REF: Bergermeer Gas Storage (PSG-DB / 18074686)

Attn:

Dr. [redacted]
Senior Inspecteur
Staatstoezicht op de Mijnen
Ministerie van Economische Zaken en Klimaat
Den Haag, Netherlands

Review of the report "3D geomechanical model study on the Gas storage Bergermeer – Report for TAQA Energy BV (March 2018)" authored by Fenix Consulting Delft

This review is based on the document above as provided in "TEN_DM-#191618-v1". No consultation with any other party or additional modelling work was requested and it relies solely on expert opinion and experience of the reviewer.

Specific questions addressed in this review:

1. We ask your expert opinion of the modelling approach taken and the assumptions made
2. What is your expert opinion of the changes made in the modelling assumptions when transferring from gas depletion to gas injection?
3. What is your expert opinion of the modelling results and the conclusions drawn based on these results?
4. Are the conclusions made properly substantiated by the modelling results and properly discussed?

Reviewer:

Dr. Stephan Arndt

1 Modelling Approach

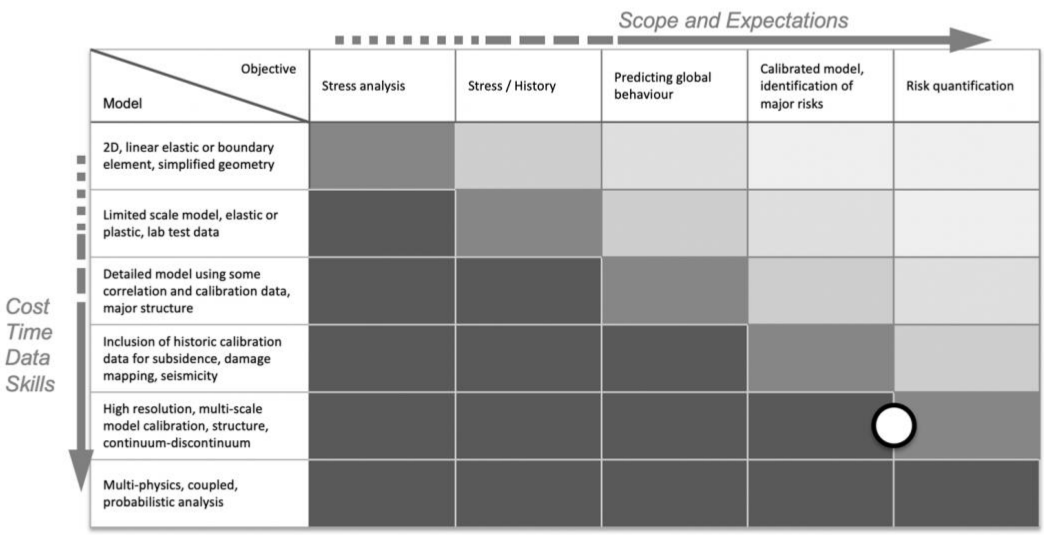
1.1 Overview

In summary, the approach described in the report can be considered high end, state-of-the-art modelling for three-dimensional reservoir geomechanics analysis. A significant history of referenced work on the Bergermeer Storage Reservoir provides the background both in evolution of complexity of modelling work over time and to discuss validation of predictions versus observations in previous studies, which assists in separating the various relationships between model assumptions (including limitations in previous models) and explanations of observed behaviours. This 3D model allows calibration against a large and detailed data set and provides scope to evaluate sensitivity where there is uncertainty. Results interpretation focuses on stress on the faults from the calibrated model, where the criticality of the faults using the Mohr-Coulomb criterion is used as an indicator of seismic risk.

It is noted that some particular workflows seem to be driven by the choice of analysis software but there is no indication this would impact results. It is understood that unlike industries that were early adopters for advanced simulation, such as the aerospace sector with established and well-defined analysis procedures, no definite standard exists for geomechanics modelling. Legislation is still unable to keep up with fast-paced changes of technology. Commonly, 3D geomechanical modelling is still an expert task and the modelling presented in the report is therefore measured against industry best practice, such as demonstrated in journal and conference publications, expert opinion and experience gained with industry leaders’ internal workflows.

