Report on the Second Workshop on Mmax for Seismic Hazard and Risk Analysis in the Groningen Gas Field

(Main Report)

13-17 June 2022

The Infinity Building, Amsterdam

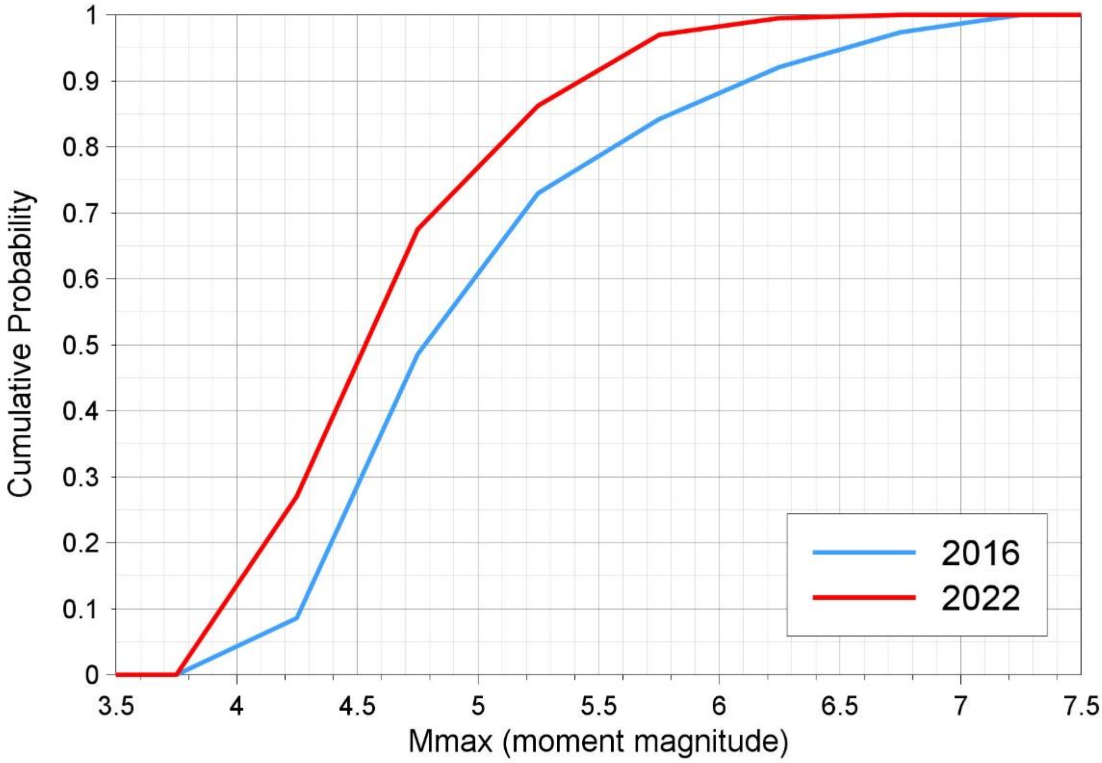
General Introduction

In probabilistic seismic hazard and risk analyses, Mmax is the largest earthquake magnitude considered physically possible within a given seismic source. For hazard studies for natural seismicity, Mmax is generally found not to exert a very strong influence on the estimates of hazard estimates. However, for hazard assessments related to induced earthquakes, where the possibility of the largest potential events being only incrementally larger than the observed earthquakes must be considered, the impact of Mmax can be appreciable. Additionally, estimates of Mmax for induced seismicity can influence the perception of the risk associated with continuation of the industrial operations causing the earthquakes. For both natural and induced seismicity, estimates of Mmax always carry considerable epistemic uncertainty, hence these estimates are presented as distributions of possible values rather than unique values.

In light of these considerations, and the potentially controversial nature of Mmax estimates for Groningen, the NAM Hazard and Risk Analysis engaged an international panel of experts to determine a distribution of Mmax values based on all of the available information and a number of proponent models. The panel members were selected on the basis of experience and expertise is seismic hazard analysis (for natural and/or induced seismicity), the characterisation of induced seismicity, and the estimation of Mmax for seismic hazard analyses. This expert panel was chaired by Kevin Coppersmith and included Jon Ake, Hilmar Bungum, Torsten Dahm, Ian Main, Art McGarr, Ivan Wong and Bob Youngs. To inform the evaluation of the available data, methods and models by this expert panel, a workshop was organised in Amsterdam by NAM in March 2016. Over several days, experts presented data and measurements from the Groningen field and several presenters put forward proponent models for Mmax. Following the workshop presentations, the expert panel deliberated on the information presented and then proposed a distribution of Mmax values to be used in the ongoing seismic hazard and risk calculations.

Four years later, NAM organised a small meeting to review the additional information and modelling that had been conducted following the issue of the 2016 Mmax report, to determine whether there would be value in re-visiting the assessment of the maximum magnitude for the Groningen field. The conclusion was that there was sufficient new information available justify a second Mmax workshop. Happily, all eight members of the original expert panel agreed to participate in this new meeting and NAM began preparations for a workshop in Amsterdam in November 2020. Due to the Covid-19 pandemic, the event was postponed until October 2021, but then had to be postponed for a second time because of the coronavirus restrictions that were still in place. The workshop was finally held in Amsterdam in week 13-17 June 2022, with the participation of many Dutch and international experts who made presentations over the course of four days. Each participant in the workshop was given full access to an extensive database of geological, geophysical, seismological and operational data for the field. Following the 4-day workshop, the expert panel then met for a day to discuss the information presented and discussed, and then continued their evaluation remotely over the ensuing weeks.

The June 2022 workshop and the subsequent discussions within the expert panel have resulted in a new distribution of Mmax for Groningen earthquakes. The full details of the new distribution and its technical bases are explained in the panel's report. The distribution has moved to the left (i.e., to smaller magnitudes) with respect to the earlier evaluation by the panel in 2016, as illustrated in the figure below. The upper tail has been truncated and the probability of Mmax being no larger than **M** 5 has risen from 60% to 77%. The median Mmax estimate is now **M** ~4.5 and the weighted mean estimate of Mmax has decreased from **M** 5.0 to **M** 4.6.



In following pages, we include the expert panel's report, the final workshop agenda, and list of participants, and all of the presentations delivered at the workshop. We express our sincere gratitude to the members of the expert panel for undertaking this important task, to all the workshop participants who contributed to this process, and to Steve Oates at Shell for compiling the databases that were shared with all workshop participants in preparation for the event.

We believe that the proposed distribution on Mmax should now be adopted in all future seismic hazard and risk analyses for the Groningen field. As always, it is important to understand these values as the probabilities associated with the appropriate upper bounds on earthquake magnitudes that could be reached—and *not* as probabilities of such events occurring.

The expert panel report makes a number of recommendations for additional work that could be undertaken to further refine the estimate of Mmax for Groningen, and it is strongly recommended that all of these be considered in ongoing work to quantify the induced seismic hazard and risk in the field.

Groningen Mmax Workshop II

Infinity Building, South Amsterdam, The Netherlands

13-17 June 2022.

Groningen Mmax Workshop II

13-17 June 2022, Infinity Building, South Amsterdam, The Netherlands

Background

For several years, NAM has been developing and refining a seismic hazard and risk model as part of the response to induced earthquakes occurring in the Groningen gas field. As part of these efforts, a workshop was conducted in March 2016 to address the question of the maximum earthquake magnitude, Mmax, that should be considered in the seismic hazard and risk modelling. An international panel of experts was appointed to make the assessment of Mmax for Groningen, informed by the presentations made at the workshop. In the time that has elapsed since the first Mmax workshop was conducted, considerable additional information has become available in the form of new data and new models, such that it is now considered worthwhile re-visiting the issue.

