TECHNICAL REVIEW OF BERGERMEER SEISMICITY STUDY
TNO REPORT 2008-U-R1071/B
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SUMMARY

The scope of the TNO study is to assess the risks of seismic activity induced by proposed gas storage and injection at the Bergermeer field. This activity would involve both pressure and temperature changes resulting from injection of cold gas (in the initial stages of the project) and from gas production. These temperature and pressure changes generate both changes in local thermoelastic and poroelastic stresses and changes in stresses associated with differential compaction and expansion.

The TNO report “Bergermeer Seismicity Study” is a comprehensive document. We reviewed the report, its conclusions and recommendations, and an extensive list of related references. The report can be divided into three parts: Reservoir Modeling, Geomechanical Modeling, and Seismic Hazard Analysis. Before addressing the main conclusions of the TNO study below, in the order in which they were given in the report, we state here what we believe is the most important conclusion: *We agree with the result of the TNO study that the maximum magnitude of an earthquake that could occur in the Bergermeer field during the proposed injection and production phase is* $M_L = 3.9$.

Reservoir Modeling

In a reservoir modeling study, temperature changes were simulated for one production cycle. The two reservoir modeling conclusions, paraphrasing the TNO summary, along with our responses (*in italics*), are:

1) The injection of cold cushion and working gas and one production phase show a decrease in temperature localized around the wells, with the temperature of the rest of the field substantially unchanged.

   The reviewers concur with this conclusion.

2) The initial two years of injection lead to the largest temperature decreases. Afterwards the reservoir pressure has increased to the point that the gas needs to be compressed, increasing the injection temperature. Subsequent gas production leads to the reheating of the previously cooled regions.

   The reviewers concur with this conclusion.

Geomechanical Modeling

The pressures and temperatures obtained from the reservoir model are used in two-dimensional geomechanical models to calculate changes in stress, deformation and fault stability. The geomechanical models depend on a large number of input parameters about the geologic structure (in both two and three dimensions), stress state, initial conditions and material properties, not all of which can be specified accurately. The reviewers believe that the results of geomechanical modeling alone, by themselves, cannot quantify the seismic hazard. They can, however, provide a useful picture of the processes in the reservoir and can contribute to the understanding of induced earthquakes. The four main conclusions from the geomechanical modeling, paraphrasing the TNO summary, along with our responses, are:

3) During modeling of depletion (1971-2006), only fault segments intersecting or bounding the reservoir showed the potential for reactivation. Large fault movements occurred on the central fault of the reservoir where reservoir rocks on both sides of the reservoir overlap. At the end of depletion, calculated stress conditions on the central and bounding faults are close to failure.

   The earthquakes that happened during production provide important observational evidence that these faults were indeed reactivated. Since 2001, the reservoir pressure has decreased by an amount comparable to that during the period between the two sets of earthquakes - 1994-2001. The significance of the conclusion is that, even if no injection/production activity were undertaken, the Bergermeer field could have earthquakes comparable in magnitude (M_L=3.0-3.5) to those that occurred in 1994 and 2001.

4) During injection, the main parts of the faults intersecting and bounding the reservoir are calculated to stabilize. Locally some fault slip is calculated on the central fault directly above and below the overlap of the reservoir. Calculated fault movements during injection are an order of magnitude smaller than during depletion.

   Production-induced stresses have accumulated since their potential release in the 2001 earthquakes. Therefore the reviewers agree that the initial pressure build-up during the early part of the injection may reduce the shear stresses on and contribute to the stabilization of faults. However, the results of the geomechanical models may not be reliable indicators of the range of fault slips that might occur during injection, because the stress conditions calculated at the time of the initiation of injection are not consistent with the observed reverse faulting. The change in pressure between 1994 and 2001 is comparable in magnitude to the change in pressure planned for reinjection. This amount of pressure change might result in fault slips comparable to those that generated the M_L = 3.5 earthquake in 2001.

5) During production of the working gas, no fault slip occurs in the geomechanical models.

   As was the case for conclusion 4, the calculations may not be reliable indicators of the fault slip that might be triggered during production of the working gas.

6) The localized temperature decreases that occur during the initial reinjection do not affect the stability of known faults if the injection wells are at least 200 m (uncertainty included) from these faults.

The reviewers agree with this conclusion.

Seismic Hazard Analysis

Magnitudes of potential seismic events were estimated from fault movements derived from the geomechanical models. The TNO study conclusions and our responses, *in italics*, are:

7) During injection, the largest slip observed in the geomechanical models corresponds to seismic magnitudes ranging between 2.4 and 2.7.

Because geomechanical models depend on large numbers of parameters with various levels of uncertainties, the reviewers find that magnitude range of 2.4 to 2.7 is too restrictive. Events larger that M_L*=2.7 cannot be ruled out.*

8) The maximum possible seismic magnitude is 3.9. Larger magnitude earthquakes are improbable due to the limited dimensions of the faults.

The reviewers agree with the maximum magnitude M_L*=3.9*

Recommendations

The reviewers find the 6 recommendations listed in the TNO report to be reasonable and support them, except for one caveat concerning recommendations 3 and 4: We recommend that consideration be given to modifying the geomechanical models so that they explain the reverse faulting earthquakes that occurred in 1994 and 2001 if these models are to be used to evaluate uncertainties in reservoir conditions.

INTRODUCTION

We were asked by the Ministry of Economic Affairs, Netherlands, to conduct a technical review of the report "Bergermeer Seismicity Study, TNO Report 2008-U-R1071/B, 6 November 2008." The TNO report was prepared to assess the seismic risk due to injection and production activities if the depleted Bergermeer natural gas field were to be used in the future as an underground gas storage facility. We were specifically instructed to submit a report containing:

a. *A critical technical review of the assumptions, conclusions and recommendations of the TNO Report*
b. *Answers to the questions raised by the Gasalarm2 Foundation and the Soil Movement Technical Committee. (APPENDIX B)*

We were provided with the TNO report and supporting confidential and public (published) documents. (See REFERENCES.) In addition, we studied a number of articles relevant to both the general theme of the report and to the specific methodologies and analyses used in the study.

A number of email exchanges and telephone conversations were held with Economic Affairs Ministry staff members (Drs. D. Voskuil, C. deZwaan) to clarify the nature and the scope of the review. Because of some difficulties in communication the reviewing process did not start until 11 September 2009. A teleconference was held between the reviewers (Drs. B. Hager and M. N. Toksöz) and representatives from the EA Ministry, KNMI, TNO and TAQA. A set of Power Point presentations that was emailed prior to the teleconference gave further details about the material included in the report and helped to clarify some points.

Additional email communications and documents transmitted to the reviewers by the participants of the teleconference were helpful for the review. In summary, the EA Ministry and the team of scientists/engineers that contributed to the report, "Bergermeer Seismicity Study," have been very responsive to the questions and to the requests of the reviewers. The only difficulty for the reviewers has been the very tight schedule.

The TNO Report "Bergermeer Seismicity Study" is a well-written, well-documented study. Most of the major aspects of assessing induced seismicity are addressed. Relevant assumptions, data and parameters used in the study are presented clearly. Well-tested modeling codes are used for reservoir simulation and geomechanical modeling. We consider the TNO report a very good study, as far as it goes.

In studies of this nature there are never sufficient data to produce models with complete certainty. It is not possible to characterize all aspects of the geologic models and conditions that give rise to tectonic forces, deformation and earthquakes. There are two approaches to deal with uncertainties. One is deterministic modeling, where an informed judgment is made about the best parameters (e.g., fault geometries, elastic moduli, fault slip, fault area) and the seismic moment and magnitude for a representative earthquake are calculated.

A few models may be generated based on "normal" conditions and on other plausible models to determine sensitivity to various parameters. Then a final model is chosen based on some selection criteria.

