Technical Note

ARUP

13 Fitzroy Street
London
W1T 4BQ
United Kingdom
www.arup.com

t +44 20 7636 1531
d +44 20 7755 2569

Project title	Salt Mine Seismicity	Job number	260166-00
cc		File reference	2.0
Prepared by	(London), (London)	Date	12 February 2018
Subject	Document Review and Initial Recommendations – Rev A		

1 Introduction

On 19 November 2017, a seismic event occurred in the vicinity of the Heiligerlee (HL) salt diapir, near Winschoten, in the Netherlands. Following the event(s), Arup has been contracted by Akzo Nobel Industrial Chemicals B.V. to provide consultancy support related to the observed seismicity. The scope of the work is presented in Arup's proposal letter dated 16 January 2018.

This technical note provides an initial review of the documents provided and the initial recommendations following examination of the following documents. Since this is an initial review, the recommendations provided are associated with a degree of uncertainty.

- Koninklijk Nederlands Meteorologisch Instituut (KNMI) provided a draft report on the analysis of the seismic event, recorded at their stations G57 and G52. [Winschoten_events_20171119.doc]
- K-UTEC provided a report on several events recorded by their microseimic monitoric network in the salt cavern located in Hengelo [Bijlage 5 - Microseismic monitoring AN Hengelo - Update report 170929b.pdf]
- The Netherlands Institute of Applied Geoscience (TNO), National Geological Survey provided a report (dated September 2000) of seismic imaging of the salt cavern together with a velocity model. [Ref_AvN_01.pdf]
- Akzo Nobel provided maps of the HL diapir and a report containing maps of the HL and ZW diapir with the location of the salt caverns and 3D models of the different salt caverns in Heiligerlee (HL) and Zuidwending (ZW) [XLT pdfs and Overzichten HL en ZW_3D + data_per 31-08-12.pdf]
- The report by Oranjewoud for Akzo Nobel [XLTAvN080105definitief-incl-kaarten (ENG).pdf March 21, 2005] re Long term planning, Adolf of Nassau Production Licenses Adolf of Nassau Adolf of Nassau Extension (translated from Dutch); and,

- Plan of HL salt dome showing locations of 12 extraction caverns and two geological cross sections (interpreted from the combination of well and seismic data) [p55_20_10_807(k).pdf, p55_20_11_961(i).pdf, and p55_20_11_969(c).pdf].

2 KNMI Analysis of the 19 November 2017 Earthquake [Winschoten_events_20171119.doc]

KNMI closest stations which recorded the event are called G57 and G52 (see Figure 1, extracted from Winschoten_events_20171119.doc): G57 is located about 1.5 km SE from the estimated epicentral location and G52 is about 3.5 km NW of the estimated epicentral location. The epicentre has an uncertainty of about 500m in all three axes (as reported in 'Bevingen in de zoutkoepel Heiligerlee.pptx'). No magnitude is provided as there is a lack of attenuation model.

