

First History Matched Full Field Coupled Geomechanics and Reservoir Flow Model of both the Valhall and Hod Fields Including Water Weakening and Re-Pressurisation.

ABSTRACT: This paper presents the development of the first coupled geomechanics and reservoir fluid flow full field model of both the Valhall and Hod chalk fields in the North Sea. The paper covers the historical development of geomechanics and reservoir flow models used to model these challenging North Sea chalk fields where reservoir compaction is exceeding 10 meters in some areas of the fields. The early models were not coupled, but increased sophistication in the way the reservoirs have been modeled have been developed with time as know-how and technology has been developed. Although two-way coupled models have been developed for the field in the past, to date one-way coupled models have been used in the daily modeling of the fields. This paper presents the process of developing a two-way coupled model to be used in the daily modeling of the fields. It is presenting how the new modeling tool was verified to the existing modeling results before a new updated model for the fields was developed.

APPLICATION OF ELFEN 3D GEOMECHANICAL MODELS

Before the VISAGE and VIRAGE softwares were verified and ready to replace the one-way coupled ISAMGEO model, the softwares were acquired by Schlumberger. This resulted in some uncertainties around further tailored developments for the Valhall license and cost. After an evaluation it was decided to continue the work to develop a suitable modeling tool for Valhall with Rockfield Software Limited (RSL) and their advanced general purpose finite element code, ELFEN. ELFEN had been used for many research projects on wellbore and geologic scale [32]. In a JIP, Integration of Petroleum Engineering, Geophysics and Geomechanics (IPEGG) between RSL, University of Leeds and University of Bristol, sponsored by a number of oil companies, links between various reservoir simulators were developed and among them, the reservoir fluid flow simulator VIP.

A Valhall model was one of the demonstration projects in the JIP. The ELFEN model can be run in explicit mode and is parallelized. Both of these features are attractive when planning to model a field like Valhall with millions of elements, elasto-plastic material behavior with water-weakening of the chalk and strain rate dependency. The explicit method allows for mass-scaling which can increase computational speed significantly compared to the implicit method used to date.

The mesh in the first ELFEN model was the same as in the ISAMGEO model presented by Kristiansen and Plischke [23]. This mesh was used in order to get a good understanding of how the ELFEN model worked in comparison to the well known model in the ISAMGEO finite element software.

Figure 7 is showing results from the fault re-activation modeling with ELFEN based on the ISAMGEO mesh. Fault reactivation and associated well failures and micro-seismic events are of interest to locate in order to find locations with long well life. More information can be extracted from the field if one can correlate the observed micro-seismic with the predicted one from the model, see examples from Valhall [29, 33, 34].

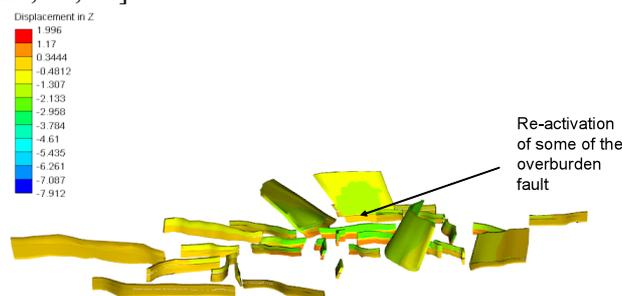


Figure 7: Vertical displacement on faults in the Valhall ELFEN model, arrow is indicating partial fault re-activation of an overburden fault.

A major change to the modeling was the decision to also use one of the constitutive models existing in ELFEN, the (Soft Rock 3 model) SR3 model. The SR3 model has been expanded previously to also be able to model liquefaction of chalk [32]. The SR3 model is a Cam-Clay type of model. The SR3 model is available in several options. For modeling the Valhall chalk we have used the SR3 model option which is strain rate dependent, so it takes into account time dependent deformations, or creep.

One additional feature that was developed in the SR3 model used for Valhall was the chalk water weakening feature. This feature was developed in a way so that the yield surface properties are dependent on the change in water saturation compared to a reference state. Figure 8 show examples of data from laboratory water-flood experiments on Valhall chalk as well as the prediction of the water weakening response based on the model developed in ELFEN. The results are very good and acceptable for prediction in a full field model. One has to keep in mind the significant variability one observe in weakening response as one compare companion core samples tested in the laboratory. There is a significant scatter.

