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Rock mechanical assessment of the reconstruction of storage cavern ZW-A1 at Zuidwending (NL)

Contractor: N.V. Nederlandse Gasunie
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1 Introduction

At the location of Zuidwending an underground natural gas storage cavern field has been developed by leaching deep salt formations. During the first phase 8 wells have been drilled for the leaching and subsequent storage operations of four caverns. These caverns are located in a depth between 1000 m and 1400 m. Their volumes are in the range of up to 0.7 million m³. In the second phase caverns were planned in a depth range between 1150 m and 1500 m with a volume of up to 1 million m³.

One cavern well of the second phase is ZW A1A which has been drilled through the overburden succession into the evaporite sequence of the Zuidwending salt dome with a total depth of 1,527.0 m. Because of a massive anhydrite layer that was found during drilling, the decision was made to change the depth of the cavern roof from 1150 m to 1050 m to ensure a final cavern volume of 1 million m³.

Cavern A1 was leached until December 2012 up to a volume of 751 Tm^3. During the last five years any kind of operation was suspended and only rock mechanical and technical observations took place.

It is now planned to continue leaching cavern ZW-A1 until a final volume of 1 million m³ is reached and then convert the cavern into a gas storage cavern. This conversion also includes drilling and completion of a second well ZW-A1B. Further, the cavern operator will change from AkzoNobel to EnergyStock, which is a subsidiary of Gasunie. In this context Institut für Gebirgsmechnik (IfG) was asked by Gasunie to prepare a rock mechanical assessment of the intended further leaching operations of cavern ZW-A1.

2 Geology

The salt dome is an upwards moved structure of the Zechstein Salt Formation, tightly sealing the huge Groningen gas field, which lies beneath almost the whole province of Groningen, in the north-eastern part of the Netherlands. The salt dome itself consists of two distinct lobes, starting at a depth of around 3000 m up to around 200 m below ground level. The cross sectional area of the salt dome is approximately 15 km².

Well ZW A1A enters the Zechstein salt sequence below the caprock. Rock salt and anhydrite belonging to a younger sequence than the Staßfurt (z2) sequence was intersected directly below the caprock at a depth of 200 m MD and again from 1,442.7 m MD to total depth.

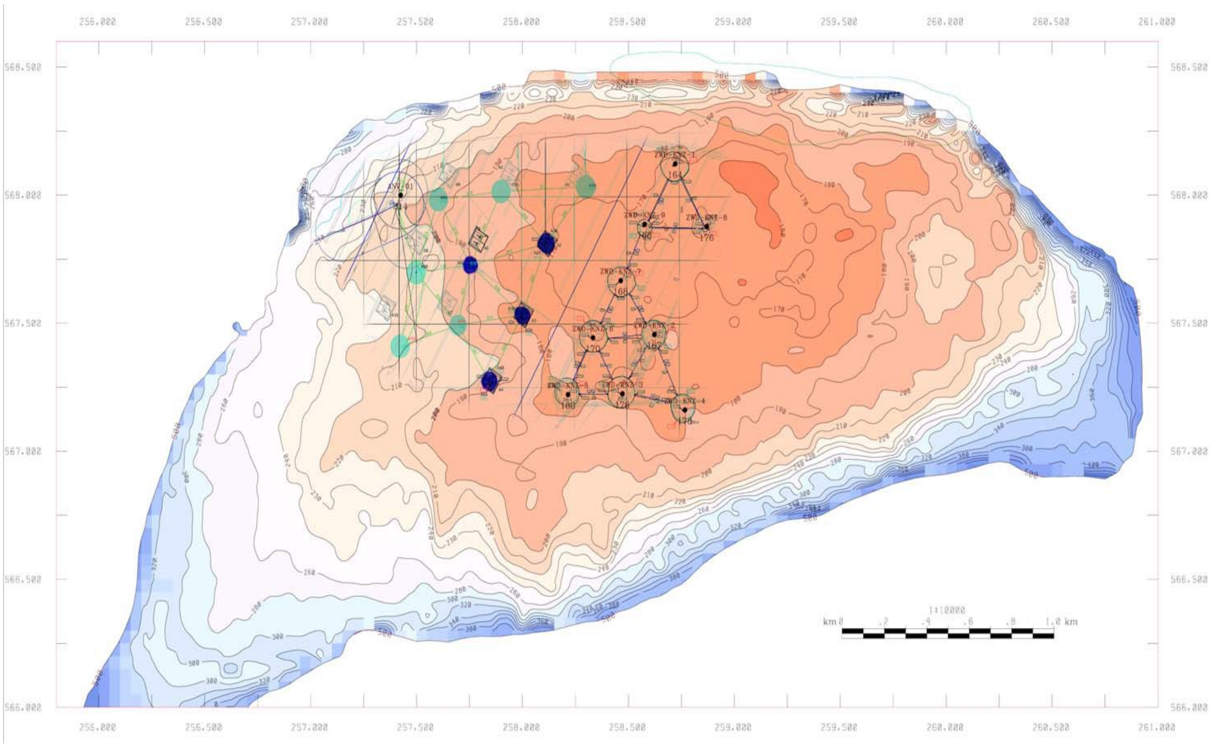

Figure 1: Depth contour map (top salt)(NITG-TNO 1999)

