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Long-Term Subsidence Study in the Wadden Sea Region

To: NAM, Shell, Steering Commmitee (SC), State Supervision of Mines (SSM), Advisory Group for Economic Affairs (AGE), Wadden Academy (WA)
From: B. Orlic
Date: 25 May 2015
Subject: Minutes of the 5th St. Com. meeting held on 11 & 12 May 2015 in Assen

Filename: *01-Minutes-5-SC-meeting-11-12May2015-public.pdf*
Legend: => Action points NAM
Abbreviations: LTS-study = Long-Term Subsidence Study in the Wadden Sea Region

Distribution list:
NAM/Shell:
Antony Mossop, Pieter van de Water, Jeroen Jansen, Dirk Doornhof, Ruud van Boom, Hermann Bähr, Wim van der Veen, Sander Hol, Arjan van der Linden, Pedro Zuiderwijk
SC (Steering Committee):
Hessel Speelman, Ramon Hanssen, Patrick Baud, Robert Zimmerman, Ryszard Hejmanowski, Rune Holt, Adriaan Houtenbos, Bogdan Orlic
SSM (State Supervision of Mines):
Hans de Waal, Annemarie Muntendam-Bos, Rob van Lieshout
AGE (Advisory Group Economic Affairs):
Jaap Breunese
WA (Wadden Academy):
Klaas Deen

Attendance:
NAM/Shell: A. Mossop, D. Doornhof, R. van Boom, H. Bähr, S. Hol (1st day), J. Jansen, S. Bierman (1st day), P. Kole, F. Hollman (1st day), E. Hogerduijn, R. van Eijs
UU (Utrecht University) R. Govers (1st day), G. Marketos (1st day)
SC: H. Speelman, R. Hanssen, A. Houtenbos, P. Baud, R. Hejmanowski, R. Holt, B. Orlic
SSM: H. de Waal
AGE: J. Breunese (except the Stakeholders meeting)

Absence:
All members of the Steering Committee attended the meeting except R. Zimmerman. R. Zimmerman was attending the Rock Mechanics Congress in Montreal and excused himself for not being able to attend the SC-meeting. He gave presentation at the Stakeholders meeting over the phone.

Meeting agenda; Technical documents prepared by NAM and distributed to the SC/SSM/AGE before the SC-meeting; Presentations given at the meeting by NAM and other organizations contracted by NAM:
Introduction by the Wadden Academy
Update on project progress by NAM
Update on aquifer modelling by NAM
Update on in situ compaction by NAM
Update on rock mechanics testing by Shell
Update on salt mechanics by UU
Update on subsidence and compaction volumes by NAM
Update on hypoplastic compaction law by NAM
Update on scale dependent pressure diffusion by NAM

Update on geodetic research by NAM
Update on workflow applied statistics by Shell
Note of discussion

Response from the SC-members received after the meeting:
-

Action points from the previous (4th) SC-meeting held in Dec 2014 in Utrecht and open points from earlier meetings:

=> Reports on subsidence modelling (internal NAM grey literature)
This point need to be addressed in final reports.

=> Preliminary recommendations for improving workflows
NAM was requested to revise the preliminary recommendations in line with suggestions given by the SC-members at the previous (4th) meeting and also after the meeting.
The revised version of recommendations was presented and extensively discussed during the 5th SC-meeting.
This action point is closed.

=> 5th Steering Committee meeting on 11 and 12 May 2015
NAM was requested to prepare progress reports and send them to the scientific secretary by 23 April 2015 (2.5 weeks before the 5th SC-meeting). Progress reports were submitted later, on 2 May, which reduced the amount of time available to the SC-members for review.
This action point is closed.

Meeting objective

- **Day 1: 11 May 2015**
  1) **Project progress review meeting** to receive an update from NAM on the research progress over the past 6 months, to review the results and to give NAM feedback on the research activities planned in the last 2 months of the project, until 1 July 2015, when the project ends.

- **Day 2: 12 May 2015**
  2) **Reflection on Progress review meeting**, Steer overall activities towards project finalization, Reporting issues
  3) **Stakeholders meeting** to inform the stakeholders about the project progress

Agenda

Day 1: 11 May 2015
Location: NAM, Assen (Schepersmaat 2, 9405 TA Assen)

Steering Committee meeting, 11 May, 11:00-18:35

11:00-11:15	WA Introduction (H. Speelman, 15')
11:15-11:30	Technical Introduction (NAM, 15')
11:30-12:30	Aquifers and Flow (NAM, 60')
12:30-13:00	***Lunch (30')***
13:00-13:30	In situ Compaction (NAM, 30')
13:30-14:30	Laboratory Tests (Shell, 60')
14:30-15:00	***Coffee/Tea (15')***

15:00-16:00 Salt Flow (Utrecht University, 60')
16:00-17:00 Geertsma, Hypoplastic compaction, Anomalous Diff. Eq. (NAM, 60')
17:00-17:05 Short break
17:05-18:05 Geodesy (NAM, 60')
18:05-18:35 Statistics & Testing (NAM, 30')

Day 2: 12 May 2015
Location: NAM, Assen, (Schepersmaat 2, 9405 TA Assen)

Steering Committee meeting, 12 May, 09:00-12:40

9:00-10:00 Wrap up conclusions etc. (NAM, 60')
10:00-10:30 Coffee/Tea
10:30-12:30 Discussion / Panel (All, 120')
12:30-12:40 WA Next steps & Closure (H. Speelman, 10')

