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Client name: Nobian

Subject: Subsidence prognosis and mitigative measures C130

Subsidence prognosis and mitigative measures TWR Cavern 130

1. Selection of input parameters

Cavern 130 is located along the Twekkelerveldweg in Hengelo. The cavern has been developed using the boreholes listed in Table 1 which also lists the stratigraphy.

Table 1: Cavern 130: wells, position and stratigraphy

TWR-C130	Position (m)			Stratigraphy (mNAP)													
Wells	X (WGS84)	Y (WGS84)	Z (mNAP)	Tertiair_top	Tertiair_basis	Muschelkalk_top	Muschelkalk_basis	Zout D_top	Zout D_basis	Anhydriet_top	Anhydriet_basis	Zout C_top	Zout C_basis	Zout B_top	Zout B_basis	Zout A_top	Zout A_basis
130	251966,3	472300,4	23,5	-26,5	-93	-93	-127	-341	-344	0	0	-345	-369	-371	-374	-375	-400
131	251999,5	472289,2	23,7	-26,3	-92	-92	-128	-340	-344	0	0	-346	-369	-370	-374	-376	-400

The wells were drilled in 1967 and a detailed interpretation of the Main Röt Evaporative Member, in particular the position and thickness of the Anhydrite-E sub-member is shown in Figure 1 below.

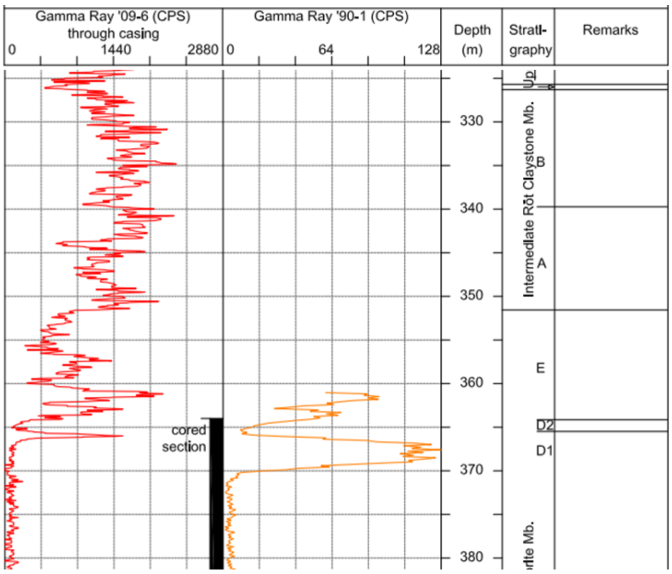

Figure 1: Detailed interpretation of the Main Röt Evaporative Member based on Gamma Ray Logs (Geowulf interpretation)

The relative position of the actual cavern in the Salt stratigraphy is shown in a side-view of the cavern in Figure 2. As can be seen, the actual cavern roof is positioned at the bottom of the Anhydrite-E member. The Claystone D1 has collapsed and the Salt D2 member has been dissolved. As such, the Hydraulic Radius (HR) for a potential migration contour has been determined as the intersection of the actual cavern with the Top of Salt C.

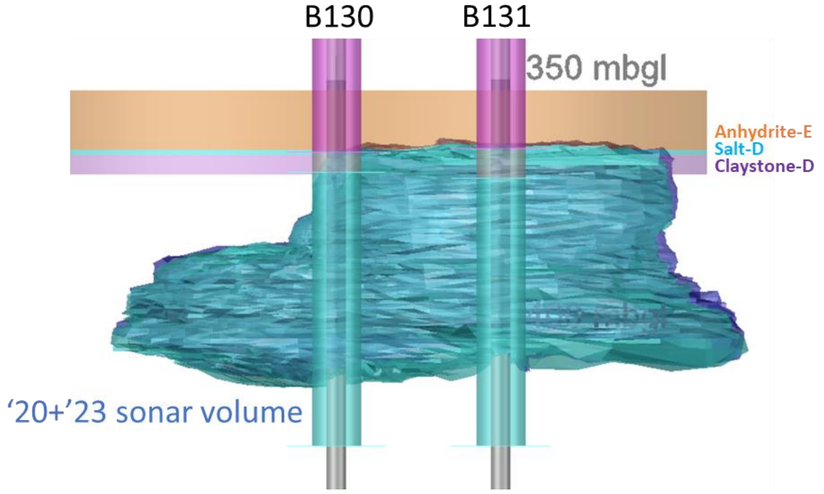

Figure 2: Position of cavern 130 in the Salt stratigraphy. Shown are the intact Salt C member, the Claystone D1 member and the Anhydrite-E member. The Salt D2 member has not been found at this location in the brinefield.