The main part of the evaporites section in ZW A1A (from 225.0 to 1,400.0 m MD) comprises z2 salt (Staßfurt Main Salt) which is characterized by bromide values of150 to 250 µg/g halite. Due to a minor drop in density, gamma ray, and bromide values between 1,400 to 1,446 m MD, rock salt members younger than the Main Salt were identified. It can be assumed that the Z2 (Staßfurt) potash seam occur between 1,443.0 to 1,446.0 m MD, due to an increase of density and gamma ray values.. From 1,446.0 to 1,448.0 m MD, a washout, and a positive gamma ray excursion indicates the occurrence of Grey Salt Clay and Pattendolomit of the basal Z3 (Leine) Formation. This is followed by the z3 (Leine) Main Anhydrite from 1,448.0 to 1,499.5 m MD, characterized by a distinct pattern in the density log. Subjacent the Main Anhydrite a rock salt succession was drilled until total depth of the well at 1,527.0 m MD.

3. Carried out investigations

The standard rock-mechanical tests have been performed on core material which was selected by IfG from the available cored sections. The rock-mechanical concept for phase II caverns allows the construction of storage caverns with a volume of approx. 1 million m³ volume (geometrical). This concept can be applied to cavern ZW A1.

Recommendations regarding the cavern shape and operation modes were given in the following reports

> “Geomechanical numerical modelling for dimensioning, the possible operating regime and the prognosis of long-term gas storage operation of the natural gas storage caverns at Zuidwending (B IfG 11/2007)”, and
>
> “Rock mechanical modelling for the assessment of the convergence behaviour of deeper caverns at the Zuidwending salt dome (Phase II)” (B IfG 61/2009).

At that time it was not state-of-the-art to include thermodynamics into rock mechanical modelling in the basic layout concept. The considered cavern operation mode represents more or less an annual storage mode with some superimposed cyclic operations.

As shown by the results of the numerical modelling and the rock mechanical assessment a safe operation of the underground storage could be proven for the intended storage mode. Furthermore, it could be stated that the stability as well as the geological tightness of the cavern is guaranteed in all operation phases with sufficient safety margins. Also the results of the assessments of the load bearing capacity of the pillar and the hanging wall are sufficient and acceptable, even in case of an uncontrolled blow-out.

Further investigation took place in 2012, when cavern ZW-A1 was subject to a case study. As part of the investigation “Case studies for cyclic operated storage caverns 'Aardgasbuffer Zuidwending' NL” (B IfG 49/2011) cavern ZW-A1 was exemplarily investigated. In this study thermodynamics were included and special recommendations were given in combination with a clearly defined operation envelope regarding limited convergence and therefore limited surface subsidence.

Rock mechanical assessment of the intended cavern reconstruction

Cavern ZW-A1 has the potential for an extended cavern volume based on the pillar dimensions, which is even greater than for cavern ZW-A5. Cavern ZW-A1 shows a sufficient distance to its neighboured caverns ZW-A2 and ZW-A5. However, cavern ZW-A1 shows a very pronounced preferred leaching direction to the North, which can be identified by the 24 m shifted balance point. Comparing the last two sonar surveys a very small to negligible development of the cavern can be observed in the south direction. This leads to a strong eccentrically development of the cross sections. Therefore, the potential for extending the cross sections of cavern ZW-A1 is given only above 1240 m.

Possibly a volume of 400.000 m3 can be leached in the roof which has to be shaped according to the recommended rock mechanical cavern envelope.

Regarding the intended conversion of cavern ZW-A1 into a gas storage cavern N.V. Nederlandse Gasunie asked for a rock mechanical assessment of the following issues:

1. Pillar width respectively distance between cavern ZW-A1 and the gas storage caverns of EnergyStock
2. Pillar width respectively distance between cavern ZW-A1 and brine production caverns AkzoNobel
3. Distance of cavern ZW-A1 to the edge of the salt dome
4. Special considerations for the second borehole
5. Location and spacing between the two boreholes
6. Depth location of the last cemented casing shoe (LCCS) of well ZW-A1B
7. Expected operating range with regard to maximum pressure (p-max), minimum pressure (p-min) and limiting pressure change rate (dp/d)

Safety pillars between gas storage caverns

The assessment of the pillars between caverns is based on the sonar survey protocols, which were presented after leaching operations were suspended. The position of the well head as well as the position of the last cemented casing shoe, which are necessary to position the measurements at the right location, were provided by DEEP, Underground

Engineering GmbH with the document „Cavern location planning – Zuidwending“ (Rev. 5e, see fig. 3).

