# Review of “Hazard and Risk Assessment for Induced Seismicity in Groningen – Update 7th November 2015”

by

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Introduction The U. S. Geological Survey (USGS) provides technical review and advice to the State Supervision of Mines of the Netherlands (SodM) under a Letter of Agreement NL-02.0000 dated June 25, 2015. At the request of the SodM, USGS has been asked to review of “Risk Assessment for Induced Seismicity Groningen – Update 7th November 2015.” This document is the review. The conclusions contained herein are solely the views of the authors and do not constitute an official position of the USGS or the U. S. Government.

Background This report presents a comprehensive evaluation of the earthquake hazard and earthquake risk posed by ongoing gas field operations in the Groningen region. The report differentiates between hazard, a source of potential danger or harm, and risk, the chance of suffering loss or harm. The earthquake hazard evaluation is based on well-established principles and methodologies of Probabilistic Seismic Hazard Analysis. The PSHA model is built from three main components: 1) the earthquake source model that describes the location and magnitudes of earthquakes in space; 2) the earthquake rate model that describes the rate of occurrence of earthquakes of different magnitudes for each location in the earthquake source model; and 3) ground motion prediction equations (GMPE) that describe the distribution of shaking expected for earthquakes as a function of magnitude, distance (and other parameters). Risk is the product of the hazard with the buildings or other structures exposed to the hazard and their fragility to earthquake shaking. Because our expertise is in the area of earthquake hazard, this review focuses on the hazard, with only a few comments on the risk sections of the report.

The main conclusion regarding hazard, summarized on p. 6 of the report is:

> Hazard maps indicate a smaller geographical area is exposed to significant (> 0.25g PGA) ground accelerations for 2016 – 2021 than was projected for the same period in the May 2015 PHRA report. The reduced hazard area is consistent with the KNMI Hazard map update published in October 2015 and now reflects the improved methodology used to predict ground motion, based on the detailed description of the soil layers in the Groningen field area.

As described on p. 7 of the report, the updated hazard model is based on a revised seismic source model that correlates the earthquake production rate with the production and compaction history of the reservoir; and the development of GMPEs that explicitly account for the local geologic characteristics of the Groningen region.

Earthquake Source and Rate Model The revised seismic source and activity model (Bourne and Oates, 2015a and 2015b) combined the earthquake history of the Groningen field with the subsidence history to develop a forecast model for future activity. It replaces an earlier model that assumed that seismic activity is proportional to reservoir compaction (Bourne and Oates, 2014) with a more fully developed geo-mechanical model. Several key elements of the model include the use of surface subsidence to estimate strain in the reservoir using a thin sheet model, development of a nucleation rate model of seismic events as a non-linear function of compaction rate, and the incorporation of an Epidemic Type Aftershock Sequence (ETAS) model into the framework.

The new model was independently reviewed by Ian Main (Appendix D). We are largely in agreement with his review. As Main points out, this is a novel model that has been calibrated to existing data. Assessing its performance prospectively should be a high priority in the future, particularly if this can be done for shorter time intervals than annual forecasts. Perhaps this will be possible if the improved seismic network reduces the magnitude of completeness.

The correlation between seismicity and compaction, while compelling, does not by itself justify the conclusion that the strain is being partitioned between dominantly aseismic deformation and brittle failure. The exponential relation between compaction and seismicity rate might reflect increasing shear stress within the reservoir. In this regard, it is surprising to us that apparently little has been done to measure the orientation and magnitude of the stress. This would seem to us to be a key component of a comprehensive geo-mechanically-based earthquake source model. What we do know about the state of stress from regional data shows that the north-northwest striking normal faults that cut the reservoir are optimally oriented for slip if the stresses are high enough. What we don't know is if any of the faults are critically stressed.