1.2 Model Complexity and Confidence Level

The chart below, providing a classification of modelling methods, allows to position this work as indicated with the circle marker. The vertical dimension relates to modelling features (Model, increasing in complexity and need for data along with cost, time and required skills), and the second relates to the objectives (described by scope and confidence levels taken from model predictions along with increasing expectations), with the level of shading in the chart area appraising suitability. A valid constraint of not including “*flow simulation in the geomechanical model*” is mentioned in the report (p.18), and the theoretically possible extension to a fully coupled model cannot be recommended for this application.



source: Monash University, Resources Engineering, “RSE4111 Numerical Modelling Lecture Notes” – Arndt (2018)

1.3 Model Construction

The model constructed for this study is a three-dimensional Finite Element Model of the Bergermeer storage reservoir (geomechanical model) and the analysis was performed in the software package COMSOL. In general, workflows for such models focus on three main qualities: First, the geometry which also includes discretisation of the problem domain with elements of variable sizes; second the (mechanical and physical) properties of all domains; and third the internal and external forces (in-situ stress of solids, fluid pressures and boundary conditions). In the process of model construction, related reports and publications for the significant amount of work that was previously done on the Bergermeer reservoir were used and are referenced throughout this report, indicating where data has been sourced and also where alternative assumptions have been made to previous models.

1.4 Geometry

Geometry construction for this model is based on the PETREL reservoir simulation model, recreating faults and horizons in a 3D geometry editing software (likely to be Rhino3D, not referenced but identified from the figures in Appendix V). This includes faults in the overburden, all terminated on the top Zechstein surface, the salt layer and the reservoir fault geometry below, therefore decoupling the two fault systems. The model volume is extended outside the reservoir/fault system with a simpler layer cake geometry about twice the typical dimension of the reservoir to reduce artefacts arising from boundary conditions. This extension is a common and widely accepted approach for this type of large-scale model. The description of the geomechanical model in chapter 4 and in appendix V is consistent with the results sections shown throughout the report. No mesh diagnostics summary (statistics about representative element length or quality) or figure is provided for the 3D mesh, only for the 2D model used to calibrate fault slip. Judging from section plots such as Figure 40– the mesh seems to be of reasonable quality with sufficient refinement around the faults and reservoir boundaries.

1.5 Properties and Initialisation

Nine separate property domains are shown in Figure 17–19 and populated uniformly with the values in Table 1, providing a sufficiently detailed approach. Some of these domain properties are later used as calibration parameters.

In-situ stress initialization is one of the main factors impacting the model results as this defines the stress state of the faults. As stated, (p.23) "*The virgin stress distribution is the result of tectonic, creep, depositional and erosional processes over geological time scales. Modelling of these processes to obtain the initial stress is not feasible because of the lack of data*, and the initial stress in the model has to be matched with available data in a calibration process. This is done in stages to ensure goals such as vertical stress, horizontal stress multipliers, effects of salt layers reducing shear stress and elastic equilibrium are respected.

Pressure data from the ECLIPSE reservoir model, which has been history matched in separate studies, is used to define the reservoir pressures as history over time. This pressure history follows the depletion until 2007, the subsequent refill due to cushion gas injection and the storage cycles. The mapping of these values and adjustments made to the faults both address valid concerns regarding the different consequences in the stepped fault with large cell sizes in modelling reservoir flow and in the geomechanical model, where an effect on fault stress values is avoided as discussed in the list f modelling assumptions below.

1.6 Calibration

The geomechanical model is calibrated using available data from subsidence, individual stress measurements, and observations of seismicity constraining the available parameters. The process of calibration against different categories of data, such as displacements and observed seismicity significantly improves the level of confidence in model results and forecasts. An advantage of this most recent work over previous studies is the availability of data from three storage cycles to update previous model calibration. One important aspect here is the change in stiffness to match subsidence and heave during refill and storage, this is discussed in the next section. Overall, a calibration strategy is presented, and the derived workflow and its dependencies are clearly outlined.

1.7 Modelling Assumptions

Other assumptions in the modelling process, either explicitly stated or implied in the discussions, that are considered important in this review based on their possible impact on the results include:

1. Fault slip
2. Seismicity
3. Salt creep
4. Analysis
5. Fault pressures

1.7.1 Fault Slip

The Mohr-Coulomb (MC) criterion without cohesion (therefore reduced to a simple friction coefficient defining the ration of possible shear vs normal stress on the fault) is used to assess criticality of faults to incur slip and possible seismicity, (p.28) "*The criterion for fault slip in the geomechanical model is simplified to the Mohr-Coulomb criterion*".