From the rock mechanical point of view the required system cross section A_{Sys} that surrounds a gas storage cavern depends on the caverns cross section and the relevant depth as follows:

$$\frac{A_{Sys}}{A_K} = 1.2 + \frac{H}{H_*}$$

with:

- A_K being the cavern cross-sectional area from a circle around the maximum diameter in the relevant depth,
- A_{PZ} being the effected cross sectional area (required pillar zone surrounding the cavern),
- A_{SYS} being the system cross section (i.e. cavern cross sectional area + pillar),
- H* being an empirically determined parameter (H* = 140 m) from,
- H being the depth.

$$R_K^2 = (A_K/\pi)$$

$$A_{SYS} = A_K + A_{PZ} = 6^* \, (R_K + a_{PZ})^2 {}^*\tan 30°$$

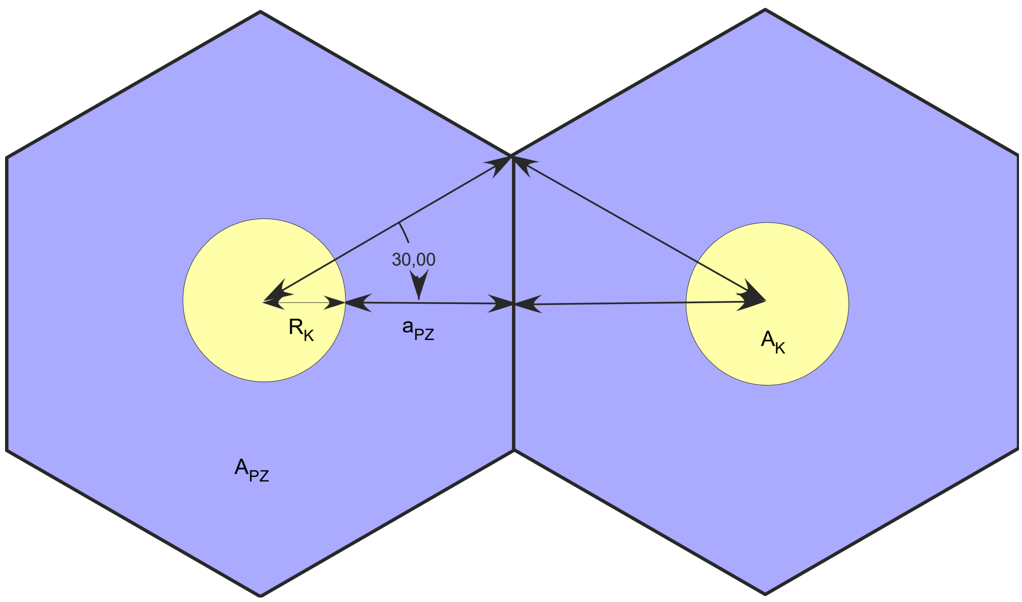

Figure 2: Two adjacent caverns situated in a hexagonal grid with radii R_K and cross-sections A_K

Assuming a cavern field with the most compact configuration of adjacent caverns, i.e. a hexagonal grid layout, the required width of the pillar zone (being the distance between the cavern wall and the outer margin of the surrounding pillar zone a_{PZ}) can be calculated by the following equations

$$a_{PZ} = \sqrt{\frac{A_K}{6 \cdot tg30^0}} \cdot \left[\sqrt{1.2 + \frac{H}{H_*}} - \sqrt{\frac{6 \cdot tg30^0}{\pi}} \right]$$

$$a_{PZ} = 0.537 \cdot \sqrt{A_K} \left[\sqrt{1.2 + \frac{H}{H_*}} - 1{,}05 \right]$$

$$a_{PZ} = \sqrt{A_K} \cdot \left[\sqrt{0.346 + \frac{H}{468m}} - 0.563 \right]$$

Assuming the characteristic radius R_K of the cavern is:

$$R_K = \sqrt{\frac{A_K}{\pi}}$$

then:

$$a_{PZ} = R_K \cdot \left[\sqrt{1.09 + \frac{H}{155m}} - 1 \right]$$

From the enveloping maximum plot of the sonar survey protocol the values for a and b representing the semi major and the semi minor axis of the enveloping ellipse, can be taken. Their relation defines the eccentricity of the leached shape. Both figures are used in order to calculate the representative cavern cross section A_K.

$$A_K = \frac{a \cdot b}{4} \cdot \pi \cong A_{Maxplot}$$

The evaluation of the necessary pillar width is related to the so called reference depth. This reference depth is in the lower section of the cavern where maximum mechanical load conditions occur or where maximum cross section onset after sump leaving the cavern sump.

Table 1: Data basis to determine the necessary pillar width

Cavern	A_{Max} (m^2)	R_{Max} (m)	H_{Ref} (m)	A_{Sys} (Tm^2)	a_{Pz} (m)
ZW-A1	6300	45	1340	55.6	89
ZW-A2	4900	40	1245	48.5	79
ZW-A5	5500	42	1400	50.6	86

Table 1 shows the results of the calculate parameters following the algorithm mentioned above. They have to be applied for rock mechanical assessment to the centre of a cylindrical cavern or, in the case of leaching deviation, to the shifted balance point.