Objectives

The same expert panel, chaired by Kevin Coppersmith and comprising Jon Ake, Hilmar Bungum, Torsten Dahm, Ian Main, Art McGarr, Ivan Wong and Bob Youngs, has been reconvened, and a new workshop scheduled to take place in Amsterdam during the week 13-17 June 2022.

As in 2016, the purpose of the workshop is to inform the expert panel through a series of presentations, questions posed by the panel members and other participants, as well as the general discussion, all of which complements data and publications provided to all participants beforehand. The expert panel is charged with three specific tasks:

1. To clearly define the concept of Mmax in relation to seismicity in the Groningen field and for application in probabilistic seismic hazard and risk analyses.
2. To define a distribution of Mmax values and their associated probabilities, in the form of as discrete logic tree with alternative Mmax values and associated branch weights.
3. To clearly distinguish between induced earthquakes and triggered earthquakes in the formulation of the logic tree, such that the hazard and risk analyses could consider the two types of seismicity separately.
4. To determine if the proposed Mmax distribution compatible with the existing PSHRA framework for Groningen, including the V6 seismological model and the logic tree.

Roles and Responsibilities

The intention is to run the Workshop following the broad principles of the SSHAC (Senior Seismic Hazard Analysis Committee) guidelines for hazard assessment, following the current implementation guidelines (https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr2213/index.html). The Expert Panel effectively assume the role of the Technical Integration (TI) Team charged with objectively and impartially developing a logic-tree for Mmax that captures the centre, the body, and the range of technically defensible interpretations of the available data, methods, and models. The Expert Panel therefore collectively have intellectual ownership of the distribution of Mmax values implied by the final logic tree. Presenters at the workshop provide input to the Panel's deliberations either as Resource Experts, who impartially share data, observations, and analyses, or as Proponent Experts, who advocate for a specific model or interpretation. Some other participants may contribute to the process of technical challenge and defence through questions and discussions. Finally, there are observers, who will be able to watch the dynamics of the presentations and ensuing discussions both from a technical perspective and in terms of the process that is followed. A list of the participants is included at the end of this document.

Schedule and Organisation

The workshop will last for 4 days, following the agenda outlined below. The final day—Friday 17th June 2022—will be reserved for a closed meeting of the Expert Panel to have exploratory discussions and prepare the planning for the preparation of their report and final recommendations. The panel will be requested to subsequently provide detailed documentation explaining the reasoning behind the proposed values and associated weights on the Mmax logic-tree.

During the workshop, a space will be provided for the panel to hold break out meetings as needed, and the panel will also have the right to request additional information or clarifications from the participants and presenters when it is identified that such addenda will enrich their evaluations.

Monday 13th June: Intro/Groningen field/Tectonic Mmax/Induced and triggered earthquakes

Start	End	Speaker	Presentation
8:30	9:00	Julian Bommer	Welcome. Introductions. Background and objectives of workshop.
09:00	09:15	Ministerie EZK	Importance of Mmax for the Groningen seismic risk assessment
9:15	10:15	Clemens Visser	Geology of the field. Past, present and future gas production.
10:15	10:45		*Coffee break*
10:45	11:30	Rob van Eijs	Subsidence and compaction of the gas field
11:30	12:15	Bob Youngs	Definition & estimation of Mmax for tectonic earthquakes
12:15	13:15		*Lunch*
13:15	14:00	Helen Crowley	Mmax values for (tectonic) seismic hazard and risk in Europe
14:00	14:45	Matt Weingarten	Induced earthquakes related to gas production
14:45	15:15		*Coffee break*
15:15	16:30	Gillian Foulger	Induced & triggered earthquakes globally: larger events
16:30	17:00	All	General discussion

Tuesday 14th June: Groningen seismicity and fault ruptures

Start	End	Speaker	Presentation
8:30	9:15	Bernard Dost	History of seismic monitoring in the Groningen field
9:15	10:30	Steve Oates	Groningen earthquakes: focal depths and fault ruptures
10:30	11:00		*Coffee break*
11:00	11:45	Chris Spiers	Properties of Groningen reservoir and fault rocks
11:45	12:30	Rick Wentinck	Geomechanical model of fault rupture in the Groningen field
12:30	13:30		*Lunch*
13:30	14:45	Jean-P. Ampuero	Physics-based models of natural and induced seismicity
14:45	15:15		*Coffee break*
15:15	16:30	Mark Zoback	Crustal stresses and earthquake triggering
16:30	17:00	All	General discussion

Wednesday 15th June: Groningen event-size distribution & Statistical estimates of Mmax

Start	End	Speaker	Presentation
8:30	9:30	Stephen Bourne	Groningen seismological model and earthquake recurrence
9:30	10:15	Laura Gulia	Re-assessment of earthquake distribution for Groningen
10:15	10:45		*Coffee break*
10:45	11:30	Jean-Ph. Avouac	Recurrence model for Groningen earthquakes
11:30	12:15	Zak Varty	Recurrence model for Groningen earthquakes
12:15	13:15		*Lunch*
13:15	14:00	A Muntendam-Bos	Groningen induced event-size distribution
14:00	14:45	Sander Osinga	Taper from recurrence relationship to Mmax
14:45	15:15		*Coffee break*
15:15	16:30	Gert Zöller	Proponent assessment for Mmax in the Groningen field
16:30	17:15	Nepomuk Boitz	Proponent assessment for Mmax in the Groningen field
17:15	18:00	All	General discussion

Thursday 16th June: Proponent models for Mmax

Start	End	Speaker	Presentation
8:30	9:15	David Dempsey*	Proponent assessment for Mmax in the Groningen field
9:15	10:0	Andrzej Kijko*	Proponent assessment for Mmax in the Groningen field
10:00	10:30		*Coffee break*
10:30	11:15	Leo Eisner	Proponent assessment for Mmax in the Groningen field
11:15	12:00	Charles Vlek	Proponent assessment for Mmax in the Groningen field
12:00	13:00		*Lunch*
13:00	13:45	Stephen Bourne	Proponent assessment for Mmax in the Groningen field
13:45	14:45	Loes Buijze	Proponent assessment for Mmax in the Groningen field
14:45	15:15		*Coffee break*
15:15	15:45	Ylona van Dinther	DEEPnl research project on Mmax in the Groningen field
15:45	16:30	All	General discussion