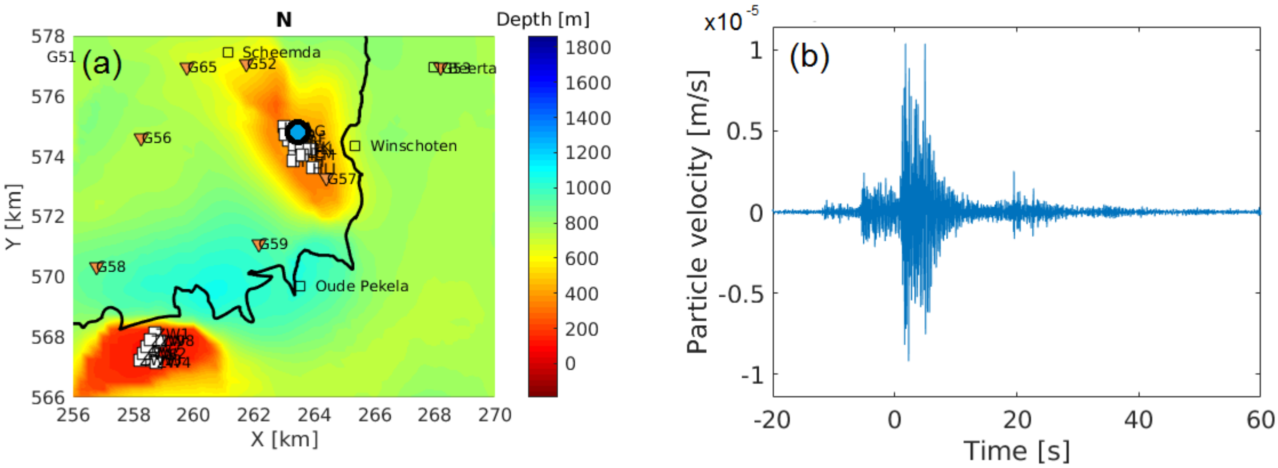

Figure 1: Figure from the KNMI report (a) Area around Winschoten showing the depth of the North Sea group sediments (colour scale), the border of the Groningen gas field (black line), KNMI seismic stations (orange triangles), salt caverns (white squares) and the Seiscomp3 location (blue dot). (b) Vertical component registration at sensor G574 (the 200 m depth level of station G57). The no-stop time corresponds to 14:00:48 UTC (15:00:48 local time) on 19/11/2017.

The KNMI report indicates that the depth of the event is 1km but does not specify the uncertainties on this value. The presentation 'Bevingen in de zoutkoepel Heiligerlee.pptx' seems to suggest that the uncertainty on this value is also 500m. The report states that this depth excludes the possibilities of a surface event or an event at the depth of the gas reservoir. The depth of the reservoir is probably not stated in the report but is known to be at about 3km. It is therefore concluded that the event is related to the activities at the HL salt diapir. The report also notes that four separate events can be distinguished on the seismogram.

The KNMI report also provides the frequency content at stations G574 and G524, which we understand are the recordings at one of the instruments located at the G57 and G52 sites. The frequency content shows that most of the energy is contained in the lower frequencies f<10Hz (Figure 2). This frequency content is the one at the seismic station, and no statement is provided about the frequency content at the source, accounting for propagation effects from the source to the KNMI station.

No clear statement is provided in this report on the type of event that happened, although the conclusion of the report alludes to a potential collapse.

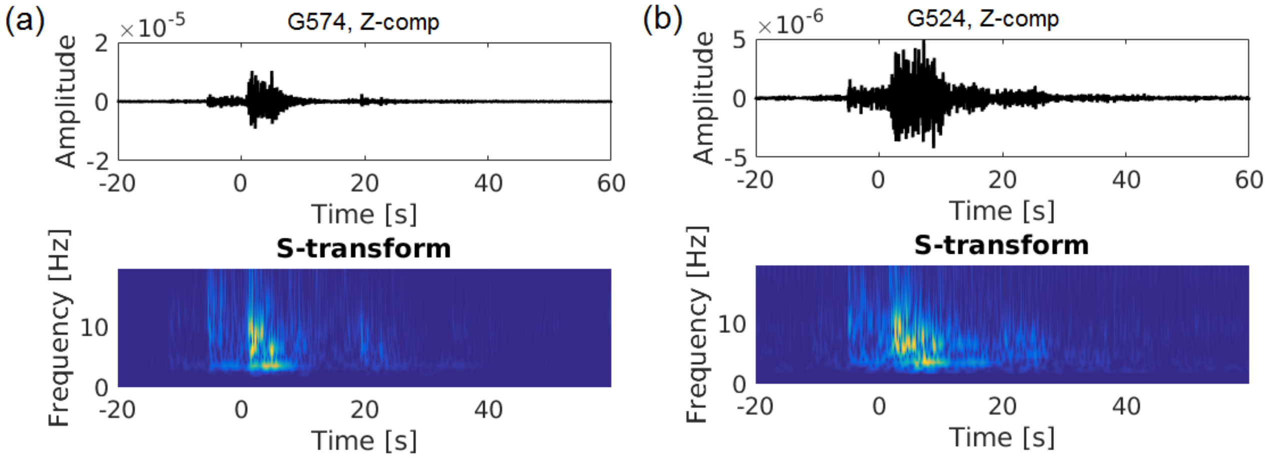

Figure 2: Figure from the KNMI report. Recording of the Winschoten 19-11-2017 events at the two nearest seismic sensors, namely G574 (a) and G524 (b). On top panels are the registration in the time domain, on underlying panels in the time-frequency domain.

3 Possible Events in Salt Diapirs [Bijlage 5 - Microseismic monitoring AN Hengelo - Update report 170929b.pdf]

The K-Utec report points out that three type of events can happen in a salt cavern:

- A usual seismic event, i.e., slip on a fault;
- The formation of a crack/fault in one of the cavern walls; and
- Rocks falling inside the cavern.