With reference to the position of the last cemented casing shoe new coordinates have been calculated for the cavern balance point in order to assess the existing distances between caverns in the storage field.

Each cavern balance point can be determined from the sonar measurements by its enveloping maximum plot that is part of the sonar survey documentation.

Table 2: Coordinates of the gas storage caverns adjacent to cavern A1

Cavern	Easting LCCSs	Northing LCCS	Easting Balance point	Northing Balance point
ZW-A1	258.265,91	567.064,93	258.113,55	567.807,50
ZW-A2	258.113,55	567.807,50	258116,09	567819,53
ZW-A5	257.953,59	568.102,44	257.880,90	567.940,67

Actual distances between cavern balances points calculated from Table2 summarized in Table 3.

Table 3: Minimum distances based on sonar survey protocols between the balance point axes of caverns adjacent to cavern as calculated using coordinates

From cavern to cavern	distance (m)	direction (°)
ZW-A1 – ZW-A2	308	210
ZW-A1 – ZW-A5	442	240

Taking into account the directions of minimum cavern distances according to Table 3 the following spacing between the balance point of the cavern and the cavern contour (wall) is measured in the enveloping maximum plot of the sonar survey.

Table 4: Distances (m) based on sonar survey protocols between the balance points of the cavern and the cavern contour in direction to the neighboured cavern.

From/To	ZW-A1	ZW-A2	ZW-A5
ZW-A1		40	42*
ZW-A2	37		40
ZW-A5	41	40	

Using these data the extent of the remaining distances between the caverns (minimum pillar width) can be calculated. These values are summarized in Table 5 combining the results of Table 3 and 4

Table 5: Minimum pillar width based on sonar survey protocols between the gas storage caverns

From cavern to cavern	distance (m)	direction (°)
ZW-A1 – ZW-A2	231	210
ZW-A1 – ZW-A5	359	240

The minimum pillar width from the rock mechanical point of view, e.g. the distance wall to wall, is the sum of the cavern related a_{Pz}. So, the required necessary pillar width between cavern ZW-A1 and adjacent gas storage caverns compared to the realised minimum pillar dimensions are compiled in Table 6.

Table 6: Determination of the necessary pillar width for caverns adjacent to cavern ZW-A1

Cavern	a_{Pz} (m)	Sum a_{Pz} (m) Necessary distance	distance (m) realised
ZW-A1 / ZW-A2	89 / 79	168	253
ZW-A1 / ZW-A5	89 / 86	175	262

It can be seen from Table 6 that the distance between the gas storage caverns neighboured to cavern ZW-A1 is given with a more than sufficient safety margin. The same conclusion can be drawn regarding the load bearing capacity of the pillars between the gas storage caverns adjacent to cavern ZW-A1.

In summary, it can be stated that long term stability of the caverns is guaranteed.

Even when the worst case scenario of a blow-out is considered, which represents the most critical load case for the pillars with potential initiation and ongoing fracture processes along the cavern contour, the pillar system is able to bear this additional load and thus is prevented from collapsing.

Safety pillars between gas storage and brine production caverns

Regarding the distance between the nearest (eastern) row of gas storage caverns (ZW A1 to ZW A4) and the westernmost caverns of Akzo Nobels's brine production field the pillar width is more than sufficiently designed in order to act as a safety pillar.

From a rock mechanical point of view the minimum distance between the centres of two neighboured caverns should be in minimum 270 m. Thereby, the so called typical Zuidwending gas storage cavern with a_K = 45 m and a_{PZ} = 95 m caverns and a typical Zuidwending brine production cavern with a_K = 65 m, a_{PZ} = 65 m has been taken into account.

This required minimum distance from cavern axis of a gas storage cavern to cavern axis a brine production cavern has been applied for the assessment of the safety pillars between the gas storage cavern ZW-A1 and the adjacent brine production caverns ZW-7, ZW-8 and ZW-9.