12:40-13:30 Lunch (50')

Stakeholders meeting, 12 May, 13:30-15:30

13:30-13:40 WA Introduction (H. Speelman, 10')
13:40-14:40 Comments & Recommendations (SC-members, 6x10'=60')
14:40-15:30 Discussion & Questions Stakeholders (All, 50')

Meeting highlights

- **Introduction by the Wadden Academy and planning finalization of the LTS-study by the end of June 2015**
  The chairman of the steering committee Hessel Speelman presented a plan for finalization of the LTS-study in the period from mid-May to the end of June. Several pre-read draft reports were already delivered by NAM before the SC-meeting.
  The 1st June deadline (for NAM): ALL draft reports to be delivered to the WA & SC.
  (1-15 June: the time available to the SC-members for review)
  The 15th June deadline (for the SC): Review of ALL draft reports by the SC-members to be delivered to NAM.
  (15-30 June: the time available to NAM for revision)
  The 30th June deadline (for NAM): NAM delivers final versions of technical reports and the Memorandum (see below) to the Ministry of EA and SSM.

  The WA will prepare the Supplementary Memorandum. The Memorandum (i.e. *de oplegnotitie*) contains assessment and advice on the outcome of the LTS-study by the SC (~10-15 pages-long). The WA will prepare the initial version and send it to the SC-members for comments.
  The 3rd June deadline (for the WA): the WA forwards the first draft of the Memorandum to the SC-members for comments.
  (3-15 June: the time available to the SC-members for comments)
  The 15th June deadline (for the SC): the SC-members send their comments to the WA.
  (15-25 June: the time available to the WA for revision)
  The 25th June deadline (for the WA): the WA delivers the final version of the Memorandum to NAM.

- **Opening remarks by NAM**
  A NAM researcher gave a status overview of the study program. Some hypothesis to explain anomalous time-dependent subsidence look less likely now than at the start of this project but cannot be rejected. It is necessary to understand uncertainties

contributing to subsidence modelling. Also, it is necessary to recommend how the modelling, prediction and monitoring workflow for subsidence prediction, currently used by NAM, can be improved. At this stage of the project, there is no new workflow in place, but there are (improved) components of the workflow.

- **Wadden Sea aquifer depletion**

  Bottom aquifer is practically always present in gas fields, while lateral aquifers are often absent due to faulting and compartmentalization of gas reservoirs. New field information collected over the period 2005-2015 shows that: (i) residual gas is likely present in aquifer, which leads to a lower aquifer depletion (then conservatively assumed in the 2005 report); and (ii) poor vertical connectivity is likely, which leads to a slow depletion of aquifer (more likely on geological timescales – 10's-100's of thousands of years - than on engineering timescales – years to decades).
  The measured pressure profiles show a limited pressure drop of a few bars in bottom aquifer close to the gas-water contact. Shale layers present in bottom aquifer probably stop depressurization progressing further downwards.
  The effects of depressurization of lateral aquifers is limited due to compartmetilized (blocky) structure of many gas fields. Therefore, lateral aquifers often do not exist (except in Ameland field) or are small and will be depressurized relatively quickly (mostly during gas production), and the effects will likely be very limited.

  A representative from the SSM asked if there was a possibility for accelerating pressure drop and residual subsidence in the post-production period. NAM presenter answered that the largest difference in pressure between the gas reservoir and aquifer is at the end of gas production. In the post-production period, the process of pressure diffusion will be diminishing and aquifer depletion will also be slowing down over time.
  Depressurizing a significant volume of aquifer rock would only be possible on geological timescales – 10's of thousands to millions of years, and it would apply only to bottom aquifer as lateral aquifers are often not present.
  A SC-member recommended analysis of the development of the Suawoude or Roden subsidence bowls for further investigation to get a grip on possible aquifer depletion rates.

  Steering committee recommendations:
  Committee expresses its satisfaction with the work done on aquifer modelling and is looking forward to the draft report. Questions and minor comments from the discussion need to be taken into account and answered in the report. It is recommended to analyse the development of Suawoude or Roden onshore subsidence bowls for a better understanding of possible aquifer depletion rates.
  NAM is requested to submit draft report on aquifer modelling for review before 1 June.

- **In situ compaction**

  Monitoring of reservoir compaction is done in 3 key wells in the northern Netherlands, outside of the Wadden Sea region. Monitoring is done by regular surveys of gamma ray (GR) markers. Survey is done once in 5 years and accuracy of the monitoring tool is 1-5 mm. Current research aims at improving the spatial/temporal resolution of the method used to interpret the in situ compaction data. The analysis yields compaction of marker intervals (usually ~10 m) throughout the wellbore.

  A SC-member asked if there was a linear relationship between pressure decline and compaction. NAM researcher answered that the relation was linear within wide error margins. There was also variability of the compaction observed at different locations. It is recommended to consider more GR markers from the same wellbore in the analysis.

  Steering committee recommendations:
  Comments from the discussion need to be taken into account in the report. The outlook for potential use of GR markers and other measuring techniques at the Wadden Sea

fields may be added to the report.
NAM is requested to submit draft report on in situ compaction for review before 1 June.