These events can be distinguished by a geophysicist with appropriate experience, mainly based on the frequency content of the signal, the amplitude of the signal and its duration. Some frequency ranges for the three types of possible events are given in the report but there is some overlap.

4 Velocity Model [Ref_AvN_01.pdf]

The TNO report provides a seismic cross section of the salt diapir in time (TWT) and a velocity model. We assume that the velocity model is a P-wave velocity model. This velocity model is only made of velocity gradients in each of the sediment layers and no velocity is provided in the salt. The time-to-depth conversion is only done in a “layer-cake” approach, which will not yield a good approximation given the steeply dipping flanks of the salt and the strong velocity contract between the sedimentary rocks and the salt.

5 General Description and Context of the Salt Caverns at HL.

[Description based on review of document **Overzichten HL en ZW_3D + data_per 31-08-12]**

At the HL salt dome 12 Akzo Nobel production salt caverns exist. In plan view the caverns form a NW-SE trend, which is parallel to the long-axis and crest of the HL salt dome. Each cavern is approximately 250m-500m distance apart. The proposed epicentral location (+/-500m) of the seismic events on 19 November 2017 is closest to cavern HL-K, which is a nitrogen storage cavern that has been ‘in production/usage’ since 1997.

The top of the salt at HL is generally between 400-500m depth below the surface. Generally, the salt cavern roofs are at ~700m-800m depth below the surface, by contrast the HL-K cavern roof begins at 1,000m depth, and the roofs of the two nearest caverns to HL-K, HL-L and HL-M, are at greater depths of 1,100m and 1,550m respectively. In terms of geometry, all caverns are cylindrical and several hundred metres in height. The HL-K cavern has a height of 492m (volume 830,000m^3), a maximum diameter at the base (65m), which is rounded and narrows to the top where the roof is 25m in diameter. The thickness of the salt overburden at cavern HL-K is 567m.

The overview document also provides information about the extraction parameters of the different caverns. Since cavern HL-K contains nitrogen there is no injection/extraction of salt at present.

6 Report by Oranjewoud (2005)

The Oranjewoud report describes the process of planned drilling. The key useful information in this document are the tables and maps in the Appendices and Annexes. Relevant to the HL salt dome are:

Appendix 6 (PDF page 41) provides a map of the modelled ‘soil subsidence’ in millimetres for the period 1969-2000 of ‘oilfield Winschoten/Heiliger’ (Figure 3). Note, the subsidence modelling is not discussed in the report. We assume that the ‘water measuring points’ shown as blue dots on Figure 3 have been used to generate the subsidence contours shown. The maximum modelled subsidence for this period is estimated to be 100-110mm and is shown to be in the centre of the HL dome with the same NW-SE elongation as the dome geometry. The total subsidence decreases to ~10-20mm over a radial distance of ~1.5km from the centre. Spatially, a low magnitude of subsidence extends further to the north than to the south. Outside of the maximum subsidence contour, which is elongate NW-SE, the other contours have a preferred NE-SW elongation, which is perpendicular to the crest of the salt diaper. The spatial pattern of surface subsidence over time might provide information about the source processes/mechanisms that accommodate subsidence in the shallow and deeper subsurface. The trends in subsidence contours at HL might be related to/controlled by the faults identified in the seismic reflection data (see Section 9.4). By contrast, the contour pattern might be related to the spatial distribution of the underlying data and the method of contouring (see Section 9.4). This requires further investigation.