An alternative method is a probabilistic approach. Uncertainties are assigned to all parameters and are incorporated into the calculations with many thousands of models, generally done using a Monte Carlo simulation. The results of such an approach are a "best estimate" and statistical confidence bounds. The choice of deterministic or probabilistic calculation depends on the nature of the problem, types and amounts of data, and the computational resources.

In the TNO study the deterministic approach was used because the problem is confined to a single field, with a relatively well-known structure. In addition, a limited amount of earthquake data is available. Also, making thousands of reservoir simulations and geomechanical calculations would have been prohibitive in time and in cost.

In deterministic modeling, the geomechanical model and parameters used are based on available data and experts' opinions. In that sense, it is subjective. There could be differences of opinions between experts. In fact, the reviewers faced this issue on some topics.

In the technical review given in the next section, we cover the topics in the order that they are discussed in the TNO report.

TECHNICAL REVIEW

The TNO Report provides detailed information about the field, the methodology, and the models and data used for the seismicity study. Chapters 2 through 7 describe the general background, subsidence modeling, reservoir engineering modeling, geomechanical analysis and seismic hazards analysis.

Background

Background material given in chapter 2 is very important because it sets the framework for the study and describes the primary data used to constrain the geomechanical models. Four earthquakes that occurred in the Bergermeer field (Table 1) provide critical data for the seismic hazard study. Table 1 lists the dates, magnitudes and intensities of the four earthquakes in the Bergermeer field and a fifth (October 10, 2001) in the neighboring Bergen field. Figure 1 shows the epicenters of the events (Ref. Haak et al., 2001; KNMI Technical report: TR-239).

Table 1. Seismic moments, magnitudes of earthquakes considered in the report

Date	Moment M_0 (Nm)	KNMI M_L[1]	Reamer & Hinzen M_L[2]	Intensity
6 August 1994	4.0×10^{13}	3.0	3.2	IV-V
21 September 1994	7.0×10^{13}	3.2	3.4	V
9 September 2001	1.9×10^{14}	3.5	3.8	VI+
10 September 2001	6.3×10^{13}	3.2	3.4	IV-V
10 October 2001	1.8×10^{13}	2.7	2.8	III+

[1] Data from Haak, 1994a, 1994b and Haak et al., 2001.

[2] Calculated using equation (9) of Reamer and Hinzen, 2004

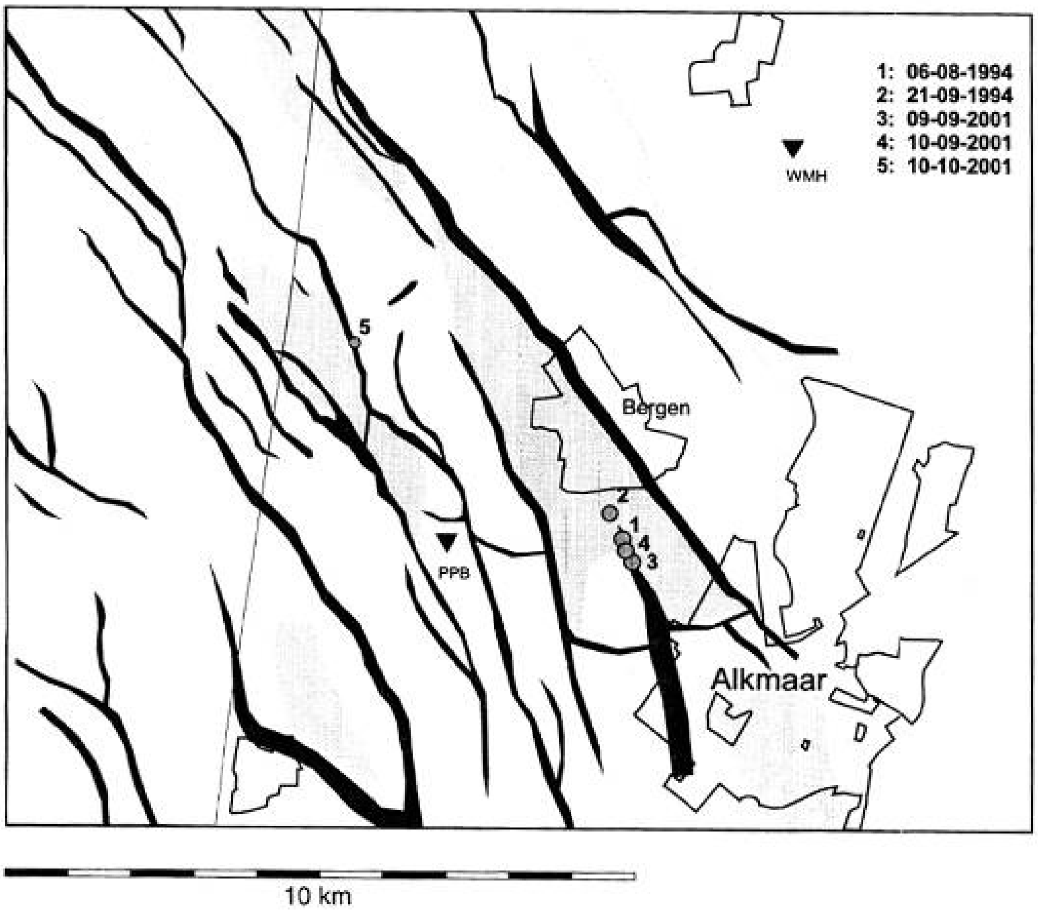


Figure 1 (from Haak et al., 2001). Epicenters of the five earthquakes discussed in the report. Epicenters of events 1-4 are on the Central Reservoir fault of the Bergermeer Field. Event 5 is associated with the neighboring Bergen field.

Seismic moment (M_0) is the most robust measure of the size of an earthquake. It is given by

$$M_0=A\cdot d\cdot \mu$$

where M_0=scalar moment, A=fault (rupture) area, d=fault slip (displacement) and μ=shear modulus. The moment can be determined from the displacement spectra (low frequency limit) of seismograms. The shear modulus is obtained from seismic velocity and density or from geomechanical modeling. Fault area and slip cannot be obtained independently without either using a simplified source model or synthetic seismograms using finite source models to match the observed. The KNMI reports used a Brune source model (Brune, 1970). This model assumes a circular fault rupture surface (radius r) and determines r, stress drop ($\Delta\sigma$) and fault slip (d) from the moment, displacement and corner frequency. The KNMI reports clearly mention the models and the equations used to calculate the radius (r) and fault slip (d).

However, the Brune model, which uses a circular fault, is not an exact match for the long rectangular faults. Faults used in the Bergermeer field geomechanical modeling are long (>2 km) and thin (width 200-450 m). Source parameters (e.g. fault slip) obtained by the Brune model provide a good approximation, but not rigid constraints, for the slip for geomechanical models. To obtain better constraints, it is necessary to calculate synthetic seismograms using a rectangular fault geometry and distributed slip to match the recorded near-field seismograms. The required geologic structure and information about seismic velocities, as well as appropriate computational algorithms, are available for such calculations.

Geologic Model

The geologic model of the Bergermeer field is well defined by ample geologic, 3-D surface seismic and well-log data. Figure 1 shows the faults that define the structure of the field and the epicenters of the Bergermeer earthquakes. The field is an elongated feature and lies on a horst block trending in the NW-SE direction. The model used for reservoir simulation and geomechanical modeling is a model that combines inputs from Horizon Energy Partners (2006 report) and from TNO and TAQA scientists. The reservoir, the Slochteren sandstone, is a fine-grained, competent sandstone. The overlying seal is the Zechstein formation, which consists of a series of evaporites. There are a number of faults trending in the NW-SE direction. The ones most relevant to the seismicity study are faults that define the NE and SW boundaries of the reservoir and one internal fault, that we call here the Central Reservoir fault. The Central Reservoir fault may be viewed as a "scissors" fault because slip on it decreases to the north, becoming too small to be imaged seismically in the middle of the field. Note that the hypocenters of the four earthquakes with magnitudes M_L=3.0 or larger (nos. 1, 2, 3, 4 in Figure 1) appear to lie on the Central Reservoir fault close to the "hinge of the scissors." The fifth earthquake, located about 5 km away, is associated with the neighboring Bergen field. (Haak et al., 2001, KNMI Technical Report TR-239).