The Hydraulic Radius of the cavern roof intersection with Top Salt C has been established to construct a representative volume as input for the subsidence prognosis. This intersection contour and the corresponding circular contour are shown in Figure 3. This contour has an area of 3.500 m², with a circular radius of 33 m and a HR of 16,5 m.

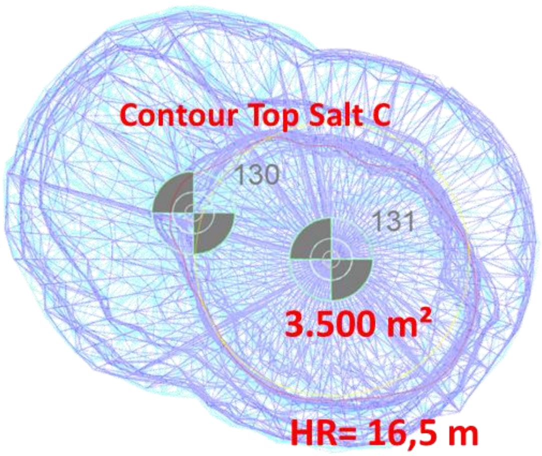

Figure 3: Top view of cavern 130. Intersection of cavern with Top Salt C shown in red, corresponding circular contour in yellow.

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The latest available sonar images of cavern 130 from 2020 & 2023 were logically (Boolean) combined to estimate the volume of the actual cavern. This volume is subsequently compared to the theoretical cavern volume based on salt production figures. The actual cavern volume is 80% of the volume based on production. This value is within the expected range as the insolubles in the salt remain in the cavern during cavern development and thus "backfill" the lower (sump) area of the cavern. Furthermore, sonar images rely on "line-of-sight" and therefor tend to slightly underestimate cavern volume as "shading" may hide some volume of the actual cavern.

To allow for the selection of conservative input parameters for the prognosis model, the construction of a representative cavern volume is based on 90% of the theoretical production volume, this is a conservative approach considering the actual sonar volume. The resulting representative cavern volume is shown in Figure 4 below.

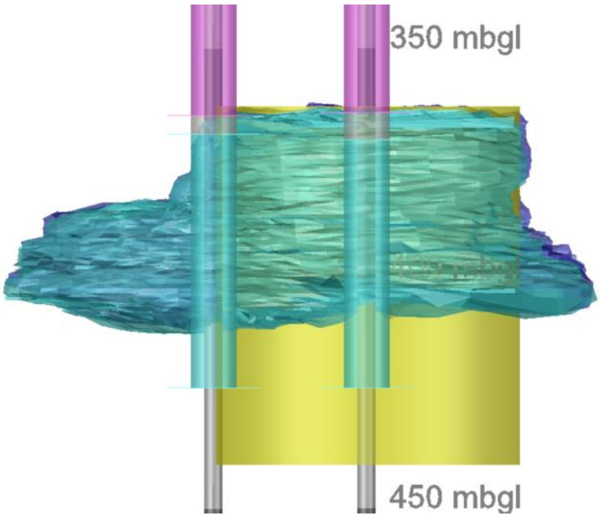

Figure 4: Representative cavern volume (yellow) and actual cavern volume as per sonar images from 2020 & 2023.

The remaining input parameters such as the depth of the cavern and the position of the Top Rock (equal to Base Tertiary) as well as the X- and Y-coordinates of the representative volume, are presented in Table 2.

The representative volume is thus a cylinder with 33m radius and 78m height with the roof positioned at 362,7 m below ground level (mbgl).

No backfill has been applied in this cavern to date, therefore the "Backfill insitu unconsolidated" (second row from the bottom Table 2) is left at 0 m³.

Table 2: Cavern 130 – Selected input parameters for the subsidence prognosis model (BJP method).

Cavern	130
Relevant borehole	131
X coordinate	251999,5
Y coordinate	472289,2
Z coordinate GL (mNAP)	23,7
Depth of top rock [mbGL]	115,7
Depth of top salt [mbGL]	370,0
Base of actual cavern [mbGL]	440,7
Base of initial cavern [mbGL]	423,9
Top of actual cavern [mbGL]	362,7
Height of cavern (m)	78,0
X coordinate migration centre	251999,5
Y coordinate migration centre	472289,2
Volume fitting	
Maximum BPB Prod.(t)	525153
Cavern vol based on BPB (m³)	**295136**
Actual volume (recon./sonar)(m³)	237523
Insolubles (bulked) (m³)	15573
Part of BPB prod. Vol. not acc. (m³)	57613
Part of BPB prod. Vol. not acc. (%)	**20%**
Cavern geometry conversion	
Migration column Surface area (m²)	3500,0
Constructed cavern radius [m]	33,0
Hydraulic Radius constructed cav. [m]	16,5
Const. cavern height (cylindrical) [m]	78,0
Const. cavern height (conical) [m]	0,0
Constructed volume (cylindrical) [m³]	266853
Constructed volume (conical) [m³]	0
Constructed volume total [m³]	266853
Part of BPB prod. Vol. not acc. (m³)	28283
Part of BPB prod. Vol. not acc. (%)	**10%**
Height correction backfill insitu [m]	
Backfill insitu unconsolidated (m³)	
Backfill consolidation (%)	