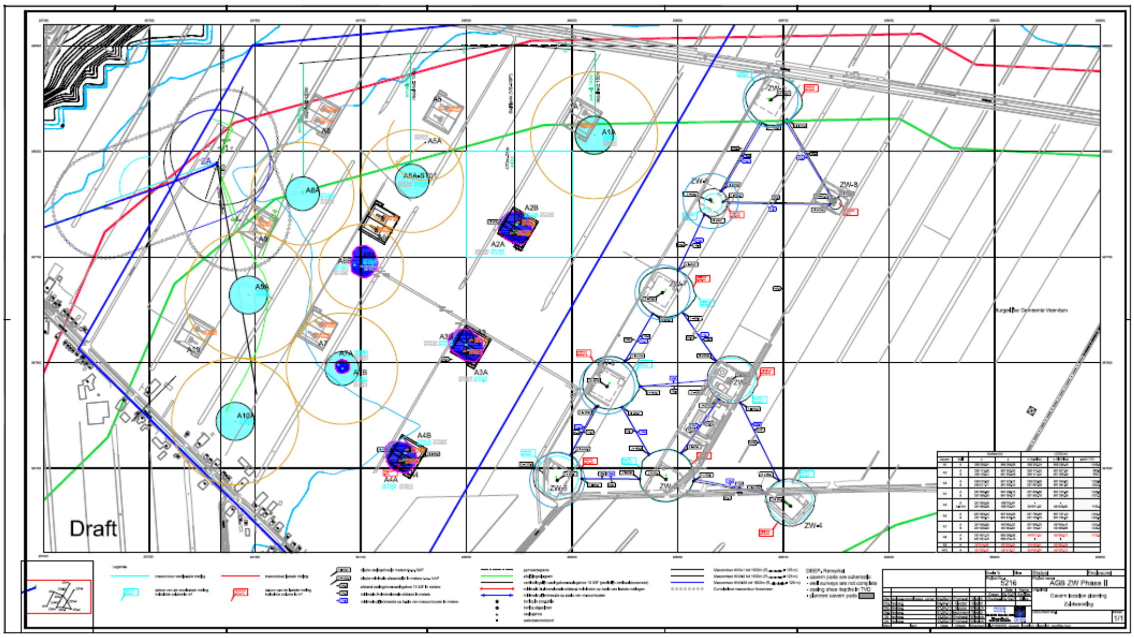

Figure 3: Cavern location planning – Zuidwending, Rev 5.e by DEEP Underground Engineering

The actual realized distances between cavern axes are:

- 395 m between brine cavern ZW-7 and gas storage cavern ZW-A1 in SSE direction,
- 317 m between brine cavern ZW-8 and gas storage cavern ZW-A1 in SE direction, and
- 412 m between brine cavern ZW-9 and gas storage cavern ZW-A1 in ENE direction.

This means that there is an additional safety barrier of more than 100 m between the gas storage cavern ZW-A1 and the brine production field of Akzo Nobel. This can be seen also from Figure 3. The blue line, which is given by the coordinates of two points (first: easting 258605; northing 568250; second: easting 257912; northing 567050) separates the gas storage field from the brine production field.

Distance from the cavern to the edge of the salt dome

Rock mechanical behavior of a solution-mined cavern is depending on several parameters. Thereby some parameters have with regard to cavern integrity significantly more importance than others. Thus the knowledge about the importance of the individual parameters helps to identify data needs and greatly enhances the modelling capabilities and methods for conducting a geomechanical assessment.

Special investigations had been conducted during construction of the Zuidwending gas storage. One of the most important tasks had been the clarification of the spatial extent of the salt dome including a well-defined assumption of the location of salt dome edge. The shape of the salt dome has been derived from seismic data. Additional a vertical seismic profiling (VSP) survey had been carried out in order to identify the salt dome edge.

Based on the knowledge about the salt dome Zuidwending, the required distance of the cavern to the salt dome edge were determined in the planning phase of the gas storage.

The cavern grid for the field extension of Phase II is generally designed with a cavern surrounding safety pillar of ≥ 150 m between the northernmost caverns (ZW-A1, ZW-A5, and ZW-A8) and the salt dome flank (see Enclosure 1).

But, the safety distance of the caverns towards the salt dome edge has been calculated by using the required pillar zone surrounding the gas storage caverns and the an additional pillar towards the salt dome flank of 50 m to cover the uncertainty inherent to the VSP method (25 m) and an additional safety margin allowing for some irregularity of the inner contour of the salt dome flank. This approach is in compliance with the ABVO[1] regulations.

According to the coordinates of the last cemented casing shoes for the cavern “A“-wells (see Table 1), caverns ZW-A1, ZW-A5, and ZW-A8 will be at a distance of more than 200 m from the flank.

Compared to state-of-the-art procedure as applied above also the most recently published literature[2,3] highlights the necessity of the modus operandi as it has been applied in planning phase of Zuidwending gas storage. Exemplarily the following citation is extracted from SMRI RR2013-1:

> *“The first step to completing a geomechanical assessment is to accurately map the salt dome edges through techniques discussed in the previous chapter. Ideally, an accurate characterization of the salt dome boundary should be determined before the solution-mining of a cavern. Secondly, the cavern shape and relative position must be determined in advance and controlled throughout the leaching process by conducting regularly scheduled sonar surveys. Finally, simulation of the cavern history, using measured and/or anticipated operating pressures, is carried out to predict the response of the cavern and rock mass with respect to safe and efficient operation.”*

[1] German mining standard regulations

[2] SMRI Research Report RR2013-1: “Salt Caverns and Salt Dome Boundaries“ unpublished Draft version

[3] Dirk Zapf, IUB, Hannover „Rock Mechanical Dimensioning of Gas Storage Caverns in the Salt Dome Edge Region” SMRI Fall 2014 Technical Conference; September 2014; Groningen, The Netherlands

Furthermore, in this context recently carried out investigations show that for caverns close to the salt dome boundary, the ratio of the salt pillar or web thickness (P) to the cavern diameter (D) is of crucial importance. Depending on this ratio (P/D ≥ 1.5 or P/D ≤ 1.5) caverns are assessed. According to Zapf (2014) the distance is estimated as sufficient in the case of P/D > 1.5.