* remote presentation

#	Name	Affiliation	Days
1	Jon Ake	Independent	Mon-Fri
2	Hilmar Bungum	Independent	Mon-Fri
3	Kevin Coppersmith	Coppersmith Consulting Inc.	Mon-Fri
4	Torsten Dham	GFZ-Potsdam	Mon-Fri
5	Ian Main	University of Edinburgh	Mon-Fri
6	Art McGarr	USGS	Mon-Fri
7	Ivan Wong	Lettis Consultants International	Mon-Fri
8	Bob Youngs	Wood Environment & Infrastructure	Mon-Fri
9	Jan van Elk	NAM	Mon-Fri
10	Dirk Doornhof	NAM	Mon-Thurs
11	Clemens Visser	NAM	Mon-Thurs
12	Rob van Eijs	NAM	Mon-Thurs
13	Bernard Dost	KNMI	Mon-Thurs
14	Stephen Bourne	Shell	Mon-Thurs
15	Steve Oates	Shell	Mon-Thurs
16	Mark Zoback	Stanford University	Mon-Thurs
17	Rick Wentinck	Independent consultant	Mon-Thurs
18	Chris Spiers	Utrecht University	Mon-Thurs
19	Laura Gulia	Independent consultant	Mon-Thurs
20	Helen Crowley	Independent consultant	Monday
21	Julian Bommer	Independent consultant	Mon-Thurs
22	Jean-Paul Ampuero	GEOAZUR	Mon-Thurs
23	Huihui Weng	GEOAZUR	Mon-Thurs
24	Jean-Philippe Avouac	Caltech	Mon-Thurs
25	Matteo Acosta	Caltech	Mon-Thurs
26	Zak Varty	Lancaster University	Mon-Thurs
27	Gillian Foulger	Durham University	Mon-Thurs
28	Matthew Weingarten	San Diego State University	Mon-Thurs
29	Gert Zöller	Potsdam University	Mon-Thurs
30	Loes Buijze	University Utrecht & TNO	Mon-Thurs
31	Serge Shapiro	Free University of Berlin	Mon-Thurs
32	Nepomuck Boitz	Free University of Berlin	Mon-Thurs
33	Leo Eisner	Seismik	Mon-Thurs
34	Charles Vlek	University of Groningen	Wed-Thurs
35	David Dempsey	University of Auckland	Thursday (remote)
36	Andrzej Kijko	University of Pretoria	Thursday (remote)
37	Annemarie Muntendam-Bos	SodM	Mon-Thurs
38	Niels Grobbe	SodM	Mon-Thurs
39	Jorien van der Wal	SodM	Mon-Thurs
40	Jaap Breunese	TNO	Mon-Thurs
41	Dirk Kraaijpoel	TNO	Mon-Thurs
42	Sander Osinga	TNO	Mon-Thurs
43	Frans Aben	TNO	Mon-Thurs
44	Bouko Vogelaar	TNO	Mon-Thurs
45	Maarten Pluymaekers	TNO	Mon-Thurs
46	Ylona van Dinther	Utrecht University	Wed-Thurs
47	Vincent van der Heiden	Utrecht University	Mon-Thurs
48	Pauline Kruiver	KNMI	Mon-Thurs
49	Karin van Thienen-Visser	Ministry of Economic Affairs and Climate	Mon-Thurs
50	Frank Wilschut	Ministry of Economic Affairs and Climate	Monday
51	Dirk Doornhof	Independent consultant	Mon-Thurs
52	Femke Vossepoel	TU Delft / KEM Panel	Tues-Wed
53	Ipo Ritsema	Deltares / KEM panel	Mon-Thurs
54	Iunio Iervolino	University of Naples / KEM panel	Mon-Thurs
55	Pierre-Yves Bard	University of Grenoble / KEM panel	Mon-Wed
56	Stefan Wiemer	SED, ETHZ / KEM panel	Mon-Tues
57	André Niemeijer	Utrecht University	Mon-Thurs

Second Report from the Expert Panel on Maximum Magnitude Estimates for Probabilistic Seismic Hazard and Risk Modelling in Groningen Gas Field

9 September 2022

Second Report from the Expert Panel on Maximum Magnitude Estimates for Probabilistic Seismic Hazard and Risk Modelling in Groningen Gas Field

9 September 2022

Introduction

This report describes the second assessment of maximum magnitude (Mmax) made by the Groningen Mmax Panel, which is charged with developing a distribution of Mmax for the Groningen gas field that is appropriate for use in a probabilistic seismic hazard analysis (PSHA) and subsequent probabilistic risk analyses (PRA). The first assessment by the Panel was made in 2016 (Groningen Mmax Panel, 2016) and the same Panel was reassembled to make another assessment in light of significant new data and information that have been developed for the project. To provide the Panel with the applicable new information, the Groningen Mmax Workshop II was held in Amsterdam on 13-17 June 2022. The agenda for that workshop and all presentation materials were provided to the Panel. The presentations and several supporting documents from the literature form the fundamental basis for the Panel's updated assessment. The members of the Panel offer their sincere appreciation for the presentations made at the workshop and for the efforts by the organizers to provide information to the Panel. In particular, the stellar work of Dr Julian Bommer in conducting, facilitating, and organizing the workshop is gratefully acknowledged.

The intended product and context for the assessment of Mmax is the same as it was during the first assessment in 2016. The definition of Mmax is in the context of its common use in seismic source characterization for PSHA. For example, as defined in USNRC (2012a, Chapter 11): Mmax is "*the largest earthquake that a seismic source is assessed to be capable of generating. The maximum magnitude is the upper bound to recurrence curves*." Mmax, as it is defined for PSHA and used here, is a time-independent upper bound. This assessment applies only to the seismicity interpreted to be caused by gas extraction from the Groningen field and is not intended to be an assessment for the maximum magnitude of naturally occurring tectonic earthquakes in the region. The Mmax is assessed as a time-independent parameter and is understood to describe an upper bound during the lifetime of a reservoir given the specific usage and production, in our case for Groningen. If the usage and production would change, another distribution for Mmax may need to be derived. The assessment of Mmax is a required input of all PSHAs. Such assessments are done routinely for purposes of engineering hazard analyses, risk analyses, and safety assessments.

This assessment of Mmax for the Groningen field is intended to capture the center, body, and range of technically defensible interpretations (CBR of TDI; see Section 3.1 of USNRC 2012b for explanation of this concept). This means that the Panel has focused on developing an Mmax distribution that includes epistemic uncertainties and is based on a consideration of tectonic and operational factors relating to the Groningen field, analyses of observed seismicity, earthquake physics, analogues, and experience in developing Mmax for PSHAs in other studies. We view our charge as not requiring statistical proof that our Mmax distribution is correct; rather, we are providing a technically-defensible distribution whose shape and limits reflect the Panel's knowledge and assessment of the uncertainties after due consideration of the available pertinent information. (See comments at the end of this document pertaining to the process followed by the Panel).

Note that the assessment, like all assessments for purposes of seismic hazard analysis, is intended to be a description of the future hazards. This assessment takes into consideration the features, events, and processes that have happened in the past (e.g., the locations, rates, and sizes of past earthquakes), but it is also takes account of processes or events that have not (yet) been observed at Groningen but have some chance of occurrence based on comparisons to analogous case histories. This is especially true for rare phenomena like Mmax that may not have been witnessed in the relatively short observational record.

The Panel would like to acknowledge and compliment the significant work done by and for the Groningen Mmax project since the 2016 workshop. The new data and analyses conducted during this period are useful in reducing uncertainties in key aspects pertaining to Mmax. These include: characteristics of the field, spatial and temporal distributions of seismicity, geodetic strain, better defined conceptual and rheological models, etc. The Panel is pleased to note that the new information and actions, on the whole, were consistent with the recommendations made in the Panel's 2016 report.

Logic Trees

The logic tree that expresses the Panel's updated assessment of Mmax for the Groningen field is given in Figure 1 and displays the key epistemic uncertainties. The first node of the logic tree expresses the two basic processes that describe the sources of potential future seismicity related to the Groningen field. The first branch indicates that the seismicity at Groningen is and will be related to induced seismicity alone; that is, related to the processes that are currently believed to occur because of the compaction of the reservoir due to withdrawal of gas. This seismicity is assumed to be localized to the region affected by the pore pressure reduction.