The use of MC and the concept of critically stressed faults has seen widespread use over decades and can be considered the standard model. Without further data or contradicting evidence there is no motivation to move to more complex criteria. Values of 0.6 for the friction coefficient are generally considered to be a default value.

1.7.2 Seismicity

Seismicity is not modelled directly as a dynamic slip process or discrete events. This is the most common approach due to the complexity, uncertainty and lack of detailed understanding of seismic events, which still finds itself to be an intense focus area in the research community. In the report the risk of seismic events is linked to the criticality of faults, and the possible event magnitude is proportional to the critically stressed area and therefore the available energy that can be released. This is considered industry standard.

All events obtained from the monitoring system are relocated to the faults, (p.8) "*All micro-seismic events could be migrated to the faults by intersecting the uncertainty ellipsoid with the fault plane*". This is supported by the data shown in Figure 9–15 and a detailed discussion is provided.

1.7.3 Salt Creep

Salt is a viscoelastic material. This is recognized throughout the report and constitutive models are presented and calibrated for different timescales. Importantly, it is part of the stress initialisation and sensitivity regarding salt creep is investigated. It is stated correctly that "*salt creep stabilizes the fault at the reservoir salt interface*" (p.51) and the decision to not take salt creep into account during refill and storage cycles is a valid assumption to obtain conservative results regarding fault slip risks based on the timing of pressure changes versus salt creep effects. The authors avoid the trap of overfitting of the creep parameters (p.36), which could result from the large amount of available data from GPS and discuss suitability for each GPS location.

1.7.4 Analysis

Finite Element Analysis of large models can be adversely impacted by limited precision when choice of units and the numbers generated in the equations for different fields differ by many orders of magnitude ("*ill-conditioning*"). Each solver has a range of standard solution controls and on occasion these are not suitable for large models, especially in terms of economic computer time. There is no mention of the use of either default values or any custom controls. With the demonstrated high quality of the work for this report it is assumed that expert users were involved in these decisions.

1.7.5 Fault pressures

The mapping of pressure values from the reservoir model and adjustments made to the permeability on the fault to match water tables creates artefacts (p. 19). To avoid effects on fault stress values from adjacent cells are used. This is a valid apporach to overcome the mapping problems inherent in the different geometries of the cells in reservoir models and the elements in geomechanics simulations. A detailed discussion of the results of the pressure mapping and its validation is provided.

2 Transferring from Gas Depletion to Gas Injection

Two major changes are introduced in the model when transferring from the gas depletion phase to the gas injection phase. These are:

1. Change of stiffness between depletion and injection
2. Stress correction for the main fault

2.1 Change of Stiffness Between Depletion and Injection

Production from the Bergermeer reservoir and its depletion down to 35 bar from the 1970’s to 2007 lead to the development of a subsidence bowl over the field. By then it is most likely that both the reservoir and the overburden will have experienced compaction mechanisms beyond poro-elastic effects. Usually these are not reversible as they can relate to permanent changes to the soil and rock layers such as pore-collapse.

For many of these mechanisms it is difficult to establish suitable constitutive laws, or these would add considerable complexity and ambivalence in the material parameters. This is acknowledged in the report by various comments such as (p.23) “*The behaviour could be modelled with an elastoplastic constitutive model*” and (p.33) “*In principle, the observed surface subsidence also includes compaction of shallow, soft layers.*”

To calibrate the surface heave in the gas injection phase, the approach taken is a change of model properties for elastic stiffness, such as Young’s Modulus and Poisson’s Ratio, (p.24) “*using different elastic compaction moduli during refill compared with initial depletion*” and Table 2. The implementation is described as “*The different stages are combined using superposition of the increments.”* and it is acknowledged that *“Such an approach violates energy conservation, because the elastic deformation is not explicitly incorporated*” (p.24).

This is a valid simplification of an inelastic modelling process, where, whilst retaining constant stress, the higher strains at lower stiffness are resolved into an in-elastic, effectively discarded, strain component, and a reduced strain at this same stress level from higher stiffness. The details of this process are not clear though, and it should be demonstrated that it has been validated and no stress artefacts occur.

