at short notice given the important discussion on the impact of production rate.
8. The limited physical substantiation of the partitioning coefficient and the uncertainties in the data on which it is based, create considerable uncertainties on its further development and hence on the development of seismicity for periods beyond a few years into the future.
9. Initial stress state, presence of (large) faults, fault density and the compressibility contrast between reservoir and overburden are not accounted for in the NAM seismicity model while they are expected to play a role in deterministic hazard studies.
10. With respect to attempts to determine a maximum earthquake magnitude for Groningen it is noted that none of the three different methodologies as applied by NAM results in values below 5.5. However, the TBO doubts whether the methods used to arrive at an estimate of an upper limit to  $M_{max}$  are applicable to the case of Groningen. Furthermore, the presented values for physically maximum possible magnitudes cannot be compared to values of probable maximum magnitude. In any case,  $M_{max}$  is not relevant for the calculation of seismic hazard.
11. Given the link between gas production, compaction and released seismic moment, the annual number of earthquakes and the annual risk of larger earthquakes scales with gas production rate.
12. After 20 years, seismic hazard could gradually decrease as a net result of the competing effects of increasing total compaction and decreasing production rates.
13. Under the same assumption of a continued exponentially increasing seismicity PGA's of 0.57g are calculated at 0.2% annual chance of exceedance during the next 10 years (average for the 10 year period). The TBO notes that the annual hazard of exceedance will not be constant during the next 10 years. Initially the hazard will be lower, rising to higher values towards the end of the period.

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14. The TBO notes that the uncertainties in all these predictions are large and that these uncertainties grow fast for predictions beyond a few years as acknowledged in the reviewed studies. Some of the uncertainties may be reduced over the coming years as new data and results from additional studies become available. Others will remain as they are a consequence of the unpredictability of the occurrence of earthquakes.
15. The TBO supports the conclusion by NAM to strongly increase the study and monitoring effort in combination with regular (annual) risk assessment updates to feed a measurement and control loop as part of the seismic risk management system.

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## Appendix A

**Table A1 TBO review of the main individual components of the NAM technical work**

<b>1. Statistical analysis of the historical Groningen induced seismicity data set</b>			
<b>NAM results</b>	<b>TBO comments</b>	<b>Consequences</b>	<b>Follow-up (NAM)</b>
An in depth statistical analysis of the historical Groningen induced seismicity data set shows that it can be described reasonably well with a Gutenberg Richter distribution for the estimation of recurrence rates and magnitude distribution.	The provided statistical seismological analysis is extensive and of high quality. The authors follow the Monte Carlo approach consistently for determining the future seismic hazard including uncertainty.	No issues with provided statistical analysis	Periodic re-assessment
The missed fraction of the released seismic moment has reduced from an initial value of around 50% in the mid-nineties to less than 3% presently.	This is due to the initially small amount of higher magnitude events with higher magnitude events increasing over time.	Total released seismic moment can be monitored accurately.	None
The statistical analysis confirms that seismic moment in Groningen follows a Pareto distribution and that total seismic moment is a Pareto sum distribution.	The TBO agrees that the cumulative seismic moment is a Pareto distribution, primarily caused by the orders of magnitude difference in released seismic moment between small and large events. The resulting distribution is long tailed where most of the total moment of all events is due to the largest events.	The long tail causes the large error bars in estimations of future seismicity. Defining an upper bound for the future seismicity is difficult and uncertain by nature.	Intrinsic problem that cannot be resolved.
No maximum possible magnitude $M_{max}$ can be derived from the statistical analysis of the Groningen data set.	Larger earthquakes with a magnitude above 3.9 cannot be excluded in Groningen.	This implies that there is no statistical bound on the magnitude.	None
The statistical analysis shows that there is no basis for justifying the additional parameter ( $M_{max}$ ) in a Bounded Gutenberg-Richter (BGR) approach as all values for $M_{max}$ above 3.9 are equally likely.		There is no advantage to using a BGR approach in Groningen as $M_{max}$ is not known.	None