For reservoir simulation and subsidence modeling, a three-dimensional geological model was used. For the geomechanical calculations a two-dimensional model based on a NE-SW cross section, perpendicular to the strike of the structures, was used. We discuss the potential effect of assuming a two-dimensional structure in the geomechanical model later in the report.

Subsidence Modeling

The surface subsidence due to gas production and resulting reservoir compaction was monitored by frequent leveling campaigns (1980, 1981, 1984, 1992, 1997, 2001, 2006). The maximum subsidence observed for the Bergermeer field is 10.5 cm. The shape of the subsidence bowl and its maximum amplitude depend on the reservoir pressure drop (compaction) and elastic properties of the overlying strata. Elastic moduli were determined for each layer in the geological model using its density and seismic velocities and using a static/dynamic correction factor. To determine the compaction parameters from the observed subsidence, elaborate forward modeling and inversion methods were used. The sensitivity of the subsidence to varying the elastic parameters of the overlying geological units and to the effects of the compaction of neighboring gas fields was investigated.

The reviewers find this study to be comprehensive and credible. The study results, which state that some uplift is expected from repressurization of the reservoir and that, "Based on the subsidence data the range (of compaction parameter) is between 0.3 10^{-5} and 1.1 10^{-5} bar^{-1}," are reasonable. The reviewers are not aware if there were borehole markers to monitor compaction in the Slochteren reservoir unit. If such data existed, it could reduce the estimated range of the compaction parameter.

Reservoir Engineering

Dynamic reservoir modeling to determine pressure and temperature during injection and production was done using state-of-the-art reservoir simulation codes. Both Eclipse 100, used for isothermal flow, and Eclipse 300, used for composition and thermal simulation, are leading reservoir simulators used world-wide. The reviewers find this study to be well done and comprehensive. The results are intuitive and logical. Important insight was gained into the thermomechanical response of the reservoir to depletion and repressurization. The temperature changes, localized around the boreholes, are most significant within about a 100 m radius of the injection wells. Keeping the injection wells at least 150 m from faults and monitoring the well temperature and pressure are sound recommendations.

Geomechanical Model

TNO calculated the stresses and fault slips accompanying reservoir production and injection using the reservoir modeling software, DIANA. The model domain assumed for computational efficiency is a two-dimensional cross section, chosen to contain sandstone in both Block 1 and Block 2 in contact across the Central Reservoir fault. The seismic hazard associated with gas storage was calculated under the assumption that the predicted fault slips and associated fault areas could be converted to moment and then to magnitude using the parameters estimated by Hanks and Kanamori (1979). The local magnitude, M_L, is assumed to be equal to the moment magnitude, M_w. (We note that the scatter in the data upon which the Hanks and Kanamori scaling relationship is based is typically ± 0.5 magnitude unit. The resulting uncertainty is not discussed in the TNO report.)

In order to have confidence in predictions of the geomechanical models during the planned injection phase, the models should be tested by comparing their predictions to available observations of subsurface conditions during the production phase. In the TNO report, model predictions were compared to the stress estimates from post-production minifrac tests in well BGM#8, several hundred meters (~ 1 ½ times the reservoir thickness) away from the Central Reservoir fault. Model predictions of surface subsidence were compared with the observed. The geomechanical parameters and the "scenarios" that matched the maximum subsidence values were selected.

In our opinion, because the purpose of the study was to assess the potential for earthquakes, the most important observations for testing the geomechanical models are the earthquakes that were associated with production. The only such events detected have fault slip in the reverse sense. In our view, there is no reason to doubt the reverse faulting focal mechanisms of the 2001 events determined by Haak et al. (2001). The suggestion by Dost and Haak (2007) that this reverse faulting resulted from differential compaction that reactivated preexisting normal faults is plausible. Although there is uncertainty in the hypocenter locations of the 1994 and 2001 events, their most likely location is on the Central Reservoir fault. In our opinion, it is important that a geomechanical model used to predict future fault movements explain these events. The TNO geomechanical model predicts that the Central Reservoir fault should have slipped in a normal, not a reverse sense, during the production phase. For this reason we do not believe that it makes reliable predictions of fault motions expected during reinjection.

We believe that one reason that the TNO geomechanical model does not predict the reverse fault motions associated with differential compaction of the reservoir is that it does not include the faults or other means to accommodate this motion where it would be expected to occur. Specifically, Fault 4 (see Figure 2) terminates just above the top of the Block 1 reservoir. As noted by Roest and Kuilman (1994), boundary effects occurring at the contact between compacting and non-compacting formations are large near the top of a reservoir. In addition to the creation of differential normal stresses, shear stresses along a fault plane extending above the reservoir would increase, leading to conditions that promote slip. However, there is no fault in the TNO model in the location most likely to have reverse motion induced by compaction of the reservoir. Alternatively, a ductile region could accommodate the compaction-induced shearing by deformation distributed over a shear zone. Because the Zechstein formation is an evaporite, it might be expected to deform in this way, but such ductile deformation was permitted in only one of the seven geomechanical models presented. (The single model with ductile deformation did not match the minifrac stress estimate, but the effects of different flow laws were not reported. This single model does not provide a basis for rejecting all models with ductile deformation.)

With a structure (fault or ductile region) to accommodate deformation, compaction of the reservoir could lead to down dropping of the footwall block above the reservoir, reducing the normal stress clamping the fault and causing shear stress in an orientation that promotes motion in a reverse sense on the preexisting (normal) Central Reservoir fault.