2.2 Stress Correction for the Main Fault

The stress correction (or slip correction) which is applied following the gas depletion phase is motivated by the stress changes that would have occurred due to earthquakes during depletion, as stated in (p.52) “*During depletion four earthquakes exceeding magnitude 3 occurred at the midfield fault*” and “*The (seismic) slip associated to these four events should be explicitly accounted for, since it will significantly affect the state of the shear stress at the end of depletion and during refill.*”.

A detailed discussion on the process is provided and it is a valid assumption that the cumulative seismic moment released through these events changes the stress in the order of magnitude described here. The effect of stress reorientation can be important as the slip reduces shear stress, and typical fault behaviours are discussed throughout the report, for example on (p.37) "*Heterogeneities in rock properties and stress initialization introduce stress rotations and stress discontinuity close to faults and domain transitions*".

2.2.1 Modelling Approach for Stress Correction

An interesting, though logically structured and well-documented, approach was chosen to include this fault slip correction to infer the stress state in the model following depletion. Apparently, this might be caused by limitations regarding the analysis capabilities which are quite common. Only few software packages would allow successfully simulating finite sliding on a fault surface in a non-linear analysis for a large-scale three-dimensional model. It is understood that simulations involving contact sliding could be computationally expensive without necessarily adding to the quality of the results.

The approach taken here involves a 2D Finite Element Model for a section at the scissor point of the main fault, accounting for the combined expected stress changes due to four earthquakes exceeding magnitude 3. The resulting stress changes are applied to the 3D model. The 2D model has a finer mesh and includes sliding on the contact interface in a non-linear analysis procedure, described in Appendix III. This can be considered an appropriate modelling approach for this type of problem.

As stated in (p.28) "*In principle, these two processes may be elastic, but it is likely that in many rocks shearing is accompanied by some micro-fracturing or plasticity when asperities yield under shear.*" For subsequent modelling of the injection phase, it is assumed that the average friction coefficient could be expected to be lower following the depletion seismic events but not higher, which is consistent with the shearing of asperities on slip.

2.2.2 Two-dimensional Section Properties

Specific properties of the stress correction can be identified as:

1. The slip correction is based on the re-distribution of stress on the fault, with the specific profile of the "average shear stress correction is zero." (p.54), therefore not interfering with the energy balance of the model.
2. The section analysed in the 2D was oriented normal to fault strike, and results from the 3D model confirm "*In the 3D simulations there is both a dip-slip and strike-slip component and the correction is done separately for both components. It turned out that most of the slip was in the dip-slip direction, with only a small strike slip component."* (p.57)
3. The magnitude in the 2D model is based on the following assumption: "*To get a measure for the seismic moment in a 2D model, it is assumed that the shear area is proportional to the shear height squared.*" (p.53). Further, in Appendix III, it is stated that (p.92) "*For the 2D simulation here, it is assumed that the missing dimension is proportional to the slip height, …*" and a coefficient *w* is introduced in Equations 28–29.

Whilst the first two points above are of no concern, the third property of this correction is not supported in the discussion. It does not address the fact that the typical dimension of the fault along dip (in section in 2D) can be a magnitude smaller than along strike. This aspect is possibly justified by choosing the value for *w,* as described in (p.92) "*To match the cumulative seismic moment in the 2D model, a coefficient of proportionality of w = 7.8 results*".

2.2.3 Recommendation to Request Further Information

It is important to note that the magnitude of this stress correction will directly affect the forecasting and statements based on the criticality of the predicted stress on the main fault, such as in Figure 83 (p.62) and its discussion. Clarification regarding the 2D model stress magnitude, the missing dimension and the value of *w*, as discussed above, should be requested from the authors to ensure validity of the report's conclusions.

Additionally, the discussion made in the report on (p.62) opens up questions about the procedure: “… the high shear stress is caused by the additional shear stress from slip on the fault by the depletion earthquakes. The normal stress fluctuates with the reservoir pressure, giving a fluctuation in critical stress ratio at the critical point and even an excess over the MC envelope. The excess shear stress gradually disappears by continued slip and the critical point stabilizes, so that the maximum magnitude drops with subsequent cycles”.

If the slip correction based on the 2D is performed once at the end of the depletion phase, before storage cycling, it is not clear how to understand the statement that the cumulative slip could stabilize these regions, as it implies the ability of the model to model fault slip as an ongoing process.