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NAM results	TBO comments	Consequences	Follow-up (NAM)
A b-value of 1 controls the probability of larger relative to smaller earthquakes for the Groningen field as a whole. There are indications for a decrease in b with increasing compaction from the local time evolution of b.	This confirms the non-stationarity of the seismicity in Groningen. It is not fully clear which methodology is applied to calculate b-values and if this could impact the calculated changes.	A decrease in b will give rise to more larger earthquakes relative to the total number or earthquakes as production continues.	Check validity of applied method to calculate b. Monitor and re-assess b value change over time.
Under the assumption that magnitudes follow a Gutenberg-Richter distribution with a b = 1 and a magnitude of completeness Mmin of 1.5, the probability of at least one earthquake exceeding magnitude 4.0 during the next 30 locatable earthquakes in Groningen is 0.09 (with a 68% confidence limit of 0.02 to 0.20).			
Not all observed events are independently distributed. Removal of 31 events occurring within 3 days of a previous event resolves this issue.	Some of the events thus removed are at large (>10 km) distance from the independent event. The 3-day period is considered arbitrary.	Minor effects only.	
There is no evidence that the amount of gas produced between consecutive events increases when gas production is lower. From this it is concluded that the number of earthquakes during the lifetime of the field will be independent of production rate.	Pore pressure diffusion effects following summer-winter swings in production rate cause different phase shifts for different parts of the field depending e.g. on the distance to the nearest well. This may have a large disturbing effect on the analysis.	No conclusions on rate sensitivity can be drawn from the results obtained.	Re-address, taking pore pressure diffusion and long term production rate variations into account.

### 2. Development of a model linking seismicity to production induced volume changes (=compaction)

NAM results	TBO comments	Consequences	Follow-up
There is significant evidence that the release of seismic moment per unit production escalates with increasing production.		Numbers and magnitudes of induced earthquakes will be significantly higher than previously recognised.	Monitor and re-assess over time.

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NAM results	TBO comments	Consequences	Follow-up (NAM)
<p>The occurrence time and areal position of earthquakes in Groningen are consistent with the temporal and areal distribution of bulk reservoir volume changes.</p>	<p>This indicates that the increase in compaction drives the induced seismicity. Other mechanisms such as initial stress state, differential compaction and presence and orientation of faults are likely relevant but not included in the present empirical seismicity model. These could also explain some of the observed variations over the field.</p>	<p>Prediction of future behaviour for areas with hitherto low seismicity is difficult as uncertainties are large and other factors have not been taken into account.</p>	<p>Improved monitoring and regular re-assessment based on new data.</p>
<p>The temporal and areal distribution of bulk reservoir volume changes can be calculated with an equation given by Kostrov.</p>	<p>The Kostrov equation is simplified by the authors. The shear strain terms are neglected while these might be driving the seismicity. The approach might work in first approximation if shear strain scales with the compaction.</p>	<p>The spatial distribution of shear strain is different from that of compaction. This has an impact on the spatial distribution of hazard.</p>	<p>Introduce the effect of shear strains by incorporating faults into the model.</p>
<p>The total bulk volume reservoir change approximately scales with the cumulative volume of gas production.</p>	<p>The assumption of a linear relation between compaction and production is an approximation and e.g. not valid for the period preceding 1995. Future compaction could well be higher. This can change the relationship between partitioning coefficient and compaction.</p>	<p>The dependence of the strain partitioning coefficient on compaction could change considerably.</p> <p>Uncertainties in past and future compaction will have a large impact on the calculated seismic hazard.</p>	<p>NAM to repeat the analysis using alternative compaction models and a range of compaction scenarios.</p>