The second branch represents the occurrence of induced seismicity as well as seismicity that is triggered by the operations of the gas withdrawal. As in the 2016 report, the Panel adopts the terminology given in McGarr et al. (2002): "*As used here, the adjective 'induced' describes seismicity resulting from an activity that causes a stress change that is comparable in magnitude to the ambient shear stress acting on a fault to cause slip, whereas 'triggered' is used if the stress change is only a small fraction of the ambient level (e.g., Bossu, 1996; McGarr and Simpson, 1997)*." In contrast to induced earthquake activity, triggered seismicity includes earthquakes whose ruptures extend significantly beyond the region affected by the compaction associated with gas production. As indicated during the discussions at the workshop, it can be concluded that triggered seismicity has not been witnessed so far at Groningen, but the possibility of its occurrence cannot be eliminated based on the existing data.

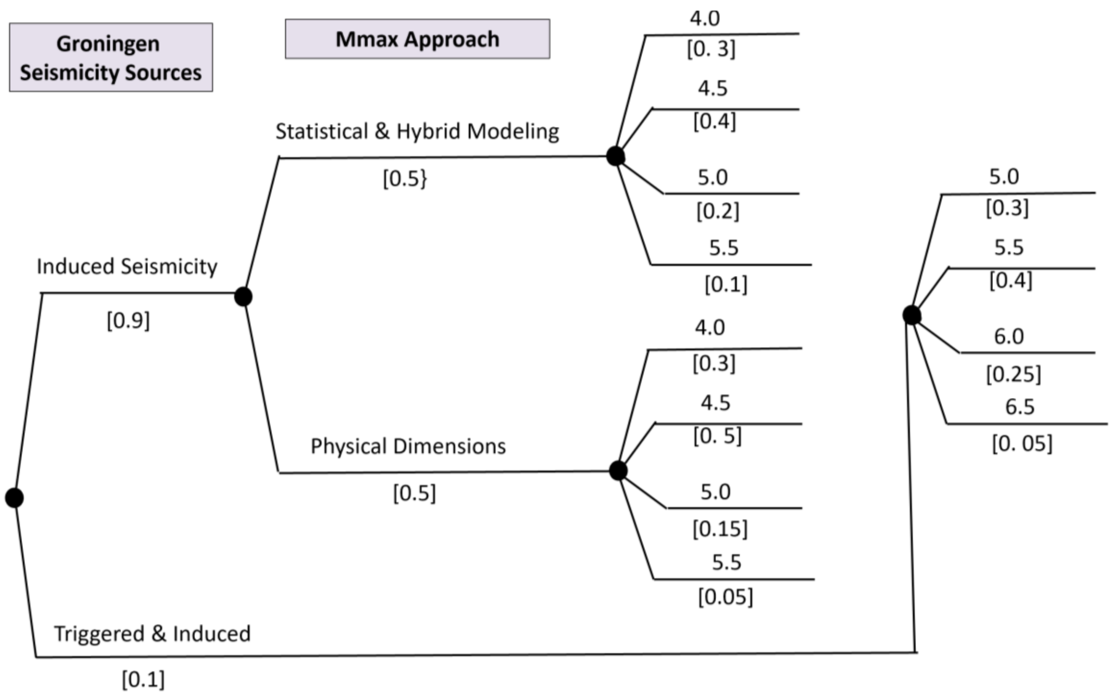


Figure 1. Logic tree showing the major elements of the assessment of Mmax for the Groningen field. Alternative branches are identified at each node and weights are assigned to each branch. The end point for each branch is the estimated maximum magnitude to the nearest half unit and its probability (in brackets).

The weights associated with the two branches of the first node of the logic tree are the following:

Induced	[0.9]
Triggered & induced	[0.1]

The weights reflect a strong belief that the future seismicity of the Groningen field area will occur as induced seismicity but with an acknowledgment that we cannot preclude the possibility that the future seismicity will include both induced and triggered components. The reasons for these weights are the following. There is abundant evidence that the current seismicity within the Groningen area is the result of gas extraction processes and associated compaction within the reservoir. For example, high-resolution earthquake hypocenters confirm that nearly all of the observed seismicity initiates within the reservoir horizon. Normal-faulting related to compaction in the reservoir units is identified based on earthquake focal mechanisms. Geodetic data confirm subsidence at the surface of several tens of centimeters as the reservoir is compacted and the spatial coincidence with such subsidence and the extraction region is clear. The data that have been collected in the past several years since the Panel last met, as presented and discussed at the workshop have led to a more highly resolved spatial and temporal picture of persistent induced seismicity. Thus, the Panel gives high weight to the notion that such activity will continue.

In contrast, the branch of the logic tree that represents the potential occurrence of both induced and triggered events is given low weight for several reasons. As already noted, there is reasonable evidence that the current observed seismicity does not include earthquakes that would readily be considered as triggered events, although the period of observation (five or six decades) is relatively short. Triggered events are commonly associated with locations or regions characterized by the presence of more active tectonics as shown, for example, by the presence of Quaternary faults, deformation related to active faults or tectonic background seismicity. Such is not the case in the Groningen region, which lies within what is considered to be a stable continental region (SCR) well away from plate boundaries and observed Quaternary deformation. Although faults and evidence of ancient fault movements lie within the Carboniferous units beneath the reservoir and in nearby regions away from the reservoir, there is no evidence from seismicity or other tectonic indicators that these units display evidence of near-critical stresses that would be susceptible to triggering by the operations of the gas field. In fact, the historical record of seismicity that predates the presence of the gas extraction operation is remarkably quiescent. For example, the only event in the region found in the European historical catalogue spanning the period 1000-1899 (*https://emidius.eu/epica/*) is an event dated October 27, 1225, which is indicated without specific location from only one source in the chronicle of the monastery of Witterwierum. Given this information, the Panel regards the basis for the 1225 "event" being an earthquake as equivocal.

Despite the abundant evidence that triggered events are likely not included in the current catalogue of events in the Groningen region and that evidence does not appear to be present for critical stresses within the Carboniferous units beneath the reservoir (inferred not from *in situ* measurements but rather from absence of documented rupture initiations), the Panel finds that the potential for triggering cannot be definitively ruled out. Gas extraction fields worldwide have arguably given rise to triggered seismicity, so this possibility should be considered. As a result, the potential for triggered seismicity as well as induced seismicity is included in the logic tree with a low weight.

The second node of the logic tree expresses the uncertainty in the approach to be taken to assess Mmax, given that induced seismicity is the mechanism for future earthquakes in the region. The two alternative approaches and their weights are the following:

Statistical and hybrid modeling	[0.5]
Physical dimensions	[0.5]

Statistical modeling of observed seismicity is a major activity that has been employed using the Groningen seismicity catalogue and was the subject of several presentations at the workshop. Hybrid modeling incorporates data related to stresses within the reservoir and uses accepted failure criteria, such as Coulomb failure criteria or frictional constitutive relations (e.g. rate-state), with physical modeling of stresses within the reservoir and simulations to predict the spatial and temporal characteristics of seismicity that would be expected. This includes modeling focused on the maximum magnitudes of forecast seismicity. As shown in the presentations at the workshop, such modeling is typically calibrated and verified by comparisons to seismicity models. We call these approaches “hybrid” and include them together with purely statistical approaches in the logic tree. The hybrid models are those that consider scenarios where earthquakes sizes may grow significantly larger than the field dimensions of the reservoir under production.

The seismicity and hybrid modeling approaches were discussed extensively at the workshop and various magnitude assessments were provided that incorporate the observed seismicity over the period of observation of the reservoir—generally in the period from about 1991 to the present. For instance, presentations by Buijze et al., Ampuero et al. and van Dinther et al. used physics-based models and numerical simulations to simulate rupture scenarios for different settings. Estimates of maximal magnitudes, if presented, are in the range of moment magnitude **M** 4.1 and 4.6. However, complex rupture geometries due to interaction of faults and possible jumps of slip between faults were not yet considered, which could lead to magnitude estimates that are somewhat larger. Based on the range of results from these models and taking account of the relatively short period of seismicity observation, the Panel arrived at a distribution of Mmax for the statistical and hybrid modeling branch shown in the logic tree in Figure 1.