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2. Results subsidence prognosis

The selected input parameters have been processed by the Bekendam-Jakob-Pinkse (BJP) algorithm developed in 2023/2024 as part of the "Update TWR Subsidence Prognosis" study. The algorithm is integrated into a Python code which uses these parameters in conjunction with a set of "constants", such as the Bulking Factor (=1,2), to produce a subsidence prognosis comprising several outputs. The script produces both graphical output (e.g. subsidence contours) and numerical output (e.g. maximum subsidence, radius of influence of subsidence, etc.).

The results of the subsidence prognosis for cavern 130 are summarised in Table 3.

Table 3: Summary of subsidence prognosis results (l) and dimensions of the potential migration (r)

Cavern	**130**
max. subsidence stage 2 [m]	0.448
max. subsidence stage 3 [m]	0
max. subsidence stage 2+3 [m]	0.448
max. subsidence stage 4 [m]	28.6
max. subsidence stage 5 [m]	2.861
max. subsidence stage 4+5 [m]	31.461
max. subsidence stage 2-5 [m]	31.909
stage type	stage 4 sinkhole
radius of influence stage 2 (cyl) [m]	318
radius of influence stage 2 (cone) [m]	124
radius of influence stage 3 [m]	124
radius of influence stage 4+5 [m]	116
radius of influence stage 4 trough [m]	-
max. tilt stage 2-5 [mm/m]	442
max. convex curvature stage 2-5 [10^-3/m]	11.8
max. concave curvature stage 2-5 [10^-3/m]	-22.5
max. extensional strain stage 2-5 [mm/m]	136
max. compressive strain stage 2-5 [mm/m]	-262
max. convex relative rotation stage 2-5 [°]	299.6
max. concave relative rotation stage 2-5 [°]	-597.4
fill (no stage 4+5) [%]	39
fill (no stage 4+5) [m^3]	103639
fill (no stage 3, with safety factor) [m^3]	109431
fill (no stage 3, w. SF 30% compensated [m^3]	142,260
fill (no stage 3, w. SF 30% + 2m compens. [m^3]	149,103

	130
dTcavfinal [mbGL]	-27.3
dTcav1m [mbGL]	-22.3
dTcavcyl [mbGL]	-27.3
dTR [mbGL]	115.7
dcrit [mbGL]	124.2
dTcavact [mbGL]	362.7
dBcavact [mbGL]	440.7
dBcavini [mbGL]	423.8
HcavTR [m]	28.6
HcavTR (Bekendam) [m]	50.8
Hcavcrit [m]	30.3
Hcav40 (Bekendam) [m]	55.2
Rcavfinal [m]	33
RcavTR [m]	33
Rcavcrit [m]	33
Rcavact [m]	33
VcavTR [m^3]	97846
Vcavcrit [m^3]	103638
Vcavcyl [m^3]	266853
Vcavcone [m^3]	0
Vcav [m^3]	266853
alpha [deg]	0
beta [deg]	0
Hmigcyl [m]	390
Hmigcone [m]	0

Table 3 shows that for cavern 130, in case of migration, Stage 4 Sinkhole subsidence can occur based on the selected input parameters. A graphical representation of the potential migration column as predicted by the BJP algorithm is shown in Figure 5 indicating the actual roof depth, the final roof depth and the critical roof depth to prevent Stage 4 subsidence (trough or sinkhole).