- **Rock mechanics testing**

  A Shell researcher gave an overview of the status of experimental testing of mechanical behaviour of Permian sandstone in the Wadden area. More than 100 m of core was retrieved from the well Moddergat-3, located at the Wadden Sea coastline. 10 triaxial compressive strength tests and over 40 Pore Pressure Depletion (PPD), i.e. creep, tests were executed. Standard creep tests last 5-6 weeks and long-duration tests focus on 2-3 months. All samples were characterized (particle size analysis, porosity, permeability). The experimental results of this study were compared with legacy data on compaction of Permian sandstone from the Wadden region.
  Results of triaxial compressive strength tests show that the values of friction angles compare well with literature data. PPD test results show that compressibility and depletion path constant evolve consistently, and compare well with existing data. 80% of the total strain response is almost instantaneous and maximum 20% strain is time-dependent. MicroCT imaging of whole plugs showed some evidence for grain microcracking, but no evidence for pore collapse.
  The overall conclusion is that volumetric compaction of the sandstone reservoir could be responsible for the magnitude of observed subsidence, but it can not directly explain the observed temporal relationship between subsidence and reservoir pressure decline. Contribution of other mechanisms, which are investigated in the LTS-study, should also be considered.
  Experimental results are partly reported in a paper accepted for presentation at the American Rock Mechanics Symposium (ARMA), which will be held later this year (making the results publicly available).

  A SSM representative made a remark that experimental results suggest that the compressibility of high porosity sandstone (porosity over 25%) can be much larger than the compressibility of low porosity samples (below 15%). The average porosity of sandstone at Ameland is about 20%. Experimental data for the 20%-porosity sandstone indicate about ½ inelastic strain.
  A SC-member commented that experimental data show no evidence for acceleration of deformation and pore collapse. Difference in strength was observed earlier on oil and water saturated sandstone, but not in elasticity.
  A SC-member questioned the applicability of geomechanical models based on linear elasticity since the experiments showed that a significant part of sandstone deformation was inelastic.

  Steering committee recommendations:
  Comments from the discussion need to be taken into account in the report. The time for executing additional experiments is very limited. The SC therefore advises to focus on finalization of the report. The SC recommends better anchoring of this research to previous work, by comparing the newly acquired results against previously published work and in-house data.
  NAM is requested to submit draft report on mechanical characterization of Slochteren sandstone and Ten Boer shale for review before 1 June.

- **Salt mechanics**

  The presentation was given by a researchers from Utrecht University (UU).
  The goal of this research is to investigate time-dependent surface deformation above depleting reservoirs overlain by a viscoelastic rock salt layer. Numerical simulations were performed using a finite element code developed at Utrecht University. Numerical models of different complexity were considered. The salt was modelled assuming different salt creep laws.
  Modelling results show that significant additional subsidence due to salt flow can be expected, at least 50% more than calculated from elastic analyses. Timescales over

which subsidence develops are poorly constrained. Maximum subsidence is also poorly constrained due to uncertainties in layer material properties. Overall conclusion is that with rocksalt flow alone we do not seem to be able to match continuing high subsidence rates. Possibly another mechanism is also active.
Outputs from this part of the project will be turned into 2-3 journal papers and 1 conference paper already accepted for presentation at a rock mechanics conference.

A SC-member noted that the relaxation time of \rock salt is very important, but it is largely unknown.
A NAM researcher commented that salt is included in the workflow for subsidence modelling at NAM. Salt viscosity is one of the uncertain input parameters.
An AGE representative advised to consider volumes of the subsidence bowl in future analyses. Salt does not contribute to volume change, it only re-distributes the volume of the subsidence bowl over time.

Steering committee recommendations:
The SC recommends to consider volumes of the subsidence bowl when comparing model predictions against measured data. Checking literature on deep solution salt mining may provide useful information to constrain, at least to some extent, the values of salt creep parameters representative of field conditions.
NAM and UU.are requested to submit draft report on salt flow for review before 1 June.

- **Subsidence and compaction volumes**
  The relationship between the subsidence volume and the internal in situ volume change (i.e. reservoir compaction) within an homogeneous, isotropic, linear elastic half-space is not straightforward and it is not as stated by Geertsma. Displacement volume and internal volume change do not have to be equal. The in situ volume strain is analysed and an expression for the in situ volume strain is derived. It is found that the in situ volume strain can be significantly larger than it has been reported in the literature.

  A SC-member expressed his satisfaction with the corrected Geertsma solution and pointed out that another model used rigid basement to constrain subsidence volumes and better match observed subsidence.
  A SC-member asked whether using Geertsma model instead of more complex numerical models was sufficient. A NAM researcher answered that the performance of Geertma model versus numerical models was tested and gave less than 10% difference, which justifies the use of Geertsma model.

  Steering committee recommendations:
  NAM is requested to submit draft report/paper on subsidence and compaction volumes for review before 1 June.

- **Implications of hypoplastic compaction laws on subsidence modelling**
  The presentation addresses the implications of hypoplastic compaction of the reservoir rock on subsidence modelling. The overall conclusion is that for the case of high aspect ratio (> 10) reservoirs that are as deep or deeper than their lateral extent, elastostatic equilibrium will be very close to that of pure uniaxial strain (< 5% difference). Corrections for hypoplastic constitutive behaviour would be relatively minor and unjustified when considered alongside the other uncertainties.

  Steering committee recommendations:
  NAM is requested to submit draft report/paper on implications of hypoplastic compaction laws for review before 1 June.

