Update Migration Study

Twenthe-Rijn – Phase 1-Part A+B
Reconstruction of cavern development, slurry filling and migration

Report Part 4 – Subsidence predictions for potential future migration and recommendations on mitigative action by means of backfilling.

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1. Introduction

1.1. Background

The historic development of the Nobian cavern fields within the Twenthe-Rijn mining permit (incl. extensions) has been divided into five phases ("Fase" 1 -5) as shown in Figure 1 below.

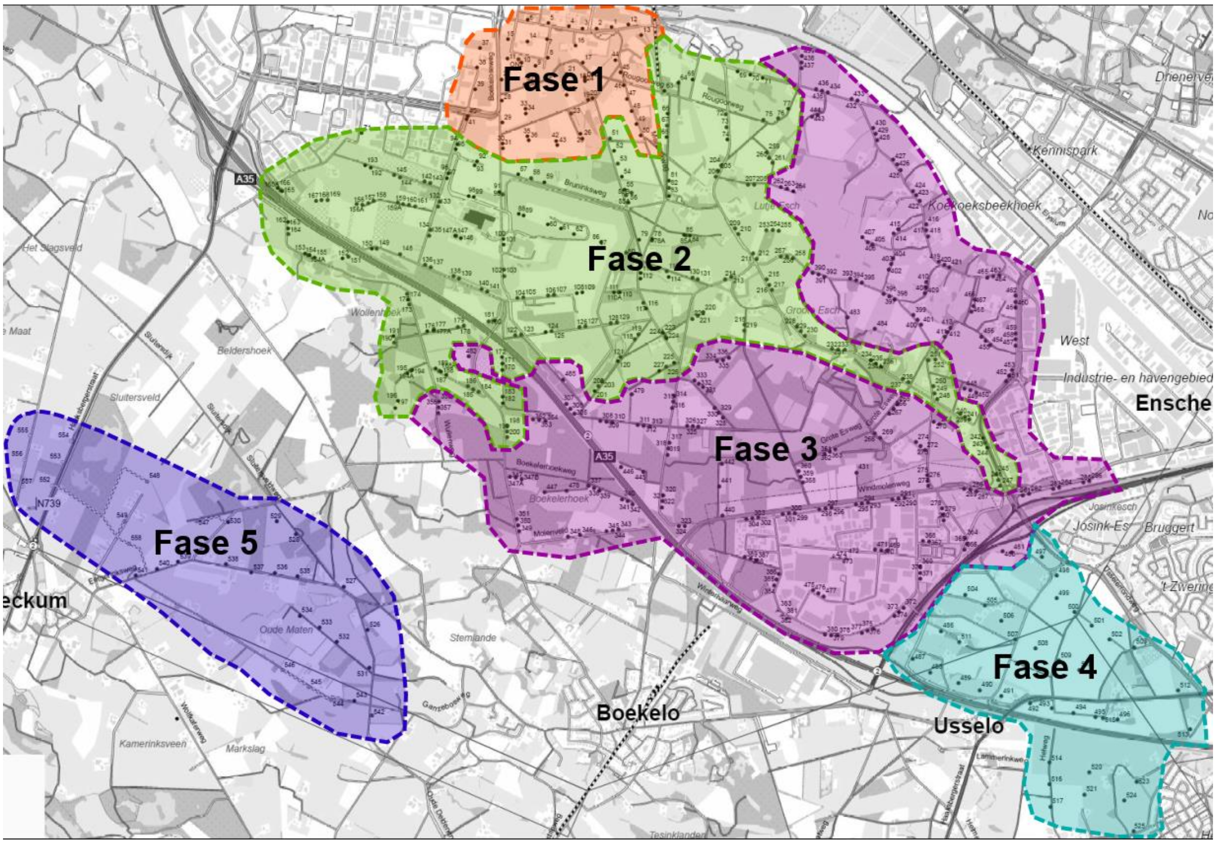

Figure 1: Historic development of Nobian cavern fields in the TWR permitting area, Twente, The Netherlands (Nobian, 20220919 – Opvolging werk Bekendam vs2.ppt)

For the caverns within the areas depicted "Fase 1" and "Fase 2" an update of the existing cavern migration assessments prepared by (late) Roland Bekendam was sought by Nobian. REinvent GmbH (Reinvent) and K-UTEC AG Salt Technologies (K-UTEC) were (sub-)contracted by Nobian to perform the study. Work was initiated in January 2023 and continues as this fourth report covering the overall study results is delivered.

The offered scope has been structured as proposed by Nobian and comprises three phases, each consisting of several parts, see paragraph 1.2 for details on the overall Scope of Work for the study.

1.2. Scope of work

The Update Migration Study Twenthe-Rijn (UMS-TWR) has been structured in three phases (I, II and III) with each up to three parts (A, B and C). The study phases and related parts are described in the following:

Phase I: Reconstruction of well documented cavern migration cases

The scope of work for Phase I, reconstruction of well documented cavern migration cases, was distributed over three parts:

Part A: Reconstruction cavern development.

Part B: Reconstruction of cavern migration process.

Part C: Effects at surface related to cavern migration.

The studied migration cases and their role in the validation process are presented Table 1 below.

Table 1: Studied TWR cavern migration cases and their role in the BJP-Algorithm validation process

Cavern (-system)	Backfill applied?	Used for initial validation	Used to strengthen validation	Used in reverse operation	Not used for validation
C15	Yes	✓			
C30-31	No			✓	
C33-34-35-36	No			✓	
C37	No	✓			
C49*	Yes	✓			
C50*	Yes	✓			
C63-64-65	Yes		✓		
C69-70-71	Yes		✓		
C72-75-76-77	Yes		✓		
C86-87	No	✓			
C104-105-106-107	Yes		✓		
C167-168-169	Yes				✓

* Caverns C49 and C50 have been discussed in Report 3 as the cavern system C49-50 in relation to the reconstruction.

The scope of work for Phase I - Part A was defined as:

> The historic cavern development of ten (10) caverns, of which 7 are (partly) backfilled, will be reconstructed based on the available historic data and information. The aim of Part A is to construct reliable cavern geometries for the 10 selected caverns as a basis for the activities in Part B of the study. The reliability of the reconstructed geometries is limited by the quality of the input data. No guarantee for the accuracy of reconstructed geometries can be provided due to the absence of validation opportunity (the caverns have already been migrated).

The scope of work for Phase I - Part B was defined as:

> Based on the reconstructed cavern geometries from Part A, the historic slurry filling (where relevant) and cavern migration processes for the 10 selected caverns will be reconstructed in Part B, incorporating further historical data and information where available.

The scope of work for Phase I – Part C was defined as:

> Combining the outputs from Part A and Part B, the effects at surface caused by the cavern migration of the 10 studied caverns will be investigated in Part C. The main task of this part is to match the actual, measured, subsidence development to the reconstructed cavern geometries and migration processes stemming from Parts A and B with the aim of establishing one (or more) formula(s) that can describe the subsidence effect at surface from cavern migration of the 10 selected caverns. This formula should be applicable to other caverns in the TWR region. The support from a geotechnical/ geo-mechanical specialist was required for Part C and Christian Jakob (K-UTEC) has taken this role.

Phase II: Update Subsidence Prognosis

The scope of work for Phase II, Update Subsidence Prognosis, was distributed over three parts:

Part A: Classification of caverns and refining prognosis algorithm.

Part B: Selection of input parameters and initial subsidence prognosis.

Part C: Finalisation of subsidence prognoses for relevant “Fase 2 and 3” caverns and superposition.

Phase III: Subsidence assessment Fase 1 caverns

(A study for Nobian internal documentation purposes)

The scope of work for Phase III aims to reconstruct the cavern development, migration and consequential subsidence for the caverns in the “Fase 1” area and comprises three parts:

Part A: Reconstruction cavern development

Part B: Reconstruction of cavern migration process

Part C: Effects at surface related to cavern migration

Iterative

The work during Phase III of the overall study will rely heavily on operating the established BJP-algorithm in “reverse”, meaning that during Part C the known subsidence values from the “Fase 1” area will be used to validate the initially reconstructed migration history (Part B) and cavern geometry (Part A). Experience with such a reverse workflow has been acquired during Phase II of the study.

1.3. Reporting structure

Report 1 [1] covering the initial insights gained during Phase I of the study and was delivered in December 2023. It describes the fundamental principles used during the reconstruction of cavern development by leaching and subsequent migration development of the 10 caverns included in the study. The aim of this report was to explain the fundamental principles related to the reconstruction of cavern development, slurry filling, migration, as well as the consequential link to subsidence. This to support the reader in the understanding of the further parts of the overall reporting. Please note that some of the parameters first presented in Report 1 have been updated in later stages of the UMS-TWR. Where relevant, this will be noted in the following chapters.

Report 2 [2] describes the Bekendam-Jakob-Pinkse (BJP) subsidence prognosis algorithm for migrating salt caverns in a bedded stratigraphy as developed through performance of Phase I and II of the study. Report 2 was delivered in November 2024. The BJP algorithm has been developed based on the historically used "Bekendam-Method" for subsidence prognosis and on several new insights from Phase I and II of the UMS-TWR.

Report 3 [3] presents detailed descriptions of the reconstructions and validates the assumptions made in the BJP algorithm such as values for Bulking Factor (BF) and migration column shape, see Report 2 and Report 3 for details. Report 3 can be considered the completion of Phase I of the UMS-TWR.

The final report, this Report 4, discusses the cavern specific selection of input parameters following the unified workflow, as well as the outcome of the BJP-Algorithm for relevant caverns in the TWR area. Report 4 can be considered the completion of Phase II of the UMS-TWR.