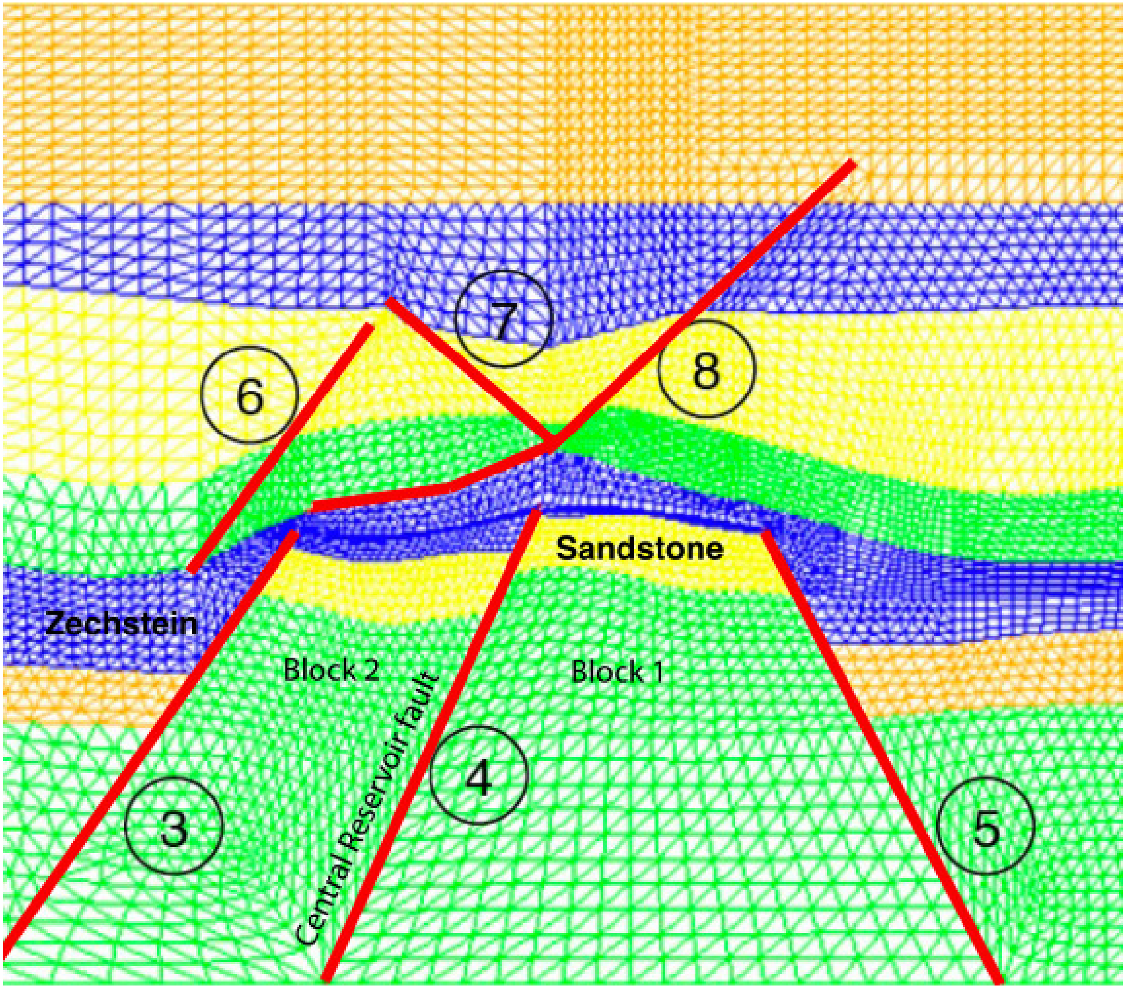


Figure 2 (modified from Figure 6.7 of TNO, 2008). Fault 4, the Central Reservoir fault, separates the reservoir sandstones (yellow) of Block 1 and Block 2. Faults 3, 4, and 5 terminate in the Zechstein formation, where it is assumed that the rocksalt composition makes seismic slip less likely than in the reservoir sandstone.

An additional important limitation of the TNO geomechanical model is that it assumes a two-dimensional geometry in a region where the structure is changing substantially along strike. A simple visualization is provided in Figure 3, modified from Haak et al. (2001), illustrating that the central fault is a scissors fault, with the separation between the reservoir rocks in Block 1 (east) and Block 2 (west) varying along strike. This three-dimensional variation in structure could be important because slip on one segment of the fault, perhaps aseismic, could transfer stress to an adjacent segment of the fault, amplifying the stress on the fault generated by differential compaction alone.

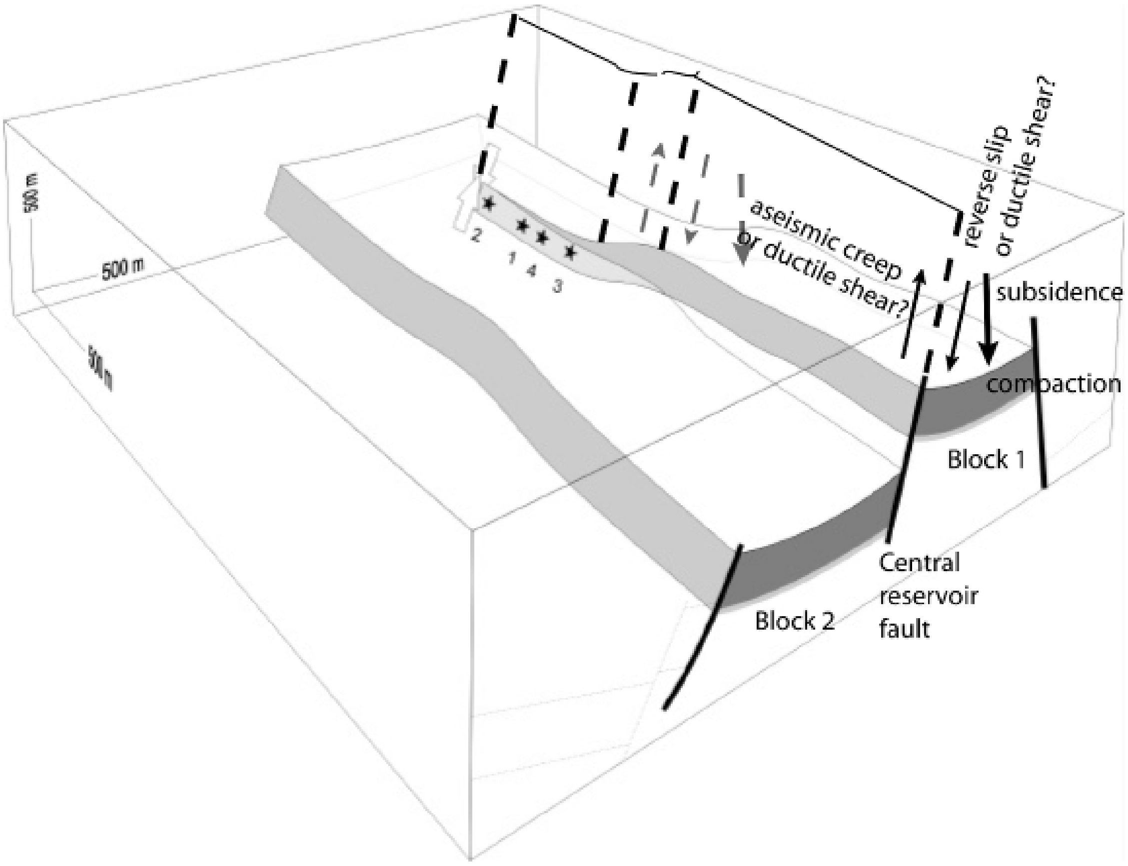


Figure 3. Block diagram of the three-dimensional structure of the Bergermeer reservoir (modified from Figure 6 of Haak et al., 2001). The dashed lines indicate the projection of the "plane" of the Central Reservoir fault above the compacting reservoir in Block 1. Compaction of the reservoir in Block 1 causes subsidence of the region in the "footwall" along the projection of the Central Reservoir fault. The resulting loading generates shear stress in a reverse sense, as sketched. Because of the properties of the Zechstein, it is likely that the region loaded by compaction of the reservoir would shear, either by local or distributed deformation, shedding stress onto the portion of the fault where more brittle sandstone is on both sides of the fault. It is in the latter region where the 1994 and 2001 reverse faulting earthquakes probably occurred.

During production, two earthquakes occurred in 1994, followed by two more earthquakes in 2001. The change in pressure between 1994 and 2001 is comparable in magnitude to the change in pressure planned for reinjection. This amount of pressure change might result in fault slips comparable to those that generated the $M_L = 3.5$ earthquake in 2001.

Seismic Hazard Analysis

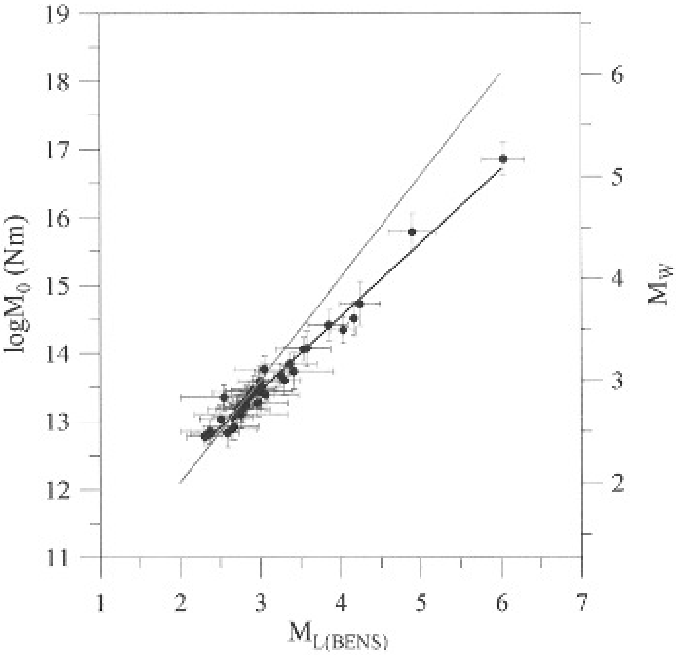
The Bergermeer region is relatively aseismic. There is no evidence of earthquakes in the historic seismicity data of the region (de Crook, 1993). It is reasonable to assume that the earthquakes in 1994 and 2001 were induced events associated with gas production. The TNO report states that production in the Bergermeer field began in 1971 and continued until its depletion in 2006. Empirically, induced earthquakes in oil and gas fields are more likely to occur during the “maturity” phase of the fields. In that sense, the history of Bergermeer seismicity conforms to the general pattern of gas fields. An unusual feature of the seismicity is that four events of magnitude M_L=3.0 to 3.5 have occurred since 1994, but there are not the large number of smaller events that are typical of natural and induced seismic patterns. The limited number of events and lack of data for a broader magnitude range limit the application of statistical analysis methods for hazard assessment.

