T017

Quantifying Time-lapse Effects of Solution Squeeze Mining

G. van Noort* (Delft University of Technology), G.G. Drijkoningen (Delft University of Technology), R.J. Arts (Delft University of Technology), J.W. Thorbecke (Delft University of Technology), J.G. Bullen (Nedmag Industries Mining & Manufacturing BV) & J. Visser (Nedmag Industries Mining & Manufacturing BV)

SUMMARY

In the northern part of The Netherlands the magnesium salts carnalite and bischofite are mined in a deep solution mine. For optimal production and also for environmental impact such as subsidence, it is vital to understand the process of salt production. To this aim, it is studied whether seismic in time-lapse mode may help to visualize and quantify the changes due to the salt production. The main questions addressed are: Can changes due to salt production be detected in seismic time-lapse mode? And if so, how big are these changes? To address these issues, a modelling study was performed. Seismic data were synthesized using acoustic and elastic finite-difference schemes, and further processed to obtain migrated seismic images. For the models themselves, different production scenarios were studied. Analysis of these data clearly shows that salt mining causes detectable changes in time-lapse seismic signals and can be quantified. The amplitude effect seems relatively larger than the induced time shift.

Introduction

Nowadays, time-lapse seismic is a well established technique for monitoring hydrocarbon production (Calvert, 2005) and, e.g., CO_2 storage (Arts *et al.*, 2006). However, for many other subsurface processes such monitoring is often too expensive or its gains are less obvious, like in the case we discuss in this paper: Seismic monitoring of salt production through solution mining at depths larger than 1.5 km. In this paper we try to demonstrate the feasibility and the added value of seismic monitoring of deep salt mining.

In the northern part of the Netherlands the Zechstein formation, deposited in the late Perm, consists mainly of salts and is found at a depth range between 1400 and 1800 meters. The main components for commercial exploration are magnesium salts, more precisely carnalite and bischofite. Mining started in 1972 in a conventional way, where the salt was dissolved by flushing fresh water through different wells. This produced brine-filled caverns of some tens of meters height and around 100 meters in diameter. In 1996, the method was adapted to squeeze mining where the salts are made more mobile using a pressure difference, i.e. a underpressure in the caverns, between the magnesium salt layers and the caverns. This makes the salt creep towards the caverns.

Apart from the commercial reasons for monitoring salt mining, there are also environmental and safety reasons: The salt mining leads to subsidence of the surface in habituated areas. To prevent the caverns from collapsing, a safety margin was set by the government of a maximum cavern size of 100 m in diameter. Furthermore, the Dutch government prescribes that the maximum subsidence of the surface may not exceed 65 cm at any point to limit damage to constructions. At the currently observed rate of subsidence this limit will be reached in a few years' time.

Due to these restrictions and the commercial stakes, it has become paramount to better understand and monitor the full process of this salt production. Although the mining engineers control the mining process, but they have little idea of the 3D geometry of the caverns in the subsurface since very no geophysical imaging and very little logging was done in the past. Seismic and its time-lapse mode, if proven successful for this application, would solve those questions and help to better understand and control the process of mining, including the overburden effect. The study presented in this paper is a seismic-modelling study where the following questions are answered:

- Can changes due to salt production be detected in seismic time-lapse mode?
- If so, can these changes be quantified?

Creating a model including synthetic seismics

Based on the interpretation of 3D time migrated data, a subsurface model of the salt mining area was constructed. To limit the computation time for the synthetic seismics, a 2D cross section of the model was selected. The properties of this model, i.e. the P-wave velocity, S-wave velocity and mass density, were derived as follows:

- The P-wave velocities were obtained from a regional velocity model, determined by Van Dalfsen et al (2006). This velocity model gives the velocities for the main formations. For the Zechstein group a sonic exists from the 1970's giving a more detailed velocity of 4600 m/s for the gypsum and halite, and 4300 m/s for the carnalite and bischofite. For the brine/fluid that replaced the rock salts, a velocity of 1500 m/s has been assumed;
- The S-wave velocities were obtained by using rock physics models. For the rocks other than the salt, Castagna's (1985) empirical relation for sandstones was used: $V_S = 0.804\ V_P - 0.856$. For the salts themselves, the shear-wave velocity has been obtained by assuming a Poisson's ratio of 0.35, as determined by Jeremic (1994). No shear-wave velocity has been assumed in the brine;
- The mass densities were extrapolated directly from a density log in a well.

Based on the model information above, pre-stack synthetic seismic data were created, using both acoustic and elastic 2D finite-difference schemes. These data were then processed up to a migrated seismic P-wave image. For the imaging, a pre-stack time-migration approach was taken. For optimal imaging results, the velocities used have been obtained through a velocity semblance gather. The resulting seismic image can be seen in Figure 1 (left), next to the corresponding 2D section extracted from the 3D data (right). Note the similarity between the main horizons of the synthetic model and the real seismic.