- **Scale dependent pressure diffusion equation**
  Derivation of a scale dependent pressure diffusion equation is presented. The derived diffusion equation is essentially a normal diffusion equation with an additional scale

dependent diffusivity term. This equation is applicable to a porous permeable rock with flow properties (hydraulic conductivity, permeability and diffusivity) that are power law distributed. Power law distributions lack a representative scale and hence exhibit scale dependent behaviour.

Steering committee recommendations:
NAM is requested to submit draft report/paper on scale dependent diffusion equation for review before 1 June.

- **Geodetic research**

  The presentation covered: stochastic modelling for levelling and InSAR, output level study for levelling and InSAR, outlier handling for levelling and data reduction for InSAR. The study area selected for analyses is close to the Wadden Sea area.
  The stochastic model for levelling and the stochastic model for InSAR were proposed for testing geomechanical model predictions.
  The output level study was presented with the results of sample simulation scenarios for levelling and InSAR. The main recommendations from the output level study are to consider covariances when processing geodetic data; use double differences with multiple reference points and epochs; use InSAR line of sight data; and, not to remove the atmospheric signal from InSAR data.
  A method was proposed for outlier handling. The method recommends testing to separate time series of double differences; the tests should be based on epoch-wise adjusted observations; and, relaxed sensitivity tests should be defined to identify and remove the most obvious levelling outliers.
  Data reduction for InSAR is recommended to be done by spatio-temporal averaging with rigorous variance propagation.

  A SC-member provided additional explanation of the stochastic model proposed in the Geodetic study. The same stochastic model applies to an area affected by subsidence due to gas extraction and to an area not affected by gas extraction. Causes of spatially correlated noise are not important (could be multiple, such as shallow compaction due to groundwater level variation and deep compaction due to gas extraction).
  Another SC-member is pleased with progress on taking more realistic covariances into account in the geodetic noise model. He however disagrees with the way shallow compaction is accounted for and the way outliers are detected. The model requires practical verification prior to adoption as a standard. Experimental verification analysis against alternatives is needed before adoption in the standard workflow.

  Steering committee recommendations:
  The effort should focus on finalization of draft report. The choices made need to be clearly explained. The reasons for adopting a simplified method for outlier handling instead of a rigorous approach proposed by the geodetic SC-members need to be clearly documented in the report.
  NAM is requested to submit draft report on geodetic research for review before 1 June.

- **Workflow applied statistics**

  The research explores statistical methodology to compare the ability of different geomechanical models for subsidence prediction used at NAM to explain the geodetic data. The Ameland gas field is used as a case study to investigate whether there is a need for a geomechanical model with anomalous time dependency.
  Conclusions from this study are as follows: a simple linear geomechanical model is not able to describe the levelling data; it cannot be concluded that a time-decay model, with one additional parameter compared to the linear model, is the best model in terms of its ability to explain data – alternative models with equal model complexity may give a better fit to the levelling data.

A SC-member strongly advised to test additional geomechanical models (e.g. the rigid basement model and the Knothe model). Comparing the ability of different geomechanical models needs to be done as a part of this Statistics study.
A SC-member commented that the crucial question to be answered here is: when is the prediction of subsidence good enough, and when it is anomalous, i.e. deviating from the measured subsidence? He recommended to first propose the method how to make a decision on whether the prediction and measurements fit well enough. Only after this stage real data can be considered.
A SC-member objected to dropping description of uncertainties in the geomechanical observables and parameters, a key element of the original project scope, from the study.
A NAM researcher explained that the uncertainty in spatio-temporal pressure estimates is taken into account by running multiple scenarios that generate pressure fields used as inputs to subsidence calculations. Reservoir simulation models are history matched. Uncertainty in time-depth conversion is taken into account in dynamic flow modelling. Subsidence models used at NAM are regularly updated by matching the geomechanical prediction against the geodetic data over time.
A Shell researcher explained that the main motivation for this research was to apply statistics on the geomechanical models currently used at NAM, which obviously deviated from the expectations by the geodetic SC-members. Study outcomes clearly indicate that a non-linear model is needed.
A SSM representative noted that the statistics study showed that a linear model cannot explain subsidence at Ameland and a time-decay model (with one additional parameter compared to the linear model) is not the optimal model. A two-parameter time-decay model may explain subsidence better.

Steering committee recommendations:
The SC strongly recommends extending the current research towards developing a method on how to make a decision on whether the geomechanical prediction and geodetic measurements fit well enough. Proposing a method and the way it can be implemented is seen as an essential part of the research.
NAM and Shell are requested to submit draft report on workflow applied statistics for review before 1 June.

- **Discussion and conclusions**

Discussion and general conclusions of the LTS-study based on observations presented by a NAM researcher.
Candidate hypotheses considered in the LTS-study, which could possibly explain anomalous time-dependent subsidence, were discussed.

(1)
Statement: There isn't a statistically significant anomaly (between the subsidence prediction and the geodetic observation).
Conclusion: There is agreement that this can be rejected.

Discussion:
A SC-member:
The crucial question to be answered is when is the prediction of subsidence good enough, and when it is anomalous, i.e. deviating from the measured subsidence? Formal statement is needed to accept or reject the hypothesis. Null-hypothesis is that both the predicted and the measured subsidence are 'the same' (that is, realizations of the same distribution). Observed subsidence comes from the geodetic data with error-bars ('error bars' is used to paraphrase the 'variance-covariance matrix'). Predicted subsidence comes from a forward model (does not matter which one, it could be an empirical or physical model, e.g. Geertsma or numerical model). When 'are we happy' with the degree of match between the observation and the prediction of subsidence? Formal statement is needed to accept the hypothesis.