Applying this recommendation to the situation of cavern ZW-A1, the maximum diameter of the suggested rock mechanical envelope is 90 m and the pillar thickness – calculated from the P/D – ratio of 1.5 – should be at least 135 m. Also, if the balance point is concerned from P/D – ratio follows 159 m (135+24m) the rock mechanical approach for the minimum pillar which demands 200 m in the direction of the salt dome edge. Taking into account the results of latest investigations it can be stated that the distance of cavern ZW-A1 is sufficient. An additional safety margin is included.

Special conditions necessary for a second borehole

Gasunie intends to drill a 2nd well into the cavern in order to increase the gas production capacity of the cavern ZW-A1. In parallel to this measure, the actual volume of cavern ZW-A1 shall be expanded up to a geometric volume of 1 million m^3. For this purpose DEEP was already asked in 2014 for an evaluation and assessment of different options to determine the most optimal timing to drill a 2nd access well.

Four options were proposed and assessed by DEEP:

- *Option 1 - drilling the 2nd well into the gas filled cavern*
- *Option 2 - drilling the 2nd well into the brine filled cavern after leaching operation*
- *Option 3 - drilling the 2nd well during leaching operation*
- *Option 4 - drilling the 2nd well prior to restart leaching operation*

In order to assess these options from the rock mechanical point of view it is necessary to consider:

- *Aspects of cavern geometry and the roof shaping*
- *The positioning of the 2nd LCCS and the possibility to test the LCCS in by the usual procedure*
- *A consistent maximum cavern pressure with regard to both LCCSs*
- *The prevention of any kind of gas traps (impairments of tightness)*

As far as the cavern geometry and roof shaping are concerned, experience from leaching operations during the first phase and second phase of creating the Zuidwending gas storage caverns has been gained.

The adherence of the rock mechanical envelope could be realised during that phase. So there is no doubt that for further leaching of cavern ZW-A1 the appropriate technic is available in order to leach cavern ZW-A1 to its final volume in compliance with the rock mechanical design.

If the casing in the 2nd well will be installed before or immediately after restarting the leaching operation, the possibility to prevent gas traps at the top of the cavern by an alternating activation of well one or two is given. Therefore, from the rock mechanical point of view the favoured option is No. 4 followed by option No. 3. Due to a lack of experience the ranking of option No. 2 is far below No.3. Option No. 1 should be excluded, because too many imponderables may influence the installation of a 2nd casing.

Generally, it can be stated that the subsequent installation of a second well does not represent any kind of endangering cavern stability and integrity.

Advised location and distance between the two boreholes

Two opposite options exist to determine an ideal location for a second borehole:

1. *Location with greater distance to the salt dome edge*
2. *Following the preferred leaching direction*

According to option 1 the advice would be: drilling a second well south of well ZW-A1A. But, the expected cavern development in this direction was marginal in the past and could be marginal also in the future. Consequently, the distance between the two boreholes would be too close. If the second well would be drilled North of ZW-A1A the distance of cavern ZW-A1 to the salt dome edge would possibly influenced.

The actually extension of the cavern in the North direction is larger than into the South direction, because the cavern has already developed preferably into the North direction. Therefore, the possibility to enter the cavern by a second well in a sufficient distance from the first well is more likely when starting from North of ZW-A1A.

Following the experience from Zuidwending cavern construction phase I the advisable distance between the two wells should be about 20 m. Therefore, the position of the last cemented casing shoe of well ZW-A1B should be located at

Easting: 258.302

Northing: 568.058

With the second well in the North the opportunity increases to create the cavern roof regarding the rock mechanical requirements as expressed by the envelope.