An alternative approach to assessing Mmax, given the induced seismicity branch, is the consideration of the dimensions of ruptures that might occur within the reservoir. This approach considers the maximum dimensions, in terms of length and width, that fault ruptures postulated to occur within the reservoir might have. The approach uses the current knowledge of the structure of the reservoir, the spatial patterns of observed seismicity (e.g., whether or not the seismicity exists beneath the reservoir in the Carboniferous units or above the reservoir in the Zechstein units), as well as the locations, patterns, and mechanisms of mapped faults within the reservoir. From these data, dimensions of possible ruptures are estimated and they, in turn, are used to estimate the associated magnitudes. For example, Stephen Bourne presented an assessment of the maximum possible fault rupture widths that might be credible given the available data and argued that empirical scaling relationships between rupture width and magnitude could be used to assess Mmax for earthquakes occurring within the repository. Rupture dimensions has been used for many years to assess Mmax for fault sources and a wide array of empirical scaling relationships exist in the literature for this purpose.

The physical dimensions branch of the logic tree includes a consideration of physical constraints on the stress perturbation induced by the reservoir usage together with rheological models and existing fault structures. During the Groningen Mmax Panel 2016 workshop the argument was discussed that the total strain energy that may build-up during the life-time of field production may be released in a single event – a scenario that is highly unlikely and questionable. At the 2022 workshop, the presentations by van Eijs et al. (day 1) and Spiers et al. (day 2) presented new results for Groningen showing that only 30-60% of the built-up deformation is elastically stored. Moreover, the stored elastic energy is released by a population of earthquakes that follow a frequency-magnitude distribution, not just by a single event. Therefore, the simplistic approach of relating the total volume change to Mmax is not considered further in this assessment. Instead, to develop the distribution, the Panel considered the potential dimensions of ruptures that might occur within the reservoir as constrained by the thickness of the reservoir, the style of faulting, possible lengths of ruptures that would initiate within the reservoir and not extend significantly outside of it. This could also involve complex ruptures or uncommon aspect ratio and rupture geometries, as partly observed for induced seismicity. An example of a complex or uncommon induced event rupture is, among others, the Ekofisk oil field Mw 4.4 rupture (for example, Dahm et al., 2015), or the Mw 5.5 Pohang (Grigoli et al 2018) or the Mw 5.1 Fairfield Oklahoma earthquake (see e.g., Lopez-Comino and Cesca, 2018).

The Panel then considered possible scaling relationships that would be applicable, such as rupture length, width, and area for normal faulting (Thingbaijam et al., 2017; Leonard, 2014 for SCR and dip slip faulting) and the magnitudes that would be calculated for the given rupture dimensions. These explorations suggest that magnitudes as large as **M** 5 to 5.5 are possible, but they would require very unusual rupture shapes with high length to width aspect ratios. Thus, the weights assigned to **M** 5 and to 5.5 for the induced rupture dimensions branch are very low but they are not zero.

The Panel considered the statistical/hybrid and rupture dimensions approaches as potential means of assessing Mmax in the induced seismicity branch, and concluded that they should be assigned equal weight. Based on the presentations at the workshop, it is apparent that the statistical and hybrid modeling approaches have been and are currently the focus of many of the studies of Groningen seismicity, but the use of rupture dimensions to constrain maximum magnitudes also covers plausible scenarios of earthquakes not included in the catalogue of observed earthquakes. Given the value of both approaches, the Panel concluded that they should be equally weighted in the logic tree for Mmax.

The Mmax distribution assessed by the Panel for the case where both induced and triggered seismicity are assumed to occur is shown in the logic tree (Figure 1). The two fundamental concepts used in assessing Mmax for this branch were the dimensions of rupture that might be applicable if seismicity was not constrained to the reservoir and appropriate analogues to the Groningen gas field and their associated observed earthquakes.

The Panel considered the possibility that triggering processes might also entail the triggering of faults within the Carboniferous units beneath the reservoir and/or structures that would extend beyond the strict margins of the reservoir into the aquifer areas and perhaps beyond. These possibilities would, obviously, lead to larger rupture dimensions than ruptures confined to the reservoir itself.

The consideration of appropriate analogues to the Groningen gas field is an important activity and must be carefully done. In general, the Panel found that the Groningen-specific data and information—particularly that gathered since the last workshop—were very useful in defining the important attributes of the field and, in turn, in defining the criteria that must be fulfilled in order to be considered an appropriate analogue. For example, identified aspects of the Groningen gas field to be considered in drawing analogies to other fields are the following:

- Gas extraction only, no injection
- Stable continental region tectonically
- Essentially no seismicity pre-operation, suggesting low tectonic stresses
- Normal faulting regime
- No Quaternary active faults in reservoir or in nearby region affected by the stress perturbation
- Observed seismicity confined to reservoir

Given these attributes and reviewing the updated information on possible analogues in the database, there are very few, if any, close analogues that would allow for a high degree of confidence in their use in the Panel's Mmax assessment. This is especially true for the case where the Groningen seismicity source is assessed to be induced only and even the case where triggering is assumed to occur.

The characteristics of the Groningen field are in many respects unique and, as a result, the use of some of the well-known possibly triggered earthquakes such as those at Gazli was found by the Panel to be inappropriate. This is because their use would violate so many of the criteria given above to draw meaningful and defensible analogies such that the earthquake magnitudes at the locations could be confidently "imported" to the Groningen field to help populate the Mmax distribution. Disregarding the clearly indefensible cases, the consideration of analogues did expand the Mmax distribution to include some larger triggered events and these are reflected in the distribution. For instance, the maximal observed magnitude at the Lacq gas field was **M** 4.2, the maximal magnitude of **M** 4.4 (e.g. Dahm et al., 2007) of the Rotenburg/Söhlingen/Völkerson gas fields in North Germany, which occurred in a similar tectonic setting and Rotliegend reservoir formation. In general, there are only a few case histories that might offer some support for triggered earthquakes associated with gas extraction.

Mmax Distributions

Given the approaches and assessments in the logic tree, various estimates of Mmax were developed by the Panel, as shown in Figure 1. The directly assessed conditional Mmax distributions in the logic trees are discussed in this section as well as the total or unconditional Mmax distribution across the entire logic tree.

Groningen Seismicity Source Alternatives

Although the branches of the logic tree have very different weights, the conditional Mmax distributions (conditioned as having a weight of 1.0 for each branch) can be compared for the two models of seismicity for Groningen, as shown in Figure 2. The Mmax distributions overlap at about **M** 5 but are otherwise quite different. The induced seismicity model leads to lower Mmax values because the approaches used are very specific to the Groningen field and generally do not include scenarios that would entail magnitudes much larger than are modeled using observed seismicity or rupture dimensions that extend beyond the immediate reservoir. In contrast, the triggered branch includes the consideration of earthquake ruptures that extend beyond the immediate field as well as the consideration of analogues in other regions that include the possibility of triggered earthquakes.

