MATHEMATICAL METHODS and MODELS for ENGINEERING

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THE LONG TERM SUBSIDENCE STUDY OF THE WADDEN SEA REGION

Review the LTS2 Final Report

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1 INTRODUCTION

NAM released on January 31, 2017, the report "Ensemble Based Subsidence application to the Ameland gas field - long term subsidence study part two (LTS II)" (Doc. nr. EP201701217189) [NAM, 2017a] and on March 17, 2017, the "Addendum" to the first report (Doc. nr. EP201703202079) [NAM, 2017b]. The documentation provides evidence of the huge work developed over the last months to implement and test the ESIP workflow, and describes the results obtained by the ESIP application to the Ameland gas field.

The main goals of the LTS2 activities are to cast light to the following issues:

- which (combinations) of the identified physical processes can explain the observed historical behavior of land subsidence due to gas production from the Ameland reservoir?
- which is the range of possible future volumetric subsidence rates? Which the uncertainty associated to the subsidence prediction over Ameland?
- which is the available control of the future subsidence on the basis of the production level carried out up to date? Which is the impact on the delayed subsidence of the "Hand on the Tap" approach?

The aims must be achieved using a methodological approach that confronts the "modelling tool" with "geodetic data" in an objective way. The application to Ameland, which is almost at the end of its production life, must be considered as a test of the ESIP effectiveness before its use for the other reservoirs in the Wadden Sea region.

Three levels of analysis are used in this report to review the documentation provided by NAM:

1. evaluation of the general achievements: the final outcomes of the study are evaluated in term of their effectiveness to provide a clear and comprehensive response to the

main questions that have require the development of the LTS2 research program itself;

2. specific components: the various ESIP components and the steps of the study are evaluated and checked against the specific recommendations listed in the report by The Wadden Academy [2015], the "Review of LTS2 Project Plan (Report 1), and arisen in the progress meetings of the LTS2 steering group;
3. presentation clearness: the documentation is reviewed from a "qualitative" point of view, checking for its clearness and usability for stakeholders.

Obviously, the importance of these aspects decreases from issue (1) to issue (3).

2 GENERAL ACHIEVEMENTS

ESIP workflow and its use in LTS2 represent major scientific advancements in the field of assessment, prediction, and management of land subsidence due to hydrocarbon production.

ESIP has been applied to Ameland. According to the work-plan, available geodetic data (levelling and GPS) have been processed to get the double-difference datasets and the related variance and covariance matrices. Multiple simulation scenarios have been developed to investigate the possible evolution in time and space of the subsidence bowl in relation to three main aspects: i) the propagation of the pressure decline in the aquifers hydraulically connected to the reservoir; ii) the constitutive relationship relating the compaction of the depleted rock to stress changes, time, and loading rate; iii) the heterogeneous nature of the overburden, in particular the characteristics of the Zechstein rock-salt layer.

Due to the stochastic framework of the approach, a large effort has been put in order to i) estimate a proper idealization noise model for the variance of double-difference observations; ii) remove outliers from the geodetic dataset; iii) develop a test statistics accounting for uncertainty in both the geodetic data and the geomechanical model; and iv) update the formula originally used in the Red Flag approach [Nepveu et al., 2010] to calculate the probability of each ensemble member. This is required to remove the so-called "collapsing" feature, which is typical of the particle filtering methods when large dataset of independent variable are used. The improvements in ESIP due to these activities are worthful. The main findings in relation to the LTS2 goals are the following:

- the expected land subsidence obtained by ESIP remains below the effective subsidence capacity [de Waal et al., 2012] of the Pinkegat area and strictly resamples the most updated outcome of the finite-element GEOMEC model [NAM, 2016a], see Figure 23 in NAM [2017b], thus increasing the confidence of the updated ESIP procedure. In the Pinkegat sand sharing area, land subsidence is expected to decrease significantly below 2 mm/yr in a few years;
- ESIP workflow is capable to distinguish, i.e. to provide a different posterior probability, between (part of) the different processes accounted for to explain the subsidence evolution. In particular, it clearly appears the minor role exerted by the depletion of the aquifers laterally connected to the reservoir (Figure 21 in NAM [2017b]). Moreover, a narrower confidence interval is associated to the scenarios with influence functions accounting for the presence of the viscous salt layer, rather than an elastic heterogeneous or homogeneous (Knothe) overburden;
- the uncertainty associated to the expected behavior of land subsidence in the Pinkegat area is quantified in 0.7 mm/yr (68% confidence interval) and ~2 mm/yr (95% confidence interval). These values remain practically unchanged after 1995 when the area experienced the maximum subsidence rate;
- future land subsidence due to production from Ameland can be controlled in part. For example, in the Pinkegat area, an emergency stop today should produce a certain deceleration of the subsidence, for example halving the expected rate at the end of the simulation period (2045) and anticipating from 2031 to 2026 a subsidence rate

smaller than 1 mm/yr (Figure 20 in NAM [2017b]). As expected, the control is limited because of the near end of the Ameland production life. The effectiveness of the "Hand on the Tap" approach should be much larger during the early stage of the production, as clearly demonstrated in Figure 20 [NAM, 2017b] showing the result related to a possible stop in 1996. This consideration is particularly important in relation to the other reservoirs, whose development is planned to start in the near future.