Improved earthquake detection and location may also provide critical information needed to identify seismically-activated faults and their relation to pre-existing structures. This is vital work. Association of seismicity with faults that extend downward into the carboniferous would raise concerns in our minds that rupture could extend below the reservoir, substantially increasing the maximum possible magnitudes of induced earthquakes. While the work on hypocenter determination by Pickering (2015) indicates that much of the seismicity occurs in the reservoir, in contrast to earlier work, it does not demonstrate that ruptures have been or will be confined to the reservoir.

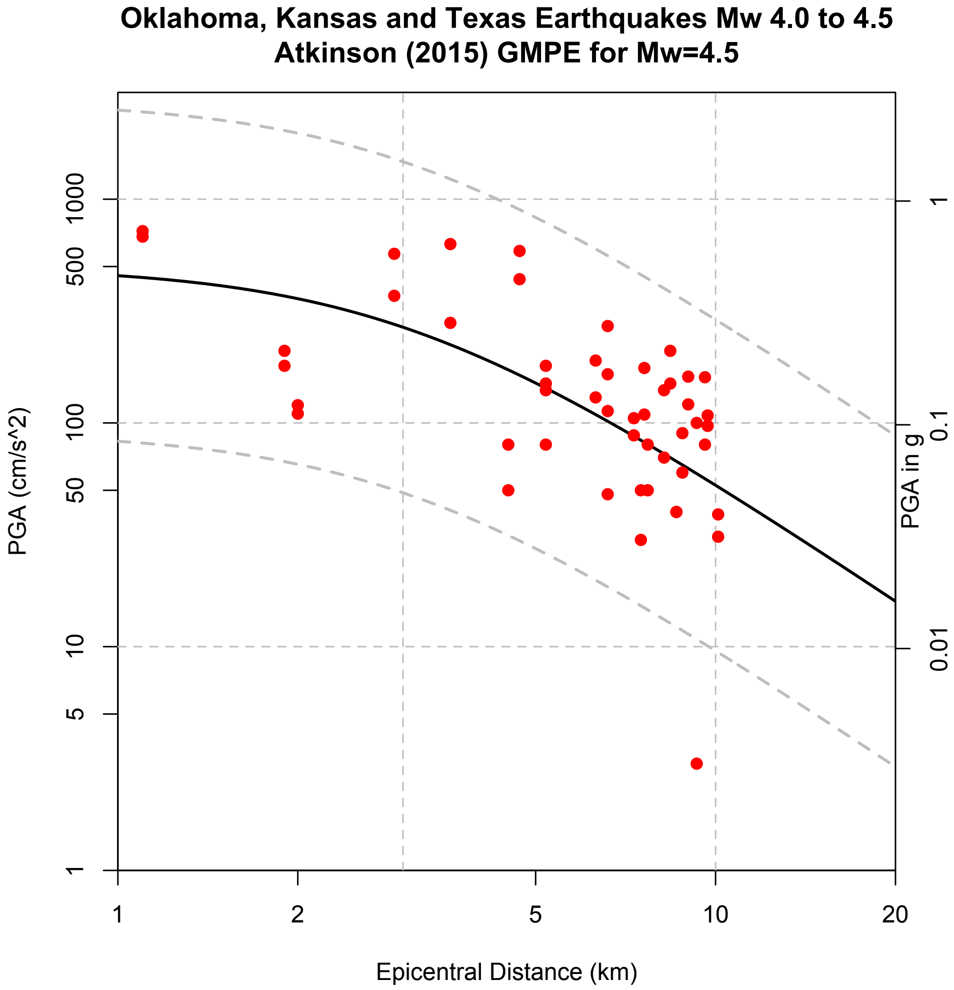
Version 2 Ground Motion Prediction Equations The report by Bommer et al. (2015) "Development of Version 2 GMPEs for Response Spectral Accelerations and Significant Durations from Induced Earthquakes in the Groningen Field" represents a comprehensive body of work that delves deeply into the problem of developing ground motion equations (GMPEs) for unobserved earthquakes in the unusual setting of the Groningen region. The very soft surficial deposits in the area pose a particularly challenging problem for GMPEs, as they are likely subject to nonlinear behavior in strong shaking. Consequently, Bommer et al. (2015) developed equations for ground motions at the top of the competent sediments ("reference rock horizon") and then applied a nonlinear formulation by Darendeli (2001) that accounts for modulus reduction and damping at high strain levels to determine the ground motions at the surface.