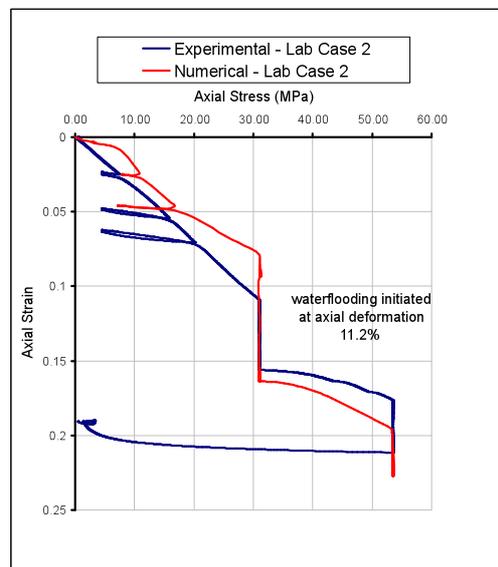


Figure 8: Comparison of laboratory tests showing loading/unloading cycles and water weakening of Valhall chalk and numerical modeling based on the extended SR3 model in ELFEN.

Figure 9 show typical results from the one-way coupled model, comparing the model to measurements and using the same stress-strain response as the ISAMGEO results [23]. The results are very close and acceptable. A number of tests were run to evaluate different aspects of the new model. Of interest was the CPU time needed for various runs. Typical CPU times for one-way coupling were found to be 41-67 hours on 4 processors. This was reduced to 33 hours in a case with mass scaling. Typical CPU time on two-way coupled cases was 63 to 67 hours on 6 processors. These times are of course dependent on the hardware used, but it is just to provide an indication. Tests with tetrahedral elements were also performed and compared to the run with hexahedral elements as used in the ISAMGEO model. The number of elements for the hexahedral case was typically around 175000, while the tetrahedral case consisted of 5.8 million elements. The CPU time for the tetrahedral case was 30 hours on 12 processors, indicating the potential for running large problems with the parallelized ELFEN software.

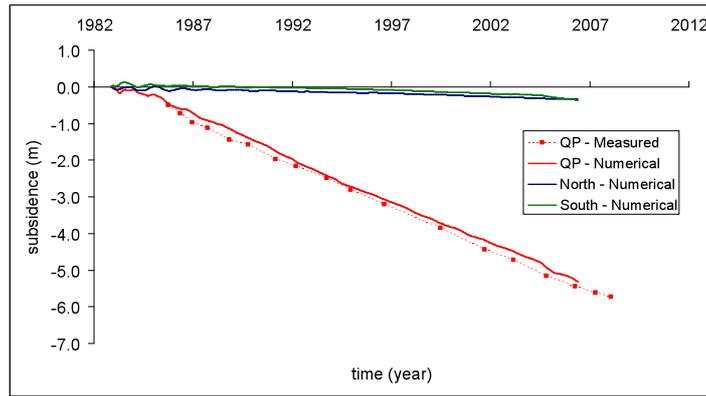


Figure 9: Comparison subsidence predictions with measurements for the ELFEN model.

Also a comparison of subsidence between one and two way coupling is interesting, see figure 10. As can be seen here, due to the direct communication between the two simulators in the two-way coupled cases, one can not achieve a history match with the same input parameters as used in the one-way coupled history matching. The difference is a couple of meters with subsidence. The one-way coupled results for the comparison between the existing history matched model by Kristiansen and Plischke [23] was found to be satisfactory. The next step was to use the new modeling software to build an updated model as part of a subsurface model update for the Valhall field.

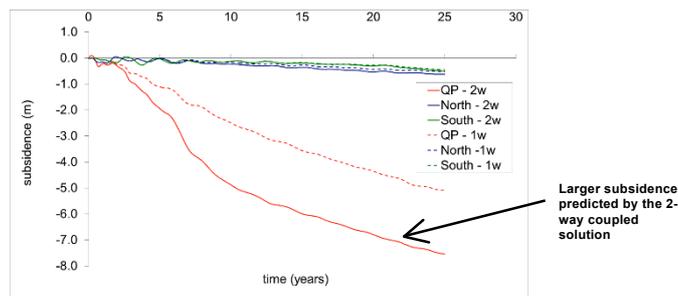


Figure 10: Comparison of subsidence predictions using one-way versus two-way coupling.

1. THE NEW MODEL

The model update is called 4A. The number 4 means it is a new significantly updated structural model. The letter A means it is the first update using the new 4 structural model. This can be compared to the results discussed in the previous section which is based on the 3E model, which is the previous structural model, 3 and the E is the 5th update of the history matched reservoir flow model, based on new wells and new well observations made since the 3A model was history matched. A major objective of the new 4A model was to integrate the geomechanics modeling deeper in the workflow used earlier [35].

1.1. De-Compaction

The first step in a new model of a chalk field like Valhall that has experienced significant reservoir compaction, in the case of Valhall exceeding 10 meters in some areas, is to de-compact the well observations in infill wells. The porosity and formation thickness in wells drilled into significantly compacted areas of the field needs to be de-compacted so that the static geologic model is as correct as possible for the initial conditions when considering initial porosity and reservoir thickness in the reservoir layers.

