**Report to the Technical Guidance Committee (TBO) Alternative production measures Part 1: Alternative depletion scenarios and hazard analysis**

Review by **Ian Main**, University of Edinburgh, 14 November 2013.

This report addresses the question of how the stress state in the subsurface may be managed to reduce the hazard from future seismicity induced by gas production from the Groningen field. It is written at quite a high level and is also quite dense, so it is not possible to check all of the details leading to a particular conclusion. Nevertheless the conclusions are based on a large body of previous work, and there are many significant new findings and recommendations. The report acknowledges many remaining sources of uncertainty in calculating the future hazard, as well as summarising strategies to reduce the uncertainty in terms of passive monitoring of the field and in better characterisation of the material properties in going forward. Some of this uncertainty will reduce with additional data from the planned monitoring programme, but a significant amount will remain.

The report explicitly considers the likely response of the reservoir to several potential scenarios aimed at reducing the hazard by planned stress state management, including an 'emergency stop' and full pressure support by injection of nitrogen as end-member strategies. The likely response of the reservoir and associated hazard is complex and hard to predict exactly, as clearly acknowledged in the report. It may depend on structural detail that cannot be resolved at present within the seismic resolution, or on model parameter uncertainty that can be addressed by more work on the materials concerned, conditioned on a large programme of monitoring of the field, including new seismic data to be acquired from borehole sites. One of the biggest sources of uncertainty is the strong effect of different models for compaction, which has a greater effect than the differences in the different mitigation strategies.

The predicted hazard is expressed sensibly by a range of measures rather than a single number, enabling risk management to be done with a sensible spread of possible outcomes. This is done by assuming a non-stationary Poisson process with a hazard rate that increases in time, conditioned on past behaviour. The effect of different sources of uncertainty in hazard forecasting is estimated using a logic tree analysis of the outcome of work conducted earlier in the programme. Overwhelmingly the main source of uncertainty that emerges is the partition coefficient between seismic and aseismic (elastic and plastic) strain, and the degree to which this may change in time. This is very sensibly identified as a priority in planning future work.

Two major new studies have been carried out using 2D and 3D geo-mechanical models, conditioned on the structural and mechanical properties of the field, supported by a technical appendix. This is a necessary and impressive contribution to stress state management for hazard mitigation. The appendix shows that a good body of field-specific data is available to condition the geo-mechanical models, though more needs to be done as acknowledged, including better characterisation of materials outside the reservoir horizon, and a study of the scaling properties of the relevant parameters. Despite this the models already provide a good history match to past data, albeit likely with a large number of parameters that are to some extent tunable, and falsifiable forecasts of reservoir response are made for different model parameters within the reasonable range. The forecasts will in time help discriminate between the competing models as new data are collected.

The 2D modelling study predicts a maximum displacement within the reservoir of 0.5 m or so. This is consistent with a maximum possible magnitude of around 6.5 in TBO report 5, based on the assumption there of a 100% partition coefficient. Typically a magnitude 6 will produce 1m or so of slip, and the modelled slip on a single fault in the present report is less than this. This may indicate the main hazard is from smaller but more common events, consistent with the conclusion reported in TBO report addressing question 5. By having such slip on many faults, and considering the potential for reactivated slip to propagate or indeed nucleate in the surrounding layers this may resolve the problem of unrealistic aspect ratios in the previous report (see also Table 6.1).

The report points out that even the 'emergency stop' scenario is not without risk – as demonstrated recently in a real case in a geothermal energy context in Basel, Switzerland, showing that transient or time-dependent effects do need to be taken into account, as considered explicitly here. Similarly maintaining 100% pressure in the reservoir may also require intrusive surface installations and workflows. In this case it is important to acknowledge the possibility of hysteresis, i.e. recovering pressure fully will not be an absolute guarantee of zero risk.

The executive summary presents a very good overview of the outcomes of the work programme so far, given such a dense and technical report. It is also a fair summary of the state of knowledge at present and presents sensible ways of moving forward, when taken in conjunction with the comprehensive list of recommended further work in Table 6.1. This work in progress highlights the operational fact that risk management will be a learning process, informed by feedback in the light of new data and the actual outcomes.

My main general comments are as follows.

1. *It might have been useful to provide a more extended discussion of the rationale for the production scenarios considered in the part 1 report. (The petroleum engineering aspects are considered separately in part 2, but a brief summary of the broad rationale and explicit cross-reference to the relevant sections might also be useful in part 1).*

2. *All of the scenarios are long-term 'smoothed' scenarios for the population of induced events. It may be useful also to examine and plan for adjustments to production as individual felt events occur, and to develop protocols in advance for hazard mitigation during such transients. Even at this stage it seems quite plausible that a temporary 'emergency stop' might turn out to be sub-optimal.*

3. *This and previous reports highlight a structural problem in the regulatory framework for seismic hazard in Europe as a whole, not just in the Netherlands, i.e. its current basis in a stationary Poisson model as a basis for probabilistic seismic hazard assessment. Here the hazard is both non-stationary and probably non-linear in time. As such the current report is very much placed at the research frontier in terms of seismic hazard forecasting.*

Non-stationary models are being developed in other contexts, and some new techniques may emerge from the literature as time goes on (for natural as well as induced seismicity). For now the approach taken is reasonable given the state of the art and the lack of clear guidelines on time-dependent hazard in Europe. It is particularly strong both in identification and assessment of uncertainties, and in making specific plans for reducing these. Much more work needs to be done of course, and there is likely an irreducible element to the uncertainty which will need to be considered in risk management and communication, but many of the key building blocks for stress state management to underpin this future effort are now in place.