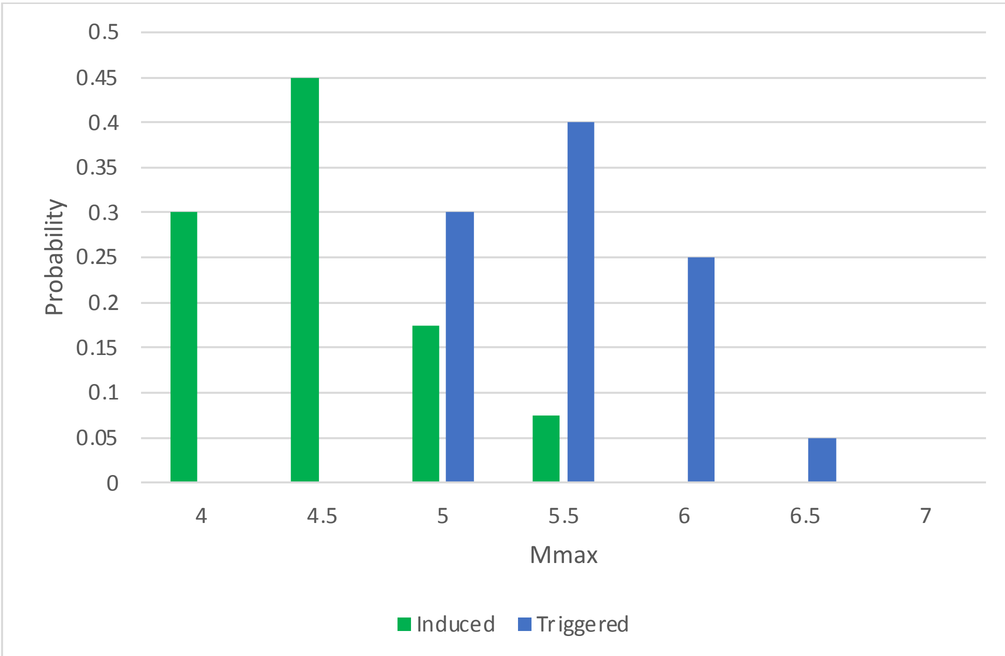


Figure 2. Conditional probability distribution for Mmax for the two models of Groningen seismicity: "induced seismicity only" (green) and "triggered and induced seismicity" (blue). The conditional distributions are normalized to a weight of 1.0 for each model for ease of comparison.

Mmax Approach, Given Induced Seismicity

As discussed above, the Panel made direct assessments of the Mmax distributions that express the epistemic uncertainties in the Mmax approach taken, given the induced seismicity branch of the logic tree. The resulting conditional Mmax distributions for the two branches are shown as probability distributions in Figure 3. Somewhat surprisingly, the Mmax distributions for the two approaches to characterizing the induced seismicity Mmax are very similar even though they are based on very different conceptual models and employ different types of data.

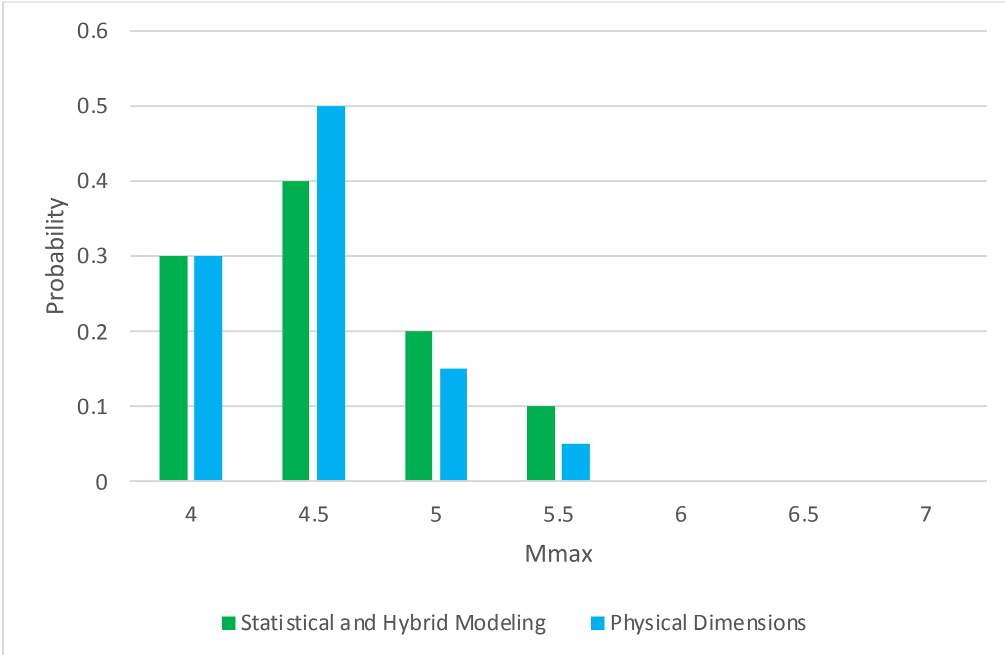


Figure 3. Conditional probability distribution of the Mmax distribution for the Groningen seismicity for the combined statistical and hybrid modelling approach (green) or the physical dimensions approach (blue), after normalising each to a total probability of 1.0.

Unconditional Mmax Distribution

In addition to the Mmax distributions assessed directly by the Panel, the logic trees and associated weights on the branches allow for calculation of the total (unconditional) Mmax distribution across all of the elements of the logic tree. That Mmax distribution is shown in Figure 4 and is compared to the Mmax distribution developed by the Panel in 2016.

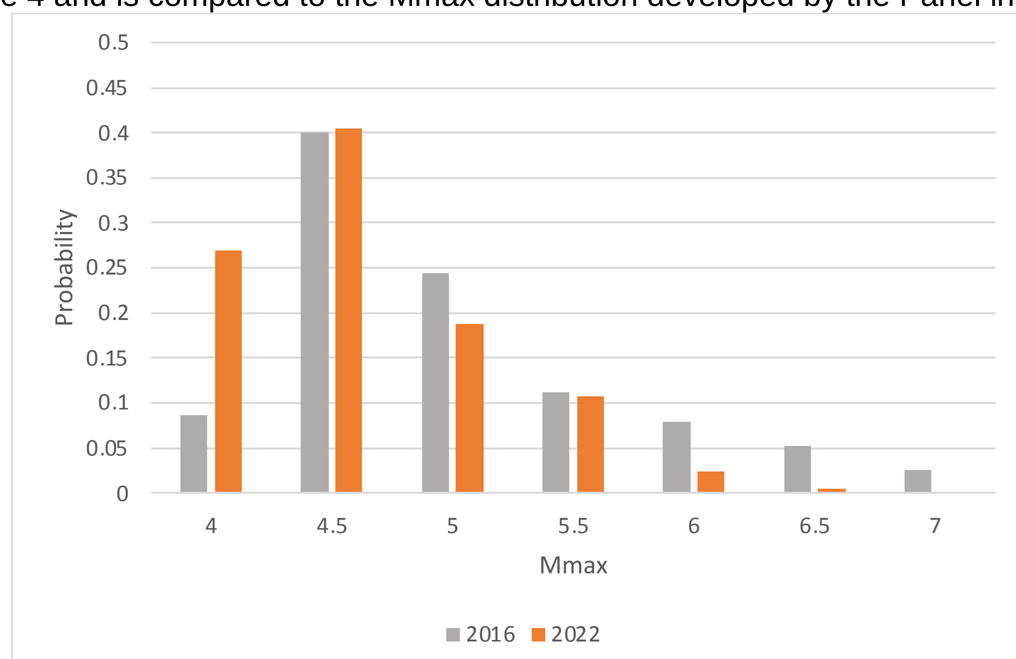


Figure 4. Probability distribution for Mmax for the Groningen seismicity source integrated across all elements of the logic tree. Shown is the distribution for the current study (orange) as well as the distribution for the 2016 study (grey).