One of the few papers on the topic of de-compaction is the one by Gauer et al. [36]. The method used in that paper is very similar to the one used at Valhall historically. As part of this work, some problems with the existing methodology had been identified, so a new method was developed Kristiansen [37] and implemented Plischke [38]. The new method should be more robust, but was also

found to be more computational intensive. It resulted in around 4000 finite element model runs. Based on the experience from the new methodology, it was concluded that a more effective method most likely could be developed, Kristiansen [39]. The de-compaction methodology deserves a separate detailed paper, which may be published in the near future.

1.2. 4A Static and Dynamic Models

Since this paper is focusing on the geomechanical aspects of the 4A model, the following is just a brief discussion of a couple of key new features in the 4A static and dynamic models that is of relevance to the geomechanics model.

The most evident change from the 3 series of Valhall model to the 4-series of model is the inclusion of the Hod field. In earlier models these two fields have been modeled as individual fields. In the 4A model they are modeled in the same model. The two fields are connected to each other via a saddle structure between the two fields, the so called Hod saddle.

The model also contains fractured hardgrounds in the crest of the field that can be only 20 cm thick. These thin layers induce some challenges with the critical timesteps for the finite element based geomechanics model, as it is run in explicit mode.

More faults have also been introduced in the reservoir and in the overburden. These faults created some problems with degenerated hexahedral elements that were not foreseen based on the verification work earlier, since the mesh used in the verification model was the same as used in the model presented by Kristiansen and Plischke [23].

The de-compaction workflow has been mentioned. In addition the frequent 4D seismic surveys from the Life of Field Seismic system [30] are used to verify both static geologic and dynamic reservoir models. Also seafloor bathymetry maps from the LoFS surveys were developed for the geomechanics history matching. The geomechanics model is also verified using the 4D as part of the history matching process as presented in earlier papers [23, 31].

1.3. 4A Geomechanics

As discussed in previous sections, construction of geomechanics models at Valhall has been ongoing for over 20 years. The input parameters and in-situ stress conditions are well known, so the initial set up and initialization of the model should follow existing field knowledge [23, 26, 29, 41].

The main objective of the 4A geomechanics model was to enable a two-way coupled modeling tool that could be used on a daily basis. One of the risks, based on past experience, is too long computational time for the coupled model. A practical turnaround time from a reservoir engineering point of view is a model that runs within 12-24 hours, but preferably quicker. A risk mitigating measure for the expected run times for the coupled model was the development of the mech2sim tool, see Pettersen and Kristiansen [40]. Mech2sim is designed to use results from a coupled run to improve the predictions for uncoupled runs before a new coupled run is performed and used by mech2seis as the cycle repeats towards the final history matched model.

A facility based on LUA scripts were developed to write input files to mech2sim. Same type of scripting was also used to generate input to the well planning workflow to reduce risk of wellbore stability problems [5], as well as to reduce risk of casing deformations.

During the work on the new 4A model it was also decided to switch from the VIP reservoir simulator to the more recently released NEXUS reservoir simulator. This resulted in some additional work to couple ELFEN to NEXUS. The result was, however, a very efficient coupling based on MPI.

1.4. Results

The main result from the new model is shown in figure 11, which show the top reservoir compaction and seafloor subsidence across the Valhall and Hod fields in 2048 for one reservoir development scenario. One can here see the subsidence bowl between Hod and Valhall is merging. The model has around 3 million hexahedral elements in the finite element model. The reservoir flow model has around 700 000 grid cells in the reservoir layers. The grid/mesh in the reservoir layers is identical and mapped directly.

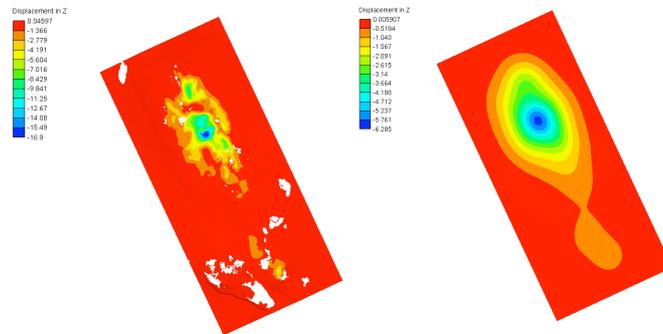


Figure 11: Vertical displacement on top reservoir layer (left) and at the seafloor (right) in a scenario for 2048 in the Valhall-Hod area.

Figure 12 show the subsidence versus time for selected platforms (Valhall QP and Hod) for one depletion scenario, including re-pressurisation by water injection. As long as the pressure is maintained, the model does not predict significant large scale water weakening. Figure 13 is showing an iso-surface representation of the vertical displacements in the Valhall-Hod region in 2048 to give a better view of the 3D distribution of the deformations.