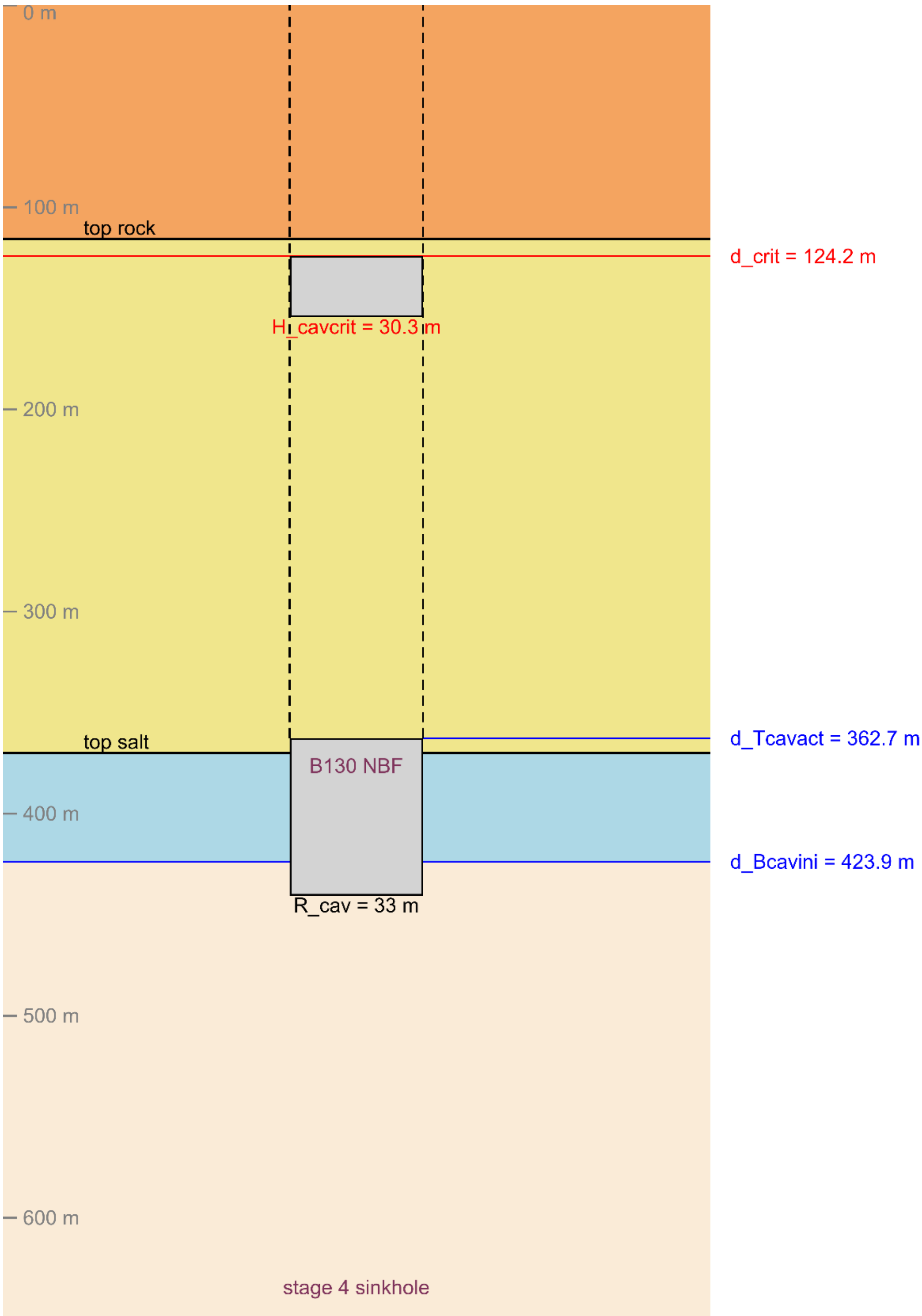

Figure 5: Potential migration column based on selected input parameters

The subsidence resulting from the potential migration shown in Figure 5 is presented in Figure 6.

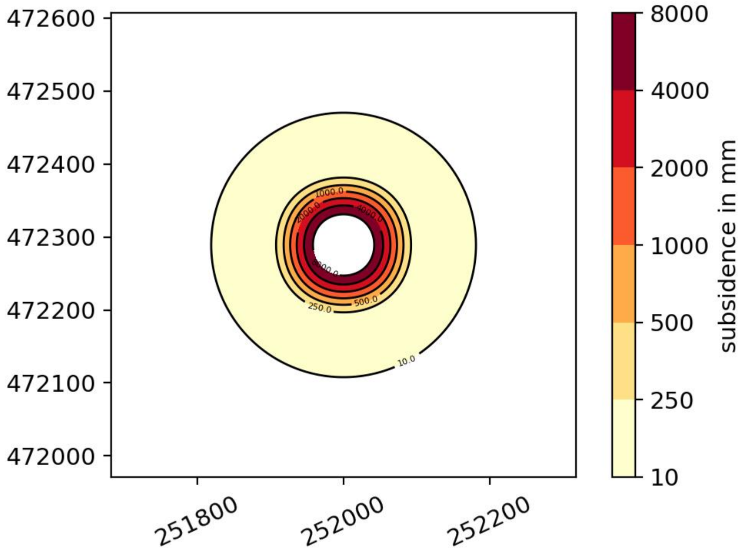

Figure 6: Cavern 130: Maximum subsidence contours when potential subsidence occurs.