Volume of the subsidence bowl, shape of the subsidence bowl and maximum subsidence need to be considered. Considering maximum subsidence only is not sufficient.
It is acknowledged that it will be difficult to retrieve a perfect VC matrix for the predictions. The point is that a course worst-case estimate is already sufficient to propose the way the method can be implemented. That is, in order of priority:
a) First propose the method how to make a decision on whether the prediction and measurements fit well enough,
b) Then, in second instance, worry about the used parameterization and the quality and representativeness of the VC matrices.
Another SC-member:
We failed to describe the problem systematically (Kepner-Tregoe). Is disproportionality observed only in absolute subsidence or also in volume, in compaction, in area with and without salt cover, etc. The answers should have shown which alternative hypotheses were most promising and which were not.

(2)
Statement: Inaccurate reservoir / aquifer modelling, especially pressure changes in aquifers at long timescales.
Conclusion: Evidence from nearby gas fields suggests that it operates on too slow timescales. It is uncertain if this hypothesis can be rejected.

Discussion:
A NAM researcher explained that there were no recent pressure measurements in Ameland field. Old measurements show small and extremely slow depletion of bottom aquifer. The measured pressure profiles show a limited pressure drop of a few bars in bottom aquifer, close to the gas-water contact. Shale layers present in bottom aquifer probably stop depressurization extending further downwards. Generally, there are no pressure measurements in lateral aquifers due to the lack of wells.
A SC-member made a remark that aquifers are sometimes considered in subsidence calculations, and sometimes not (for the same field), and this is done in a non-consistent manner. In the case of Ameland field, it is particularly interesting if a lateral aquifer to the south is depleting.
A NAM researcher noted that aquifers were added at the request of the regulator.

(3)
Statement: Artifact of geodetic data sparsity and salt flow.
Conclusion: Salt flow is very likely to be a significant process. Wide range of salt viscosities make this difficult to quantify. The temporal behaviour seems to exclude this as a ‘sole’ explanation.

Discussion:
A SC-member disagrees using “artifact of geodetic data sparcity” as a reason for not being able to observe the effects of salt flow on the spatio-temporal evolution of the shape of the subsidence bowl. Salt caprock causes deepening of the subsidence bowl in the centre and shallowing at the edges. Currently we are able to measure vertical and horizontal displacements on the order of millimetres. It needs to be defined what density and precision of measurements is needed to constrain the shape of the subsidence bowl, especially towards limbs where displacements are small (~a few millimetres). This can be done by simple calculations and would strengthen the argument.
Another SC-member made a remark that we measure spatial height differences over larger areas, not absolute heights of individual points. All measurements over the area and in time taken together allow reliable and precise determination of subsidence.

(4)
Statement: Artifact of geodetic data. Geodetic data are known to have more complex spatial and temporal correlation and noise structure than is generally assumed.

Conclusion: This hypothesis can be rejected. Spatially and temporally correlated noise are not negligible and could have significant impact for long time scale prediction. However, the estimated magnitudes are too small to explain the observed time dependence.

Discussion:
A SC-member objects using the term “artifact of geodetic data”. The term suggests bias in the geodetic data. The suggestion that spatially and temporally correlated, random noise in geodetic observables could somehow result in disproportionality between subsidence and pressure decline, not in a single case, but systematically in all cases, bears testimony to a deep seated misconception on the nature of geodetic data.

(5)
Statement: Viscoplastic compaction (of the reservoir rock).
Conclusion: The temporal behaviour is not an ideal fit, but the field determined evidence is noisy and uncertain, and hence not a reason to reject. Magnitudes and basic time scales seem to be a good match to observed anomalous time dependence.

Discussion:
A SC-member commented that samples in long-term compaction experiments showed no sign of weakening and no acceleration of compaction. The state of stress in samples is therefore still far from the cap. Acceleration of compaction could be expected at much higher stresses, on the order of a few 100’s MPa. This conclusion should be emphasized in the report. He asked whether it would be possible to execute compaction tests at even higher axial loads.
A Shel researcher replied that the limits of experimental set-up at the Shell Rijswijk lab have been already reached. Compaction tests were executed at high axial stress (~80 MPa), which corresponds to the in situ stresses at the reservoir depth of 4 km. Further substantial increase of axial load is practically not possible. Needs to be checked whether Shell lab in Houston could do the tests, but transport of samples is then a problem. Ameland is an overpressured field, which can have an effect on deformation behaviour of reservoir sandstone.
An AGE representative noted that the subsidence at Annerveen field stabilized after the end of gas production. Field evidence could be used to support the statement that subsidence acceleration has not been seen in other fields.
A SSM representative noted that the Annerveen reservoir rock has a lower porosity (~12 %) then the Ameland reservoir: the central part of the reservoir has a porosity of ~25 % and the overall porosity average is ~20 %.

(6)
Statement: Pressure diffusion where permeability has 'long tail' statistical distribution.
Conclusion: Large parameter range and high uncertainty means that it remains a possibility (i.e. can't easily reject at this stage).