The work incorporates an extensive suite of geophysical and geotechnical measurements into the development of both the reference rock ground motions and the spatially detailed site amplification functions. The resulting model is as detailed as any that we are familiar with and represents a significant step forward in developing a comprehensive, geologically-based, site-specific GMPE. Considerable attention is paid throughout the development of the model to uncertainty, ultimately needed in the PSHA to capture the epistemic uncertainty in hazard. As with any model of this complexity, there will be an ongoing need to test its predictions against prospective data, as they become available.

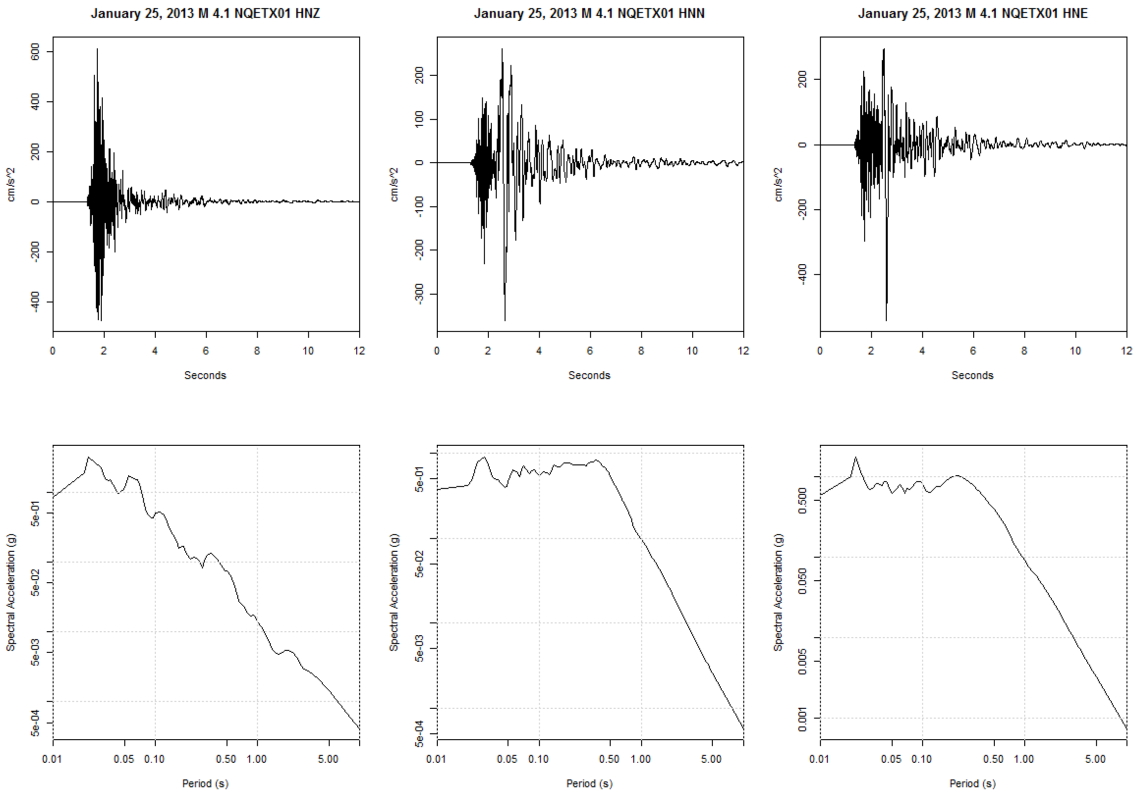
We first discuss the reference rock ground motions. It is scientifically challenging to predict the shaking from earthquakes that are significantly different from those in the existing database. The approach taken here uses theoretical models of earthquakes to synthesize ground motions. The physics of wave propagation is well understood, as is the radiation of seismic waves by the earthquake source. Successful prediction of ground motions thus depends on knowledge of the Earth structure and seismic source processes. At close epicentral distances for shallow earthquakes, wave propagation effects are straightforward, leaving characterization of the average properties of the rupture process the primary unknown. The extensive work on the velocity structure and the attenuation structure from source to top of the engineering rock should be sufficient for accurate modeling of ground motion, given the appropriate source model.