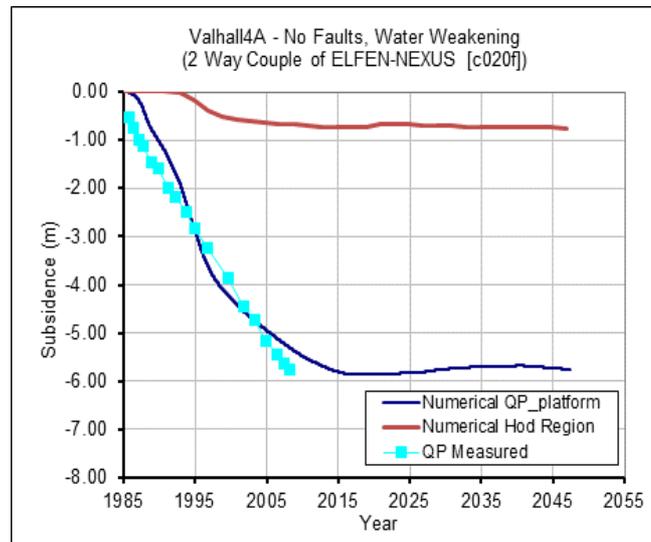


Figure 12: Subsidence versus time for Valhall QP platform and a potential Hod platform location for one potential scenario.

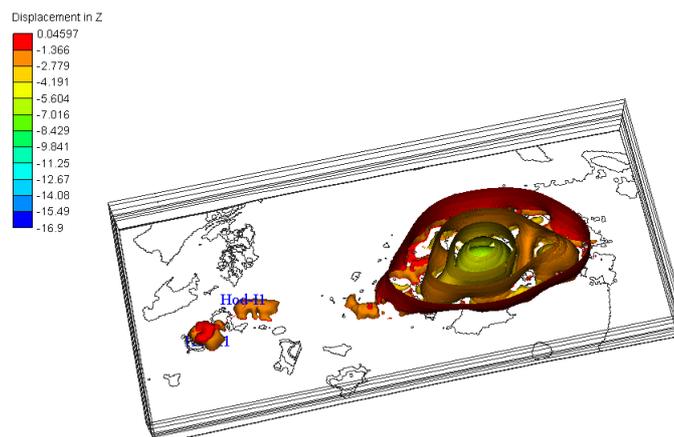


Figure 13: Iso-surfaces of vertical displacement in the Valhall-Hod area in 2048 for one potential development scenario.

We have used a monthly coupling between the reservoir flow model, NEXUS and the geomechanics model ELFEN, to date. This means that the two models are iterating to a joint solution on pore pressure and pore volume changes every month. Other coupling frequencies has also been used and tested. The run times have been improved by adding up to 24 processors for the parallelized finite element code. We are currently running history or prediction runs in 2-3 days (history and prediction from 1982 to 2050 in 4-6 days), but with a new computer cluster soon to be installed, will bring us down to the targeted goal of 24 hours turnaround time and maybe shorter.

The use of two-way iteratively coupled reservoir fluid flow and geomechanical models, brings together the best of two worlds in terms of reservoir engineering and geomechanical engineering. The joint history matching, however, is more complex than the one-way history matching from the past. We will return with some of our learning's in this area in a later publication.

Another area of improvement we have identified is the construction of the finite element mesh based on the geologic and reservoir engineering grids, especially around faults. This is still a too time consuming process, but with the developments in this project, and other ongoing activities, it is believed that this process will be improved significantly in the near future.

2. FUTURE FOR FIELD

The giant Valhall field has a significant future production potential. With the new field center put on production late 2012, Valhall is ready to produce through 2050 and it is opening up for other field developments and re-developments of tie-ins like Hod. It also opens up opportunities for optimized developments like a new wellhead platform at Valhall. The model and workflow developed in this project and presented in this paper will be a very useful tool for managing the Valhall-Hod fields in the future following the concept presented by Kristiansen [42] to manage fields with large subsurface deformations.

3. CONCLUSIONS

- A review of compaction and subsidence modeling for the Valhall field indicate a historic challenge in matching the compaction drive energy, but with incremental improvements as know-how and technology has progressed.
- A two-way coupled model that can be used on a daily basis by the drilling, well planning and reservoir teams for the Valhall-Hod fields have been developed and implemented as presented in this paper.
- The run times of the coupled model is currently getting close to the target of a turnaround time of 12-24 hours.

- At the time of writing this paper more work was ongoing to achieve a detailed history match with the two-way coupled models.
- The project also identified a need for improvements in the construction of the finite element mesh based on the geological and reservoir flow model grids.