As can be seen, the Mmax distribution spans a range of magnitudes from **M** 4.0 to 6.5, with the bulk of the probability mass in the range of **M** 4.0 to 5.0. In comparison to the 2016 distribution, there is considerably more weight at the **M** 4.0 level. This is largely because the magnitude assessments using modeling of the observed seismicity and evidence for ruptures to be confined to the reservoir are given more credibility than they were in 2016 due to the improved data and understanding of the reservoir. Another significant difference lies at the larger magnitudes of **M** 6.0 to 7.0. The consideration of appropriate analogues as well as the better understanding of the Groningen characteristics led to the rejection of analogues that were not judged to be defensible. Thus, in general, the new data and studies conducted over the past six years have led to a reduction in the uncertainties and this is reflected in the Mmax distribution itself.

Table 1 Assessed discrete Mmax distribution shown in Figure 4.

M	Weight
4.0	0.27
4.5	0.405
5.0	0.1875
5.5	0.1075
6.0	0.025
6.5	0.005
7.0	0

The assessed Mmax distribution is represented discretely by the probability mass function (PMF) shown above with values centered in 0.5 magnitude unit bins. In addition, a continuous cumulative distribution function (CDF) is provided in Table 2. The CDF is constructed by assigning the probability mass in each discrete magnitude bin uniformly over the 0.5 magnitude unit bin width centered on the magnitudes shown in Figure 3 and listed in Table 1. The resulting CDF is shown in Figure 5.

Table 2. CDF of Mmax distribution shown in Figure 5.

M	Cumulative Probability
3.75	0
4.25	0.27
4.75	0.675
5.25	0.8625
5.75	0.97
6.25	0.995
6.75	1

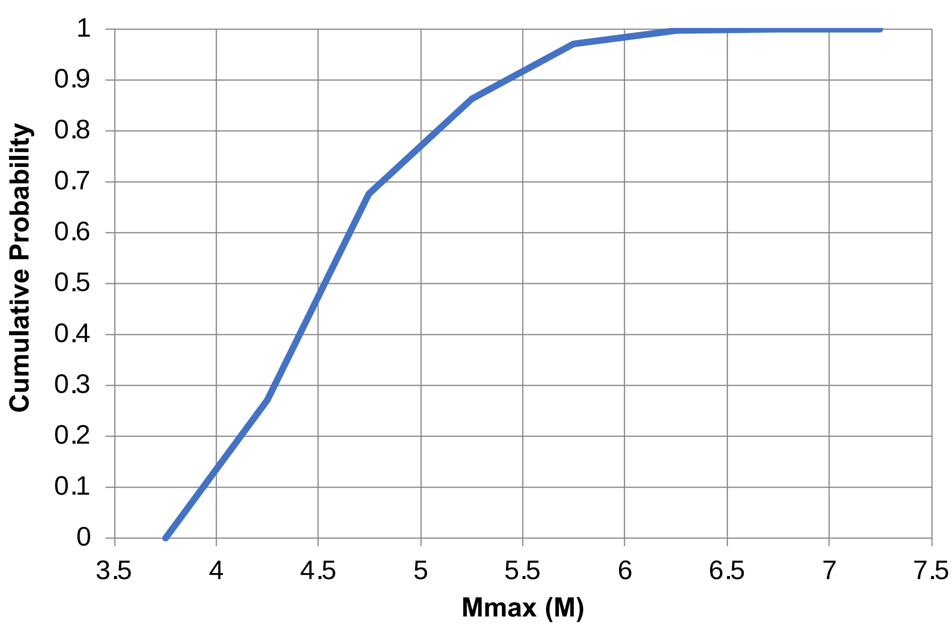


Figure 5: Assessed Mmax CDF.

Recommendations

Assuming that studies pertaining to seismic hazard will continue in the future at Groningen, the Panel offers the following recommendations.

- We commend the project for continuing to improve the resolution of seismicity studies that allow the detailed assessment of the locations of induced seismicity within the reservoir. With respect to the seismogenic potential of the geologic units beneath the reservoir horizon, reduction of uncertainty would best be done by obtaining information on the stress state of the Carboniferous units. Such information could shed light on the triggering of potential of faults within this unit that may be related to the gas extraction process.

- Consider applying state of the art high-resolution data mining and machine learning techniques, including automated phase picking and double-difference hypocentral location, to analyze the seismicity from full-waveform digital data. Based on applications elsewhere, this is likely to better resolve the locations of hypocenters and determine whether events are located outside of the reservoir. It is also likely to reduce the magnitude of completeness, and hence reduce the uncertainty in the frequency-magnitude parameters by having a broader dynamic range and number of observations.

- Conduct detailed studies to look at the geometry of the faults that are implied by the seismicity (e g. dips of faults from focal mechanisms and source inversions), detailed geometries can be used for constraining potential rupture dimensions.

- Consider using Groningen as a test case for prospective operational earthquake forecasting by submitting competing hypotheses for future seismicity, for instance to Collaboratory for the Study of Earthquake Predictability (CSEP) testing platform. Alternatively, an independent testing platform for induced seismicity may be developed at Groningen. Typically, this will involve submitting five year forward predictions for alternative event rate models developed using the extensive Groningen database, including a suite of purely statistical and hybrid forecasting models. This will also allow a more rigorous hypothesis test than retrospective 'out of sample' analyses.

A Note Regarding Process

Throughout the process of developing these assessments of Mmax for the Groningen gas field, reference has been made to how the approach used "follows the broad principles of the SSHAC guidelines for hazard assessment, following the current implementation guidelines." This is true from the standpoint of broadly defining the products, roles of participants, the need to capture the CBR of TDI, and consideration of alternative data, models, and methods. However, once one moves from the "broad principles" and the "general spirit" of a SSHAC process to the details of exactly what is required in regulatory implementation guidance, the process used for the assessment of Mmax for Groningen falls far short of the requirements for a SSHAC project—even the lowest SSHAC Level 1 process level. We offer our perceptions regarding this issue in Attachment A because it has been raised in the materials provided to the Panel, such as the workshop agendas, summaries of the first workshop process (Bommer & Van Elk, 2017), and the recent commentary provided in Bommer (2022). Although the Panel argues that the technical assessment of Mmax documented in this report is defensible, the assessment would be much more robust if it was an integrated component of a full SSHAC study of seismic hazard and risk for Groningen.

References

Bommer, J.J., (2022). Earthquake hazard and risk analysis for natural and induced seismicity: towards objective assessments in the face of uncertainty. *Bulletin of Earthquake Engineering*, *20*(6), pp.2825-3069.

Bommer, J.J. and Van Elk, J., (2017). Comment on "The maximum possible and maximum expected earthquake magnitude for production-induced earthquakes at the gas field in Groningen, the Netherlands" by Gert Zöller and Matthias Holschneider. *Bulletin of the Seismological Society of America*, Vol. 107, No. 3, pp. 1564-1567.

Bossu, R. (1996). PhD Thesis, University Joseph Fourier, Grenoble.

Dahm, T., Krüger, F., Stammler, K., Klinge, K., Kind, R., Wylegalla, K., & Grasso, J. R. (2007). The 2004 Mw 4.4 Rotenburg, Northern Germany, earthquake and its possible relationship with gas recovery. *Bulletin of the Seismological Society of America*, *97*(3), 691-704.