The approach taken here models the source process using a point source approximation. We note that this method is far from state of the art. A stress parameter (equivalent to static stress drop) is used to set the corner frequency in the source model. Stress drop is difficult to measure, as the dispersion of measured stress parameters for the V1 and V2 models as a function of magnitude illustrates (Figure 6.3 of Bommer, et al., 2015). More information about how stress drop was measured would have been helpful for evaluating the results. The low stress parameter model (10 bars) appears to be only marginally consistent with the data for M 3 and above. Low stress drop values often reflect lack of bandwidth in data, which is suggested by the overall trend of increasing stress drop with magnitude and hence greater bandwidth as the corner frequency moves to lower frequency.

As with the V1 GMPEs we reviewed earlier, the resulting reference ground motions surprise us as being rather modest for earthquakes with magnitudes in the range of interest at short epicentral distances. The figure below compares recorded geometric mean peak ground acceleration (PGA) values with the recent GMPE for induced earthquakes proposed by Atkinson (2015). This GMPE curve is for Mw=4.5 and a focal depth of 3 km. The 2.5% and 97.5% confidence bounds are also shown. The earthquake magnitudes are all between Mw 4.0 and 4.5 and have focal depths between 3 and 5 km.



An example of the seismograms and response spectra (5% damping) is shown below for a Mw 4.1 earthquake that occurred at 3 km depth in east Texas. The recording was made very close to the epicenter (~ 1 km). The wave path from the hypocenter to surface traverses a thick stack of carbonates, anhydrites and salt before encountering soft sediments in the upper hundred meters.



As seen in the above two figures, peak ground accelerations, or, equivalently, spectral accelerations at 0.01 s, in the central U.S. are typically about 0.5 g.

For comparison, we see that the response spectral ordinates at 0.01 s period in Figure 6.43 (M 4.5 at 0 km distance) or Figure 6.45 (M 5.0 at 5 km distance) from Bommer et al. (2015) (reproduced below) are at about 0.1 g, or lower.

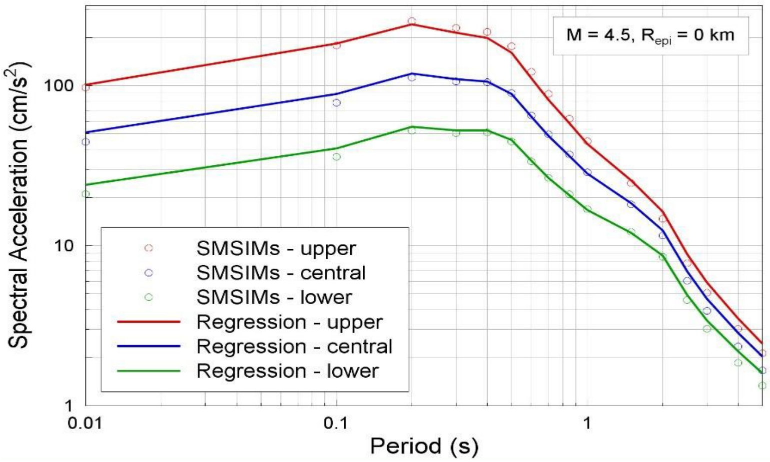


Figure 6.43. Comparison of simulated and predicted response spectra at NU_B due to a M 4.5 earthquake at an epicentral distance of 0 km.