Technical Note

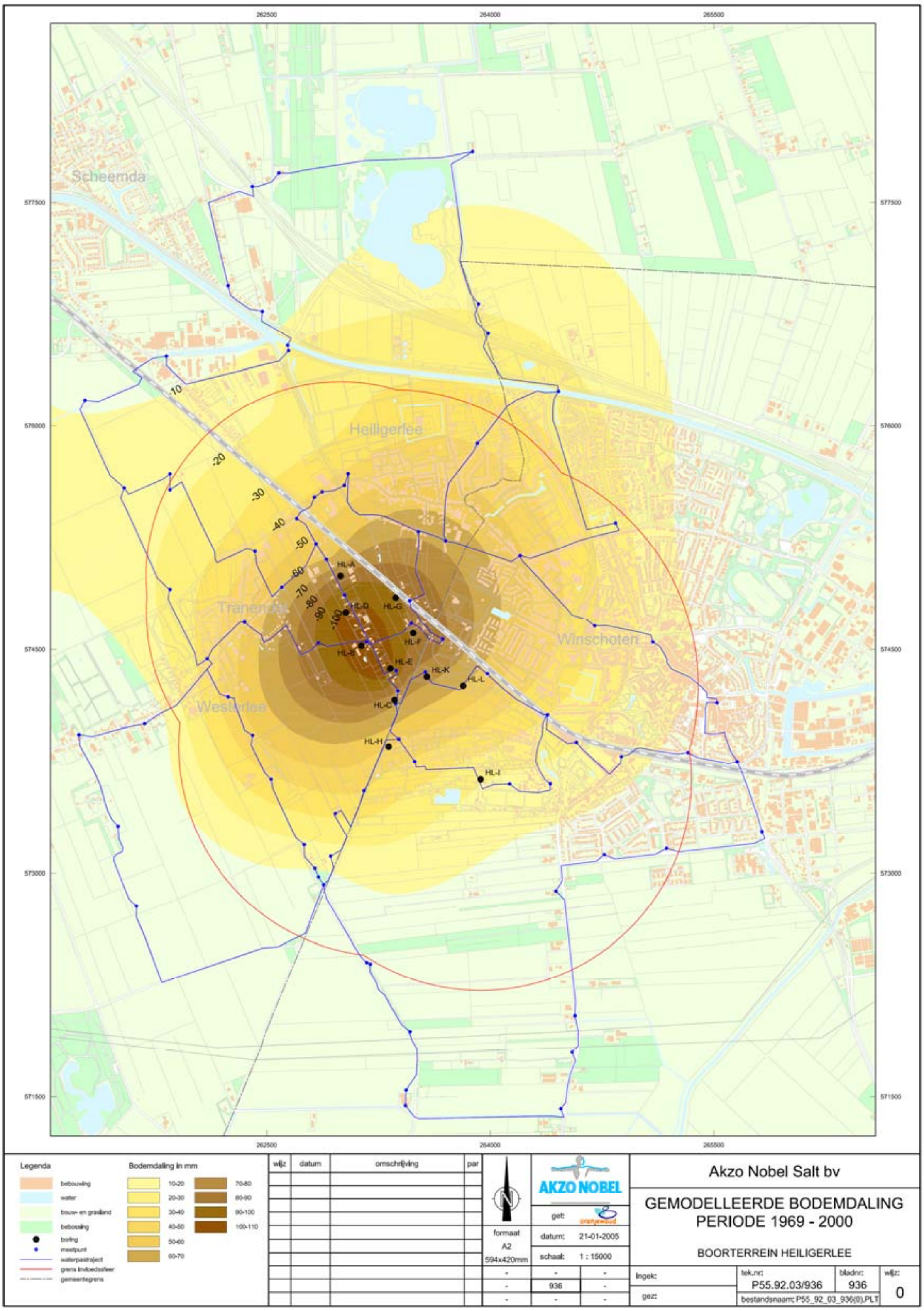

Figure 3: Modelled soil subsidence map, period 1969-2000, assuming the subsidence modelling is based on data collected at the blue water pressure measurement points.

Appendix 10 and **Annex 12** provide the 'current situation map', with 11 cavern well locations marked and dome (diapir) depth contours (depth to top salt), and the 'long-term planning map' in terms of planned drilling locations for the HL dome, respectively. These maps do not add much information to what we already know.

The tables provide the values of 'in tons of salt per year' for the historical and future salt production at Winschoten/Heiligerlee, including 'Planned salt production Winschoten/Heiligerlee and Zuidwending 2005-2019' and also 2020-250, and the 'Production history Winschoten/Heiligerlee and Zuidwending 1957-2004'. See Section 9.4 for some discussion.

7 TNO-Report 'Mapping of the Winschoten Salt Dome'

This report contains the most useful geological and structural information regarding the HL salt diapir.

