Review of
"Threat assessment for induced seismicity in the Twente water disposal fields"

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<u>Introduction</u> 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-03.0000 dated August 13, 2015. At the request of the SodM, USGS has been asked to provide an urgent review of "Threat assessment for induced seismicity in the Twente water disposal fields". This document is the review. Consultations with Ole Kaven and Art McGarr of the Earthquake Science Center, USGS, are gratefully acknowledged. The conclusions contained herein are solely the views of the author and do not constitute an official position of the USGS or the U. S. Government.

<u>Introduction</u>

Four depleted gas fields in the Twente area of the Netherlands are being used for disposal of produced water from the Schoonebeek oil field. To address the concern that disposal by injection could induce earthquakes large enough to present a seismic hazard, the State Supervision of Mines (SodM) requested the operator, Nederlandse Aardolie Maatschappij (NAM) to conduct a detailed study of the potential seismic hazard posed by injection in the Twente area.

In their report to SodM, "Threat assessment for induced seismicity in the Twente water disposal fields" (EP201310201845, 2015 and hereafter NAM15) NAM concluded that the hazard of induced earthquakes was low because 1) no seismicity occurred either during the 55 years of production from the field or during the first 4 years of injection into the depleted reservoirs; 2) the state of stress in the injection zones is nearly isotropic making fault reactivation unlikely; and 3) maximum permitted pressures will be lower than the pre-development pore pressure.

Because all forecasts have uncertainty, additional steps were recommended by NAM15 to provide an additional safety margin for wastewater disposal operations. These included 1) improved seismic monitoring by the KNMI permanent earthquake monitoring network; 2) installation of accelerometers to record local shaking, should it occur; and 3) implementation of a seismic risk management protocol or "traffic light" system.

The SodM asked the U. S. Geological Survey (USGS) to provide an independent review of NAM15. The purpose of this report is to examine the foundations of the conclusions and the recommendations of NAM15 and to make specific recommendations for consideration by SodM.

Geologic Setting and Tectonic Overview

Northwestern Europe, including the Netherlands is an area of low to moderate tectonic activity as evidenced by regions of active subsidence and small to moderate earthquake activity (Dirkzwager et al, 2000). Measurements of the horizontal stress from borehole breakouts show the maximum compression to be oriented northwest-southeast throughout most of the country. The tectonically active Roer Valley Rift System, located approximately 100 km southwest of the Twente area produced a Mw 5.4 normal faulting earthquake in 1992 (Camelbeeck and van Eck 1994), the largest in recorded history. In the vicinity of Twente, no earthquakes are known from either the modern instrumental era or historical sources (Grunthal and Wahlstrom, 2003).

The main production zones of the Twente area gas fields primarily consist of fractured carbonates with low matrix permeability. The Tubbergen field and Rossum-Weerselo field are domal structures capped by Halite and Anhydrite. The Tubbergen-Mander field occupies a pop-up structure and reflects a more complex geologic history. This reservoir is sealed by Anhydrite with salt absent. All of the reservoir intervals being used for injection are cut by minor faults with maximum offsets ranging from as few as 5 m up to 80 m (EP201310201845, 2015). Many of these faults (Figure 9 in NAM15) strike from NNW to WNW, and thus could potentially be reactivated as normal faults in the contemporary stress regime. The Tubbergen-Mander field is also bounded on the east by the Gronau Fault, a northwest trending normal fault of regional extent. There is no clear evidence for recent movement on this fault (van Balen et al., 2005).

Production and Deformation within the Twente Area Reservoirs

The long-term production of gas from the Twente area fields caused the reservoirs to contract, as gas (and other fluids?) was withdrawn. The characterization of the reservoirs as fracture-dominated carbonates with low matrix permeability suggests that deformation would preferentially occur by closing of fractures or shear displacement on fracture surfaces, and not as collapse of pore volume as would occur in a sand reservoir. Although data are limited, the analysis of the evolution of stresses within the reservoirs during production (NAM15, p. 11-12) indicates a stress path (Zoback, 2010) that would not lead to production-induced normal faulting for reasonable values of the coefficient of friction (see Figure 4 of NAM15). Consequently, the absence of detected seismicity during production does not place a strong constraint on the state of stress, as production would stabilize normal faults, even those subject to near-critical stress levels. Specifically, the statement on p. 4 of NAM15 “These observations confirm that faults in the area are not critically stressed” may not be correct. If there is independent evidence such as stress measurements made in the formation to support the assertion that the stress state is nearly isotropic, it was not presented.

Stresses external to the reservoirs would likely have been at least partly relaxed by deformation in the bounding Halite and Anhydrites during the 5 decades of production, as both are weak materials that creep in response to differential loads. This raises the question of the reversibility of the deformation due to injection of water into the fractures once occupied by gas, as the boundary conditions on the reservoir have changed. Consequently, the safety analysis needs to account for the possibility that the stress path during injection may not follow the same trajectory as during depletion. If the stress path were shallower, it would intersect the failure condition at a lower pressure than the pressure in the reservoir.