To enable the subsidence impact assessment by Nobian, several derivatives of the maximum subsidence shown in Figure 6 have also been produced by the script, namely tilt, curvature, strain and relative rotation. The contours of these derivatives of the maximum subsidence in case of migration of cavern 130 are presented in Figure 7 below.

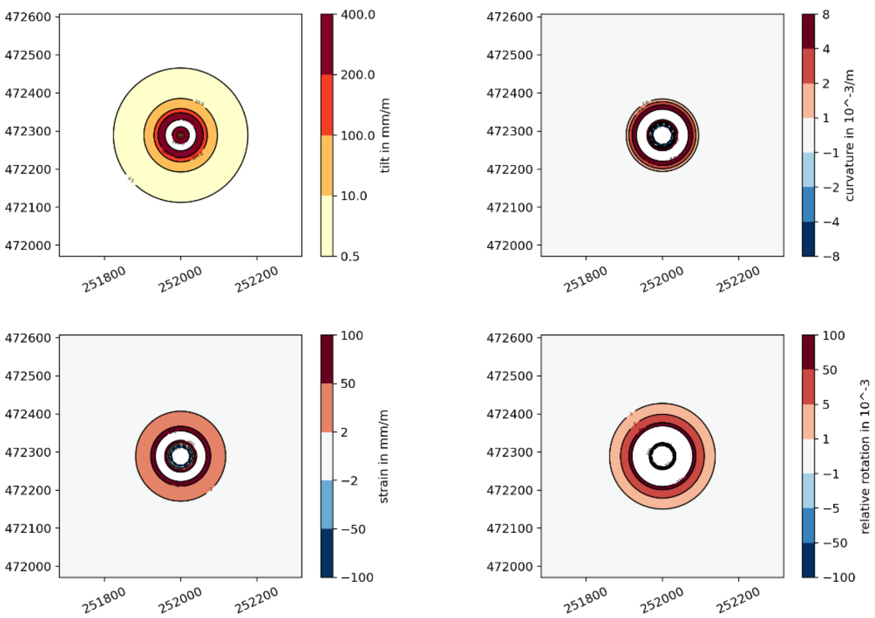

Figure 7: Cavern 130: Maximum tilt, curvature, strain and relative rotation when cavern migration occurs.

3. Likelihood of migration

The likelihood of migration has been assessed based on four criteria: hydraulic radius, Anhydrite-E exposure, water exposure of the Anhydrite-E and the presence of faults nearby. The summary of this assessment for cavern 130 is presented in Table 4.

Table 4: Cavern 130: Likelihood of migration assessment – Score = 6/8

Cavern	July-'24 Classification	BJP Category	BJP (unmitigated)	Migrated?	Backfilled?	Salt C 5m Safety Roof intact?	Hydraulic Radius (m)	Score	Anh.-E exposed?	Score	Water exposure Anh.-E?	Score	Blanket used?	Faults nearby?	Score	Likelihood Score
130	S4F4	Cylinder	Stage 4 - sinkhole	No	No	No	16.5	3	Yes	2	Blanket	1	Yes	No	0	6

As can be seen from Table 4, the likelihood of migration score equals six (6) of a maximum score of eight (8) meaning that the likelihood of migration for this cavern is moderate based on the studied cases of cavern migration in the TWR brinefield.

4. Mitigative measures: backfilling

As the subsidence prognosis based on the BJP method shows that Stage 4 Sinkhole subsidence can potentially develop when the cavern would migrate, mitigative action, i.e. backfilling, is recommended. The BJP method calculates the minimal volume of backfill required to avoid the formation of Stage 3, Stage 4 and Stage 5 subsidence. The results table that is produced by the script provides two volumes:

- Required "effective" backfill volume to avoid Stage 4 and 5 subsidence
- Required "effective" backfill volume to avoid Stage 3 ,4 and 5 subsidence with the application of a Safety Factor of 2 with regards to the minimal beam thickness to avoid deflection of the roof beam resulting in Stage 3 subsidence. This volume is used for the preparation of a backfill recommendation as a conservative approach.

The stated "effective" backfill volume needs to be compensated for the expected 30% consolidation under the load of a migration column as well as for the deduction of a 2 m thick layer of backfill to which no bearing capacity can be attributed. Both of these values can be considered conservative as the following applies:

1. The 30% consolidation value due to the loading of backfill with bulked overburden is the maximum value found during the validation of the BJP-Algorithm using the well-documented cavern migration cases. This maximum value is applied regardless of the height of migration. In reality, the consolidation of the backfill by loading with bulked overburden is a gradual process whereby the consolidation increases with migration height. When migration is limited by backfill, the full migration column does not develop thereby also limiting the consolidation of the backfill by loading with bulked overburden.