The key points are:

- A 35 km^2 fully migrated 3D seismic reflection survey ('Blijham-Groningen') has been collected, interpreted, and mapped in terms of geology and structures (see example below);
- The stratigraphical interpretations are based on well data existing from the Akzo Nobel Salt wells;
- The seismic mapping was focussed upon the upper part of the salt dome, where Akzo Nobel salt exploits the rock salt;
- The report presents a series of 'depth to base of' (different Formation) contour maps at 1:25,000 scale, 3D model perspective views of the dome with some structural sections, and projected well locations, also some timeslices of the seismic reflection data;
- The seismic data captures the geometry of the salt dome well: the long axis (dome crest) trends around 4-5km NW-SE, it is ~2km wide at the cap rock depth and widens to the NW with the geometry becoming slightly more complex. The dome has steep flanks and apparently 'no observed overhangs' have been detected;
- The stratigraphy is of the overburden (Formations that are above the actual salt), includes from shallowest to deepest (at the top of the salt):
  - Miocene (Upper North Sea Group) – top most strata imaged
  - Upper Tertiary (North Sea Supergroup)
  - Lower Middle Tertiary
  - Cretaceous Chalk Group – thickness on top of the dome ranges from 0m to 50m and increases to 650m away from dome.
  - Lower Cretaceous – Caprock, 25m thick anhydrite bed

  NB: all Formations of the overburden are 'domed'/convex with decreasing magnitude toward the surface, this geometry results from the gradual upward movement of the salt over geological time.

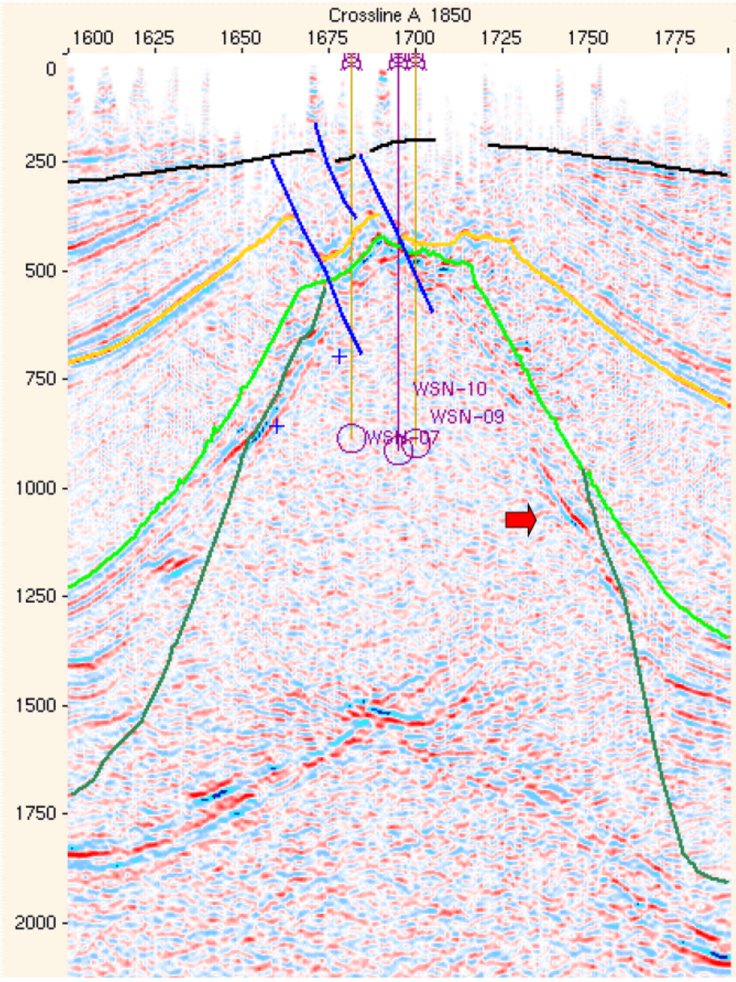

Figure 4: Example of an E-W seismic line from the Blijham-Groningen 3D survey. Three wells are projected on this line. The data hiatuses in the uppermost part of the section are due to data acquisition problems. The top of the dome is imaged by the dark green line. The red arrow indicates the position of an anhydrite floater or a caprock relict.

- Faults are interpreted from the seismic data; these interpretations look reasonable/sensible based on the vertical offsets estimated along linear structures observed in the overburden Formations;
- Faults are observed in the overburden at the western and northern flanks, and are interpreted to have accommodated extension related to the upwards motion of salt emplacement over the last 60-20 million years (Ma);
- The faulting has caused collapse in the overburden. It is not clear from the available data if the collapse has affected the salt (i.e. whether collapse structures could affect the caverns);
- Faults trend N-S and NW-SE, extend up to several kilometres length, and are present at depths between 200m-800m;
- On the depth contour map, faults are not interpreted in the top caprock, however, on the seismic section example shown and in the description, the faults are interpreted to extend into the uppermost tens of metres of the shallowest part of the dome;

- The faults interpreted in the base of the Miocene Formation are close to several production wells, the relative vertical offsets across these faults, since ~20Ma, amounts to ~100m;
- The base of the Tertiary Formation at the northern margin of the dome has been offset by several faults that indicate relative vertical offsets amounting to up to 300-400m during last 60Ma; and
- The report infers that the salt movement was triggered by motion along a normal fault at depth. Evidence of the deep normal fault is not discussed. There is no discussion/description of the regional tectonic/geological setting.