Table 1 shows moments and local magnitudes of the four earthquakes that occurred in the Bergermeer field. These data are taken from detailed technical reports of KNMI (Haak 1994a, 1994b; Haak et al., 2001). The table shows differences between empirical relations used to convert seismic moments to magnitudes. The KNMI uses conversion calibrated for the Netherlands. In general, KNMI magnitudes agree with those calculated using the empirical relationship of Hanks and Kanamori (1979) based on a global average. Reamer and Hinzen (2004) have a somewhat different relationship based on data from southern Netherlands and Germany. Their moment-magnitude relationship gives slightly larger magnitudes, as shown in Table 1 and in Figure 4. The purpose of this comparison is to demonstrate that there could be differences in magnitudes assigned to a given event by different observatories. Typically, uncertainties for a given magnitude should be about ± 0.1 magnitude.

One way to estimate the maximum magnitude of a likely event is a common sense approach: “Any future event could be at least as large as an event that occurred in the past.” For conservative estimates, generally, a safety factor is added to the observed maximum magnitude. With the data in Table 1, a conservative estimate of the maximum magnitude would be M_L=3.9.

The approach taken in the TNO study is to use geomechanical modeling to calculate the deformation, stress evolution and fault slip during pressurization and depletion of gas. This approach is useful for evaluating the impact of various conditions in the reservoir on fault movements. However, the modeling requires many inputs about the initial conditions, fault parameters, failure criteria and rheological properties, all of which have uncertainties that could affect the seismic event magnitudes. The maximum magnitude is limited by the size of the fault and the displacement (i.e. fault slip) that could occur on the fault. It cannot exceed the value that would result from the rupture of the whole fault.

The maximum magnitude M_L=3.9 cited in the TNO report (p. 87, conclusion #8) is an appropriate value. The probability of an event of this magnitude is extremely low (Ref. van Eck, et. al., 2006; Figure 3). A magnitude of M_L=3.9 would correspond to a peak intensity **VI+**, a value between intensities **VI** and **VII**, but closer to **VI**.



▲ **Figure 9.** Filled circles are seismic moments plotted versus the local magnitude $M_{L(BENS)}$. Error bars represent the standard deviations of the average event magnitudes and moments, respectively. The heavy black line shows the best linear fit to the data from this study in a least-square sense. The gray line represents $M_L = M_W$.

Figure 4: Illustration of local M_L vs. M_w and M_o, from Reamer and Hinzen (2004)

CONCLUSIONS AND RECOMMENDATIONS

The TNO report, "Bergermeer Seismicity Study," is a comprehensive document. It utilizes large amounts of data combined with elaborate modeling of phenomena related to seismicity and potential earthquake hazard during gas injection and production. Based on our review of the report and on the extensive list of related publications, we conclude:

1. The Report addresses, broadly, the issues related to the seismicity and seismic hazard at the Bergermeer field.

2. The computations and numerical models are done with "state-of-the-art" computer codes.

3. The results of the subsidence study and the reservoir simulations, for flow and for temperature, are clearly presented. We agree with their conclusions and recommendations.

4. Geomechanical analysis for stress and deformation modeling is done by finite element modeling, including poroelasticity and frictional fault behavior. The models provide insights into potential deformation and fault slip (i.e. earthquakes) on the faults included in the mesh. However, as elaborated earlier in this report, the approach has some serious shortcomings for the prediction of location and magnitudes of potential earthquakes.
    a. It is a two-dimensional model dealing with a three-dimensional reservoir that varies substantially along strike of the model, particularly along the Central Reservoir "scissors" fault.
    b. Fault structures or other means of accommodating anelastic deformation are not included in the regions immediately above the reservoir, where large stresses are generated by production and injection. (In only one model was this region allowed to deform by ductile flow, and this model was discounted for other reasons.)
    c. It assumes two-dimensional planar fault surfaces without heterogeneities, asperities or stress concentration from slip variations in the third dimension.
    d. It relies heavily on fault displacement (slip) for determining the seismic moment and hence the magnitude of induced earthquakes. The moment depends on the product of fault slip times fault area. Independent knowledge of the fault area is needed to determine the slip.

5. Because of the limitations of the geomechanical modeling, the reviewers suggest relying more heavily on available earthquake data for estimating the maximum magnitudes of potential earthquakes. For the maximum magnitude, the reviewers agree with the value of M_L=3.9 cited in the report.

6. A detailed analysis and modeling of seismic records from close-in stations of the 2001 Bergermeer earthquakes would provide more detailed information about their source mechanisms. The reviewers do not expect further analysis to change the conclusion that these are reverse faulting events. However, more accurate determination of the depth, amount of fault slip, and dimensions of the faults that slipped could be obtained. The reviewers recommend that this be done.

7. Probabilistic seismic hazard estimate for induced earthquakes in the Netherlands has been done for gas fields in the Netherlands (van Eck et al., 2006). This includes the Bergermeer field, albeit with few data. The results are consistent with those of the TNO report in that the probability of any event of M_L=3.9 or greater is extremely low.

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ANSWERS TO THE QUESTIONS OF THE GASALARM2 FOUNDATION

1. TNO uses elasto-plastic geomechanical models to calculate potential slip on a fault plane. A critical geometry of reservoir and fault structure is chosen, which is sensitive for reactivation of the fault. Plastic (reversible) slip is calculated on the fault, during depletion and injection assuming permanent equilibrium conditions (implying the assumption that all potential slip created by the preceding depletion of the field has been accommodated).
Gasalarm2 is of the opinion that in reality discrepancies from the ideal shape of the fault plane as used in the model may be present, in the following called obstructions, preventing incremental a-seismic movement along the fault, and that therefore it cannot be excluded that the reservoir fault(s) are (is) in a meta-stable condition ("hanging earthquake" that could be triggered).
In the opinion of Gasalarm2 the model predictions in the TNO study concerning maximum possible slips that could be created by the, relatively small, pressure changes during one injection-production cycle (corresponding to M = 2.4 - 2.7, should they be accommodated in an non-elastic (seismic) manner) are self-evident given the model assumptions and, therefore, provide no proof that no larger event can be triggered.
Question: Is the above-mentioned TNO approach a complete and reliable way to explore maximum potential slip during the project phase?

Answer: *The TNO approach assumes that all of the yielding calculated in the models on a given fault could occur during a single earthquake. Strong asperities that did not fail as the result of loading that has already occurred would tend to reduce the amount of coseismic slip. Because the stress loading is cyclical during depletion and injection, stress would not be expected to accumulate on asperities in the same way it does on tectonic faults, where the loading stress is always applied in the same direction. Thus the TNO conclusions might appear to be conservative from the standpoint of the effect of slip hanging up on obstructions (or asperities).*

However, the two-dimensional models might underestimate the stress that could accumulate on asperities if loading is transferred "out of the plane" along strike of a fault, as shown in Figure 3

It therefore seems plausible from a geomechanical perspective that larger magnitude events than those predicted by the TNO geomechanical analysis could occur. This conclusion agrees with both the TNO seismic hazard analysis and our inference from seismicity models that a maximum expected earthquake of magnitude 3.9 might occur.