1.4. Structure of Report 4

This Report 4 titled "Subsidence predictions for potential future migration and recommendations on mitigative action by means of backfilling" delivers the subsidence prognoses for caverns in the TWR area for which an update of a subsidence prognosis was required as explained in paragraph 1.1. After this introduction in Chapter 1, this report continues with an exemplary selection of input parameters for C130-131. This chapter provides a step-by-step description of the input parameters selection process for the BJP-Algorithm. Chapter 3 comprises firstly an overview of all caverns which have been assessed during Phase II of the UMS-TWR, i.e. all caverns for which an updated subsidence prognosis is required. This overview also contains the Cavern Migration Likelihood Scoring results for the assessed caverns. The key information and the selected parameters per assessed cavern are included in APPENDIX I to this report. Secondly, Chapter 3 provides cavern specific notes on the input parameter selection process for a selection of the assessed caverns. Cavern specific notes are provided for caverns where information in APPENDIX I in combination with the exemplary input parameter selection process described in Chapter 2 are not sufficient to understand the reasoning behind the selected parameters. The BJP-Algorithm produces minimal backfill volumes required to prevent Stage 4 subsidence. These volumes in combination with the 80% filling grade volume for caverns with a relevant migration likelihood are presented in Chapter 4. This report concludes with conclusions and recommendations in Chapter 3. References are listed in Chapter 6. APPENDIX I to Report 4 is delivered as a separate document to ease parallel reading of the report and this appendix.

2. Exemplary workflow Input-Output: Cavern 130

The BJP-Algorithm input selection process and output products are explained by example of cavern 130-31 (C130-131). The steps in this example were taken and recorded for all caverns for which a subsidence prognosis was required. The information presented in this chapter, i.e. the selected input parameters and algorithm output, have been included in APPENDIX I to this report for all assessed caverns. As such, APPENDIX I can be considered as the final delivery of the UMS-TWR Phase II.

2.1. Selection of input parameters

C130-131 is located along the Twekkelerveldweg in Hengelo. The cavern has been developed using the boreholes listed in Table 2 which also lists the stratigraphy. More details on this cavern and all other caverns discussed in this report can be found in APPENDIX I.

Table 2: C130-131: 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 2 below.

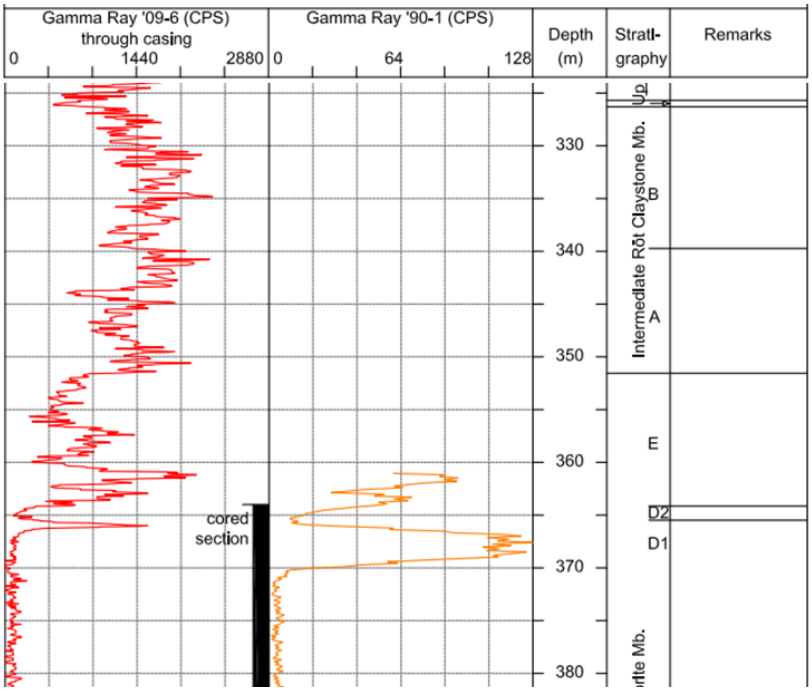

Figure 2: Detailed interpretation of the Main Röt Evaporative Member based on Gamma Ray Logs (Geowulf Laboratories interpretation)

The relative position of the actual cavern in the Salt stratigraphy is shown in a side-view of the cavern in Figure 3. As can be seen, the cavern roof is positioned at the bottom of the Anhydrite-E member.

The Claystone CD has collapsed, and the Salt D 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.

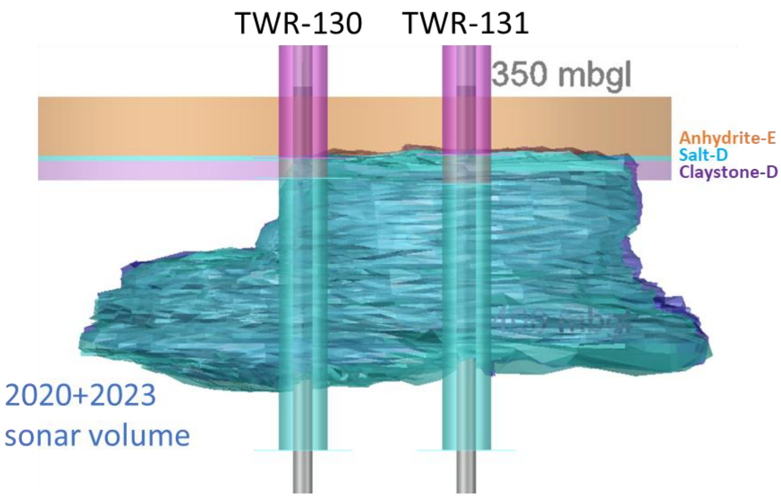

Figure 3: *Position of cavern 130 in the Salt stratigraphy. Shown are the intact Salt C member, the Claystone D1 member and the Anhydrite-E member. The Salt D2 member has not been found at this location in the brinefield.*

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 4. This contour has an area of 3.500 m², with a circular radius of 33 m and a HR of 16,5 m.

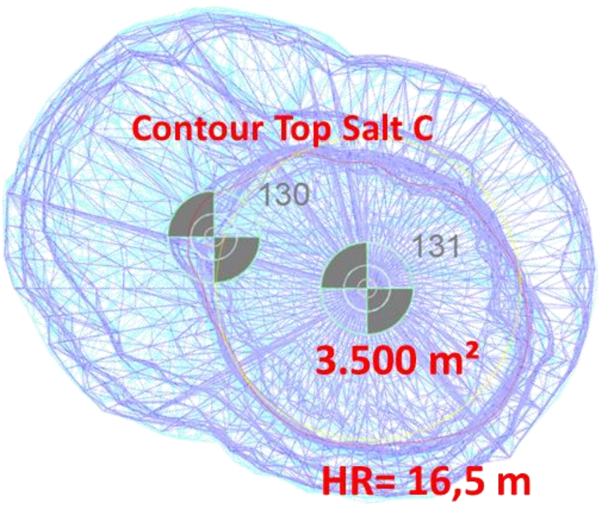

Figure 4: *Top view of cavern 130. Intersection of cavern with Top Salt C shown in red, corresponding circular contour in yellow.*

The latest available sonar images of C130-131 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 therefore 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 cylindrical representative cavern volume is shown in Figure 5 below.

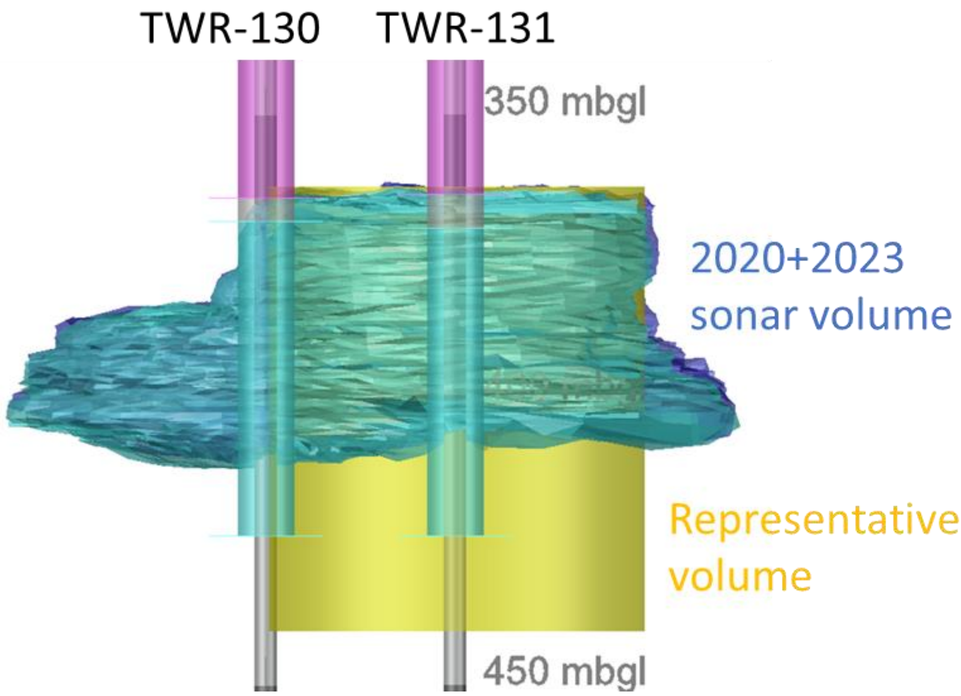

Figure 5: Representative cavern volume (yellow) and actual cavern volume as per sonar images from 2020 & 2023

The cylinder bottom reaches below the salt member as can be seen in this figure due to the relatively small area of the intersection of the cavern with the Top of Salt C. In case of migration, bulked overburden could spread over the larger lower half of the cavern. This is thus a relatively unfavourable cavern shape for potential migration as the resulting migration column will reach higher than a column based simply on the maximum height of the actual cavern. This is a conservative approach in the input selection workflow. The representative volume is a cylinder with 33m radius and 78m height with the roof positioned at 362,7 m below ground level (mbgl).

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 3.

No backfill was applied in this cavern at the time the sonars from 2022 and 2023 were taken, backfilling of this cavern started in April 2024. The "Backfill insitu unconsolidated" (second row from the bottom in Table 3) is left at 0 m³ for the prognosis.