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2. The 2 m value for the layer thickness of backfill to which no bearing capacity can be attributed has been determined by applying a "point"-load onto the actual backfill in the cavern, i.e. by pushing a drilling rod into the top of the backfill mount (maximum penetration 1,5 m during field testing). This point-load is not representative of the typical load applied by the bulked overburden as this comprises a more spread-out loading of the backfill top surface. The actual layer thickness of backfill to which no bearing capacity can be attributed is therefore very likely (much) thinner.

The volume of backfill required to avoid Stage 3 and higher subsidence, can be practically validated by before-and-after sonar measurements, taking a suitable period for self-weight consolidation into account.

The minimal required volume of insitu, self-weight-consolidated, backfill in cavern 130 is:

fill (no stage 3, w. SF 30% + 2m compens. [m^3]	149.103

The resulting maximum subsidence when applying this volume of backfill is:

max. subsidence stage 2+3 [m]	0,574

The potential migration column and subsidence contours for the minimal backfill scenario are shown in Figure 8.

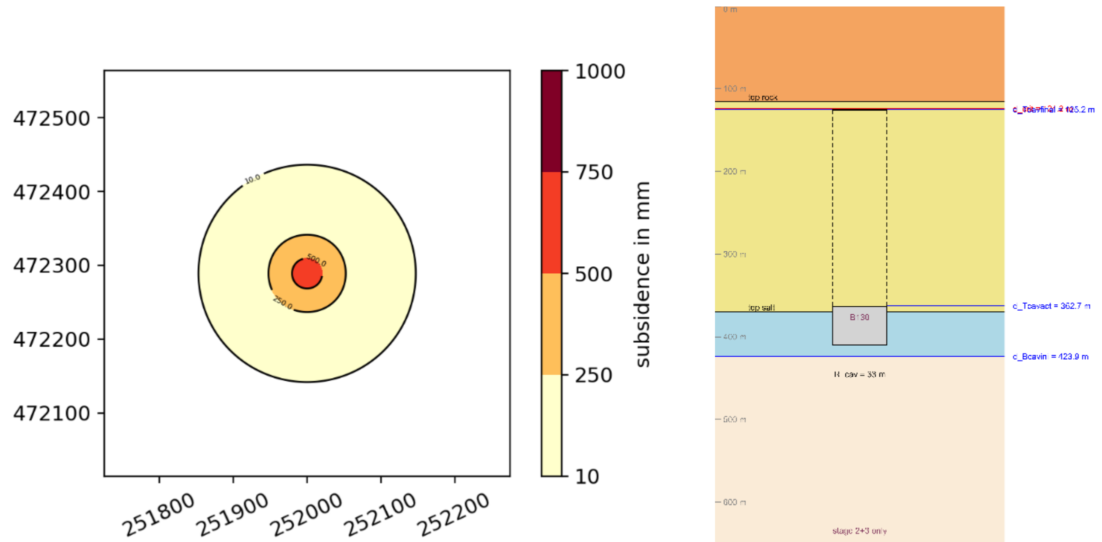

Figure 8: Migration column and Subsidence contours after application of minimal backfill volume.

The practically maximum attainable backfilling grade of a cavern is approximately 80% after self-weight consolidation has taken place, i.e. 80% of the actual cavern volume is visibly (sonar) backfilled.

The "80% filling grade" volume of insitu, self-weight consolidated, backfill in cavern 130 is:

fill (80% of Vcavact + 2m compens.) [m^3]	220.325

The resulting maximum subsidence when applying this volume of backfill is:

max. subsidence stage 2-5 [m]	0.201

The potential migration column and subsidence contours for the minimal backfill scenario are shown in Figure 9.