2. (With reference to the calculations in Chapter 7 of TNO (2008))
Gasalarm2 states (see Q1) that part of the calculated slip, which did not show up in the 4 (historic) earthquakes may still be present as a 'hanging' quake. On the basis of Table 7-1 of TNO (2008) the magnitude of such a quake can be 3.8 (taking the dynamic shear-modulus for the estimate of slip/magnitude, rather than the static as

in Table 7.1), or larger, given the uncertainty in parameters and dimensions (see e.g. Q4).
Question: What is the opinion of the expert(s) about this issue?

Answer: *We agree with the TNO report that the static shear modulus is the appropriate modulus to use to calculate the stress state on faults caused by quasi-static loading. It is this stress, associated with slow loading, that is released during an earthquake. Increasing the magnitude of a potential earthquake by using the dynamic modulus is not appropriate.*

Other uncertainties, which are addressed in the answer to the first Gasalarm2 question, support the Gasalarm2 estimate that a magnitude 3.8 event is plausible, but not for the reasons stated in posing the second question.

3. Figure 3,2 of the Seismicity Report shows a 3D view of the Bergermeer gas field (based on a model of Horizon 2006). From this view Gasalarm2 concludes, that the main (internal) fault may be longer than anticipated. According to Gasalarm2 the length of the fault is probably 4.1 to 5.9 kilometres and not 2.5 kilometres. Consequently, Gasalarm2 assumes, that the probable size of the reactivated part of the fault plane may be much larger than is stated in table 2.2 of the TNO report (page 18) and therefore the potential magnitude of earth tremors may be much higher (M=4.1).

Question: What is the relation between the length of the fault plane, the probable activated part of the fault plane during the events and the maximum magnitude of a seismic event? How important is the estimation of the total length of the central fault?

Answer: *The magnitude of a seismic event is proportional to the area of the part of the fault that ruptures during an event, not the total length of the fault. Thus it is the estimate of that part of the Central Reservoir fault that would break, not the total length of the fault, that is important. We agree with the TNO report that the part of the Central Reservoir fault that cuts through the rocksalt of the Zechstein formation is unlikely to slip in a seismic event. Therefore, the length of 2.5 km is appropriate.*

4. Gasalarm2 assumes that the stabilisation of the fault structures at reservoir level due to pressure increase during injection will be of minor importance as compared to potential previously created unreleased tensions (see Q1 and Q2).
TNO assumes that the re-pressurization of the reservoir will lead to a more stable fault structure (see chapter 6.3 of the TNO Seismicity report).

Question: what is the opinion of the expert(s) about these views?

Answer: *While repressurization will generally tend to reduce the stresses caused by production, the amount of repressurization planned is substantially less than the amount of depressurization, so stresses on some faults might not be completely* *reversed. There is often a time delay between when a fault is stressed and when it eventually ruptures in an earthquake. Indeed, it is fairly common for earthquakes to occur in a reservoir even after production ceases. Thus, earthquakes at Bergermeer might well occur even if repressurization did not proceed*.

5. Gasalarm2 observes that for the operating phase of the BGS only the first production/injection cycle has been modelled by TNO. In particular, the recovery phase of the cushion gas has not been covered (based on a realistic estimate of the then prevailing reservoir conditions). Apart from risks resulting from phenomena such as erosion of the fault plane and fatigue, (see TNO recommendation page 87, #3), the seismic risks associated with final cushion gas recovery should not be ignored.
Question: What is the opinion of the expert(s) about the missing analysis?

Answer: *In our view, including the final recovery of the cushion gas would not change the conclusions in an important way. The recovery phase is expected to be similar to the second half of the initial production phase.*

6. According to Gasalarm2 the temperature effects are not fully addressed in TNO (2008).
In particular did Gasalarm2 expect an estimation of the effect of potential preferential flow as a result of the presence of cracks, minor faults and flow channels generated in the past gas production phase and a judgement on the necessity of a corresponding *additional* safety margin for the distance between well and fault.
Question:
a. What is the opinion of the expert(s) on this subject? (distance to the faults, heating by compression, cooling by expansion, long-term effects; overall size of the surface area of the reservoir influenced by temperature effects)
b. Practical detail: What, in this respect, is the opinion of the expert(s) about the use of the existing wells to inject the cushion gas (taking into account their proximity to the internal fault)?

Answer: *The volume of rock affected by the temperature changes associated with the initial storage is small compared to the source dimensions of damaging earthquakes. Also, since the permeability of reservoir rock is high, flow along fractures may not be critical. Preferential flow paths are likely to be oriented parallel to faults along the tectonic fabric. In our opinion, the thermal models are sufficiently conservative.*

7. *Hypothesis*: based on reservoir dimensions, parameters and history there is a probability ≥15% that, due to project activities, the central part of the municipality of Bergen NH will during the project life-time (including final depletion at the end of the project) be hit by an earthquake with a 10 times stronger impact than the one experienced in 2001, and that this will cause severe financial damage (given the fact that the 2001 event already caused significant damage (M = 3.5, EMS intensity VI^{+}

near epicenter; KNMI (2001)). (Approx. 4x stronger event (3.9 vs. 3.5), approx. 2x stronger felt in Bergen due to epicenter extending immediately within the build-up area). Ref. to European Macro Seismic scale: http://www.gfz-potsdam.de/portal/-?$part=binary-content&id=1883158&status=300

Question: Does, in the opinion of the expert(s), the TNO study present convincing evidence to reject this hypothesis?

Answer: *In our opinion, given the uncertainties in relating fault parameters to local magnitude (see Figure 4 for typical scatter), the occurrence of a* $M_L = 3.9$ *earthquake associated with the Bergermeer reservoir is possible, but it is unlikely, with a probability much less than the 15% probability that the scenario posed by Gasalarm2 in this question suggests. First, the probability that a* $M_L = 3.9$ *event would occur in the Bergermeer field is less than 1% over the life of the project (van Eck et al., 2006). Second, the region covered by the built up area of Bergen covers only a small fraction of the area affected by production of the Bergermeer reservoir. Third, slip on the scissors fault dies out towards Bergen and the geometry of the reservoir appears to be simpler there.*

8. Further to Q7: *Hypothesis*: given the uncertainty margins in reservoir rock parameters, precise fault dimensions, reservoir rock homogeneity, uncertainty about the precise mechanism underlying the 2001 earthquake and other uncertainties (e.g. concerning thermal effects during injection/production, effects of water injection), there is a probability ≥5% of an earthquake with an even 20x stronger impact (M = 4.1) than the 2001 event.
Question: Does, in the opinion of the expert(s), the TNO study present convincing evidence to reject this hypothesis?

Answer: In our opinion, the probability of such a high impact event is substantially less than 5%. As stated above, the probability of a magnitude 3.9 event in the field is less than 1% and the probability of a magnitude 4.1 event is even lower.

9. *Question:* what is the expert(s) opinion about the treatment/reporting of uncertainty/error margins and confidence intervals in the model calculations and scenario choice in the TNO study?