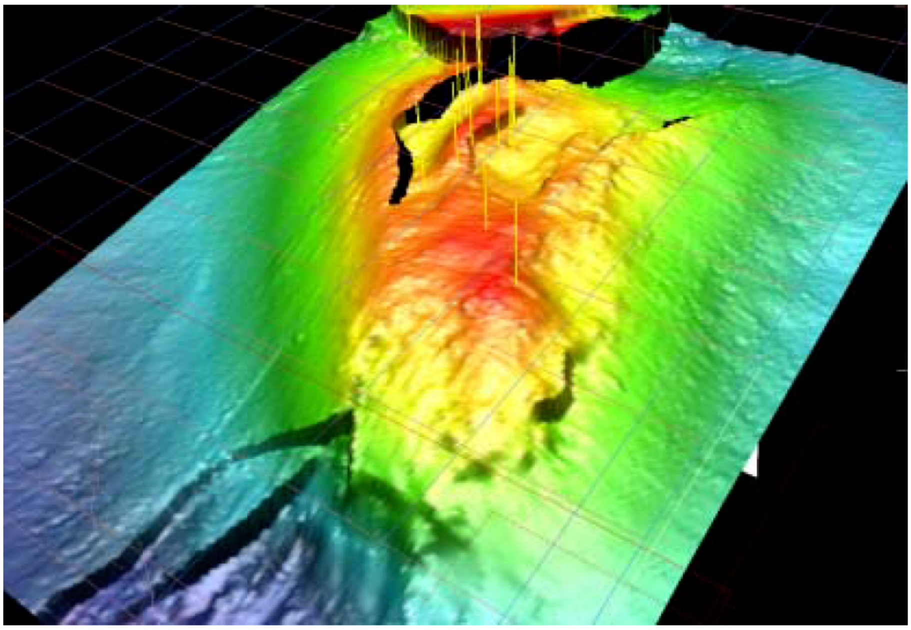

Figure 5: 3D perspective view of the base Tertiary. The horizon is situated on top of the dome close to the caprock. Hence, the picture shows the shape of the top of the dome. The yellow lines represent the well trajectories above the base Tertiary. Obvious are the faulted areas, caused by salt dissolution, at the top and next to the dome.

8 Summary

- The recordings at some of the KNMI stations suggest that four events happened around the HL salt diapir. These events are not at the surface and did not happen at the depth of the gas field (~3km depth);
- Depending on the frequency content, the amplitude, and duration of the signal, it is in principle possible to distinguish between three types of events that may occur in a salt diapir: a regular seismic event, a crack opening, and rocks falling inside a salt cavern;
- The frequency content of the events in the KNMI report is the frequency content at the recording station, not at the source. An assessment of the potential frequency content at the source is needed to assess which type of event occurred. The frequency content at the recording instruments has been naturally low-pass filtered by the Earth, because of frequency dependent attenuation by the Earth crust during wave propagation;
- A velocity model is available for the sediments above the salt diapir, but is based on simplistic assumptions;

- Faults that extend up to several kilometres in length exist in the overburden Formations of the HL diapir, on the northern and western flanks;
- The faults exist at depths (below the surface) of ~200-800m placing them within range of the +/-500m bounds of uncertainty estimated for the 19 November 2017 seismic event(s);
- The geometry of the faults that have been interpreted and mapped from the seismic data are quite well determined, it would probably be difficult to improve on this with any additional data collection;
- Over geological time (20-60Ma) the faults have accommodated up to several hundred metres of vertical offsets caused by extension related to upwards motion of the salt;
- The faults are close to several production wells;
- Such faults could be reactivated (seismically) under favourable stress conditions; and
- The maximum modelled ‘soil’ subsidence over a ~30-year period (1969-2000) has been estimated to be 100-110mm and is shown to be in the centre of the HL dome.