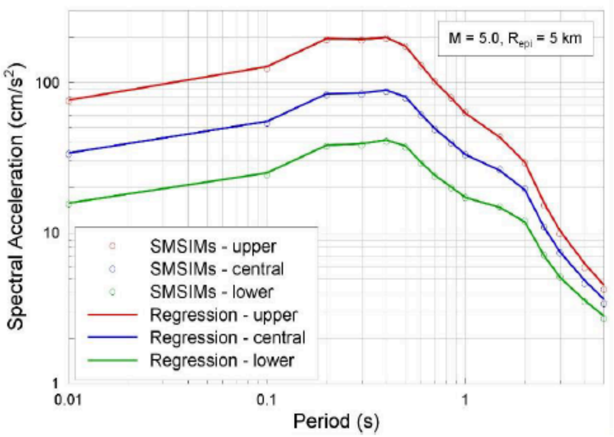


**Figure 6.45. Comparison of simulated and predicted response spectra at NU_B due to a magnitude M 5.0 earthquake at an epicentral distance of 5 km**

Thus, there is a substantial difference between ground motion parameters for earthquakes induced in the central U.S. and those in the Groningen field. The observed values from induced earthquakes in the central U.S. all exceed the central model and most also exceed the upper model response spectrum. It can also be seen that the observed response spectra for the Texas earthquake above exceed the upper model at all periods (even if divided by 2 to approximately account for the free-surface effect).

We do not claim that induced earthquakes in the central U.S. have the same source spectra as earthquakes of comparable magnitude that might someday occur in the Groningen field. But we can find no valid reason for rejecting them out of hand either. Consequently we caution that when model epistemic uncertainty bounds are inconsistent with data for earthquakes that are nominally similar, but induced by other processes, it is important to understand why this is the case. This question is central to the discussion, as the evaluation of risk is dependent on the hazard model. Perhaps the internal review committee that met in London on October 27-28, 2015 discussed this topic?

<u>Site response.</u> The micro-zonation necessary for assessing risk depends heavily on site response, which, in turn, is a function of the shallow velocity structure. Surface deposits in the Groningen region are highly variable, but generally characterized by soft soils and young geologic deposits that can be expected to have a significant effect on wave propagation through them. To account for the nonlinear behavior of these materials, the theory of Darendeli (2001) has been used. Chapters 7-9 of Bommer, et al. (2015) describe the development of the site response model, site response analysis and site amplification factors, respectively. Although we are impressed with the comprehensive approach taken by Bommer et al. (2015) in accounting for the effects of site response on ground motion at the surface, we are not sufficiently specialized in this area to be critical of their analysis. Although, from our perspective, their results seem reasonable, it might be worth considering the possibility of having an expert, such as Jonathan Stewart, assess this material.

From Hazard to Risk and Probabilistic Risk Assessment  Chapters 5 and 6 of the report cover the extensive work being done to identify vulnerabilities to future earthquakes and steps that can be taken to reduce the risk. This is a very impressive effort, balancing collection of instrumental data in structures with engineering testing of representative building types and construction methods. We are equally impressed with the survey results of potential hazards, with on the order of 150,000 buildings surveyed used to develop the detailed exposure database.

Brief summary. The V2 GMPEs reduce the ground motions and consequently both the hazard and risk are lower than previously believed. Moreover, the GMPSs give ground motion parameters that are significantly lower than found for comparable magnitude earthquakes elsewhere. It is important to understand why the ground motion models for the Groningen field are so much lower than for their counterparts in the central U.S. The questions we have asked about the new GMPEs suggests to us the need for additional research to improve the model, especially if it turns out that much larger magnitude earthquakes may need to be taken into consideration. If so, then it may be necessary to employ state-of-the art methods for synthesizing finite ruptures in place of point source models. Disaggregation of the hazard identified moderate magnitude events (M 4-5) as the primary contributor in the area of greatest hazard (Loppersum), but larger events pose a greater hazard to the city of Groningen. If events with M > 5½ are possible, it is likely that they would involve fault rupture extending downward into the carboniferous. This suggests the need to continue to improve the physics-based earthquake source and rate model. New data on the state of stress would, in particular, be extremely valuable, as would an improved understanding of the locations and source processes of the microearthquakes.

## References

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