Answer: *The TNO study addresses the effects of many of the uncertainties in material properties by running a substantial number of models assuming different properties. It does not discuss some other sources of uncertainty/error propagation that could, influence the interpretation of some of the results. However, their most important conclusion, that the maximum local magnitude expected is less than 3.9, is robust and sufficiently conservative.*

As indicated in our report, the uncertainties in the geomechanical models associated with fault geometry are not adequately addressed. In particular, the possible effects of three-dimensional structure are not investigated. As indicated in Figure 3, shearing in *a reverse sense in the region of the projection of the Central Reservoir fault in the weak Zechstein formation driven by differential compaction of the reservoir in Block 1 could load that part of the Central Reservoir fault at the pivot point of the "scissors," where sandstone is present on both sides of the fault. We emphasize that this could affect whether or not smaller earthquakes occur during storage, but would not affect the conclusions about earthquakes with magnitudes greater than* $M_L = 3.9$ *being extremely unlikely.*

ANSWERS TO THE QUESTIONS OF THE SOIL MOVEMENT TECHNICAL COMMITTEE

The following questions were asked by the Tcbb (Technische commissie bodembeweging; english: Soil Movement Technical Committee):

1. What is the opinion of the evaluator on the risk estimates and are they compatible with the physics (ref. TNO report and KNMI risk reports)?

Answer: *In the view of the reviewers, the estimate in the TNO report that the maximum magnitude earthquake that could be expected is* $M_L = 3.9$ *is compatible with the physics.*

2. The fault dissecting the Bergermeer field is (partly) sealing: what pressure difference between the hanging- and foot-wall may cause earthquakes?

Answer: Determining a quantitative estimate of the pressure difference across this fault that could lead to earthquakes is beyond the scope of this review. However, the 1994 and 2001 earthquakes appear to have occurred on this fault, so pressure changes associated with seven years of production may have been sufficient to trigger earthquakes.

3. The Tcbb considers the possibility of seismic monitoring at reservoir level, since only larger events (M>3) have been recorded with the current monitoring system. Is this a justified approach or are there alternatives?

Answer: *This approach is justified by the importance of monitoring the behavior of the reservoir. In addition, we recommend a more comprehensive geodetic monitoring including the use of GPS to measure horizontal motions, in addition to vertical motions.*

4. How is excessive movement to be prevented? Can this be done by changing the rate or volume (maximum pressure difference) of production?

Answer: *The probability of triggering earthquakes depends upon both the stress level and the rate at which the stress changes.*

APPENDIX A

Project Description

Technical Review of TNO's Bergermeer Seismicity Study

Introduction

In the near future TAQA Energy B.V. wants to utilize the depleted Bergermeer gas field as an Underground Gas Storage facility. The Netherlands Organisation for Applied Scientific Research (TNO) has performed a study regarding the seismic risk of the injection/production activities and is called the Bergermeer Seismicity Study. Assumptions made in the report have raised questions and concern among the local community. The local community fears that the gas storage activity will cause a considerable earthquake resulting in substantial damage to their homes and other buildings. Therefore, the Minister of Economic Affairs has been asked to have the report of TNO reviewed by an independent expert. This Project Description contains the scope of work for this technical study.

Deliverables

The Ministry of Economic Affairs expects :

1. A report containing:
    a. a critical technical review of the assumptions, conclusions and recommendations of the Bergermeer Seismicity Study, TNO report 2008-U-R1071/B, 6 November 2008.
    b. answers to the questions raised by the "Gasalarm2 foundation" and the Soil Movement Technical Committee (see appendices)

The report as mentioned should be submitted in both hard copy (20 copies) and in electronic form. The final report will be preceded by a draft report.

Optional:

2. An oral presentation in the municipality of Bergen (The Netherlands) for representatives of the local community.

Timing

The report is to be completed and delivered by September 21st, 2009.

Remarks:

1. Some of the questions raised in the appendices will need an explanation from the governmental experts who are involved in the Bergermeer project. The Ministry of Economic Affairs is willing to organize an information meeting between the reviewer and these experts.
2. TAQA Energy B.V. supports the study and is willing to supply any information needed.

Reports supplied:

- Logan, J.M.; Higgs, N.G.; Rudnicki, J.W.; Seismic risk assessment of a possible gas storage project in the Bergermeer field, Bergen concession, 1997
- Van Eck, Torild; Goutbeek, Femke; Haak, Hein; Dost, Bernard; Seismic hazard due to small-magnitude, shallow-source, induced earthquakes in The Netherlands; KNMI scientific report, 2004 http://www.knmi.nl/~goutbeek/Submitted-seismic-hazard.pdf
- Van Eijs, R.M.H.E.; Mulders, F.M.M.; Nepvue, M.; Kenter, C.J.; Scheffers, B.C.; 2006; Correlation between hydrocarbon reservoir properties and induced seismicity in the Netherlands. Engineering Geology, 84, 99-111.

Reports or papers that need to be purchased can be reimbursed.

APPENDIX B

QUESTIONS I

Questions of the Gasalarm2 foundation

1. TNO uses elasto-plastic geomechanical models to calculate potential slip on a fault plane. A critical geometry of reservoir and fault structure is chosen, which is sensitive for reactivation of the fault. Plastic (reversible) slip is calculated on the fault, during depletion and injection assuming permanent equilibrium conditions (implying the assumption that all potential slip created by the preceding depletion of the field has been accommodated).
Gasalarm2 is of the opinion that in reality discrepancies from the ideal shape of the fault plane as used in the model may be present, in the following called obstructions, preventing incremental a-seismic movement along the fault, and that therefore it cannot be excluded that the reservoir fault(s) are (is) in a meta-stable condition ("hanging earthquake" that could be triggered).
In the opinion of Gasalarm2 the model predictions in the TNO study concerning maximum possible slips that could be created by the, relatively small, pressure changes during one injection-production cycle (corresponding to M = 2.4 - 2.7, should they be accommodated in an non-elastic (seismic) manner) are self-evident given the model assumptions and, therefore, provide no proof that no larger event can be triggered.
Question: Is the above-mentioned TNO approach a complete and reliable way to explore maximum potential slip during the project phase?

2. (With reference to the calculations in Chapter 7 of TNO (2008))
Gasalarm2 states (see Q1) that part of the calculated slip which did not show up in the 4 (historic) earthquakes may still be present as a 'hanging' quake. On the basis of Table 7-1 of TNO (2008) the magnitude of such a quake can be 3.8 (taking the dynamic shear-modulus for the estimate of slip/magnitude, rather than the static as in Table 7.1), or larger, given the uncertainty in parameters and dimensions (see e.g. Q4).
Question: What is the opinion of the expert(s) about this issue?

3. Figure 3,2 of the Seismicity Report shows a 3D view of the Bergermeer gas field (based on a model of Horizon 2006). From this view Gasalarm2 concludes, that the main (internal) fault may be longer than anticipated. According to Gasalarm2 the length of the fault is probably 4.1 to 5.9 kilometres and not 2.5 kilometres. Consequently, Gasalarm2 assumes, that the probable size of the reactivated part of the fault plane may be much larger than is stated in table 2.2 of the TNO report (page 18) and therefore the potential magnitude of earth tremors may be much higher (M=4.1).

Question: What is the relation between the length of the fault plane, the probable activated part of the fault plane during the events and the maximum magnitude of a seismic event? How important is the estimation of the total length of the central fault?

4. Gasalarm2 assumes that the stabilisation of the fault structures at reservoir level due to pressure increase during injection will be of minor importance as compared to potential previously created unreleased tensions (see Q1 and Q2).
TNO assumes that the re-pressurization of the reservoir will lead to a more stable fault structure (see chapter 6.3 of the TNO Seismicity report).

Question: what is the opinion of the expert(s) about these views?

5. Gasalarm2 observes that for the operating phase of the BGS only the first production/injection cycle has been modelled by TNO. In particular, the recovery phase of the cushion gas has not been covered (based on a realistic estimate of the then prevailing reservoir conditions). Apart from risks resulting from phenomena such as erosion of the fault plane and fatigue, (see TNO recommendation page 87, #3), the seismic risks associated with final cushion gas recovery should not be ignored.
Question: What is the opinion of the expert(s) about the missing analysis?