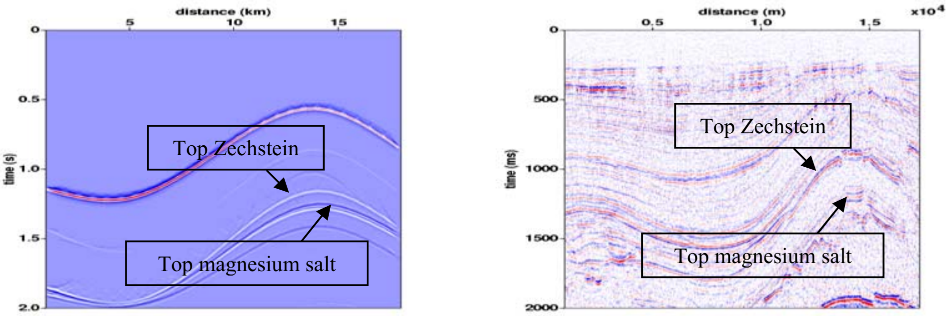

Figure 1: *Seismic images obtained from: (left:) synthetic modelling, pre-stack time migrated. (right:) real 3D seismic.*

As a next step, the model was adapted to mimic one year of salt production. Based on real production data, 27,500 m^3 per year per well was assumed. Since the formation of caverns due to production is uncertain, several scenarios were defined. Here we will show the effects of three scenarios (Figure 2), with the production taking place in the vertical direction (changing layer/slab thicknesses) and in the horizontal direction (extending finite slab, one year of production compared after scenario 2).

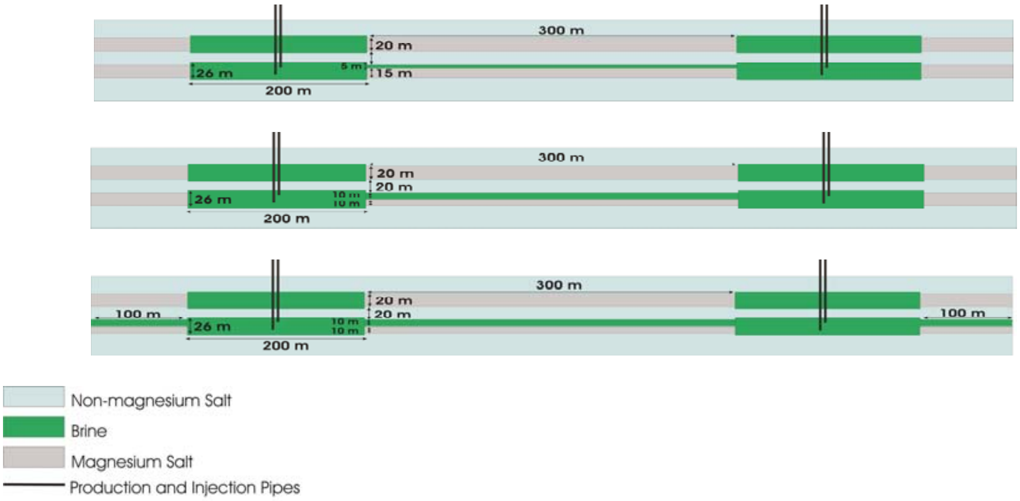

Figure 2: *(Top:) Scenario 1: The reference model. Salt production changing layer thicknesses. (Middle:) Scenario 2: Salt production changing the vertical extent of slab.(Bottom:) Scenario 3: Salt production changing lateral extent of slab. This scenario represents one year of production after scenario 2.*

Results for time-lapse seismic

Based on the two scenarios, we have produced seismic time-migrated images. The initial synthetic data were obtained with purely acoustic modelling. For the processing, we used the same velocity model as for the reference model. The results for Scenario 1 (see Figure 2) and the differences with the reference section are shown in Figure 3. One can clearly see time shifts and amplitude changes occur due to the salt production.