These outcomes demonstrate that NAM is able to properly apply the ESIP workflow to a real field case. Two specific issues could be probably investigated in more detail:

- the reason of the quite large uncertainty associated to the expected land subsidence, irrespective of the effort put by the LTS2 consortium to reduce its value. This outcome yields that the 2σ upper bound remains above the effective subsidence capacity [de Waal et al., 2012] of the Pinkegat area. Probably, the large uncertainty could be related, at least in part, to the present ESIP impossibility to take into account the whole planned scenarios, in particular those characterized by the rate type compaction behavior (the time-dependent subsidence evolution seems to suggest this as the most likely compaction model) and those with influence functions derived for a visco-elastic parameter distribution representative of the actual heterogeneity of the geologic architecture (restrictions are required to run AESUB when a viscous salt layer is accounted for in the computation). Moreover, as stated by NAM itself, the large initial overpressure (~200 bar) characterizing Ameland has not properly managed in the parameter definition of the time–decay compaction model. Finally, available data provide evidence that the Zechstein salt layer is characterized by a largely uneven thickness (ranging from 200 to 2000 m) above Ameland. If properly accounted for, this variability could led to a certain shift of the computed subsidence bowl with a possible improvement of the measurement match. Hence, the analysis of these more physical scenarios, accompanied by the removal of evidently unrealistic hypotheses, e.g. the linear elastic compaction model, could narrow the uncertainty interval;

- the ESIP applicability to neighboring unproduced reservoirs. The ESIP use described in NAM [2017a] for the scenarios accounting for the creep salt formation above the reservoir, has required to apply a sort of calibration parameter (Cm, see Section 7.7 in NAM [2017a]) to compensate for AESUB limitations and a strong simplification in the depth distribution of layer thickness and stiffness. In the present set-up, the approach appears somewhat test-case dependent, with the use of GEOMEC outcomes to finalize the AESUB setup. It is not clear whether the same procedure should be used for fields in virgin condition (where subsidence measurements are still unavailable for the calibration of a finite element model) or how it could be applied to investigate the cumulative subsidence caused by the simultaneous production of reservoirs located, for example, at different depths.

3 SPECIFIC COMPONENTS

Before the application of ESIP to Ameland, NAM has developed a specific analysis to test the various components of the workflow in agreement with the recommendations provided during the progress meetings between the LTS2 consortium and TNO-AGE and SodM or listed in the review reports of the LTS1 / LTS2 working plan. A short discussion is provided in the following for each of the main topics:

- regional geology and geological structure of the reservoir [NAM, 2017a]: sufficient basic information is provided. Some considerations are needed in relation to the possible link between the natural stress regime at the reservoir depth with the dense fault network that compartmentalized the gas field, and between the stress regime and the geomechanical properties of the gas bearing formation and the overburden;

- use of the geodetic data: CUPIDO represents a powerful software to manage the available geodetic data according with the LST1 guidelines. An interesting discussion is provided in both the LTS2 report [NAM, 2017a] and the addendum [NAM, 2017b] on the idealization noise model although, in the end, the spatio-temporal noise component is inexplicably assumed zero in the modelling calculations. Concerning the outlier handling, it should be preferable to detect benchmarks characterized by "abnormal behavior" using a different criterion (or reference) rather than the outcome of a geomechanical model;
- compaction models: the four compaction models accounted for in ESIP are properly described;
- Red Flag confrontation and conditioning: an advancement in term of narrowing the uncertainty interval has been obtained by introducing a factor related to the uncertainty of the geomechanical model in the test statistic. Moreover, the probability function has been updated with respect to the original form [Nepveu et al., 2010] in order to remove the ensemble collapse into a few members having very high probability and all the others with probability equal to zero;
- upscaling and interpolation steps: it has been properly demonstrated that the upscaling of the pressure distribution from the production model to the geomechanical model has a negligible impact on the accuracy of the calculated compaction volume;
- reproducibility of the ESIP outcome: it has been properly verified that, irrespective of the ESIP complexity, runs carried out on the same input dataset by different operators (an ESIP developer and a NAM engineer) provide the same results;
- ESIP capability to discriminate between different compaction models: a test has been carried out using a dummy model to verify the ability of ESIP to provide a reasonable (high) probability to a specific compaction law (among the four

introduced in ESIP) when this is used to develop a "synthetic truth". In particular, linear vs bi-linear models are tested, with a positive outcome obtained when the subsidence measurements are characterized by a sufficiently high nonlinearity. Probably, a more interesting test could involve the time-decay and/or the rate type models which should more likely able to reproduce the delayed subsidence observed above Ameland;