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NAM results	TBO comments	Consequences	Follow-up (NAM)
<p>The major factor governing the onset and the amount of seismicity is the compaction in the reservoir. The almost a-seismic northern and southern part of the Groningen field are due to either low depletion with a thick reservoir section in the north or large depletion with a thin reservoir section in the south.</p>	<p>The TBO concurs with the observation that the onset of seismicity so far corresponds to a compaction larger than 10 cm and smaller than 20 cm for the linear compaction model.</p>	<p>Prediction of future behaviour for areas with hitherto low seismicity is uncertain.</p>	<p>Improved monitoring and regular re-assessment based on new data. Incorporate outcomes of the Geomechanical study as they become available.</p>
<p>The fraction of induced strain accommodated by earthquakes is likely increasing with increasing reservoir compaction. This is consistent with the observed temporal and areal distribution of earthquakes. In the seismicity model this is accommodated by the introduction of a strain partitioning coefficient, increasing <u>exponentially</u> with increasing compaction. This finding is based on an areal analysis of the distribution of cumulative seismicity and cumulative reservoir compaction in 2012. The derived exponential increase of the partitioning coefficient (fraction of total reservoir moment released as earthquakes) with increasing compaction is supported by the time history of the induced seismicity in Groningen between 1995 and 2012.</p>	<p>The TBO considers this a credible approach for the short term but notes that uncertainties grow fast with time. Whether the strain partitioning factor will continue to increase in the future remains to be proven by continued monitoring. The partitioning coefficient allows for the possibility that only some of the strain is partitioned onto faults. To some extent, it is a fit factor that can be used to absorb/hide data inadequacies or other physical processes such as an intrinsic rate dependence.</p>	<p>Only, if the present trend continues, the annual number of earthquakes and the risk of larger magnitudes will increase significantly over the coming ten years.</p>	<p>Improved monitoring and regular re-assessment based on the new data.</p> <p>Investigate the influence of other credible physical mechanisms on changes in the strain partitioning coefficient over time and space.</p>
<p>The present fraction of bulk reservoir volume changes accommodated by seismic slip is about 0.1%.</p>	<p>Seismic slip does not accommodate bulk volume change. Seismicity can scale with increasing (differential) compaction.</p>	<p>Limited for overall seismicity but possibly significant for areal distribution.</p>	<p>Improved monitoring and regular re-assessment based on the new data.</p>

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NAM results	TBO comments	Consequences	Follow-up (NAM)
If the above trends continues with future production than the footprint of the earthquakes will continue extending from the centre towards the edges of the field with continued localisation of the abundance of the earthquakes in the regions with the largest compaction (centre of the field).	The model used by Bourne and Oates does not take the presence or absence of faults into account. It is implicitly assumed that there will always and everywhere be enough faults present to seismically release the increasing fraction of the reservoir moment generated by the increasing compaction. Smaller faults not seen on seismic are sure to exist. Larger events will have to occur on the larger faults or on a fault network present in the field. The criticality of faults and Coulomb stress transfers onto the faults are not taken into account. Knowledge about the geomechanics of faults is not incorporated.	Local fault density is likely to influence the future localisation of earthquakes, in particular for larger magnitudes.  The criticality of the faults will determine whether the shear stresses on the faults are sufficient to induce earthquakes.	Integrate the B&O statistical approach with geomechanical modelling to investigate if fault density can be incorporated in the model  idem
Total bulk reservoir volume change approximately scales with the cumulative volume of gas production	Non-linear and/or delayed compaction is observed in many fields in the Netherlands including the Groningen field. This will change the derived compaction dependence of the fault strain partitioning coefficient and the PGA exceedance maps.	Possibly large, needs to be checked.	Investigate the impact of non-linear compaction models (e.g. delayed compaction, rate type compaction).
There is a 1 in 2 chance of an earthquake with $M > 4.3$ , a 1 in 10 chance of $M > 4.9$ and a 1 in 100 chance of $M > 5.4$ before the end of 2023. For the total remaining field life these numbers are 1 in 2 for $M > 4.5$ , 1 in 10 for $M > 5.4$ and 1 in 100 for $M > 5.8$ . All under the assumption that the results of the present analyses can be extrapolated into the future	Uncertainties in these numbers are large and grow fast at later times.	These findings imply the need for a measurement and control loop based seismic risk management system for Groningen.	Develop a measure and control loop based seismic risk management system.