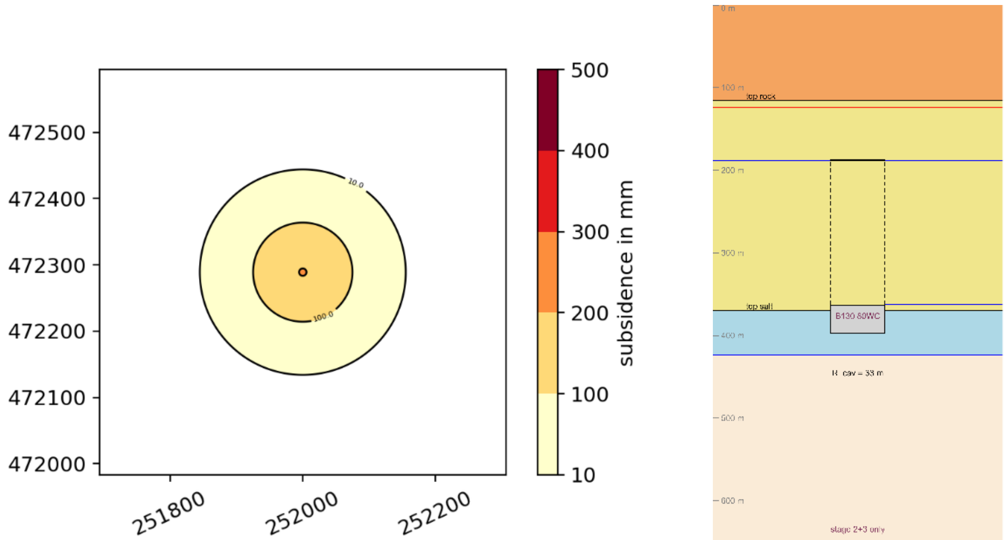

Figure 9: Migration column and Subsidence contours after application of maximum practically attainable backfill volume (80%).

5. Sensitivity of results

To illustrate the sensitivity of the results of the subsidence predictions discussed prior, the just presented 80% backfilling scenario, considered the "Conservative Case" (CC), is compared to a Realistic Conservative Case (RCC), a Realistic Optimistic Case (ROC) and an Optimistic Case (OC), all with 80% backfilling applied.

The parameters for these scenarios have been selected as follows:

80% Backfilling CC:	All input parameters as described prior.
80% Backfilling RCC:	A 1 m non-load-bearing layer thickness instead of 2 m as based on a spread-out loading of the backfill with bulked overburden rather than point-loading.
80% Backfilling ROC:	A 1 m non-load-bearing layer thickness and 25% of consolidation under load of bulked overburden instead of 30% as the migration height is limited by the backfill.
80% Backfilling OC:	A 1 m non-load-bearing layer thickness and 25% of consolidation and the actual sonar volume used as the representative volume instead of 10% extra volume as in the CC.

Figure 10 presents a comparison of the subsidence prognosis results for these scenarios and the Minimal backfill scenario shown in Figure 8. For each of the depicted scenarios, the subsidence contours and maximum subsidence in metres, as well as the relative rotation contours and maximum concave and convex rotation in ‰ are shown.

As can be seen from Figure 10, the gradual reduction of conservatisms decreases the subsidence bowl and maximum relative rotation with each step.

The first step from the Conservative Case to the Realistic Conservative Case, reducing the layer thickness of the non-load bearing backfill, results in the smallest percentual reduction in maximum subsidence. The following step, reducing the consolidation of backfill from 30% to 25%, has a larger impact on the results. The final step in which the 10% additional volume over the sonar volume is not applied results in the largest reduction of subsidence, in line with the relatively large volume reduction of the cavern by adapting this parameter.