Table 3: 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 (m^3)	**295136**
Actual volume (recon./sonar)(m^3)	237523
Insolubles (bulked) (m^3)	15573
Part of BPB prod. Vol. not acc. (m^3)	57613
Part of BPB prod. Vol. not acc. (%)	**20%**
Cavern geometry conversion	
Migration column Surface area (m^2)	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) [m^3]	266853
Constructed volume (conical) [m^3]	0
Constructed volume total [m^3]	266853
Part of BPB prod. Vol. not acc. (m^3)	28283
Part of BPB prod. Vol. not acc. (%)	**10%**
Height correction backfill insitu [m]	
Backfill insitu unconsolidated (m^3)	
Backfill consolidation (%)	

2.2. 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, see Report 2 [2]. The algorithm is integrated into a Python code which uses these parameters in conjunction with a set of "constants", such as the Bulking Factor (=1,20), 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 4.

Table 4: C130-131: Summary of subsidence prognosis results `(l) and dimensions of the potential migration (r)

	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 sir
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

	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 4 shows that for C130-131, 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 6 indicating the actual roof depth, the final roof depth and the critical roof depth to prevent Stage 4 subsidence (trough or sinkhole).

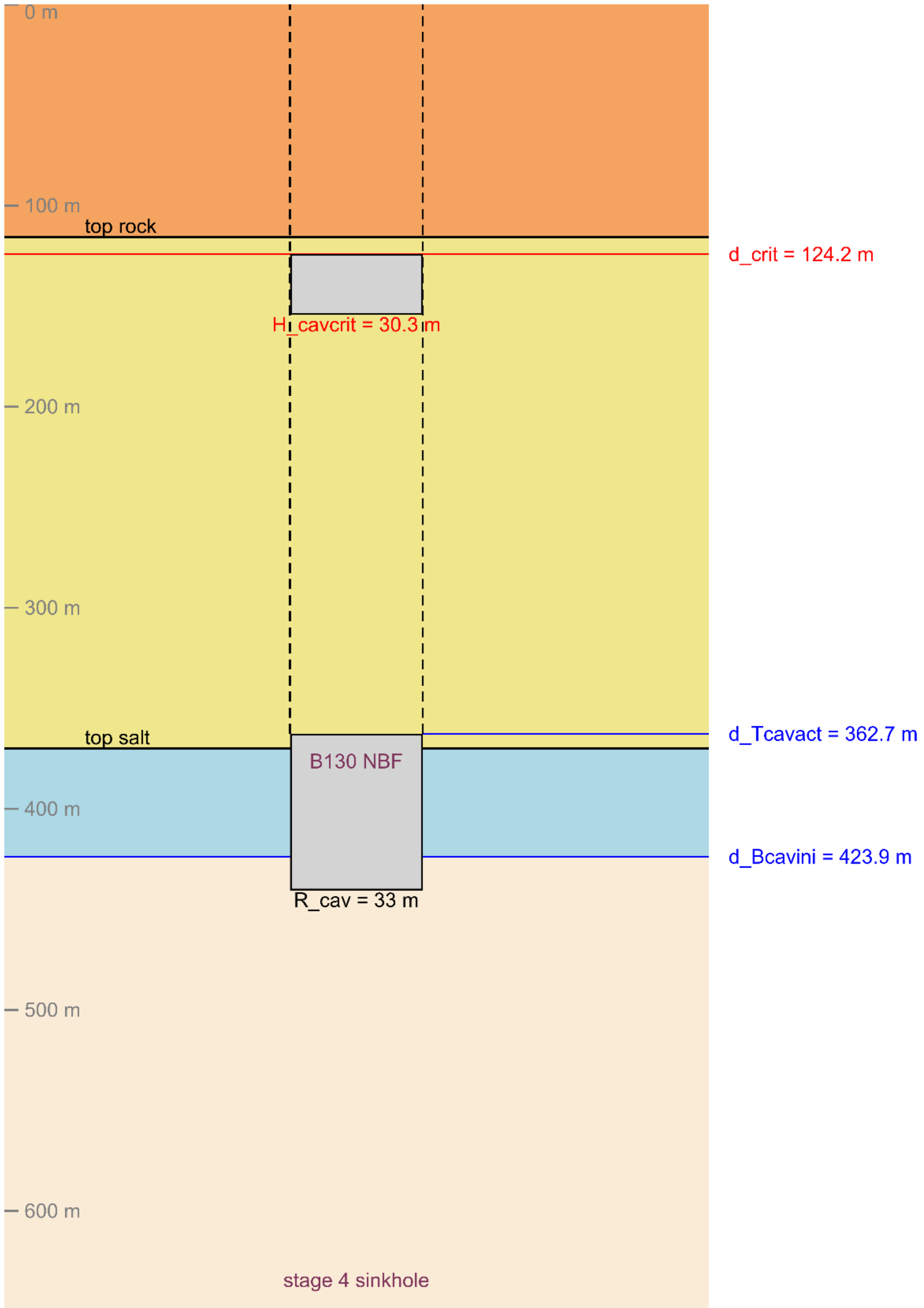

Figure 6: C130-131: Potential migration column based on selected input parameters.

The subsidence contours resulting from the potential migration as presented in Figure 6 are shown in Figure 7.

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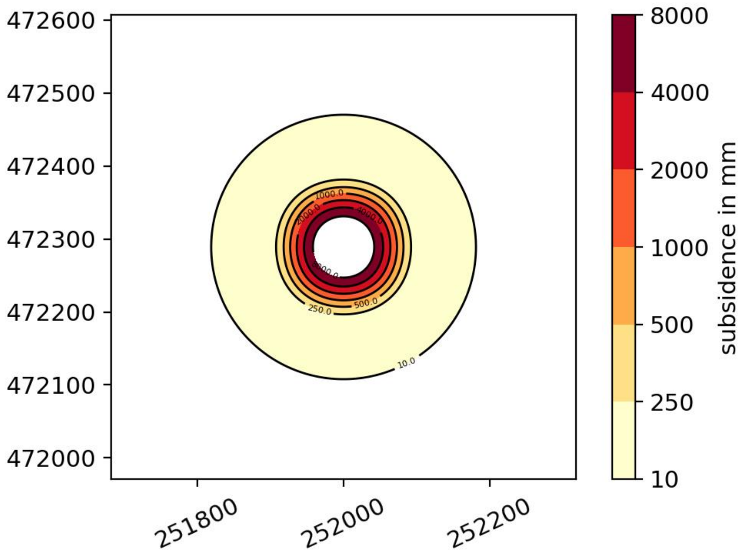

Figure 7: *C130-131: Maximum subsidence contours when potential subsidence occurs.*

To enable a subsidence impact assessment by Nobian, several derivatives of the maximum subsidence 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 8 below.

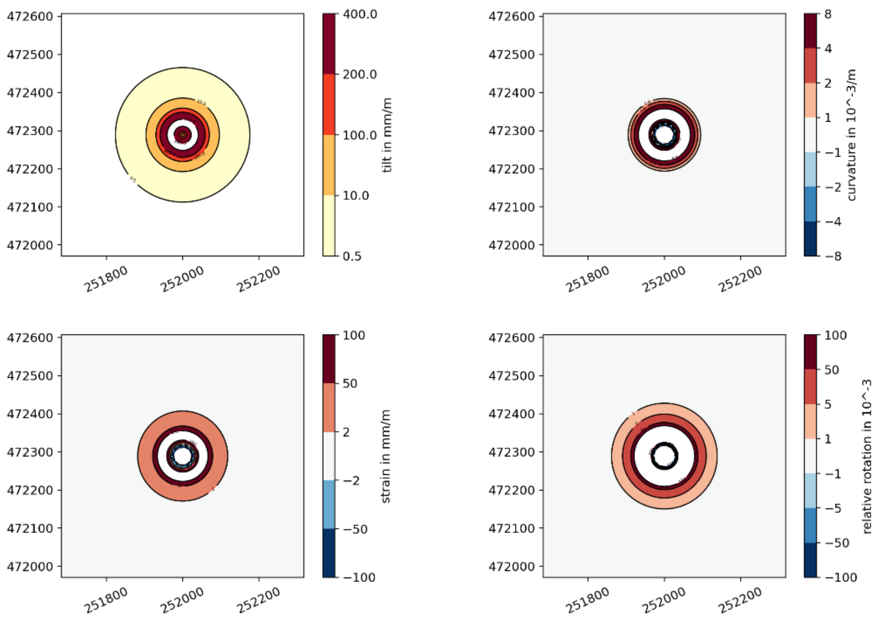

Figure 8: *C130-131: Maximum tilt, curvature, strain and relative rotation when cavern migration occurs.*

2.3. Likelihood of migration

The likelihood of migration has been assessed based on four criteria: Hydraulic Radius, Anhydrite-E exposure (i.e. after collapse/dissolution of Salt D when present and collapse of Claystone CD), water exposure of the Anhydrite-E and the (nearby) presence of faults in the under- and/or underlying strata of the salt. The summary of this assessment for C130-131 is presented in Table 5. For an explanation of the scoring system see Table 6 on page 19.

Table 5: C130-131: 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 5, the likelihood of migration score for C130-131 equals six (6) of a maximum score of eight (8) meaning that the likelihood of migration for this cavern is probable based on the studied cases of cavern migration in the TWR brinefield.

2.4. Preventive measures: backfilling

Backfilling is recommended as a preventive measure, because the likelihood of migration is probable and in case of migration the abovementioned subsidence prognosis predicts the formation of a Stage 4 Sinkhole. 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 only 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 (SF=2) with regards to the minimal beam thickness to avoid deflection of this roof beam resulting in Stage 3 subsidence. This volume is used for the preparation of a backfill recommendation as a conservative approach and is thus considered the “Minimal backfill scenario”.

Post-processing of the results table subsequently produces an 80% filling grade backfill volume as the practically maximum attainable backfilling grade of a cavern. This scenario is further called the “Maximum backfill scenario.