9 Recommendations

9.1 Type of Event Recorded

- In the KNMI report, the frequency content of the events is provided at two stations only (G574 and G524, Z component in both cases). The frequency content should be provided at the other KNMI stations and along all three components. As was explained in the K-Utec report, the frequency content of the event can help an experienced geophysicist to confirm which type of event was measured;
- Arup requests access to the data recorded by KNMI at their different instruments in ASCII format, in order to review KNMI’s assessment of the data;
- Some other seismic events have been recorded in the vicinity of the salt cavern by the KNMI network (see Figure 6). Arup requests the waveforms of these events and the frequency content on the same stations that recorded the salt-diapir event and at similar KNMI stations close to these events. We believe the comparison of these events to the 19 November 2017 events might provide some valuable information on the type of event that occurred in the salt cavern on 19 November 2017;
- The frequency content of the events at the source should be estimated and used to assess which type of event occurred in Heiligerlee (seismic event, crack opening or rocks falling in the cavern). K-Utec’s expertise would be valuable in telling apart these events: they could provide a database of recordings corresponding to different event types; and
- Akzo Nobel has asked DEEP.KBB (salt mining & leaching consultant) to perform simulations with falling blocks of several size and shape through caverns in brine and gas to determine the energy release at impact. The modelling of rocks falling in the cave by DEEP will add some valuable information. The modelling could include both rocks falling into brine and into gas, in order to see if the responses can be told apart. Ideally their modelling should also account for the wave propagation from the cavern to the KNMI instruments.

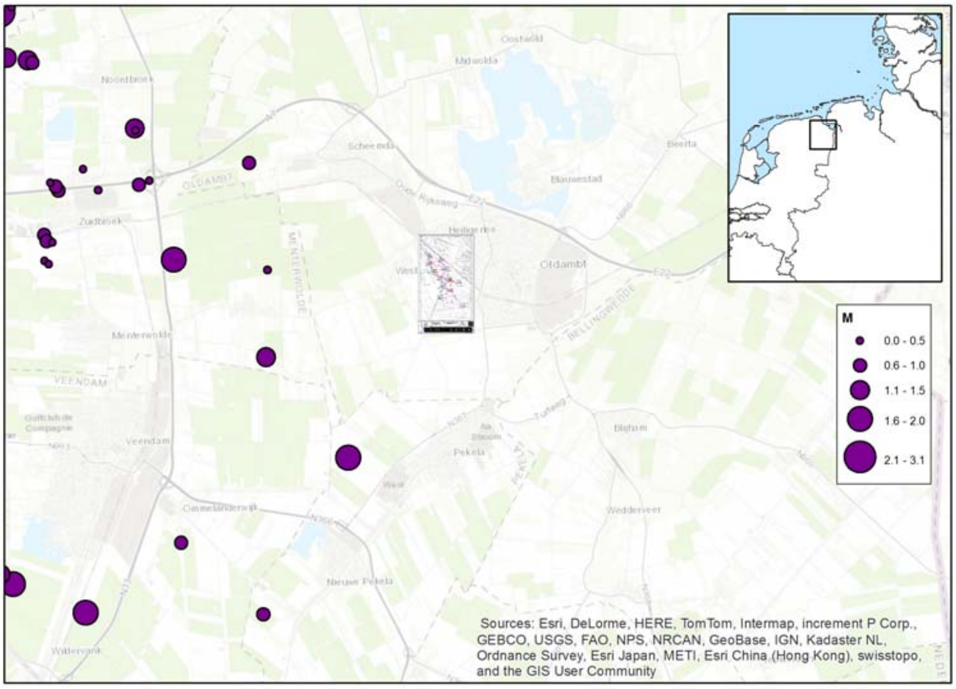

Figure 6: Map of earthquakes from KNMI website between 2010 and 2018.

9.2 Velocity Model

- Given that seismic reflection data is available, it should be used to perform a proper depth imaging of the area (with depth migration rather than time migration) and a P-velocity and S-velocity model building. These velocity models are of paramount importance in order to perform a good localisation of the events in the salt once a local seismic monitoring network will be in place. Given the small surface area of the site, the velocity model building should be achievable in a relatively short time (one to two months); and
- More specifically, since the signal below the salt is not needed for the current purpose of localising seismic events in the salt, a fast-track velocity-model building should be sufficient:
    - Seismic reflection tomography performed in the sedimentary layers; and
    - Velocity in the salt determined by migrating the seismic data with different constant velocity values in the salt. The velocity that provides a flat base of salt is usually the one to choose.