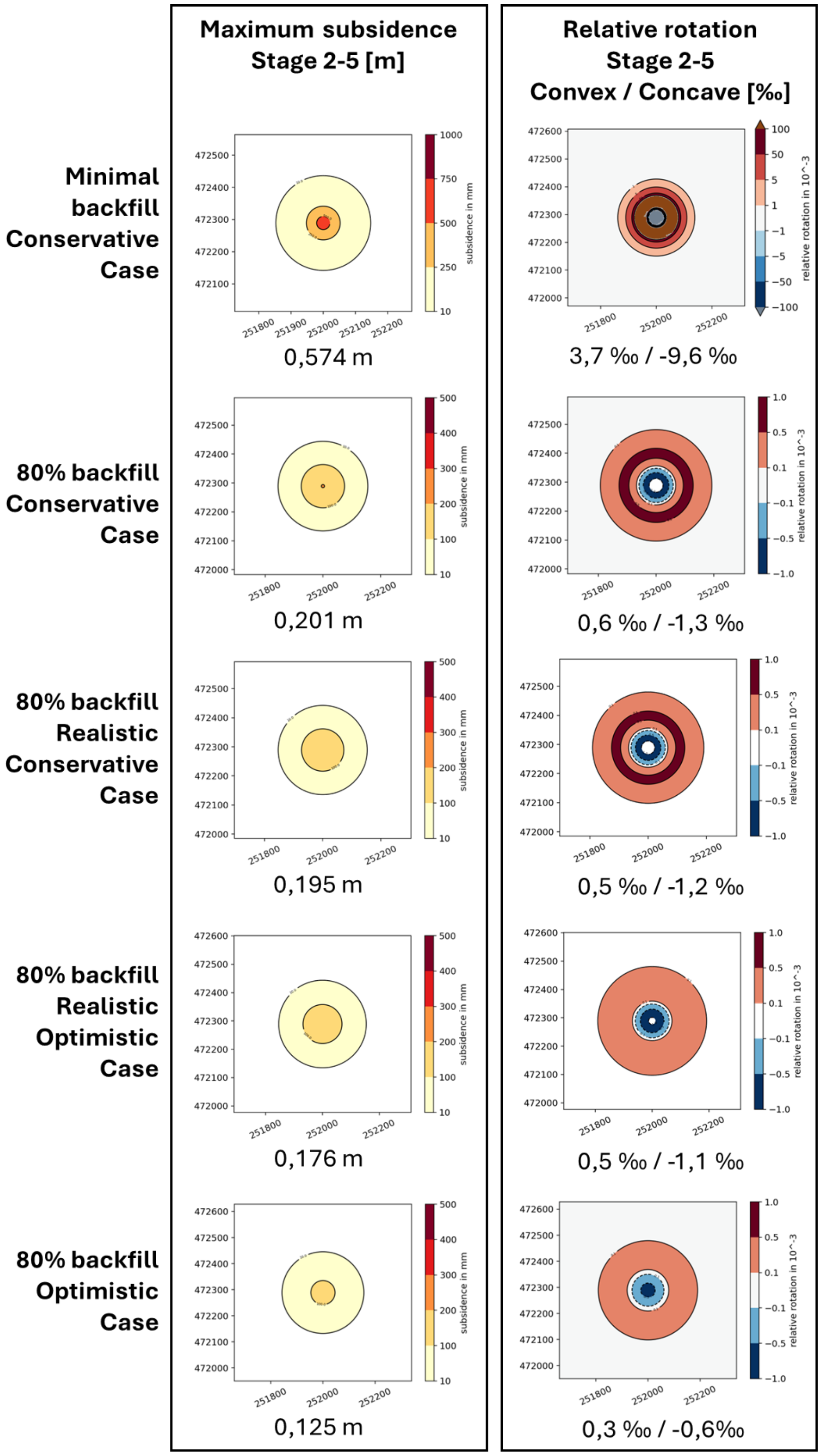

Figure 10: Sensitivity scenarios Minimal backfill CC, 80% backfill CC, RCC, ROC and OC.

A comparison of the maximum subsidence values and their derivatives for all presented scenarios is shown in Table 5 below.

Table 5: Comparison of No backfill, Minimal backfill CC, 80% backfill CC, RCC, ROC and OC

	Dim.	No backfill	Minimal Backfill CC	80% Backfill CC	80% Backfill RCC	80% Backfill ROC	80% Backfill OC
Max. subsidence Stage 2+3	[m]	0,448	0,574	0,201	0,195	0,176	0,125
Max. subsidence Stage 4	[m]	28,6	0	0	0	0	0
Max. subsidence Stage 5	[m]	2,861	0	0	0	0	0
Max. subsidence Stage 4+5	[m]	31,461	0	0	0	0	0
Max. subsidence Stage 2-5	[m]	31,909	0,574	0,201	0,195	0,176	0,125
Max. subsidence Stage type	[-]	stage 4 sinkhole	stage 2+3 only	stage 2+3 only	stage 2+3 only	stage 2+3 only	stage 2+3 only
Max. tilt Stage 2-5	[mm/m]	441,724	8,36	1,922	1,88	1,658	1,083
Max. convex curvature Stage 2-5	[‰]	11,805	0,15	0,022	0,022	0,019	0,011
Max. concave curvature Stage 2-5	[‰]	-22,5	-0,383	-0,05	-0,049	-0,042	-0,026
Max. extensional strain Stage 2-5	[mm/m]	136,045	1,965	0,683	0,667	0,59	0,388
Max. compressive strain Stage 2-5 [mm/m]	[mm/m]	-262,42	-6,025	-1,528	-1,494	-1,32	-0,867
Max. convex relative rotation Stage 2-5 [‰]	[‰]	299,593	3,747	0,558	0,549	0,473	0,286
Max. concave relative rotation stage 2-5 [‰]	[‰]	-597,407	-9,567	-1,251	-1,231	-1,059	-0,64

It can be concluded that the parameters used by the BJP-Algorithm provide a sufficiently conservative result that the outcome can be considered the Conservative Case. Application of further safety factors on the required backfill volume is therefore not necessary from a purely numerical perspective.

The choice of which backfill scenario to execute, i.e. the minimal scenario or the 80% scenario, will need to be made based on an impact analysis considering the current use of the ground surface within the predicted subsidence contours. As such this choice is left to Nobian.

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REinvent GmbH, Sondershausen, 10 January 2024