The stated ”effective” backfill volume for the Minimal scenario need 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.

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 drill string 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, can be practically validated by before-and-after sonar measurements, taking a suitable period for self-weight consolidation into account.

The minimum 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 9.

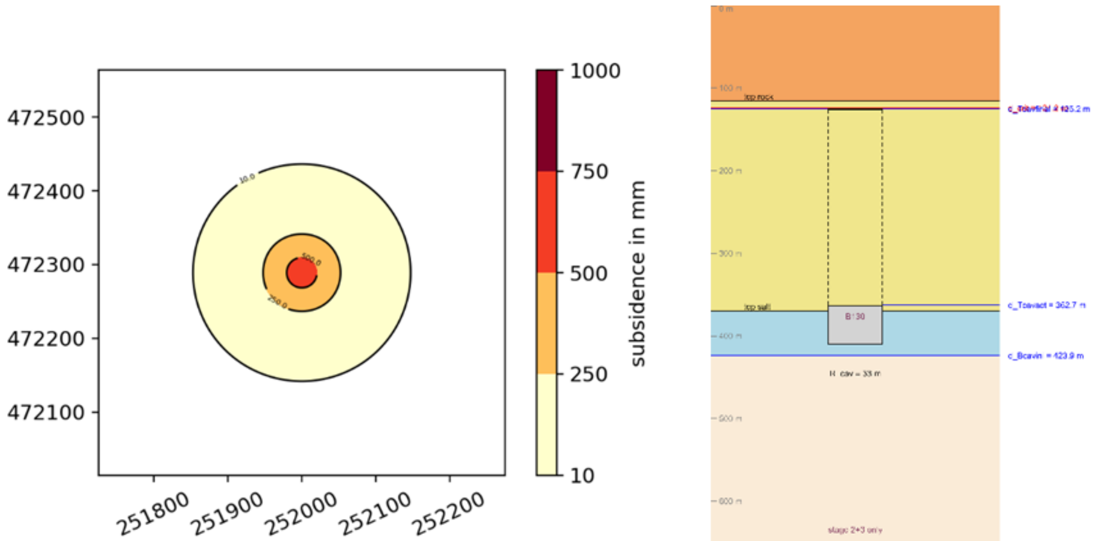

Figure 9: C130-131: Minimal backfill scenario: Subsidence contours (l) and migration column(r).

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. This filling grade thus goes beyond the minimum required volume of backfill required to prevent Stage 3 subsidence with a SF.

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 Maximum backfill scenario (80% filling grade) are shown in Figure 10.

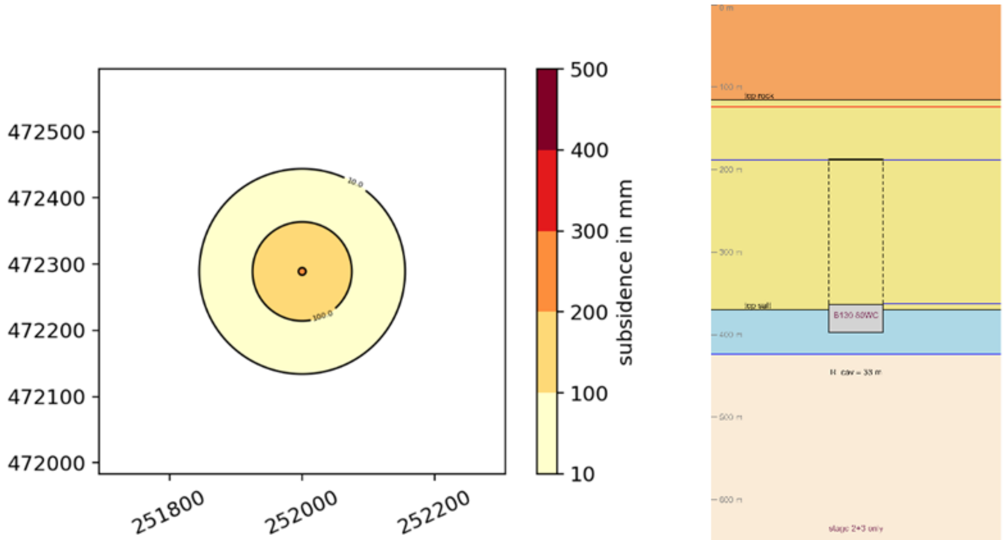

Figure 10: C130-131: Maximum backfill scenario: Subsidence contours (l) and migration column(r)).

2.5. Sensitivity of cavern backfilling grade

To illustrate the sensitivity of the results of the subsidence predictions discussed prior, the just presented maximum practically attainable 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 11 presents the comparison of the subsidence prognosis results for scenarios. For each of the scenarios, the subsidence contours and maximum subsidence in metres, as well as the relative rotation contours and maximum concave and convex rotation in ‰ has been shown.

As can be seen from Figure 11, the gradual reduction of conservatisms decreases the subsidence bowl and maximum relative rotation with each step.

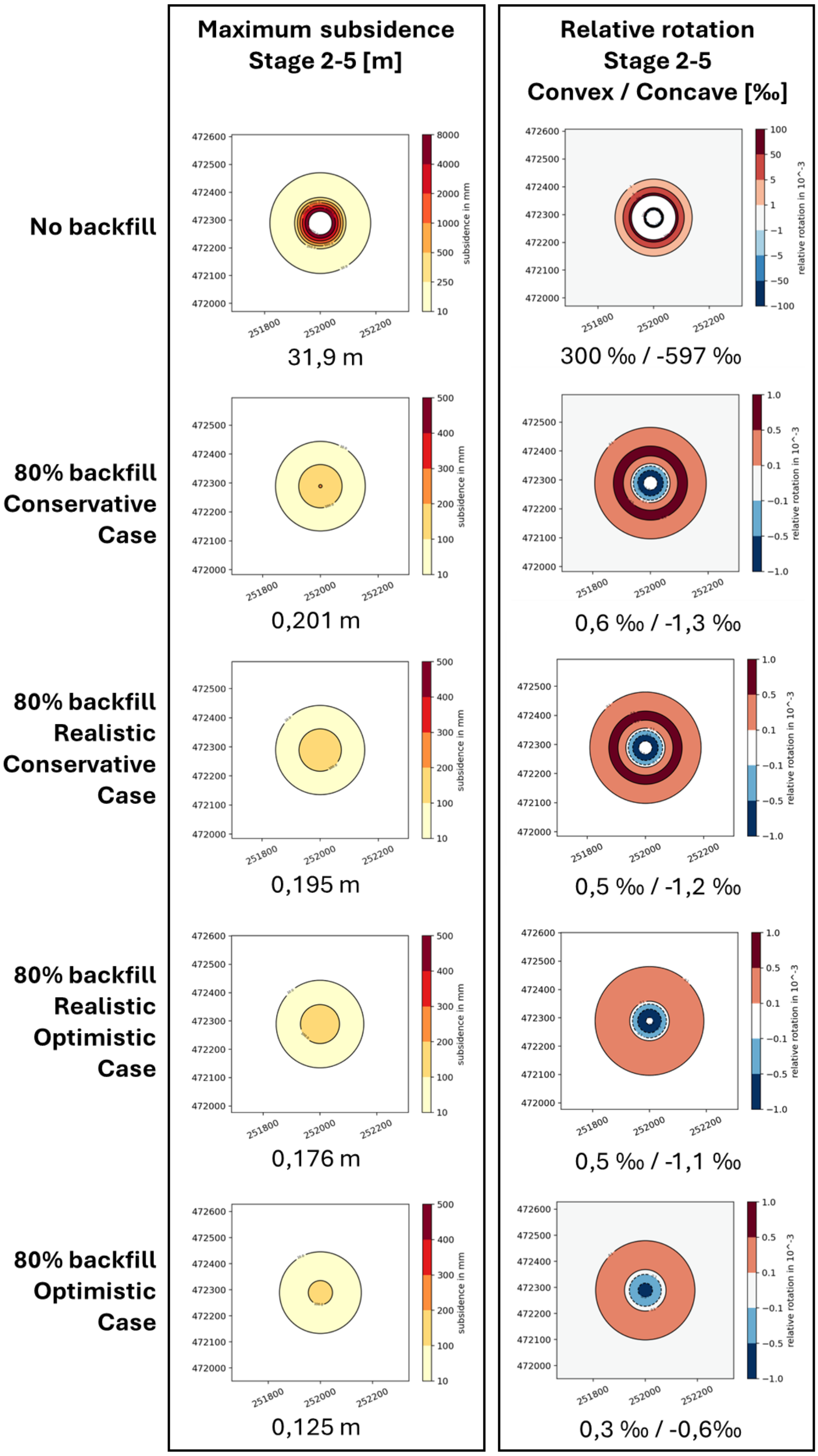

Figure 11: C130-131 – comparison results No backfill, 80% backfill CC, RCC, ROC and OC.

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.

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 required scenario or the maximum attainable (80% filling grade) scenario, will need to be made based on an impact analysis considering the current use of the ground surface within the predicted subsidence contours. Furthermore, potential measures to safely abandon caverns with a low likelihood of migration but potentially a high impact in case of migration need to be considered by Nobian. As such these choices are left to Nobian. Consequently, subsidence prognoses for caverns after application of the minimum and/or maximum scenarios, as just presented for C130-131, are not included in this report at this time. The BJP-Algorithm output values with regards to the minimum required and maximum attainable backfill volumes are presented in Chapter 4 for caverns with a relevant migration likelihood.

3. Likelihood of migration and cavern specific notes

The detailed assessment of the likelihood of migration for the well-documented cavern migration cases has enabled the development of a “Cavern Migration Likelihood Scoring System” (CMLSS), see Report 3, paragraph 6.4 for details [3]. The establishment of a unified CMLSS has now enabled Nobian to systematically determine the appropriate “Frequency (F)-class” for each studied cavern in their TWR cavern risk matrix as elaborated in [4]. The CMLSS distinguishes the scoring criteria, categories and scores as defined by Table 6.