2.2.4 Sensitivity

A number of sub-sections on the sensitivity of the model results regarding most of the assumptions that were made in the modelling process are included in the report. This applies in particular with respect to the stress state on the fault:

1. The impact on seismic risk when no slip correction is applied after depletion (p.63) “*As a worst case we can also assume that the stress is not released and the critically stressed regions would have persisted after the earthquakes*”
2. The possibility of part of the slip being non-seismic with events below the detection limit (p.59) “*so the critical area was also computed for a lower friction coefficient of 0.6, which can be considered a default value*”
3. The impact of friction coefficient (p.64) “*Using a friction coefficient of 0.6 will give a larger critical area and a stronger stress correction. This results in more criticality during refill, although the effect is insignificant if the fault is assumed to slip and remain on the MC envelope, see Figure 86.*”

Overall, the consistent evaluation of sensitivity allows to understand the impact of a range of assumptions made in the modelling process and provides a range of outcomes to include scenarios that can be considered possible but having lower probabilities. Demonstrating that none of these scenarios would significantly change the outcomes and conclusions strengthens the confidence in the conclusions made in the report.

3 Modelling Results and Conclusions

The results and conclusions are mainly based on the analysis of the stress state in the three-dimensional model, which is provided in contoured section plots and graphs of both time history of results values and along critical features such as the fault section at the scissor point.

The quality of results presentation in the report is demonstrated by:

1. Each plot or graph has labels and annotations.
2. Consistent use of units
3. Contour plots are of good quality
4. Colour schemes assist with the interpretation of results
5. Figure captions are provided
6. Plots and graphs are referenced in the discussion in the text
7. A list of figures is provided following the contents section

It is clear from the quality of the report and the model description that the preparation and execution of the models was performed by expert users and that a significant amount of work was involved in the process.

4 Substantiation of Conclusions and Results Discussion

The report provides a detailed account of the modelling process, is well structured and all material and constitutive parameters are captured in tables in the various sections and their relevance together with their role as either input or calibration parameters are discussed. Modelling results and conclusions are presented and discussed in a consistent manner.

The conclusions are based on the established framework of stress and criticality of faults using a (cohesionless) Mohr-Coulomb criterion (which equates to friction), consistent with industry best practice, and the sensitivity analysis, previously discussed in this review, increases confidence in the conclusions. A key concept is the depletion induced stress changes at the fault due to effects of poro-elasticity, as expected in geomechanical modelling for reservoirs. The statement in the conclusions (p.72) “*Assuming that during depletion the Midfield fault has slipped to a stable configuration, given by a single friction coefficient, it is possible to compute the stress distribution*” is the most plausible explanation for the history of the reservoir from depletion to injection.

As outlined before, a large and detailed dataset is used to calibrate the model using subsidence, individual stress measurements, and observations of seismicity constraining the available parameters. The process of calibration against different categories of data, such as displacements and observed seismicity significantly improves the level of confidence in model results and forecasts. There are no gaps in the argumentation from model results to the conclusions, other than the highlighted request for further information about the magnitude of stress in the 2D fault slip modelling. The consequences of this part are constrained by the sensitivity analysis’ no-slip scenario. Validating assumptions such as role of seismic events or friction coefficient in the calibration process as part of the sensitivity analysis assists the understanding of the calibration process and a number of discussions are included about those observations that do not fit model data or expectations.

Remaining uncertainty is acknowledged in the discussion and conclusions. The most relevant question that remains open relates to the West Fault being potentially seismically active or not. It is possible that no events occurred due to higher friction or cohesion on the fault rather than due to non-seismic slip. As discussed in the report, (p.47) “*Since no micro-seismicity activity was seen during at a later stage either, it is likely that the West fault was never seismically active.*” And (p.72) “*The West fault was critically stressed but showed no activity at all, indicating that it is non-seismogenic. It may have slipped in a creeping fashion, but could also have remained inactive because of high strength of the fault.*”. Although considered to be likely and plausible, sufficient data to answer this question either way is not available at this stage and monitoring should continue to focus on this area.

Overall, with the technology currently available and the data set obtained for the Bergermeer reservoir to date it is difficult to conceive a more comprehensive geomechanics analysis and the detailed report would certainly pass quality assurance in specialist consultancies. Again, this review of the report and its results and conclusions is based on the document provided only and does not include any additional modelling or validation work.

End of Review