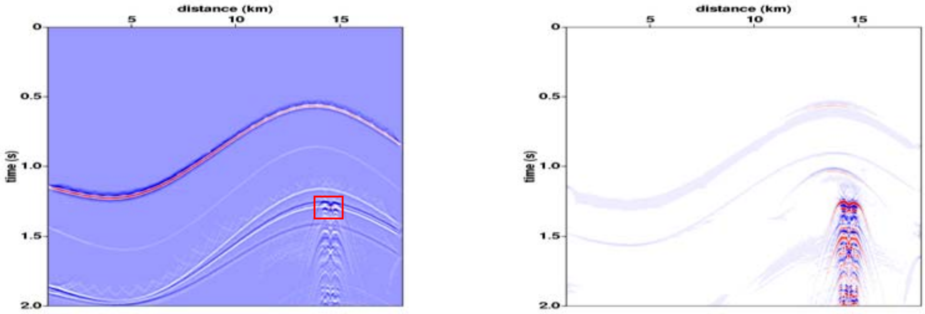

***Figure 3**: (Left:) Migrated seismic image for scenario 1. The red box indicates the area of interest. (Right:) Differences with reference image.*

In order to quantify the time-lapse changes, we performed 2D cross-correlations between the sections and normalised them with the autocorrelation of the reference section. For this correlation, we only used the area of interest, around the main reflection from the salt mine, to avoid the effect of unwanted diffractions and multiples, that are still present in the time migrated images.
The main conclusion here is that no time-shift of about can be observed between scenario 1 and 2, and a time-shift of 0.25 ms between reference model and scenario 3. For amplitudes comparing the time-lapse seismic data to the reference model, a change of 3.4% can be observed for scenario 2 and 6.0% for scenario 3.

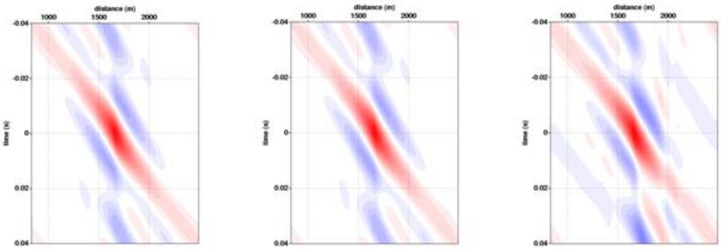

***Figure 4**: Zoomed-in normalised auto-correlation of reference section (left), cross-correlation of the reference model with scenario 2 (middle) and cross-correlation of the reference model with scenario 3 (right), using acoustic modelling.*

So far, we showed the results for acoustic modelling, but because of the displacement of rock by a fluid/brine we would expect also a large effect in the elastic response. In the migrated post-stack domain the results are higher, namely a amplitude change of 4.8% and 18.3% between the reference model and scenario 2. The time-shifts is 1.0 ms.

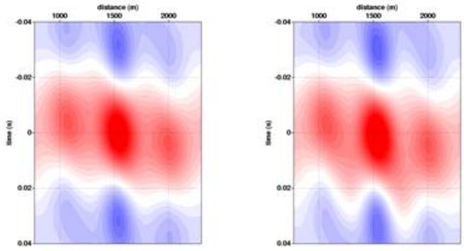

***Figure 5**: Zoomed-in normalised auto-correlation of reference section (left), and cross-correlation of the reference model with scenario 2 (middle)), using elastic modelling.*

Discussions and conclusions

This seismic modelling study clearly shows that salt mining can cause detectable changes in time-lapse seismic signals. Elastic modelling gives much more pronounced results than purely acoustic modelling. The amplitude effect seems relatively larger than the induced time-shift. The inversion of the time-lapse seismic data to the geometry of the cavern is less obvious. A rather complex interference pattern arises, similar as observed for example in CO_2 storage at Sleipner, where the CO_2 spreads in thin layers below thin shales (Arts et al., 2006). The lateral extent of the anomaly is easer to detect. In a follow-up study we intend to focus more on the inversion process.
Of course success for field surveys would still depend on several other factors such as noise conditions encountered in the field, with a particular challenge on land, repeatability of the time-lapse seismic data and the successfulness of migration/imaging due to structural complexity in and around the salt body. However, especially by using fixed arrays, we are optimistic about detecting caverns with time-lapse seismic data.

References

Calvert R. 2005. *Insights and methods for 4D reservoir monitoring and characterization*, EAGE/SEG Distinguished instructor short course, No. 8, 2005.

Arts R.J.,, O. Eiken, A. Chadwick, P. Zweigel, L. van der Meer and B. Zinszner, 2006. Monitoring of $C0_2$ injected at Sleipner using time-lapse seismic data, *Proc. 6th International Conference on Greenhouse Gas Control Techniques,* Vol. **29** (9-10), p. 1383-1392.

Castagna J.P, M.L. Batzle and R.L. Eastwood, 1985. Relationships between compressional-wave and shear-wave velocities in clastic silicate rocks, *Geophysics*, Vol. **50** (4), p.571-581.

Dalfsen W. van, J.C. Doornenbal, S. Dortland and J.L. Gunnink, 2006. A comprehensive seismic velocity model for the Netherlands based on lithostratigraphic layers, *Netherlands Journal of Geosciences*, Vol. **85** (4), p. 277-292.

Jeremic, M.L.. Rock Mechanics in Salt Mining. Lisse: A.A. Balkema, 1994.