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3. Maximum possible magnitude of induced earthquakes in the Groningen field			
NAM results	TBO comments	Consequences	Follow-up
Of the various methods (see 1-6 below) used to derive an upper limit for the maximum possible magnitude of the induced earthquakes in Groningen (Mmax), none yields values below 5.5	See below.  There will be an upper limit, but its value cannot be derived from the applied methodologies.	A value for Mmax cannot be determined.	None
<b>1. Finite strain limit method</b> (Bourne and Oates Groningen seismicity model) The maximum possible magnitude on the basis of the maximum available reservoir moment (calculated from the predicted reservoir volume change/compaction) is in the order of 6.5.	An earthquake in which all reservoir moment is released in a single event is highly unlikely, but can theoretically not be excluded.	High magnitude events cannot be excluded on the basis of finite strain.	None
<b>2. Monte Carlo method</b> A Mmax cannot be derived from the statistical analysis of the Groningen data set.	But is also not necessary in the Monte Carlo method. Instead of Mmax the available seismic moment is used.	A bounded Gutenberg-Richter (BGR) relation cannot be deduced for the Groningen events. This implies that there is no statistical bound on the magnitude.	None
<b>3. Energy method</b> Estimating Mmax from the fluctuations in the historical plot of released cumulative seismic moment vs time is not reliable.	There is no justification to assume that future fluctuations will not exceed historical fluctuations.	Energy method cannot be used to estimate Mmax in Groningen.	None
<b>4. Finite fault size limit method</b> Calculation of Mmax based on the maximum fault sizes in Groningen gives a value around 5.8.	If lagging compaction due to build-up of shear stress on faults (and not total compaction) drives the maximum magnitude, it will be smaller than the 5.8 reported. Also, the height of the faults that can move could be more limited than assumed while the high aspect ratio fault movements required for magnitudes above 5.0 are probably not realistic (see comments external reviewer). Assumption of a more realistic aspect ratio lowers the Mmax.	Magnitudes above 5.0 cannot be excluded based on the finite fault size limit, but this requires a larger fault width than the assumed 0.3 km.	Geomechanical calculations to assess which strain drives seismicity, the impact of aspect ratio and the height of faults that can move.

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NAM results	TBO comments	Consequences	Follow-up (NAM)
<b>5. Finite mass limit method</b> Applying the upper limit of the Klose correlation between reduced mass and magnitude to Groningen suggests an Mmax of around 6.0.	TBO has doubts about the analyses made by Klose and its applicability to Groningen. Especially high magnitude examples are most likely triggered.	The Klose method cannot be used to estimate Mmax for Groningen.	None
<b>6. Rule of thumb methods</b> These methods should be considered unreliable	These methods are not applicable for Groningen as they assume stationarity and sufficiently long observation periods.	Rules of thumb methods are not to be used to estimate Mmax in Groningen.	

4. Calculation of the future seismic hazard			
NAM results	TBO comments	Consequences	Follow-up
Disaggregation shows that the main contribution to the seismic risk comes from earthquakes with magnitudes between 3.5 and 5.5 at hypo-central distances of up to 10 km.	Higher magnitudes have less influence on the risk mainly due to their lower probability of occurrence combined with a saturation of ground motion amplitudes for these higher magnitudes. The risk is therefore not mainly determined by the maximum magnitude.	Maximum magnitude is not an appropriate means of characterising the seismic hazard. Risk reduction is most effective by focussing on the less rare intermediate magnitude events ( $3.5 < M < 5.5$ ).	Monitoring is needed to check future development against present expectations.
Monte Carlo based ground motion prediction maps for 0.2% chance of exceedance are provided for a number of production scenarios and production periods.	Initial outcomes suggest PGAs and PGVs at a level that causes serious concern. Exact procedure to calculate seismic catalogues is not fully clear to the TBO.	No definitive numbers are available at this moment.	Further work needs to be done at short notice.
Sensitivities are provided for the impact of GMPE magnitude scaling and GMPE uncertainty scaling, switching GMPE, reference period and b-value. Some of these uncertainties turn out to have a major influence of the results.	Uncertainties need to be reduced where possible e.g. through monitoring. Unfortunately some uncertainties are intrinsic (stochastic) and will remain large.	Uncertainties will remain large.	Monitoring in order to reduce uncertainties in future, where possible.  Full wave form modelling to