Table 6: Cavern Migration Likelihood Scoring System (CMLSS): criteria, categories and scores

Criterion	Catergories	Score
HR of intersection cavern with Salt C-5m contour measured in latest sonar. HR=0 refers to a fully intact Salt C- 5 m Safety Roof over the cavern.	HR = 0 : HR = 1 – 10 m: HR = 10 – 15 m: HR > 20 m:	0 1 2 3
Anhydrite-E exposed in the cavern roof by leaching and/or collapse of the Claystone CD bench?	No Likely Yes	0 1 2
Prolonged exposure of Anhydrite-E to water during cavern operation?	No: Likely or blanket medium: Yes	0 1 2
Faults in nearby (in under- / overlying strata)	No Yes	0 1

The scoring system collates the individual categories to a total likelihood score between 0 and 8. Tabel 1 in [4] provides the conversion of likelihood score to F-class, see Table 7.

Table 7: Conversion likelihood scores to Frequency-class.

F-class	F0	F1	F2	F3	F4	F5	F6
Description	Extremely unlikely	Highly unlikely	Unlikely	Limited	Possible	Probable	Very likely
Likelihood scores	0 & 1*	1* & 2	3	4	5	6-8	Active migration

* See paragraph 4.3.1 in [4] for an explanation of how a likelihood score of 1 is distributed across F0 and F1 classes

3.1. Overview of assessed caverns and likelihood of migration

All caverns assessed in relation to their likelihood of migration as part of Phase II of the UMS-TWR are listed in Table 8 ordered by cavern number. The scores for the likelihood of migration for each cavern are also included in this table. The final column in the table indicates if a cavern specific note has been included in paragraph 3.2. The likelihood of migration for the well-documented cavern migration cases discussed in Report 3 [3] is also included in Table 8 for reference and marked in blue.

Cavern C167-168-169 has a very complex development history which was challenging to reconstruct. A plausible reconstruction was eventually achieved but proved of little value for the validation process due to the uncertainties in relation to the position of cavern volume and the influence of faults in the overburden. The performed reconstruction work on this cavern will be delivered in an addendum to Report 3, to be delivered in Q1-2025. Due to the mentioned uncertainties, the likelihood of migration has not been established at this time and C167-168-1698 is thus not included in Table 8.

Table 8: UMS-TWR – Phase I + II - Likelihood of migration and cavern specific notes

Cavern	July-'24 Risk Matrix	BJP-Output (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	Cavern specific note?
15	--	Stage 2+3 only	Yes	Yes	No	24,5	3	Yes	2	Yes	2	No	Yes	1	8	No
30	--	Stage 4 - trough	Yes	No	No	25	3	Likely	1	Likely	1	No	Yes	1	6	No
35	--	Stage 4 - trough	Yes	No	No	35	3	Yes	2	Yes	2	No	Yes	1	8	No
37	--	Stage 2+3 only	Yes	No	No	20	3	Yes	2	Yes	2	No	Yes	1	8	No
49	--	Stage 2+3 only	Yes	Yes	No	16,5	3	Yes	2	Yes	2	No	Yes	1	8	No
50	--	Stage 2+3 only	Yes	Yes	No	22	3	Yes	2	Yes	2	No	Yes	1	8	No
51	S2F4	Stage 2+3 only	No	No	No	11,5	2	Yes	2	Yes	2	No	Yes	1	7	Yes
52	S1F4	Stage 2+3 only	No	Partly	No	33,5	3	Yes	2	Yes	2	No	Yes	1	8	Yes
55	S1F5	Stage 2+3 only	No	yes	No	21	3	Yes	2	Yes	2	No	No	0	7	Yes
57	S3F4	Stage 4 - sinkhole	No	No	No	20	3	Likely	1	Likely	1	Yes	Yes	1	6	Yes
60	S4F4	Stage 2+3 only	No	No	No	33,5	3	Yes	2	Yes	2	No	Yes	1	8	No
63	--	Stage 2+3 only	No	No	Yes	Not relevant	0	No	0	No	0	No	Yes	1	1	No
64	--	Stage 2+3 only	Yes	Yes	No	33,5	3	Yes	2	Yes	2	No	Yes	1	8	No
67	S4F4	Stage 2+3 only	No	No	No	28	3	Yes	2	Yes	2	No	Yes	1	8	No
69	--	Stage 4 - sinkhole	Yes	Partly	No	25	3	Yes	2	Yes	2	No	Yes	1	8	No
72	S1F5	Stage 2+3 only	Yes	Yes	No	27,5	3	Likely	1	Likely	1	No	Yes	1	6	No
73	S1F4	Stage 2+3 only	No	No	No	38	3	Yes	2	Yes	2	No	Yes	1	8	Yes
75	--	Stage 2+3 only	No	Partly	No	20	3	No	0	No	0	No	Yes	1	4	No
76	--	Stage 2+3 only	No	Yes	No	14	2	No	0	No	0	No	Yes	1	3	No
77	--	Stage 2+3 only	No	Yes	No	10	2	No	0	No	0	No	Yes	1	3	No
78	S1F4	Stage 2+3 only	No	Partly	No	20,5	3	Yes	2	Yes	2	No	Yes	1	8	Yes
80	S3F3	Stage 4 - sinkhole	No	No	No	13	2	No	0	No	0	Yes	No	0	2	Yes
81	S3F4	Stage 4 - sinkhole	No	No	No	22	3	Yes	2	Blanket	1	Yes	No	0	6	No
84	S2F3	Stage 2+3 only	No	Partly	No	5	1	No	0	No	0	Yes	Yes	1	2	Yes
86	--	Stage 2+3 only	Yes	No	No	22	3	Yes	2	Blanket	1	Yes	No	0	6	No
90	S4F4	Stage 4 - sinkhole	No	No	No	13,5	2	Yes	2	Yes	2	No	Yes	1	7	No
94	S1F4	Stage 2+3 only	No	Partly	No	27	3	Yes	2	Yes	2	No	Yes	1	8	Yes
98	S1F3	Stage 2+3 only	No	Yes	No	19	3	Yes	2	Yes	2	No	Yes	1	8	Yes
100	S1F3	Stage 2+3 only	No	Yes	No	16,5	3	No	0	No	0	Yes	No	0	3	Yes
102	S1F3	Stage 2+3 only	No	Yes	No	27,5	3	No	0	No	0	Yes	No	0	3	Yes
104	S1F4	Stage 2+3 only	No	Yes	Yes	Not relevant	0	No	0	No	0	Yes	No	0	0	No
106	--	Stage 2+3 only	Yes	Yes	No	25	3	Yes	2	Blanket	1	Yes	No	0	6	No
108	S1F4	Stage 2+3 only	No	Yes	No	24,5	3	Yes	2	Yes	2	No	No	0	7	Yes
110	S3F4	Stage 4 - sinkhole	No	No	No	14,5	2	Likely	1	Likely	1	No	Yes	1	5	No
112	S1F3	Stage 2+3 only	No	Partly	No	26,5	3	No	0	No	0	Yes	Yes	1	4	Yes
114	S4F4	Stage 2+3 only	No	No	No	26,5	3	Yes	2	Blanket	1	Yes	Yes	1	7	No
116	S3F4	Stage 2+3 only	No	No	No	21,5	3	Yes	2	Blanket	1	Yes	No	0	6	No
118	S4F3	Stage 2+3 only	No	No	No	22	3	Yes	2	Yes	2	No	No	0	7	No
120	S3F3	Stage 2+3 only	No	No	No	5	1	No	0	No	0	Yes	No	0	1	Yes
122	S1F3	Stage 2+3 only	No	Partly	No	25,5	3	No	0	No	0	Yes	No	0	3	Yes
124	S2F3	Stage 2+3 only	No	Partly	No	17,5	3	Yes	2	Blanket	1	Yes	No	0	6	Yes
126	S2F3	Stage 2+3 only	No	Partly	No	16,5	3	Likely	1	Likely	1	No	No	0	5	Yes
128	S2F4	Stage 2+3 only	No	No	No	20,5	3	Yes	2	Blanket	1	Yes	No	0	6	No
130	S4F4	Stage 4 - sinkhole	No	No	No	16,5	3	Yes	2	Blanket	1	Yes	No	0	6	No
132	S4F4	Stage 2+3 only	No	Yes	No	23,5	3	No	0	No	0	Yes	Yes	1	4	Yes
134	S3F3	Stage 2+3 only	No	No	No	13,5	2	Likely	1	Likely	1	Yes	Yes	1	5	No
136	S3F4	Stage 2+3 only	No	No	No	21	3	Yes	2	Blanket	1	Yes	No	0	6	No
138	S4F3	Stage 4 - sinkhole	No	No	No	13,5	2	Likely	1	Likely	1	Yes	No	0	4	No
140	S4F3	Stage 4 - sinkhole	No	No	No	17,5	3	Yes	2	Blanket	1	Yes	No	0	6	No