Dahm, T., S. Cesca, S. Hainzl, T. Braun, and F. Krüger (2015), Discrimination between induced, triggered, and natural earth-quakes close to hydro-carbon reservoirs: A probabilistic approach based on the modeling of depletion-induced stress changes and seismological source parameters, *J. Geophys. Res. Solid Earth*, 120, doi:10.1002/2014JB011778

Grigoli, F., Cesca, S., Rinaldi, A.P., Manconi, A., Lopez-Comino, J.A., Clinton, J.F., Westaway, R., Cauzzi, C., Dahm, T. and Wiemer, S., (2018). The November 2017 M w 5.5 Pohang earthquake: A possible case of induced seismicity in South Korea. *Science*, *360*(6392), pp.1003-1006.

Groningen Mmax Panel (2016). *Report from the Expert Panel on Maximum Magnitude Estimates for Probabilistic Seismic Hazard and Risk Modelling in Groningen Gas Field*, 25 April 2016, 13p.

Leonard, M. (2014). Self-consistent earthquake fault-scaling relations: Update and extension to stable continental strike-slip faults. *Bulletin of the Seismological Society of America*, *104*(6), 2953-2965.

López-Comino, J. A., & Cesca, S. (2018). Source complexity of an injection induced event: The 2016 Mw 5.1 Fairview, Oklahoma earthquake. *Geophysical Research Letters*, *45*(9), 4025-4032.

McGarr, A. and D. Simpson (1997). In: *Rockbursts and Seismicity in Mines*. pp. 385-396, Balkema.

McGarr, A., D. Simpson, and L. Seeber (2002), *Case histories of induced and triggered seismicity.* In International Handbook of Earthquake and Engineering Seismology, vol. 81A, pp. 647–661, Academic Press, San Francisco, Calif.

Pijnenburg, R. P. J., Verberne, B. A., Hangx, S. J. T., & Spiers, C. J. (2019). Inelastic deformation of the Slochteren sandstone: Stress-strain relations and implications for induced seismicity in the Groningen gas field. *Journal of Geophysical Research: Solid Earth*, 124, 5254–5282. https://doi.org/10.1029/2019JB017366

Thingbaijam, K. K. S., Martin Mai, P., & Goda, K. (2017). New Empirical Earthquake Source-Scaling Laws. *Bulletin of the Seismological Society of America*, *107*(5), 2225-2246.

USNRC (U.S. Nuclear Regulatory Commission). (2012a). *Central and Eastern United States Seismic Source Characterization for Nuclear Facilities*. NUREG-2115, Washington, D.C.

USNRC (U.S. Nuclear Regulatory Commission). (2012b). *Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies*. NUREG-2117, Rev. 1, Washington, D.C.

Respectfully submitted,

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Attachment A
Comments Regarding Process

Throughout the process of developing these assessments of Mmax for the Groningen gas field, reference has been made to how the approach used "follows the broad principles of the SSHAC guidelines for hazard assessment, following the current implementation guidelines." While this is true from the standpoint of broadly defining the products as needing to capture the CBR of TDI, the general role of the Panel as technical integrators, and the resource and proponent experts providing their data and interpretations in a workshop environment that encourages the "challenge and defense" that has marked SSHAC workshops for other projects. But once one moves from the "broad principles" and the "general spirit" of a SSHAC process to the details of exactly what is required in regulatory implementation guidance, the process used for the assessment of Mmax for Groningen falls far short of the requirements for a SSHAC project—even the lowest SSHAC Level 1 process level. We offer our perceptions regarding this issue because it has been raised in the materials provided to the Panel, such as the workshop agendas, summaries of the first workshop process (Bommer & Van Elk, 2017), and the recent commentary provided in Bommer (2022).

In the interest of time and space in this document, we will provide our views on just a few of the clear departures between this Groningen Mmax study and accepted practice for a SSHAC study—particularly a study conducted at SSHAC Level 2 or 3. These example departures relate to the development and evaluation of a project database, the integration phase of a SSHAC project including feedback, and participatory peer review.

Development and Evaluation of Project Database

The first phase of a SSHAC process includes the identification, compilation and evaluation of the data that the Technical Integration (TI) team identifies as being pertinent to the assessments that they will be making. Typically, a comprehensive database is developed and is made available to the TI team for their consideration in a manner that allows for adequate time and evaluation—typically over a period of months. As the project proceeds, the project database continues to be supplemented with new information identified by the TI team and/or new data collected specifically for the project to reduce uncertainties in the ultimate assessments. The evaluation of the database is an important activity that allows the TI team to consider the alternative datasets, models and methods that have been proposed by the larger technical community.

In the case of the Groningen Mmax project, the expert panel faced the challenge of entering the project in 2016—and coming back into the project after 6 years in 2022—and attempting to absorb and evaluate a vast amount of new information, identified by others, in a very short period of time. This does not conform to the SSHAC principle of subject-matter experts becoming experts on the specific application through exposure to the available data, methods, and models over several months of data compilation and collection, evaluation, and integration.

Integration Phase of the Project Including Feedback

After the data, models, and methods have been evaluated during the evaluation phase of a SSHAC project, the model-building or integration phase is conducted. The models that are built provide the technical assessments required for the technical products of the study and the uncertainties are quantified such that the products reflect the CBR of TDI. Typically, the model-building process is a collaborative process involving all members of the TI team as they assess the important technical approaches that will be followed, the viability of alternative models and methods in light of the available data, and the proper representation of uncertainties given current knowledge. This process typically requires multiple meetings of the team, side calculations to understand the processes and uncertainties, and consideration of feedback regarding the potential hazard significance of the assessments being made. Feedback also provides a basis for prioritization of the model-building process to focus on the assessments that are most important to the hazard results and on the uncertainties that contribution most to the hazard uncertainties.

The model-building process for the Groningen Mmax assessment was contracted to essentially a single one-day meeting of the Panel to consider the data and assessments made by project participants, followed by remote correspondence amongst the Panel members to consider the range of possible assessments and the technical defense of the uncertainties quantified. No feedback was provided regarding hazard significance or implications of the uncertainties quantified to their subsequent use in risk analyses. As a result, the Panel was left to estimate the potential importance of the elements of their assessments based on their own experience on other projects.

Participatory Peer Review

A hallmark of a SSHAC process is the continual peer review that occurs from a participatory peer review panel (PPRP) throughout the course of the project. A PPRP must have the experience and range of expertise that the TI teams possess in order to provide their commentary and feedback throughout the project. In addition, the PPRP is charged with ensuring that a defensible SSHAC process has been followed such that the products of the study capture the CBR of TDI. Experience has shown that the rigorous process of peer review not only improves the quality and defensibility of the products of a SSHAC hazard assessment, it provides the regulatory assurance that is required to enhance public acceptance.

No peer review process was invoked in the Groningen Mmax assessment process. The Panel was provided with the applicable data and the charge to develop and document an Mmax distribution that could be used for future hazard and risk assessments. Independent peer review would have ensured that the process followed was defensible and that the technical assessments made properly capture the CBR of TDI. Such peer review would likely enhance the regulatory and public acceptance of the Panel’s assessments and conclusions.

Conclusions Regarding Process

Although the Panel argues that the technical assessment of Mmax documented in this report is defensible, the assessment would be much more robust if it was an integrated component of a full SSHAC study of seismic hazard and risk for Groningen. It is our understanding the attempt to apply SSHAC to this critical and controversial problem was proposed but was frustrated by the regulator (summarized in Bommer, 2022). However, if the decision to close the field is ever reversed and the hazard and risk study is ever restarted, the Panel would strongly recommend that the study be conducted as a SSHAC process.