Discussion:
A NAM researcher noted that the work on this topic was still ongoing.

- **Preliminary recommendations**

  Recommendations based on the outcomes of the LTS-study were presented by a NAM researcher and discussed. Recommendations are related to improving current workflows at NAM used for objective modelling, prediction and monitoring of subsidence. These recommendations are an update on the recommendations presented and discussed at the previous (4th) steering committee meeting held in Utrecht on 1 and 2 December 2014.
  Recommendations for improving workflows are an important outcome of the LTS-study, besides the goal of identifying the causative physical processes to the observed

anomalous time dependent subsidence.

Steering committee recommendations:
It is recommended to revise the preliminary recommendations for improving current workflows at NAM used for objective modelling, prediction and monitoring of subsidence according to suggestions given by the SC-members during discussion. Recommendations should be included in final reports.

- **Closing remarks**
  Closing remarks were made by the chairman Hessel Speelman who reminded the researchers and the SC-members of the tasks and the timeline presented in the opening session (see the section: *Introduction by the WA and planning finalization of the LTS-study by the end of June 2015*).
  The chairman encouraged researchers to publish the results of the LTS-study in open literature. Publishing results in open literature will ensure transparency and yet another external review of the study outcomes. The chairman expressed his satisfaction that a number of papers was already accepted for presentation at international scientific conferences later this year. There are currently several other papers in preparation and a number of technical reports is written in the format suitable for scientific papers.

  A SC-member commented that the time available for review was too short and that an additional SC-meeting should be planned.
  The chairman of the SC replied that the time available for review in this project is quite common in the industry and scientific community. The LTS-project deadline on 1 July 2015 was set long ago and the detailed planning of review tasks was discussed in separate meetings between the WA and each member of the SC in April 2015. 5 members of the SC are available to review submitted draft reports (from 2 May till 15 June), while 1 member is not available for review in the period from 31 May to 17 June (assuming that the SC review was required in last 2 weeks of June).
  .
- **Splitting Review Tasks**
  All members of the SC are requested to review draft Summary report.

  All members of the SC are requested to provide recommendations for future work.

  Review of draft reports covering different topics is split over different members of the SC. Splitting is based on the expertise and the preference given by each member of the SC, and a fair share of work.

- **Stakeholders Meeting**
  12 May 2015, 13:30-15:30 (planned); 13-13-16:30 (actual)

  Attendance:
  Wadden Association: E. Gerbens, E. Kuipers
  Dutch Forestry Commission: E. J. Lammerts
  retd RWS: J. de Vlas
  NAM: A. van Haeringen, NAM/Shell researchers (see page 1)
  SC: All the members except R. Zimmerman (see page 1)
  SSM: H. de Waal

  Absence:
  It Fryske Gea: C. Bakker (excused himself from the meeting)

  Agenda Stakeholders Meeting and Introduction:
  00a-(WA Intro+Agenda)-Stakeholders-meeting.pdf
  List of (8) questions sent by the Wadden Association to the Wadden Academy and the SC-members on 30.4.2015:

List of questions by the Wadden Association (included in document 00a)
Presentations by the members of the SC at the Stakeholders Meeting:
Presentations and comments by the SC-members

Agenda:
13:30-13:40 WA Introduction (H. Speelman, 10')
13:40-14:40 Comments & Recommendations (SC-members, 6x10'=60')
14:40-15:30 Discussion & Questions Stakeholders (All, 50')

The chairman of the steering committee Hessel Speelman opened the meeting and presented the detailed plan for finalization of the LTS-study by the end of June 2015. This plan can be found in section: *"Introduction by the WA and planning finalization of the LTS-study by the end of June 2015".*

After introduction, each of the SC-members had a time slot of about 10 minutes to make his own observations, comments and recommendations related to the LTS-study. The SC-members were asked to:
a) comment on how the research carried out in this project has contributed to better understanding of the physical backgrounds of measured time dependent subsidence behavior and its influence on expected future subsidence in the long term;
b) comment on whether his steer and advice was taken up and followed by NAM;
c) recommend possible future work that can contribute towards better understanding of the physical processes causing anomalous time dependent subsidence and improving forecasts of future subsidence in the Wadden Sea region.

1. R. Zimmerman (Professor at Imperial College, London, UK) gave his presentation over the phone. Selected highlights from the presentation by R. Zimmerman are as follows:
(i) rock mechanical property data, which can only be obtained from laboratory measurements on cores, will be crucial for future subsidence modelling efforts; (ii) therefore, rock mechanics tests must be carefully designed and conducted; (iii) the problems posed by trying to understand and predict the subsidence in the Wadden Sea region are scientifically non-trivial, and require data collection, as well as numerical and conceptual modelling; (iv) the NAM researchers have generally been receptive to my suggestions regarding the rock properties testing and subsidence modelling; (v) the rock properties testing campaign that has been conducted has been well conceived and carefully carried out, and has yielded very valuable data; (vi) In the next two months, I will carefully read the various reports in order to: (a) attempt to decide if the data and modelling studies have succeeded in developing a sufficient understanding of subsidence in the Wadden Sea region due to gas production; (b) if necessary, suggest additional experimental or modelling work that should be carried out in the second phase of this project.

Stakeholders asked R. Zimmerman to give his opinion about monitoring. R. Zimmerman replied that monitoring was outside of his area of expertise.
Stakeholders asked whether R. Zimmerman was positive about the study results. R. Zimmerman replied that he could not say at this point with certainty whether we solved the problem or not.