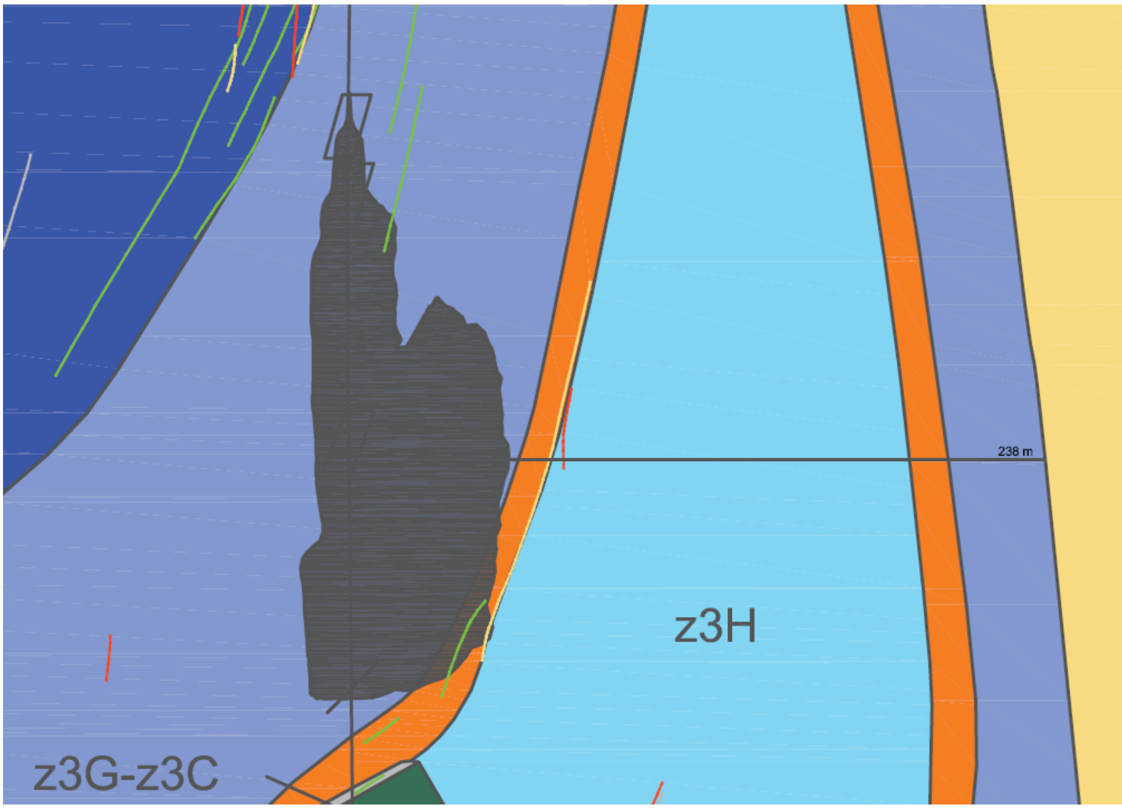

Figure 4: Geological interpretation of the horizon Cavern A1 is situated (after DEEP 2017)

According to Figure 4 the geological interpretation reveals a minimum distance between cavern ZW-A1 and salt dome edge of 236 m. The violation of the required minimum distance of at least 200 m seems to be unrealistic. This also applies to the case when the second well is drilled in the North of the ZW-A1A.

Second well – depth of the last cemented casing shoe

Without other influencing factors, e.g. from a gas production or leaching operation, the last cemented casing shoe of the 2nd well – from the rock mechanical point of view – should be installed in a depth position comparable to the first one. By this implementation the same maximum cavern pressures will be possible provided after the mechanical integrity test (MIT) can be performed successfully. Setting the casing shoe at a deeper depth, no advantage arises for the recommendable maximum operation pressure, because the reference depth then will be the depth of the casing shoe of the first well ZW-A1A. Vice versa a minor depth of the last cemented casing shoe of ZW-A1B would lead to a decrease of the maximum storage capacity, because the maximum pressure would have to be reduced respectively.

The rock mechanical recommendation for the setting depth of the last cemented casing shoe of well ZW-A1B is 1050 m TVD.

Expected operating range of cavern A1

The rock mechanical appraisal of the supposed operation conditions of cavern ZW-A1 is based on the numerical modelling that was carried out in connection with the case studies[4] reported in 2013. The aim of these case studies was to prove the estimated values for the convergence rate related to the different cavern types at Zuidwending. At the same time the criteria in order to guarantee the stability and tightness of host rock surrounding the caverns had to be fulfilled. For this purpose, numerical simulations had been performed under consideration of the site-specific situation of the salt deposit and the respective properties of the relevant rock formations. As a prerequisite for numerical modelling due to the intended cyclic operation mode of gas storage, the thermo-dynamic behaviour of the caverns had been coupled with the thermos-mechanic behaviour of the rock mass.

In the above mentioned report cavern ZW-A1 had been represented by the case 3 cavern, which had been characterised by a casing shoe depth of 1,050 m TVD and a geometric volume of 1 million m^3.

At Zuidwending it has further to be taken into account that the recommendable maximum cavern pressure may be influenced by the tall and shallow brine production cavern adjacent to gas storage caverns.

From an undisturbed initial stress state a value of 222.3 bar could be expected as typical overburden pressure at Zuidwending. Considering in case of cavern ZW-A1 the neighbourhood of the huge brine production caverns ZW-7 and ZW-1, the typical value of the overburden pressure may have been reduced over time due to creep processes around the brine production caverns.