It would be valuable to know if any deformation was detected either within the reservoirs, the confining Halite and Anhydrite layers, or at the surface during either depletion or injection. For example, did casing damage occur at any time and where did it happen?

The discussion of the stress state and potential for bringing faults to failure focuses on conditions inside of the reservoir. In addition to discussing the stress path model for conditions within the reservoir employed in NAM15, Zoback (2010) considers stress changes on impermeable, reservoir bounding faults. This analysis shows that production can induce both stress rotation and reduction of normal stress across reservoir-bounding faults. For a fault such as the Gronau Fault that bounds the Tubbergen-Mander and has a strike parallel to the regional SHmax direction, poroelastic contraction during production would increase the shear stress acting on the fault by reducing the horizontal normal stress. Depending on the stress path during injection, the effective normal stress acting on the fault could either decrease, further destabilizing the fault, or increase by following a stress path that returns it to the pre-production state.

Earthquake Potential and Faulting Calculations

Fluids have long been injected into producing oil fields to enhance the recovery of oil. In the vast majority of cases, this activity causes no induced earthquakes. There are, however, some exceptions. Among those, the well-studied cases, such as the earthquake control experiment in the Rangely, Colorado oil field in the late 1960s and early 1970s confirm the hypothesis that faults can be induced to failure by raising the pore pressure above a critical value. This value depends on the values of both the shear stress acting on the fault and the normal stress that prevents it from slipping. Rarely are either known, which is why monitoring for small earthquakes becomes an essential part of a hazard management plan such as a “traffic light system.”

NAM15 considers a number of faulting scenarios on p. 16-18 designed to explore the range of earthquake magnitudes that would result from fault movement within the reservoirs. The analysis attempts to develop conservative upper bounds on the earthquake magnitudes by assuming that the strain energy comes from production-induced compaction and that strain release will be confined to the production layer. Potential strain was estimated using layer thicknesses and laboratory measurements on core samples from the formations. Under this hypothesis, the maximum earthquake magnitudes were computed from the potential fault displacement and fault dimensions using the appropriate shear modulus for the formation.

I am not as confident as the authors that rupture would be confined to the layer in which it initiates. For example, both Halite and Anhydrite deform seismically when subject to fast loading. The hypothesized ruptures in the ROW DC reservoir (Table 3, p. 18 of NAM15) have throws of 11 cm. This corresponds to a shear strain drop of about 0.001, which is an enormous number. If it occurred, rupture could quite possibly continue to propagate, leading to a larger earthquake than the hypothesized Mw 3.0 – 3.2.

It is clear from the description of the total throw on the faults that they must have continued to much greater depth when they were active, and consequently have some potential for local reactivation given the favorably-oriented tectonic stress field. A more conservative approach to selecting the fault height would be to use the top-to-bottom thickness of the reservoir, including any Halite, Anhydrite or non-producing carbonate interbeds. In addition, since the production-induced compaction is inferred, rather than measured, an alternate approach to estimating the slip could be considered. For example, the dip-slip formula relating seismic moment to fault length, width, stress drop and elastic constants of Kanamori and Anderson (1975) could be used with a representative range for the stress drop. I think that this will lead to somewhat larger earthquake magnitudes, probably in the M 3.5 range. The difference, fortunately, may not be large, but a more careful analysis considering alternative models might be needed.

Ground Motion Considerations The issue of peak ground acceleration from earthquakes induced in the Twente fields are only briefly considered in the report. The Mw 3.6 August 16, 2012 earthquake in the Groningen studied by Dost and Kraaijpole (2013) was well-observed by accelerometers in the near source region. It would form a reasonable basis for anticipating the shaking that would occur if earthquakes were induced in the Twente fields, but only if the earthquakes are no larger than the mid-magnitude 3.5 range.

Recommendation It should be possible to safely dispose of wastewater in the depleted gas fields of the Twente, but this must be done with monitoring and safeguards in place. Assumptions about the total volume that can be injected, the state of stress in the reservoir and stress path that will be followed during injection may be valid, but need to tested and monitored as the injection operations proceed. The main safeguard for safe disposal operations, however, should take the form of sensitive seismic monitoring. Detection of earthquakes smaller than M_L 1.5 is strongly advised, with a target completeness threshold of no larger than M_L 0.5 to 1.0. Should even such small earthquakes occur, they would be a clear indication that conditions in the reservoir were not what was assumed and that there is potential for inducing larger earthquakes. Sensitive detection also gives more time for decisions to be made in the operation of a hazard mitigation protocol before earthquake activity reaches unacceptable levels.

References

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