6. According to Gasalarm2 the temperature effects are not fully addressed in TNO (2008).
In particular did Gasalarm2 expect an estimation of the effect of potential preferential flow as a result of the presence of cracks, minor faults and flow channels generated in the past gas production phase and a judgement on the necessity of a corresponding additional safety margin for the distance between well and fault.
Question:
a. What is the opinion of the expert(s) on this subject? (distance to the faults, heating by compression, cooling by expansion, long-term effects; overall size of the surface area of the reservoir influenced by temperature effects)
b. Practical detail: What, in this respect, is the opinion of the expert(s) about the use of the existing wells to inject the cushion gas (taking into account their proximity to the internal fault)?

7. Hypothesis: based on reservoir dimensions, parameters and history there is a probability ≥15% that, due to project activities, the central part of the municipality of Bergen NH will during the project life-time (including final depletion at the end of the project) be hit by an earthquake with a
10 times stronger impact than the one experienced in 2001, and that this will cause severe financial damage (given the fact that the 2001 event already caused significant damage (M = 3.5, EMS intensity VI^{+} near epicenter; KNMI (2001)) (Approx. 4x stronger event (3.9 vs. 3.5), approx. 2x stronger felt in Bergen due to epicenter extending immediately within the build-up area). Ref. to European Macro

Seismic scale: http://www.gfz-potsdam.de/portal/-?$part=binary-content&id=1883158&status=300

Question: Does, in the opinion of the expert(s), the TNO study present convincing evidence to reject this hypothesis?

8. Further to Q7: Hypothesis: given the uncertainty margins in reservoir rock parameters, precise fault dimensions, reservoir rock homogeneity, uncertainty about the precise mechanism underlying the 2001 earthquake and other uncertainties (e.g. concerning thermal effects during injection/production, effects of water injection), there is a probability ≥5% of an earthquake with an even 20x stronger impact ($M = 4.1$) than the 2001 event.
Question: Does, in the opinion of the expert(s), the TNO study present convincing evidence to reject this hypothesis?

9. Question: what is the expert(s) opinion about the treatment/reporting of uncertainty/error margins and confidence intervals in the model calculations and scenario choice in the TNO study?

QUESTIONS II

Questions of the Soil Movement Technical Committee

The following questions were asked by the Tcbb (Technische commissie bodembeweging; english: Soil Movement Technical Committee):

5. What is the opinion of the evaluator on the risk estimates and are they compatible with the physics (ref. TNO report and KNMI risk reports)?

6. The fault dissecting the Bergermeer field is (partly) sealing: what pressure difference between the hanging- and foot-wall may cause earthquakes?

7. The Tcbb considers the possibility of seismic monitoring at reservoir level, since only larger events (M>3) have been recorded with the current monitoring system. Is this a justified approach or are there alternatives?

8. How is excessive movement to be prevented? Can this be done by changing the rate or volume (maximum pressure difference) of production?

APPENDIX C

Resumes

Bradford H. Hager

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Professional Preparation

Ph.D. in Geophysics, Harvard University,1978.
A.M. in Geology, Science, Harvard University, 1976.
B.A. in Physics, Amherst College, 1972.

Appointments

Associate Department Head, 2008 – present
Cecil and Ida Green Professor of Earth Sciences, MIT, 1989 - present.
Professor of Geophysics, Caltech, 1989.
Associate Professor of Geophysics, Caltech, 1984 – 1989.
Assistant Professor of Geophysics, Caltech, 1980 – 1984.
Assistant Professor, Department of Earth and Space Science, SUNY Stony Brook, 1979 – 1980.

Selected Awards and Honors

Alfred P. Sloan Foundation Fellow, 1982 – 1986
American Geophysical Union – Fellow; James B. Macelwane Award, 1986
Orson Anderson Scholar, Los Alamos National Laboratory, 1996
Woolard Award, Geological Society of America, 2001
Fellow, American Academy of Arts & Sciences, 2009

Relevant Publications

Hager, B. H., R. W. King, and M. H. Murray, Measurement of crustal deformation using GPS, *Ann. Rev. Earth Planet. Sci.,* 19, 351-382, 1991.

Donnellan, A., B. H. Hager, and R. W. King, Discrepancy between geological and geodetic deformation rates in the Ventura basin, *Nature, 366,* 333-336, 1993.

Hager, B. H., G. A. Lyzenga, A. Donnellan, and D. Dong, Reconciling rapid strain accumulation with deep seismogenic fault planes in the Ventura basin, California, *J. Geophys. Res., 104,* 25,207-25,219, 1999.

Hetland, E. A., and B. H. Hager, Postseismic and interseismic displacements near a strike-slip fault: A two-dimensional theory for general linear viscoelastic rheologies, *J. Geophys. Res., 110*, B10401, doi:10.1029/2005JB003689, 2005.

Meade, B. J., and B. H. Hager, Block models of crustal motion in southern California constrained by GPS measurements, *J. Geophys. Res*., *110*, B03403, doi: 10.1029/2004JB003209, 2005.

Meade, B. J., and B. H. Hager, Spatial localization of moment deficits in southern California, *J. Geophys. Res*., *110*, B04402, doi: 10.1029/2004JB003331, 2005.

Committee on Earth Science and Applications from Space: A Community Assessment and Strategy for the Future, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, Space Studies Board, Division on Engineering and Physical Sciences, National Research Council of the National Academies, The National Academies Press, Washington, D.C., 2007.

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Professional Preparation

Colorado School of Mines	Geophysics	B.S., 1958
California Inst. of Technology	Geophysics	M.S., 1960
California Inst. of Technology	Geophysics	Ph.D., 1963

Appointments

Robert R. Shrock Professor of Geophysics, EAPS, MIT, 2005–
Director, Earth Resources Laboratory, MIT, 1982–1998
Director, Wallace Geophysical Observatory, MIT, 1975–
Professor of Geophysics, MIT, 1971–
Associate Professor of Geophysics, MIT, 1967–1971
Assistant Professor of Geophysics, MIT, 1965–1967
Postdoctoral Research Fellow, Geophysics, Caltech, 1963–1965

Section 1.01 Selected Awards and Honors

Exceptional Scientific Achievement Award, NASA, 1976
Distinguished Achievement Medal, Colorado School of Mines, 1995
Honorary Membership, Society of Exploration Geophysicists, 1999
Harry Fielding Reid Medal, Seismological Society of America, 2006

Principal Research Interests

Seismology, earthquake mechanisms, induced seismicity, reservoir characterization and petrophysics

Relevant Activities

EPRI – Eastern U.S. Earthquake Hazard Study (for nuclear power plant safety), Member, Senior Advisory Board, 1988-1995
Seismic hazard evaluation, gas field in Oman (PDO), 2001
Seismic hazard study evaluation for natural gas storage site in Turkey, Technical Consultant to World Bank, 2003

Selected Publications

Gibson, R.L., Jr. and M.N. Toksöz, Permeability estimation from velocity anisotropy in fractured rock, *J. Geophys. Res.*, *95*, 15643-15655, 1990.

Toksöz, M.N., B. Mandal and A.M. Dainty, Frequency-dependent attenuation in the crust, *Geophys. Res. Lett.*, *17*, 973-976, 1990.

Toksöz, M.N., A.M. Dainty and E.E. Charrette, Coherency of ground motion at regional distances and scattering, *Phys. Earth Planet. Int., 67,* 162-179, 1991.

Cicerone, R.D. and M.N. Toksöz, Fracture characterization from Vertical Seismic Profiling data, *J. Geophys. Res., 100,* 4131-4148, 1995.

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Michelet, S. and M.N. Toksöz, Fracture mapping in the Soultz-sous-Forets geothermal field from microearthquake relocation, *J. Geophys. Res.*, in press, 2007.

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Sarkar, S., H.S. Kuleli, M.N. Toksöz, H. Zhang, O. Ibi, F. Al-Kindy and N. Al Touqi, Eight years of passive seismic monitoring at a petroleum field in Oman: a case study, extended abstract, SEG Annual Meeting, 2008.

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