2. A. Houtenbos (Independent Subsidence Analyst, Haren)
Selected highlights from the presentation by A. Houtenbos are given below.
The problem is that, contrary to standard theory, subsidence does not develop proportionally to pore pressure decline. This threatens cash flow (as seen by EA/NAM), gives unreliable prognoses and proves inability to control unexpected impact via production rate (as seen by society). EA ordered a study without specific deliverables. The LTS-study provided interesting insights, but no tangible improvement of prediction reliability. The study has a theoretical character, with too little experimental verification.

The SC did not operate independently in the LTS-study and the Wadden Academy represented the view of NAM rather that those of the SC. There was not enough preparation time and no time for discussion at the SC-meetings, it was not clear which suggestions were made and how the SC decided on it. Many suggestions were ignored. Requests to perform a rigorous problem analysis and statistical testing of alternative theoretical hypotheses were ignored.
A. Houtenbos is not prepared to take part in any new phase unless independent steering is guaranteed and suggestions are rejected only after reasoned and minuted weighting op pros and cons.
A. Houtenbos gave the following suggestions: (i) delay close out date of the LTS-study and start a new phase only if the old one is completed; (ii) do not accept a time table for completion of phase one of the LTS-study; (iii) the SSM is advised to reject current study.

Stakeholders commented that it was difficult to judge what was precisely studied in the LTS-study and what came out from this study. We are interested to know whether we can expect larger subsidence in the future. Now we can only get opinions of different scientists.
Stakeholders asked how the different parts of the research will be combined to draw overall conclusions.
Stakeholders commented that according to A. Houtenbos something in the process was wrong.

3. R. Holt (Professor at NTNU Norwegian University of Science and Technology, Trondheim, Norway)
The new insights from the LTS-study are as follows: (i) lab studies show that reservoir rocks are not likely to produce significant creep in the anticipated stress regime resembling the stress conditions of Ameland field; (ii) time effects can be caused by salt flow, but the time-scale for expected response needs to be constrained; (iii) time effects could be due to possible slow depletion of aquifers with residual gas; (iv) lab studies show that the reservoir rock deformation is elastic and inelastic; (v) lab studies show evidence of non-linear behaviour (deletion dependent compressibility).
There are also non-resolved issues, namely: (i) slow depletion of (Ten Boer) shale as a candidate for time-delayed subsidence has not been fully addressed; (ii) implementation of depletion dependent compressibility in subsidence model – need to go beyond Geertsma model?
In general, this is a high quality research, which needs anchoring to scientific community and, in particular, to previous work.
Recommendations for further work are as follows: (i) pin-point the time scale of salt response; (ii) elasticity vs plasticity vs time dependent deformation; (iii) use of a novel refined Geertsma model for subsidence prediction; (iii) clarification of the impact of slow depletion zones.

Stakeholders asked for a clarification of elastic versus inelastic deformation of reservoir rock.
R. Holt replied that a homogeneous rock, when loaded (i.e. depleted) can deform elastically and inelastically at the same time. It is essential to define what kind of compressibility we should put in subsidence models. We need an appropriate material model to correctly handle the observed deformation behaviour.
A SSM representative asked whether subsidence could accelerate over time.
R. Holt answered that experimental testing was done under in situ conditions, which is in line with good practice. The stress conditions in samples at the end of depletion are far from failure to get accelerating subsidence.

4. R. Hejmanowski (Professor at AGH University of Science and Technology, Krakow, Poland)
Subsidence prediction is a difficult problem as the physics is complex and there are many influencing factors. R. Hejmanowski deals with subsidence prediction due to mining in Poland, which is generally one order of magnitude larger than subsidence due to gas extraction in the Netherlands. He is generally satisfied with the geodetic part of the LTS-study. Stochasticity and uncertainty of geodetic data are now known, and the geodetic data from different sources are available. However, hypothesis testing with real data from Ameland was not done in the LTS-study.
R. Hejmanowski agrees with the conclusions from the LTS-study presented by NAM.
R. Hejmanowski expressed his satisfaction with the role of the SC in the LTS-study. The remarks that R. Hejmanowski made were followed up and implemented by NAM specialists. The only problem was due to late delivery of some reports before SC-meetings, which shortened the time available to the members of the SC for preparation.
R. Hejmanowski made the following recommendations for a follow-up study: (i) introduce and test new time-decay models with additional parameters; (ii) compare new models against those already in use at NAM; (iii) check the impact of anisotropy on subsidence; (iv) try to constrain Maxwell time by measuring salt convergence *in situ* in salt mines.

Stakeholders asked if the problem analysis had been done at the start of the study, would it have been possible to reach some conclusions earlier?
R. Hejmanowski replied that now we know much more than at the start of the LTS-study due to the results achieved in the study.
Stakeholders asked whether different models for subsidence prediction were compared in the LTS-study. Which model is the best, i.e. has the lowest uncertainty?
R. Hejmanowski replied that this was not done. However, an important outcome of the LTS-study is a refined Geertsma model for subsidence prediction.
A NAM researcher noted that a literature review of different models for subsidence prediction was left out from the LTS-study.