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NAM results	TBO comments	Consequences	Follow-up (NAM)
			<p>Provide a physical basis for the GMPE.</p> <p>Study of intrinsic uncertainty in order to ascertain if reduction is feasible.</p>
<p>Application of a Eurocode 8 type approach is difficult given the non-stationary character of the induced seismicity in Groningen.</p>	<p>A topic for the TBB to comment on.</p>		
<p>The presented event density map shows that the area of high seismic risk will remain localised around the present area of highest seismicity.</p>	<p>Differences in gas pressure will remain limited over the field life. Hence the spatial distribution of the compaction is determined by the geometry (reservoir thickness) and rock properties (compressibility as derived from porosity). The relative increase in compaction will therefore be the same in all areas of the field with some exceptions due to pressure drop delays in some poorly connected areas of the field. The increase in compaction could result in an increase in the absolute risk towards the edge of the field, even when the largest risk remains in the center.</p>	<p>The relative risk remains the same as now. The absolute risk will increase which will have an impact on the risk of the region.</p>	<p>The impact of higher magnitude events at the edges of the Groningen field (e.g. Groningen city and Industry Delfzijl) should be addressed as well.</p>
<p>There are large uncertainties in the translation of PGAs and PGVs into risk using the location of buildings and building fragility curves. In particular due to the effect of ground motion duration and the lack of calibration data in Groningen for higher magnitude earthquakes.</p>	<p>This translation is important and should be approached in a manner similar to the derivation of PGAs/PGVs in order to properly include uncertainty and obtain proper personal and group risk estimates.</p>	<p>The estimation of seismic risk due to gas production of Groningen is dependent on many uncertain variables. The outcome will give a large range of possible risk scenarios.</p>	<p>Seismic risk to be calculated with Monte Carlo to obtain proper personal and group risk estimates taking the uncertainties into account.</p>

## Bijlage4 TBO Review of the geomechanical studies of the Groningen gas field

### 1. Introduction

At the request of the Steering Group, the TBO (Technische Begeleidingscommissie Ondergrond) has reviewed the results of the geomechanical studies carried out by, NAM, as part of the NAM/Shell studies to address investigation 5. The work reviewed in this report is related to Research Question 5 raised by the Minister of Economic Affairs.

Investigation 5: Maximum magnitude of earthquakes in the Groningen gas field

In the context of investigation 5, NAM commissioned a geomechanical study to provide geomechanical insight into the occurrence of seismicity due to the depletion of the Groningen field. The work reviewed has been documented by a draft report of and several presentations made available to the TBO.

1. P. A. J. van den Bogert. Fault stability assessment Groningen field, presentation May 2013.
2. P. A. J. van den Bogert & R. M. H. E. van Eijs. Fault stability assessment for the Groningen Field, draft report July 2013.
3. P. A. J. van den Bogert. Second TBO workshop on Induced seismicity in the Groningen field : Fault stability analysis, presentation July 2013
4. P. A. J. van den Bogert, R. M. H. E. van Eijs, O. van der Wal. Update Geomechanical studies, presentation August 2013.

The geomechanical work can be subdivided into the following main components:

1. Fault stability analysis
2. 2-D geomechanical modelling
3. Compaction modelling

Results of the TBO review of the geomechanical work related to each of the above components are summarised in the appendix in tabular form. The first column summarises the main results obtained. In the next two columns, TBO comments and potential consequences are listed. The fourth column lists the TBO recommended follow-up actions where appropriate. This approach does not result in a chronological discussion of the above mentioned draft report and presentations.

Some of these uncertainties are intrinsic, due to the lack of geomechanical data. Solutions are not to be expected. Some uncertainties can be reduced over time as new data and results of additional geomechanical analysis become available. Lastly there is a category of uncertainties caused by different scientific insights and opinions. For some of these, further work, including independent scientific review and advice is recommended. The uncertainties in each of these categories are discussed in some detail.