Cavern	July-'24 Risk Matrix	BJP-Output (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	Cavern specific note?
144	S3F4	Stage 2+5 only	No	No	No	20	3	Yes	2	Blanket	1	Yes	Yes	1	7	No
146	S1F2	Stage 2+3 only	No	Partly	Yes	Not relevant	0	No	0	No	0	Yes	No	0	0	No
148	S1F3	Stage 2+3 only	No	No	Yes	Not relevant	0	No	0	No	0	Yes	No	0	0	No
149	S1F4	Stage 2+3 only	No	Partly	No	24,5	3	Yes	2	Blanket	1	Yes	Yes	1	7	Yes
151	S3F3	Stage 2+5 only	No	No	No	13	2	No	0	No	0	Yes	Yes	1	3	Yes
153	S1F4	Stage 2+3 only	No	No	No	31	3	Yes	2	Blanket	1	Yes	Yes	1	7	No
156	S3F2	Stage 4 - sinkhole	No	Partly	Yes	Not relevant	0	No	0	No	0	Yes	Yes	1	1	Yes
159	S3F3	Stage 2+3 only	No	Partly	No	5	1	No	0	No	0	Yes	Yes	1	2	Yes
162	S3F4	Stage 2+3 only	No	No	No	18,5	3	Yes	2	Blanket	1	yes	No	0	6	No
165	S1F4	Stage 2+3 only	No	Partly	No	21	3	Yes	2	Blanket	1	Yes	Yes	1	7	Yes
173	S4F4	Stage 2+3 only	No	Partly	No	21	3	Yes	2	Blanket	1	Yes	No	0	6	Yes
176	S2F3	Stage 2+3 only	No	No	No	5	1	No	0	No	0	Yes	No	0	1	Yes
178	S1F3	Stage 2+3 only	No	Yes	No	5	1	No	0	No	0	Yes	No	0	1	Yes
180	S4F3	Stage 2+3 only	No	No	No	12,5	2	No	0	No	0	Yes	No	0	2	No
184	S2F3	Stage 2+3 only	No	No	No	22	3	Yes	2	Blanket	1	Yes	No	0	6	No
187	S2F3	Stage 4 - sinkhole	No	No	No	10	2	Likely	1	Blanket	1	Yes	Yes	1	5	No
190	S3F4	Stage 2+3 only	No	No	No	23,5	3	Yes	2	Yes	2	Yes	No	0	7	No
192	S1F4	Stage 2+3 only	No	No	No	14,5	2	Yes	2	No	0	Yes	No	0	4	No
194	S2F3	Stage 4 - sinkhole	No	No	No	10	2	Yes	2	Blanket	1	Yes	Yes	1	6	No
201	S3F3	Stage 4 - sinkhole	No	No	No	5	1	No	0	No	0	Yes	No	0	1	Yes
204	S4F3	Stage 2+3 only	No	Partly	No	29	3	No	0	No	0	Yes	Yes	1	4	Yes
207	S2F2	Stage 2+3 only	No	No	Yes	Not relevant	0	No	0	No	0	Yes	No	0	0	No
209	S3F2	Stage 4 - sinkhole	No	No	Yes	Not relevant	0	No	0	No	0	Yes	Yes	1	1	Yes
211	S3F2	Stage 2+3 only	No	No	Yes	Not relevant	0	No	0	No	0	Yes	No	0	0	No
213	S3F2	Stage 2+3 only	No	No	Yes	Not relevant	0	No	0	No	0	Yes	No	0	0	No
215	S4F3	Stage 4 - sinkhole	No	No	No	19,5	3	No	0	No	0	Yes	No	0	3	Yes
218	S2F2	Stage 2+3 only	No	No	Yes	Not relevant	0	No	0	No	0	Yes	No	0	0	No
223	S4F3	Stage 2+3 only	No	No	Yes	5	1	No	0	No	0	Yes	No	0	1	Yes
225	S3F3	Stage 4 - sinkhole	No	No	No	11,5	2	No	0	No	0	Yes	No	0	2	No
228	S2F2	Stage 2+3 only	No	No	Yes	Not relevant	0	No	0	No	0	Yes	No	0	0	No
231	S4F2	Stage 2+3 only	No	No	Yes	Not relevant	0	No	0	No	0	Yes	No	0	0	No
234	S2F3	Stage 4 - sinkhole	No	No	No	10	2	No	0	No	0	Yes	No	0	2	No
239	S3F2	Stage 4 - sinkhole	No	No	Yes	Not relevant	0	No	0	No	0	Yes	No	0	0	Yes
242	S3F2	Stage 2+3 only	No	No	Yes	Not relevant	0	No	0	No	0	Yes	No	0	0	No
245	S3F2	Stage 2+3 only	No	No	Yes	Not relevant	0	No	0	No	0	Yes	Yes	1	1	No
248	S2F2	Stage 2+3 only	No	No	Yes	Not relevant	0	No	0	No	0	Yes	No	0	0	No
253	S2F2	Stage 2+3 only	No	No	Yes	Not relevant	0	No	0	No	0	Yes	No	0	0	No
256	S4F2	Stage 2+3 only	No	No	Yes	Not relevant	0	No	0	No	0	Yes	No	0	0	No
259	S2F3	Stage 2+3 only	No	No	No	29,5	3	No	0	No	0	Yes	Yes	1	4	No
347	S2F2	Stage 4 - sinkhole	No	No	Yes	Not relevant	0	No	0	No	0	Yes	Yes	1	1	Yes
347B	S2F2	Stage 4 - sinkhole	No	No	Yes	Not relevant	0	No	0	No	0	Yes	Yes	1	1	Yes

3.2. Cavern specific notes to input parameter selection

A note on the BJP-Algorithm input parameter selection workflow is included in this paragraph for caverns which the last column of Table 8 is noted as “Yes”. The input and output for these caverns are included in APPENDIX I. Caverns for which this column is noted “No” are not further discussed, the selection process is deemed clear, and the input and outcome is presented in APPENDIX I.

Cavern 51

Cavern 51 (C51) is very similar in shape and age to C49 and C50 discussed in Report 3. As such, the representative volume for C51 comprises a cone-shaped sump (filled with insolubles and claystone material) and a cylindrical top part. The subsidence prognosis is based on this conservative shape rather than the cylindrical shape of the available sonar image from 2023.

Cavern 52

A total of 631.310 m³ of slurry has been pumped to C52-53-54 according to [5]. This equates to 227.413 m³ of insitu backfill in the cavern after consideration of 15% SWC. It is expected that the lower part of the cavern is (partly) backfilled.

Cavern 55

A total of 1.337.722 m³ of slurry has been pumped to C55-56 according to [5]. This equates to 227.413 m³ of insitu backfill in the cavern after consideration of 15% SWC. A sonar from 2021 confirms that the cavern is backfilled as much as practically possible.

Cavern 57

Due to the geometry of C57-58-59, bulked overburden will not likely fill the entire cavern volume in case of cavern migration. An estimation of the part of the cavern that will be filled with bulked overburden has derived from the subtraction of a cone-shaped volume with a 30 °slope angle from the combined sonar volumes. This cone is illustrated by the grey triangle on the relevant page in APPPENDIX I. The remaining cavern volume after cavern migration is also noted in this appendix in a yellow box. The representative volume is adapted to reflect the partial filling of the cavern with bulked overburden. This situation is relevant to several other assessed caverns such as C162, C180 and C215 to name a few. To aid legibility, these situations are not further elaborated specifically in the notes in this paragraph.

Cavern 73

The 2020 sonar volume of C73-74 shows a slight cone-shaped bottom. To maintain a conservative approach, the representative volume comprises a cone-shaped bottom and a cylindrical top part.

Cavern 78

Cavern volume around well TWR-079 is imaged by sonar measurements. The unaccounted volume is 47% of the cavern production volume. The representative volume conservatively assumed only 19% of unaccounted volume. A total of 542.438 m³ of slurry has been pumped to C78-79 according to [5]. This equates to 92.214 m³ of insitu backfill in the cavern after consideration of 15% SWC. A sonar from 2009 confirms that the cavern is partly backfilled.

Cavern 80

The intersection of cavern C80 with the Top Salt C – 5 m criterion is limited to only 900 m² with a HR of 8,5 m. As such this contour is not likely to form a potential migration contour. To obtain the basis for a potential migration contour, a significantly more conservative, larger migration contour can be constructed deeper in Salt C. The representative volume is based on this larger contour.

Cavern 84

The intersection of cavern C84-85 with the Top Salt C – 5 m criterion is very limited with a HR of less than 5 m. As such this contour is not likely to form a potential migration contour. To obtain the basis for a potential migration contour, a significantly more conservative, larger migration contour can be constructed deeper in Salt C. The representative volume is based on this larger contour. A total of 603.990 m³ of slurry has been pumped to C84-85 according to [5]. This equates to 102.678 m³ of insitu backfill in the cavern after consideration of 15% SWC.

Cavern 94

The sonar images of C94-95 are not representative for the actual cavern volume considering 59% of unaccounted volume due to backfilling. The sonar images do show a possible cone-shaped bottom. To maintain a conservative approach, the representative volume is taken as 80% of the production volume and comprises a cone-shaped bottom and a cylindrical top part. A total of 163.473 m³ of slurry has been pumped to C94-95 according to [5]. This equates to 27.790 m³ of insitu backfill in the cavern after consideration of 15% SWC.

Cavern 98

The cavern volume based on the salt production could not be derived for this cavern as part of the production from this cavern is attributed to the production of adjacent caverns after their hydraulic connection. An estimated production volume was based on the total calculated insitu backfill volume in this cavern before subtracting 15% SWC and assuming the cavern was fully backfilled. A total of 787.090 m³ of slurry has been pumped to C98-99 according to [5]. This equates to 133.805 m³ of insitu backfill in the cavern after consideration of 15% SWC.

Cavern 100

The sonar images of C100-101 are not representative for the actual cavern volume considering 70% of unaccounted volume due to backfilling. The sonar images do show a possible cone-shaped bottom. To maintain a conservative approach, the representative volume is taken as 80% of the production volume. A total of 665.319 m³ of slurry has been pumped to C100-101 according to [5]. This equates to 113.104 m³ of insitu backfill in the cavern after consideration of 15% SWC.

Cavern 102

A total of 747.395 m³ of slurry has been pumped to C102-103 according to [5]. This equates to 127.057 m³ of insitu backfill in the cavern after consideration of 15% SWC. A sonar from 2022 confirms that the cavern is largely backfilled.

Cavern 108

A cone-shaped cavern bottom is visible for C108-109 in sonar images. As such and to maintain a conservative approach, the representative volume comprises a cone-shaped sump and a cylindrical top part. A total of 653.329 m³ of slurry has been pumped to C108-109 according to [5]. This equates to 111.066 m³ of insitu backfill in the cavern after consideration of 15% SWC.