5. R. Hanssen (Professor at Delft University of Technology, Delft)
Overall, considerable progress has been made in the LTS-study. R. Hanssen is satisfied with what has been done in the LTS-study and positive about the outcomes of the study. The LTS-study has clear aims, which are described in ToR. The problem analysis was done (in the process of writing ToR, before the project started. The process was generally ok. Discussion is used as a means to convince people and reach a decision. This is in line with good academic practice.
The crucial question to be answered is: when is the prediction of subsidence good enough, and when it is anomalous, i.e. deviating from the measured subsidence? One of the possibilities is to reduce error-bars of geodetic measurements. We can define quality measures explicitly. This was not done enough in the LTS-study. Therefore recommendations were given to propose the method how to make a decision on whether the prediction and measurements fit well enough.
Several measuring techniques exist nowadays: levelling, radar, GPS. We obtain different results from different techniques and do not understand why. We need quality characterization of geodetic data in much better sense.

Stakeholders asked which geodetic technique was the best.
R. Hanssen answered that the best could be defined in terms of different criteria: quality, spatial coverage, frequency, value for money, etc. In terms of quality, the best technique is the old-fashioned levelling (which is expensive and therefore not done frequently); in terms of spatial coverage it is the satellite radar; in terms of the ability to detect anomalous subsidence, it is the GPS. Monitoring is not a matter of choice as, for example, satellite data are collected anyway. Despite development of new techniques, it is recommended to maintain levelling network.

6. P. Baud (Professor at University of Strasbourg, Strasbourg, France)
Selected highlights from the presentation by P. Baud are as follows:
(i) short-term laboratory experiments can provide some degree of constraint on the constitutive law for Permian reservoir sandstone; (ii) extensive series of compaction tests showed that the compressibility is a function of porosity; there is inelastic behaviour; there is no evidence of acceleration of deformation; and, there is no effect of pore fluid and temperature.
Viscoelastic behaviour of reservoir sandstone is a candidate to explain at least part of observations. The question is how to integrate this process in predictions.
Regarding the salt mechanics research, more data on salt rheology is needed. Uncertainty on parameters (grain size, impurities, etc.) make it difficult to make precise quantitative predictions.
In conclusion: (i) experimental program was discussed in SC-meetings and evolved according to the advices of the SC; (ii) the work gave very valuable results; (iii) it improved the understanding of some of *in situ* processes leading to time-dependent subsidence; (iv) the work contributed to better understand the situation in the Wadden Sea region; and (v) future work should consider carrying on experimental work to provide an upper bound for acceleration to occur and quantifying stress-induced micro-cracking.

General discussion:
Stakeholders asked whether levelling is necessary when other techniques are available.
A SC-member replied that it is preferable to use combined techniques. Levelling can be reduced, but not abandoned, because satellite data are now available weekly.
A NAM researcher noted that levelling provides only vertical signal, while other techniques like InSAR provide lateral and vertical component of displacements.
A SC-member expressed his dissatisfaction with the correspondence between the geodetic experts serving on the SC. There was much more interaction between the rock mechanics experts serving on the SC and the researchers. He repeated that the problem analysis was requested but not done. Also, there is a lack of time to do the synthesis.
Stakeholders noted that the problem analysis was not done, but could have helped to better focus the research.
A SC-member replied that the problem analysis was done. The LTS-study has clear aims, which are described in ToR. The process was generally in order.
A SSM representative commented that there were framing sessions and brainstorms before ToR was written and the project started.
A SC-member commented that one of his suggestions that were followed up by NAM was that related to Geertsma model. Research effort resulted in the development of a novel refined Gertsma model.
The SC-chairman commented that some members of the SC were sceptical about the salt research, but the results of this study showed that salt can play a significant role in time dependent subsidence.
Stakeholders asked how decisions were made. The process was not transparent. She also complained about the brevity of public version of minutes of the SC-meetings.
A SC-member replied that the process of decision-making was ok. Discussion is used as a means to convince people and reach a decision.
Stakeholders commented that we are not interested in individual opinions of the SC-members. We need to know how the LTS-study contributes to the understanding of subsidence? Is there more certainty in subsidence prediction? What is the ecological effect on long term?
A NAM manager commented that we have achieved academic results in the LTS-study, which will be applied to field data in a follow-up study (phase 2 of the LTS-study).
A SSM representative noted that a number of mechanisms were identified. These need to be applied to a field case.
Stakeholders expressed his satisfaction with the fact that the impact of aquifer depletion

on subsidence, as proposed by the stakeholders at the 1st SC-meeting, was picked up by NAM and further studied.
A SC-member noted that we are now half-way through with the research with respect to where we should have been. The phase 2 of the LTS-study should have been finished.
Stakeholders noted that practical application will take place in a follow up study, i.e. in the 2nd phase of the LTS-study. The role of the stakeholders in the 2nd phase of the LTS-study needs to be discussed.
Stakeholders asked whether the time available to the SC-members for review was too short. Also, whether the SC-members will be actually available for review.
The SC-chairman replied that the project deadline of 1 July 2015 was set long time ago and the detailed planning of review tasks was discussed in separate meetings between the WA and each member of the SC in April 2015. 5 members of the SC are available to review submitted draft reports (in the period from 2 May till 15 June), while 1 member indicated that he is not available for review in the period from 31 May to 17 June.

Requests and Action points NAM

- ⇨ **Reporting**
  Detailed planning of activities and the deadlines are given in the section: *"Introduction by the WA and planning finalization of the LTS-study by the end of June 2015"*.