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## Appendix A

**Table A1 TBO review of the main individual components of the geomechanical work**

1. Fault stability analysis			
NAM results	TBO comments	Consequences	Follow-up
The study gives a good overview of data available on in-situ stress conditions, fault orientations and fault and reservoir properties.	The study can be used to give a first indication of the criticality of the faults. Results should not be over interpreted.	Study can be used as a first indicator which faults are likely candidates for slip.	None
The authors use a simple geomechanical model to explain the onset of fault slip in Groningen. The model is based on a stress based failure criterion (Coulomb's friction law), and the assumption that faults will slip if the shear stress exceeds the shear carrying capacity at any location on the fault surface. Important underlying assumptions of this simplified model are: 1) virgin in-situ stress conditions are only depth dependent and uniform across the field 2) stress evolution during depletion is represented by a (constant) stress path coefficient 3) fault slip and stress changes only occur within the reservoir 4) depletion is uniform across the field	The approach used is generally accepted for studying the reactivation potential of faults. However, the underlying assumptions are severe limitations of the model (see also individual comments on main assumptions below). Reservoir heterogeneity, reservoir geometry and differential pressure depletion are not taken into account, but are relevant for the Groningen Field. Also uncertainties in input parameters of this simplified model (regional stress field, stress path coefficients and fault cohesion and friction) are large. The model can be used as a <b>first indicator</b> (ranking) which faults are likely candidates for fault slip.	Study can be used as a <b>first indicator</b> which faults are likely candidates for slip (based on their USC). However other factors should be taken into account (by means of 2D/3D geomechanical models)	None
The authors show that the faults aligned with the direction of maximum horizontal stress (i.e. NNW-SSE) have highest SCU (Shear Capacity Utilisation) and therefore have highest tendency to slip. The authors also find that faults with NNW-SSE orientation have the largest number of seismic events with magnitudes $M > 1.5$ within 500m.	Consistency of the predicted Shear Capacity Utilisation and recorded seismicity indicates that the fault orientation (in the regional stress field) can be used as a <b>first indicator</b> which faults are likely candidates for fault slip. However, other factors not taken into account in the present model are expected to have an important effect on fault reactivation and seismicity (e.g. geometry and spatial variation)	See above	Use 2D and 3D modelling to investigate the effect of geometry, juxtaposition, heterogeneity, offset, stiffness contrasts, non-uniform depletion, constitutive behaviour.

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NAM results	TBO comments	Consequences	Follow-up
The static subsurface model contains 1800 faults. 707 faults have been selected based on their relevance for dynamic reservoir modelling. These 707 faults are also used for fault stability analysis – to maintain consistency between the geomechanical assessment and results of reservoir pressure evaluation.	The 707 faults selected for their relevance to dynamic reservoir modelling may not correspond to the critical faults on the basis of the seismicity. The authors have introduced a possible bias here.	About 1100 faults are not taken into account in this study but may be relevant for the seismicity. The alignment of faults (NNW-SSE) most critically stressed will not change using the entire dataset. The relation of seismicity and the faults may change.	none
Assumption 1) Virgin in-situ stress conditions and pore pressures are only depth-dependent and uniform across the field.	The initial stress conditions (initial SCU) on the fault are only determined by the orientation of the fault and the orientation and magnitude of regional stress field. In reality, local stress variations are expected, due to, amongst others, reservoir heterogeneity, stiffness contrasts, fault offset and juxtaposition and the presence of rocksalt.	Local stress variations are not taken into account.	Use 2D and 3D modelling to investigate the effect of geometry, juxtaposition, heterogeneity, offset, stiffness contrasts, non-uniform depletion, constitutive behaviour.
Assumption 2) stress evolution during depletion is represented by a (constant) stress path coefficient	The evolution of stresses ( $S_v$ , $S_{hmin}$ and $S_{Hmax}$ ) during depletion will not only depend on stress path coefficient (directly related to poisson ratio), but will also depend on parameters like fault offset, stiffness contrasts, differential depletion etc. Furthermore, the range of values of the stress path coefficients is large.	Evolution of stress path during depletion is uncertain.	See above, analysis can be extended by taking into account other effects in 2D and 3D geomechanical modelling. Stress path coefficients in the reservoir can be further constrained by monitoring of stress path (additional mini-frac tests)