On the basis of the current volume and height of the brine production caverns as well as their distance to cavern ZW-A1, a reduction of the overburden pressure in the vicinity of cavern ZW-A1 must be assumed. Ignoring the smaller well ZW-8, the converted gas storage cavern ZW-A1 will be in a distance of approx. 390 m from the brine production cavern ZW-7 and 410 m from brine production cavern ZW-1. According to Figure 5, which shows the redistribution of the rock mass stress due to the operation of a huge brine production, a reduction of the initial stress state at the depth position of the last cemented casing shoe of well ZW-A1A may be possible. But, a full 3D-analysis is advised taking into account all secondary stresses surrounding the gas storage cavern including those induced during cavern operation. By the means of such a modelling the permissible p_{max} should be demonstrated with regard to the real cavern situation and the accuracy of the assumptions

[4] IfG (2013): "Case studies for cyclic operated storage caverns 'Aardgasbuffer Zuidwending' NL; report to Gasunie

and estimations made for modelling input-parameters like salt density, overburden pressure or rock mechanical salt behavior (sensitivity analyses).

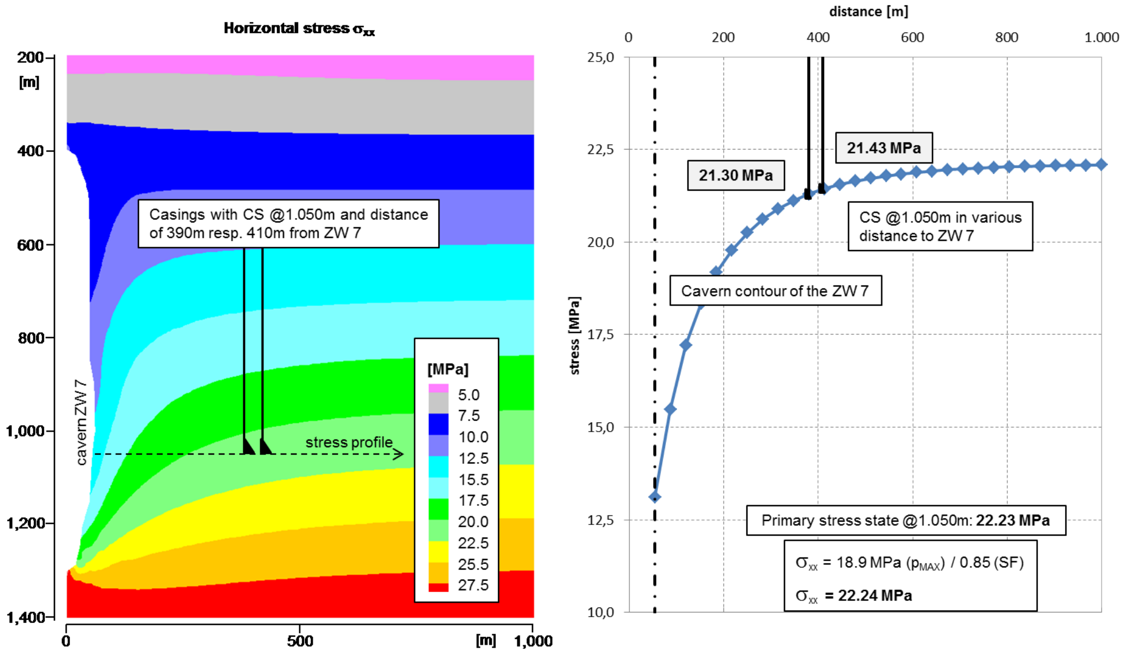

Figure 5: predicted reduction of the initial stress state by large brine production cavern ZW7

For the minimum operation pressure the suggestions of the case study prepared in 2013 can be followed. Against the background of the operation mode of caverns ZW-A2, ZW-A3, ZW-A4 and ZW-A6 a modified suggestion is justified in the case of a limited minimum pressure at 84 bar. When the lower pressure range down to 60 bar (minimum pressure in an annually cycled cavern) will not be exploited, the aimed at limitation for the convergence and the associated overburden subsidence will be achieved by far. Therefore the admissible minimum cavern pressure of 84 bar can be assumed in case of long term cyclic cavern operations of cavern ZW-A1.

Concerning the gas withdrawals and injections, the gas operation of cavern ZW-A1 should preliminary follow the suggestions of the case study prepared in 2013. A maximum pressure change rate of 10 bar/day was recommended therein, when the cavern is operated in the range between p_{Max} and 90 bar.

An optimisation of the operation mode regarding constant flow rates is conceivable but needs a corresponding check.

Conclusion

Summarizing the above performed rock mechanical assessment of cavern ZW-A1 converted to a gas storage cavern, there are no concerns from the rock mechanical point of view with respect to the conversion and further leaching operations of cavern ZW-A1.

This assessment is based on the available knowledge and information about the conversion process as well as on the rock mechanical studies performed in the past within the scope planning, construction and operation of the existing gas storage caverns at Zuidwending.

The question about the allowable p_{max} for ZW-A1 can only be answered after the execution of a 3D-analysis. Therefore, IfG recommends executing such an advanced analysis in preparation of the gas storage operation.