9.3 Further Seismic Monitoring

Further monitoring of the seismic activity in the salt dome is required in order to assess the potential for seismic hazard. In other salt mines (e.g. Bayou Corne, Lousiana, USA), the spatio-temporal evolution of the seismicity was a good indication of general seismic hazard (e.g., Shemeta et al, 2013). The monitoring network will be designed in order to achieve the following technical specifications:

- A horizontal location accuracy of about 50m, in order to tell apart next to/in which salt cavern seismic events might happen. This is based on the fact that the minimum horizontal distance between two salt caverns is 121.2 m (distance between HL-E and HL-C);

- Record a frequency content wide enough, from 1Hz to 1,000Hz, in order to record micro tremors as well as possible rock collapse in brine. Rock collapse in brine would typically have a frequency range 3 Hz < f < 30 Hz according to the K-Utec report. Frequencies up to 1kHz should be recorded to be able to characterize micro-tremors (e.g., Mercerat 2010, Klein 2011); and
- A sensitivity high enough to record micro tremors, of the order of 1 μm/s (or equivalent for hydrophone) and therefore a good signal-to-noise ratio for both P- and S-waves. This value is based on the tremors recorded at the brine-filled cavern of Cerville-Buissoncourt in France (e.g., Mercerat 2010).

The documents provided by Akzo Nobel will be helpful in the design of a seismic monitoring network, as it shows the locations and 3D extent of the different salt caverns.

- We need to know which caverns are potential candidates to receive a recording instruments and which ones of them cannot be considered. This information will be used to design a seismic network; and
- Once several tremors (more than a hundred) will have been recorded by the local monitoring network, some post-processing of the seismicity recorded at the network should be considered in order to achieve better characterization of seismic source parameters:
    - Double-difference relocalisation of the events will allow a much more accurate relative localisation of the events. A freeware such as HypoDD can do this (Waldhauser, 2001); and
    - Spectral Ratio method in order to compare the frequency spectra of the different events recorded in the salt diapir. This provides the difference of frequency spectrum at the source, which should help identify the type of events observed.

9.4 Geology

- A quick review of the overall tectonic and structural setting of the salt dome region is required to better understand the overall structural patterns/controls of the region and whether there is available data/evidence of regional longer-term subsidence;
- Understanding any potential relationship between the faults and the seismicity at HL requires better accuracy of xyz location for the seismic event(s) and, if possible, determination of the seismic event mechanism. This should be possible for any potential future events from the proposed monitoring network;
- We need clarification of how the modelled subsidence map (Oranjewoud Report) was derived and, if possible provision of the raw data;
- The annual 'in tons of salt per year' information for each cavern at HL might be useful if we can compare this to other analogous case examples (where salt solution extraction seismicity has been observed), to get a feel for the magnitude of the processes that led to induced seismicity elsewhere. This should be reviewed;
- Using the modelled subsidence map, it may be possible to look at similar data from an analogous context to identify an approximate threshold or 'triggering' rate of subsidence. This should be reviewed; and

- The faults identified in the seismic reflection data should be mapped onto the subsidence map. This can clarify any correlation or lack of correlation between the two data i.e. whether a link exists between the spatial pattern of surface subsidence and spatial pattern of faulting in the shallow and deeper subsurface (top ~1km below the surface). However, first, the raw subsidence data is required.

10 Other References

[1] Shemeta, Julie, Mark Leidig, and Dario Baturan (2013). "Passive Seismic Observations at Grand Bayou, Louisiana, USA Associated with the Failure of Oxy Geismar #3 Solution Cavern", Solution Mining Research Institute Fall 2013 Technical Conference.

[2] Waldhauser, Felix (2001). *hypoDD* -- A Program to Compute Double-Difference Hypocenter Locations, Open File Report 01-113.

[3] Mercerat Diego, Lynda Driad-Lebeau, and Pascal Bernard (2010). Induced Seismicity Monitoring of an Underground Salt Cavern Prone to Collapse. Pure Appl. Geophys. 167: 5. https://doi.org/10.1007/s00024-009-0008-1.

[4] Klein Emmanuelle, Isabelle Contrucci, Ngoc-Tuyen Cao, Pascal Bigarre (2011). Mining induced seismicity: monitoring of a large scale salt cavern collapse. 73. EAGE conference, May 2011, Vienna, Austria. pp.NC, 2011.

DOCUMENT CHECKING (not mandatory for File Note)

	Prepared by	Checked by	Approved by
Name	(London), (London)		
Signature			