- effect of data density on model discrimination: it has been demonstrated that a clear distinction can be made between different aquifer scenarios with both a relative low and high data density above the reservoir when a significant subsidence occurs also above the aquifer;
- testing the AESUB salt behavior with FE numerical simulations: the goal is to demonstrate that, specifically for the Ameland area, the analytical solution of AESUB matches the GEOMEC outcome also when the linear-viscous salt behavior is addressed in the computation. Due to the present limitations of AESUB (which cannot handles a combination of viscous layer and elastic layers with large stiffness contrasts), the actual Ameland layering implemented in GEOMEC has been simplified in AESUB, and the stiffness contrast has been reduced. It has been verified that, by adjusting the Cm parameter of the time-decay compaction model, AESUB matches the GEOMEC outcome in term of both the shape of the subsidence bowl and the behavior vs time of the maximum subsidence. The validity of this procedure/result with respect of the specific goal of the section is questionable. Several approximations have been introduced in the model set-up, with the AESUB and GEOMEC models that result substantially different. The Cm value is calibrated to compensate this difference, but what should happen for a different reservoir? A different value of the calibration parameter should be obtained? What happen if a more "complex" compaction model should be used? A more easy and

unexceptionable test should be based on a GEOMEC model simplified as needed to run in ESIP too;

- effect of the salt layer on a possible transition of the maximum subsidence: the results are clear and point out that a major role in the prediction of the shift is played by the development of the pressure with time. As noticed above, it is not clear if the large variability of the Zechstein thickness has been accounted for in this analysis

4 PRESENTATION CLEARENESS

Finally, some suggestions are provided to improve the clearness of the report and make the readers (stakeholders) more confident in understanding and using the huge amount of information provided in this documentation. A list with the main issues is given below:

- fig. 15 left: are all the terms of the covariance matrix < 0 ? If yes, the color scale can be changed to increase the color variability in the representation;
- fig. 19: the extraction depth must be identified by D (not H), see the beginning of p.36;
- fig. 20: add the pressure unit of measure in the color bar;
- figs. 21, 22, 23: use the same subsidence range in the vertical axis of the various sub-panels;
- figs. 27 and 29: does the same color represent the same weight in the two figures? It should be preferable to make clearer the comparison between the two cases;
- fig. 30: the panels show the final pressure (for the high and the low depletion cases) and not the pressure depletion as reported in the caption. Add the unit of measure similarly to Fig. 20;
- fig. 39: “six” locations instead of “three”. Moreover, the colors mentioned in the top of p.56 and referring to figs. 39 and 40 are almost impossible to be distinguished;

- table 4: why the reservoir sandstone is much more compressible than the surrounding layers (5 times)? Even more compressible than the chalk located much shallower than Rotliegendes;
- p. 59: the number "5" (Table 5) is missing at the end of the first paragraph after table 4. "Table 1" must be removed in the second line of the last paragraph ;
- fig. 52: the color bar values are difficult to read. The maximum value (0.35 m) could be added in the figure caption;
- fig. 54: the two panels use different color ranges and the comparison is difficult. The font size in the color bar is too smaal;
- figs 56 bottom (and similarly 84, 89): the legend texts are unreadable and one larger legend would suffice for all the subpanel. Use the same range along the y-axis for each corresponding subpanel;
- p. 76: provide the Cm unit of measure for the equation in the last line;
- p. 79: remove the first 3 lines (already written in p. 78); should "Geomec" be "AEsub" in the last-but-one line?
- fig. 64 (and similarly 72, 79): the font size for the computed (contour-lines) and measured (benchmark) subsidence values are too small;
- p. 81: what are the MOVE3 data?
- fig. 65 (and similarly 73, 80): the panels are over-small and very difficult to compare. The legend font is too small. What is the grey strip? What are the dots? They must be indicated in the legend or in the caption. Why some measurement sets (dots) start from the origin of the axes and other in the center of the panel? How do you select the position of the first measurement for these latter? Can you add the error bar representing the measurement error?
- p. 82, second line: what are the "elastic boundary conditions"?
- p. 89: Figure 72 instead of Figure 71;

- figs.74 and 81: use the same color as in fig.67;
- figs. 81, 85, 86, 87, 90: use the same range for the y-axis.

5 CONCLUSIONS

The ensemble based approach ESIP has been applied in LTS2 to the Ameland case study. The results have demonstrated the capability i) of the approach to properly manage land subsidence measurements and geomechanical models to reconstruct the past displacements and predict the future behavior in a stochastic framework; ii) of the NAM team to properly apply this complex tool. The LTS2 main aims have been substantially achieved and a tangible progress has been made in the field of modelling land subsidence due to hydrocarbon production.

The results could be improved in the sense of reducing the uncertainty associated to the expected behavior of the land subsidence. ESIP workflow is ok, but some specific components probably need some more work to become fully usable in the context of a real reservoir. From my point of view, this is only a problem related to the time restriction that LTS2 consortium had to face with to complete the documentation released in January and March 2017, as also explicitly declared at p. 84 in NAM [2017a].

6 REFERENCES

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