Cavern 112

The sonar images of C112-113 are not representative for the actual cavern volume considering 64% of unaccounted volume due to backfilling. To maintain a conservative approach, the representative volume is taken as 80% of the production volume. A total of 421.052 m³ of slurry has been pumped to C112-113 according to [5]. This equates to 71.579 m³ of insitu backfill in the cavern after consideration of 15% SWC.

Cavern 120

The intersection of cavern C120-121 with the Top Salt C – 5 m criterion is very limited with a HR of less than 5 m. As such this contour is not likely to form a potential migration contour. To obtain the basis for a potential migration contour, a significantly more conservative, larger migration contour can be constructed deeper in Salt C. The representative volume is based on this larger contour. A total of 91.831 m³ of slurry has been pumped to C120-121 according to [5]. This equates to 15.611 m³ of insitu backfill in the cavern after consideration of 15% SWC.

Cavern 122

A total of 594.983 m³ of slurry has been pumped to C122-123 according to [5]. This equates to 101.147 m³ of insitu backfill in the cavern after consideration of 15% SWC.

Cavern 124

A total of 211.322 m³ of slurry has been pumped to C124-125 according to [5]. This equates to 35.925 m³ of insitu backfill in the cavern after consideration of 15% SWC.

Cavern 126

A slight cone-shaped bottom of the cavern can be recognized from the 2022 sonar images. Despite this shape, a cylinder-shaped representative volume was assumed as the cone-shaped bottom is laterally offset from the intersection of the cavern with the Top Salt C. A total of 146.079 m³ of slurry has been pumped to C126-127 according to [5]. This equates to 24.833 m³ of insitu backfill in the cavern after consideration of 15% SWC.

Cavern 132

A total of 1.152.005 m³ of slurry has been pumped to C132-133 according to [5] until February 2024. This equates to 195.841 m³ of insitu backfill in the cavern after consideration of 15% SWC. This cavern is now used as a back-up for slurry pumping when other caverns are temporarily unavailable.

Cavern 149

A total of 91.831 m³ of slurry has been pumped to C149-150 according to [5]. This equates to 15.611 m³ of insitu backfill in the cavern after consideration of 15% SWC.

Cavern 151
The intersection of cavern C151-152 with the Top Salt C – 5 m criterion is very limited with a HR of 10 m. As such this contour is not likely to form a potential migration contour. To obtain the basis for a potential migration contour, a significantly more conservative, larger migration contour can be constructed deeper in Salt C. The representative volume is based on this larger contour.

Cavern 156
There is no intersection of cavern C156-157-158-156A with the Top Salt C – 5 m. As such, no Hydraulic Radius can be attributed. To obtain the basis for a potential migration contour, a significantly more conservative, larger migration contour can be constructed deeper in Salt C. For the representative volume, an intersecting contour at Top Salt C – 10 m is used. Considering the presence of approximately 8-9 m of intact Salt C and a total of 23 m Salt C up to Anhydrite-E as a roof beam, C156-157-158-156A can be considered a stable cavern. A total of 1.012.831 m³ of slurry has been pumped to C156-157-158-156A according to [5]. This equates to 172.181 m³ of insitu backfill in the cavern after consideration of 15% SWC.

Cavern 159
The intersection of cavern C159-160-161-159A with the Top Salt C – 5 m criterion is very limited with a HR less than 5 m. As such this contour is not likely to form a potential migration contour. To obtain the basis for a potential migration contour, a significantly more conservative, larger migration contour can be constructed deeper in Salt C. The representative volume is based on this larger migration contour with a HR of 22 m constructed at a depth of Top Salt C – 20 m. A total of 457.049 m³ of slurry has been pumped to C159-160-161-159A according to [5]. This equates to 77.698 m³ of insitu backfill in the cavern after consideration of 15% SWC.

Cavern 165
A total of 481.186 m³ of slurry has been pumped to C165-166 according to [5]. This equates to 81.802 m³ of insitu backfill in the cavern after consideration of 15% SWC.

Cavern 173
A total of 569.902 m³ of slurry has been pumped to C173-174-175 according to [5]. This equates to 96.883 m³ of insitu backfill in the cavern after consideration of 15% SWC.

Cavern 176
The intersection of cavern C176-177 with the Top Salt C – 5 m criterion is very limited with a HR less than 5 m. As such this contour is not likely to form a potential migration contour. A more plausible larger migration contour with a HR of 21 m has been constructed at a depth of Top Salt C – 15 m.

Cavern 178
The intersection of cavern C178-179 with the Top Salt C – 5 m criterion is very limited with a HR less than 5 m. As such this contour is not likely to form a potential migration contour. To obtain the basis for a potential migration contour, a significantly more conservative, larger migration contour can be constructed deeper in Salt C. The representative volume is based on this larger migration contour with a HR of 28,5 m constructed at a depth of Top Salt C – 25 m. A total of 1.642.078 m³ of slurry has been pumped to C178-179 according to [5]. This equates to 279.153 m³ of insitu backfill in the cavern after consideration of 15% SWC.

Cavern 201
The intersection of cavern C201-202-203 with the Top Salt C – 5 m criterion is very limited with a HR less than 5 m. As such this contour is not likely to form a potential migration contour. To obtain the basis for a potential migration contour, a significantly more conservative, larger migration contour can be constructed deeper in Salt C. The representative volume is based on larger migration contour with a HR of 12,5 m constructed at a depth of Top Salt C – 15 m.

Cavern 204
A total of 133.389 m³ of slurry has been pumped to C204-205-206 according to [5]. This equates to 22.676 m³ of insitu backfill in the cavern after consideration of 15% SWC.

Cavern 209
There is no intersection of cavern C209-210 with the Top Salt C – 5 m. As such, no Hydraulic Radius can be attributed. To obtain the basis for a potential migration contour, a significantly more conservative, larger migration contour can be constructed deeper in Salt C. For the representative volume, an intersecting contour at Top Salt C – 7 m is used. Considering the presence of approximately 6 m of intact Salt C and a total of 26 m Salt C up to Anhydrite-E as a roof beam, C209-210 can be considered a stable cavern.

Cavern 215
The intersection of cavern C215-216-217 with the Top Salt C – 5 m criterion is very limited. As such this contour is not likely to form a potential migration contour. To obtain the basis for a potential migration contour, a significantly more conservative, larger migration contour can be constructed deeper in Salt C. The representative volume is based on larger migration contour with a HR of 19,5 m constructed at a depth of Top Salt C – 15 m.

Cavern 223
The intersection of cavern C223-224-224A with the Top Salt C – 5 m criterion is very limited with a HR less than 5 m. As such this contour is not likely to form a potential migration contour. To obtain the basis for a potential migration contour, a significantly more conservative, larger migration contour can be constructed deeper in Salt C. The representative volume is based on larger migration contour with a HR of 19,5 m constructed at a depth of Top Salt C – 10 m.

Cavern 239
There is no intersection of cavern C239-240-241 with the Top Salt C – 5 m. As such, no Hydraulic Radius can be attributed. To obtain the basis for a potential migration contour, a significantly more conservative, larger migration contour can be constructed deeper in Salt C. For the representative volume, an intersecting contour at Top Salt C – 10 m is used. Considering the presence of approximately 6 m of intact Salt C and a total of 21 m Salt C up to Anhydrite-E as a roof beam, C239-240-241 can be considered a stable cavern.

Cavern 347
There is no intersection of cavern C347-347A-347B with the Top Salt C – 5 m. As such, no Hydraulic Radius can be attributed. To obtain the basis for a potential migration contour, a significantly more conservative, larger migration contour can be constructed deeper in Salt C. For the representative volume, an intersecting contour at Top Salt C – 35 m is used. Considering the presence of approximately 20+ m of intact Salt C and a total of 50 m Salt C up to Anhydrite-E as a roof beam, C347-347A-347B can be considered a stable cavern.

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4. Preliminary backfill volumes

The BJP-Algorithm produces required backfill volumes for each cavern that reaches Stage 4 subsidence or higher. These volumes are presented in Table 9 for caverns at which migration can potentially lead to Stage 4 subsidence AND with a migration likelihood of three (3) and higher. See Table 8 in the previous chapter for all migration likelihood scores per cavern. Two scenarios are included in Table 9:

1. Minimal backfill scenario to prevent Stage 3, Stage 4 and Stage 5 subsidence with a SF=2.
2. Maximum backfill scenario (80% filling grade), i.e. the maximum practically attainable filling grade.

An exception is made for C60-61-62 for which migration would lead to Stage 2+3 subsidence only. The BJP-Algorithm does not output a minimal backfill volume to prevent Stage2+3 subsidence for this cavern, but as this cavern has a likelihood score of 8 and is located underneath the landfill of Twence B.V. in Hengelo, backfilling of this cavern is recommended, see also [4]. As a conservative approach, only an 80% filling grade scenario is included for this cavern in Table 9 at this time.

Table 9: UMS-TWR Phase II: Backfill volumes for caverns with Stage 4 or higher subsidence prognosis and a cavern migration likelihood score of 3 and higher.