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NAM results	TBO comments	Consequences	Follow-up
Assumption 3) fault slip only occurs within the reservoir and is the root cause of the recorded seismic events	Uncertainty of (vertical) location of seismic events is very large (>1 km). We do not know for certain that seismicity is located within the reservoir. Geomechanical 2-D/3-D modelling shows that slip also may occur above and below the reservoir.	Based on this study and the monitoring data, it cannot be excluded that events may occur below or above the reservoir	Further seismic monitoring and 2D/3-D geomechanical modelling may provide an answer
Assumption 3) Stress changes only occur within the reservoir. Stress conditions above and below the reservoir formation remains undisturbed.	This is only valid for a horizontal, laterally extended uniform reservoir and uniform reservoir depletion. Geomechanical 2-D/3-D modelling for more complex geometrical situations shows that the stress conditions above and below the reservoir can be affected by compaction of the reservoir.	Based on this study and the monitoring data, it cannot be excluded that stress changes may occur below or above the reservoir.	Further seismic monitoring and 2D/3-D geomechanical modelling may provide an answer
The reservoir is a uniform thickness	Not true according to the Petrel model. Also, reservoir offset along faults can cause differential shear displacements along fault.	Differential compaction cannot be excluded as a mechanism for shear stress release	2D/3D geomechanical modelling will give insight.
Assumption 4: Depletion pressure across the faults and within the reservoir is uniform.	According to the reservoir model this is the case. It is, however, not unlikely that small compartments may be shut-off from the main depleting system. Also reservoir offset with equal pore pressure depletion on both sides of the fault may result in differential shear displacements along the fault.	Differential compaction cannot be excluded as a mechanism for shear stress release	See above
Fault slip does not change the stresses and pressures in the reservoir	Fault slip changes the stresses in the reservoir. The Mohr-Coulomb stress transfer is known and used within the international seismological community	Events due to an increase due to Mohr-Coulomb stress transfer may occur as well.	Mohr-Coulomb stress transfer due to the occurrence of events should be taken into account.
The shear capacity utilisation (SCU) is defined as the ratio between the obtained shear stress and the shear stress carrying capacity of the fault. It is assumed that fault slip occurs if the SCU is found greater than one at any point on the fault	The exact value of the SCU is uncertain due to the uncertainties on the in-situ stress. In-situ stresses used in the report are roughly consistent with values found by one-dimensional modelling of GMI. In general however, especially value of SHmax is difficult to determine and uncertain.	The ranking of faults based on SCU may give insight, but not the 'true' values	None



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NAM results	TBO comments	Consequences	Follow-up
Number of faults exceeding the SCU at some point on the fault plane is increasing with depletion and horizontal stress-path coefficient.	The increase in SCU is determined by the combination of friction angle and stress path coefficient –in this study a combination is chosen in such a way that depletion leads to an increase in SCU. This is not a main finding – but a consequence of the input parameters chosen.	Evolution of stress path during depletion is uncertain (intrinsic uncertainty).	Stress monitoring during depletion may provide answers.
Fault cohesion, fault friction angle and horizontal stress path are the most sensitive parameters in the prediction of onset of fault slip using the current model.	Fault friction, cohesion and stress path are not well constrained. Values of friction and cohesion in this study are based on results for intact rocks, which are assumed to form an upper bound for the faults. The GMI study gives lower cohesion values and higher friction values for intact rock.	Stress path coefficients and friction angle are constrained in such a way that depletion leads to fault reactivation. Other mechanisms are ignored.	Other mechanisms for fault reactivation need to be taken into account.

2. 2-D geomechanical modelling			
NAM results	TBO comments	Consequences	Follow-up
Shear and normal stress peaks develop at the top and bottom of the reservoir with increasing depletion	Results are in line with earlier work. Larger fault throw = higher stresses	Fault throw is important for the occurrence of seismic events	Further 2D/3D geomechanical modelling.
Depletion on one side of fault results in fault slip at the top of the reservoir extending upwards and downwards	Results are in line with earlier work.	Differential compaction is an important mechanism for the occurrence of events	Further 2D/3D geomechanical modelling.

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3. compaction modelling			
NAM results	TBO comments	Consequences	Follow-up
NAM uses three compaction models: <ul style="list-style-type: none"> <li>- Bi-linear model</li> <li>- Time decay model</li> <li>- Isotach model</li> </ul>	Different compaction models have different consequences for the behaviour of compaction with production.	As production stops, the bi-linear model stops immediately, the time decay model stops after ~ 15 years, the isotach model stops depending on the chosen cm.	The compaction model and time delay behaviour of compaction need to be studied.
All compaction models have a comparable fit to the 2012 measured subsidence. Differences between measured and calculated subsidence remain particularly in the Delfzijl area and the northern part of Groningen.	The compaction models cannot be differentiated based on the observed subsidence.	The future compaction is uncertain	Subsidence needs to be measured (every year) as well as permanent GPS stations are necessary to identify which compaction model is valid
Future subsidence (2080) differs 25 cm depending on the compaction model	Since compaction is the driving force for the seismic events this is very important for the seismic hazard.	Seismic hazard for end of field life is very uncertain	Future subsidence, and therefore also future seismic risk, can only be determined for the coming 5 years with any degree of confidence