		Cavern													
		58-2	60	82	90	110	130	139	140-2	151	188	194	205	215	
	Likelihood	6	8	6	7	5	6	4	6	3	5	6	4	3	Note:
	Totals	**Minimal backfill scenario (no Stage 3 w. SF=2)**													
Effective backfill volume required [m³]	**549.434**	**49.263**	**-**	**58.750**	**18.701**	**40.979**	**109.431**	**13.844**	**27.714**	**3.744**	**76.809**	**53.883**	**4.294**	**49.906**	1
2m thickness non-load bearing backfill [m³]	***156.205***	*10.053*	*-*	*12.164*	*4.580*	*5.284*	*6.842*	*4.580*	*7.697*	*4.247*	*2.513*	*2.513*	*21.137*	*9.557*	2
30% consolidation under load bulked overburden compensation [m³]	***234.297***	*17.795*	*-*	*21.274*	*6.984*	*13.879*	*34.882*	*5.527*	*10.623*	*2.397*	*23.797*	*16.919*	*7.629*	*17.839*	3
15% SWC compensation [m³]	***179.642***	*11.567*	*-*	*13.989*	*5.268*	*6.077*	*7.869*	*5.268*	*8.851*	*4.885*	*2.890*	*2.890*	*24.307*	*10.990*	4
Total volume for Minimal backfill scenario (no Stage 3 w. SF=2) [m³]	**882.883**	**88.678**	**-**	**106.177**	**35.533**	**66.219**	**159.024**	**29.219**	**54.886**	**15.273**	**106.009**	**76.205**	**57.367**	**88.292**	5
Total slurry volume for Minimal backfill scenario @ S/B = 5:1 [m³]	**4.788.375**	**443.388**	**-**	**530.887**	**177.667**	**331.094**	**795.121**	**146.096**	**274.428**	**76.367**	**530.046**	**381.027**	**286.835**	**441.459**	6
	Totals	**Maximum backfill scenario (80% filling grade)**													
Effective backfill volume required [m³]	**2.446.638**	225.190	349.745	233.554	106.266	141.615	213.482	119.091	184.726	107.035	130.690	112.594	308.578	214.070	7
2m thickness non-load bearing backfill [m³]	***131.203***	*10.053*	*28.205*	*12.164*	*4.580*	*5.284*	*6.842*	*4.580*	*7.697*	*4.247*	*2.513*	*2.513*	*21.137*	*9.557*	8
15% SWC compensation [m³]	***384.902***	*35.286*	*56.693*	*36.858*	*16.627*	*22.035*	*33.049*	*18.551*	*28.863*	*16.692*	*19.981*	*17.266*	*49.457*	*33.544*	9
Total volume for Maximum backfill scenario (80% filling grade)	**3.220.497**	**270.529**	**434.643**	**282.576**	**127.474**	**168.934**	**253.374**	**142.222**	**221.286**	**127.975**	**153.184**	**132.374**	**379.172**	**257.171**	10
Total slurry volume for Maximum backfill scenario @ S/B = 5:1 [m³]	**16.102.483**	**1.352.646**	**2.173.213**	**1.412.878**	**637.369**	**844.671**	**1.266.868**	**711.112**	**1.106.429**	**639.875**	**765.921**	**661.869**	**1.895.861**	**1.285.856**	11
Δ Slurry volume (Maximum - Minimal) [m³]	**11.314.108**	**909.258**	**2.173.213**	**881.991**	**459.702**	**513.577**	**471.747**	**565.016**	**832.001**	**563.508**	**235.875**	**280.842**	**1.609.027**	**844.397**	12

The following notes per row in this table explain the stated backfill/slurry volumes in more detail.

Minimal backfill scenario:

1. Minimum required “effective” backfill volume as resulting from the BJP-Algorithm output to prevent Stage 3 subsidence or higher with a Safety Factor of 2 (SF).
2. Volume required to compensate the value under 1. for a 2 m thick layer of backfill to which no load bearing capacity is attributed.
3. Volume required to compensate the values under 1. + 2. for 30% consolidation of backfill under the load of the bulked overburden in case of cavern migration.
4. Volume required to compensate the values under 1. + 2. + 3 for 15% SWC.

5. Total volume of backfill required for the Minimum backfill scenario (= 1. + 2. + 3. + 4.).
6. Total slurry volume for the Minimum scenario based on a Slurry / Backfill ratio of 5 (as validated in Report 3 [3]).

Maximum attainable backfill scenario (80% filling grade):

7. Maximum attainable “effective” backfill volume for 80% filling grade of the cavern.
8. Volume required to compensate the value under 7. for a 2 m thick layer of backfill to which no load bearing capacity is attributed.
9. Volume required to compensate the values under 7. + 8. for 15% SWC.
10. Total volume of backfill required for the Maximum attainable backfill scenario (= 7. + 8. + 9.).
11. Total slurry volume for the Maximum scenario based on a Slurry / Backfill ratio of 5.

Final row:

12. Difference between the slurry volume stated under 11. and 6. as an indication of how conservative the 80% filling grade is per cavern mentioned in the table.

Please note that the compensation for 30% consolidation under the load of bulked overburden is not applied to the Maximum backfill scenario with 80% filling grade as this would no longer fit in a cavern:

80% x 1,3 = 104%.

The effect of the UMS-TWR outcome on the total backfill volume required to prevent sinkhole or trough subsidence is presented in Table 10. In this table the historical backfill volumes and the volumes for the Minimal and Maximum backfill scenarios based on the new BJP-Algorithm are compared.

Table 10: Effect op UMS-TWR on total required backfill volume to prevent sinkhole or trough formation

Bekendam Method		
Total backfill volume (no Phase III subs.)	[m³]	6.180.681
Total backfill volume (no Phase III, 30% cons. + 15% SWC compensated	[m³]	9.240.118
Total slurry volume @ S/B = 5:1	**[m³]**	**46.200.590**
BJP-Algorithm		
Total backfill volume (no Stage 3 w. SF)	[m³]	549.434
Total backfill volume (no stage 3, w. SF, 30% + 2m comp. + 15%SWC)	[m³]	179.642
Total slurry volume (no Stage 3 w. SF, 30% + 2m + 15%SWC @ S/B = 5:1)	**[m³]**	**4.788.375**
% Total slurry comparison BJP vs Bekendam		**10%**
Total backfill volume (80% of Vcavact + 2m comp.+15%SWC)	[m³]	3.220.497
Total slurry volume (80% filling grade @ S/B = 5:1)	**[m³]**	**16.102.483**
% Total slurry comparison BJP (80%) vs Bekendam		**35%**

As can be seen in this table, the total backfill volume required historically to prevent sinkhole or trough subsidence was estimated at 9,2 million m³ after compensation for 15% SWC and 30% consolidation under the load of bulked overburden. This equates to 46,2 million m³ of slurry at a Slurry / Backfill ratio of 5. Prior to the completion of the UMS-TWR it was believed that production and pumping of this slurry volume to the relevant caverns would take well over a century to complete.

When comparing this historical figure to the Minimal backfill scenario, a total of 4,8 million m³ of slurry is required. This is 10% of the historical value and can be considered the lower boundary of the expected slurry volume required as a preventative measure.

When considering backfilling the 13 caverns listed in Table 9 to 80% filling grade, i.e. the Maximum backfill scenario, the total slurry volume required is 16,1 million m³ or 35% of the historical figure. This can be considered the upper boundary of the expected slurry volume required as a preventive measure.

In conclusion, the Update Migration Study enabled a significant reduction of the overall time needed to backfill relevant caverns in the TWR area. Completion of the required backfilling based on the outcome of the BJP-Algorithm as presented in this Report 4 is deemed attainable within a "single generation" rather than taking well over a century.

The choice of which backfill scenario to execute, i.e. the Minimal or Maximum backfill scenario, or anything in between, will need to be made based on an impact analysis considering the current use of the ground surface within the predicted subsidence contours. Furthermore, potential measures to safely abandon caverns with a low likelihood of migration but potentially a high impact in case of migration need to be considered by Nobian. As such these choices are left to Nobian and subsidence prognoses for caverns after application of the minimal and/or maximum scenarios as presented for C130-131 in Chapter 2 are therefore not included in this report at this time. It is recommended that separate backfill recommendations are produced on a case-by-case basis at the request of Nobian.

3. Conclusion and recommendations

The Update Migration Study Twenthe-Rijn (UMS-TWR) was initiated to update the subsidence prognoses for the relevant caverns in the TWR area. A new prognosis algorithm was developed and presented in Report 2. Validation of the algorithm has been achieved by demonstrating that the derived relationships and selected input parameters are applicable to 9 out of the 10 well-documented migration cases in Report 3. The applicability to poorly documented migration cases was demonstrated by operating the algorithm in reverse for a further 2 caverns to reconstruct the migration column and the likely original cavern shape based on the measured subsidence and salt production figures. The validation successfully demonstrates that the algorithm is applicable to the entire TWR area.

To update the subsidence prognoses for relevant caverns in the area, the BJP-Algorithm was used to process input parameters and produce graphical and numerical output. At each stage of the parameter selection process care was taken to maintain a conservative but realistic approach.

The result of this approach is an updated and validated set of prognoses based on the BJP-Algorithm as well as a likelihood of migration score per cavern. In terms of recommended backfilling volumes, a very significant reduction of the material required to prevent Stage 4 sinkhole or trough subsidence has been achieved. The new set of prognoses and the corresponding likelihood of migration scores allows Nobian to update the TWR Cavern Risk Matrix and plan the future backfilling with brine purification residues in the TWR area.

Based on the output of the BJP-Algorithm for all assessed caverns in the TWR area discussed in this report, a total of 13 caverns are recommended to be backfilled. This recommendation is based on the formation of Stage 4 subsidence AND a migration likelihood score of 3 or higher which is true for 12 caverns. In addition, cavern C60-61-62 is recommended to be backfilled due to its location underneath the Twence B.V. landfill in combination with a migration likelihood score of 8, i.e. the maximum score possible.

The methodology and the results should be updated when new information arises from the operation of caverns in the Hengelo brinefield.

4. References

[1] REinvent GmbH, “Update Migration Study - Report 1 – Fundamental principles used in reconstruction,” REinvent GmbH, Sondershausen, 2023.

[2] REinvent GmbH / K-UTEC AG Salt Technologies, “Report 2 - The Bekendam-Jakob-Pinkse (BJP) subsidence prognosis algorithm for migrating salt caverns in a bedded stratigraphy,” REinvent GmbH, Sondershausen, 2024.

[3] REinvent GmbH, “Report 3 - Validation of the input parameters by the assessment of migration behavior of migrated caverns and determination of the likelihood of migration,” REinvent GmbH, Sondershausen, 2024.

[4] Nobian - Mining Development & Compliance - NH20241220, “Beleid Monitoren en Vullen Cavernes Twente,” Nobian, Hengelo, 2024.

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