Industrial Salt B.V.
Mining Development & Compliance

CSIMS

NOBIAN'S CAVERN STABILITY and INTEGRITY MANAGEMENT SYSTEM

March 28, 2024

CONFIDENTIAL

Version	2.0
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Version / update history:
1.0: original version.
1.1: update based on SodM review + minor rewrite edits.
1.2: minor additions on CSIMS Dashboard
2.0: major update (CSIMS dashboard + broader SodM review)

Executive Summary

Nobian produces salt using solution mining techniques. Broadly speaking this technique entails drilling wells into salt deposits, injecting fresh water to dissolve the salt deposits which is resulting in producing brine. As a result, a cavern is formed within the salt body or host rock. There can be multiple caverns in a field. Maintaining the integrity of the caverns and cavern field during operation and the entire life cycle of the cavern (field) is essential to safe and sustainable salt production including the period after mining.

This document describes Nobian's Cavern Stability and Integrity Management System (CSIMS) through all the phases of caverns within a field and considering the latest scientific insights as well as other regulatory and/or societal aspects. Chapter one defines the general policy and legal framework. Chapter two goes into the organisational requirements within Nobian. Chapter three describes the method to assess risks associated to cavern integrity/stability. Chapter four lists the technical, geological and physics-based framework behind cavern stability throughout the cavern lifecycle. With the physics and risk assessment framework detailed, chapter five describes the "cavern failure model", bringing together chapters 3 and 4. The following chapter (six) goes a step further and lists specifically what the risk for Nobian's caverns are, and what can be done as risk mitigation. How Nobian monitors those risks (indirectly) can be found in chapter seven, including the CSIMS dashboard. Further chapters (eight to eleven) describe other organisational aspects.

The document is based on meeting all applicable regulatory requirements and conforming to Nobian's internal standards. The content of CSIMS forms an integral part of Nobian's existing management systems. Adherence to CSIMS is mandatory for all Nobian employees as well as outside contractors or service providers. CSIMS is applicable to all Nobian locations that produce salt via solution mining techniques: Hengelo (NL), Delfzijl (NL)), Mariager (DK)), as well as possible future locations. Nobian uses the CSIMS Dashboard to continuously monitor cavern stability performance.

Implementation of CSIMS will safeguard the environment and communities in line with Nobian's Health Safety and Environment (HSE) philosophy and allow for safe, sustainable brine production by:

- Identifying potential hazards and rate the risks to cavern (field) integrity during the lifecycle.
- Set mitigation actions (if required), and
- Defining required inspection and maintenance processes

CSIMS addresses cavern stability and integrity throughout the lifecycle, from development to post-mining. Nobian ensures the integrity of its caverns by identifying potential hazards in each phase of the cavern lifecycle and then quantifying the risks posed by the hazards. Existing management systems in Nobian are then used to manage these risks, these systems are the Nobian HSE rules & procedures. These contain, for example the standard procedures 1 (Leadership & Managing HSE&S Improvement), 5 (Emergency Response & Community Awareness) and 6 (Process Safety & Asset Integrity) as well as the operational procedure 5 (Emergency & Incident Management).

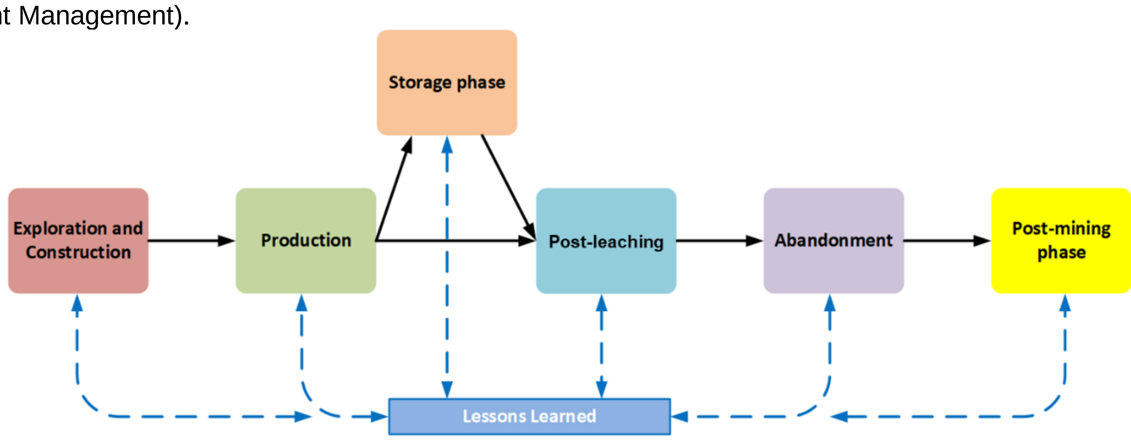

Figure 1 The Cavern Stability and Integrity Management System (CSIMS) applied to the Cavern lifecycle

As illustrated in the figure above, CSIMS is a living document throughout the phases of the cavern lifecycle meant to integrate lessons learned and advances in industry best practices. Note that Nobian primarily focusses on production of salt and does not focus on storage, i.e., secondary use (with exceptions). The storage phase is implemented between the production and post-leaching phases, and information specifically relevant to storage is touched upon throughout the document.

Contents

1. Cavern integrity policy and strategy

1.1. Cavern integrity policy

Nobian operates brine fields at several locations, being Hengelo/Enschede area, Heiligerlee & Zuidwending in the Netherlands, and Hvornum in Denmark. The brine which is used to produce salt is obtained from caverns near the relevant production sites (boreholes) and transported to the production factory by means of a pipeline system.

The policy on integrity of caverns used for brine production sets the minimum standard to implement a management system that ensure safe cavern operations during the five phases: construction, production, post-leaching, abandonment, and post-mining.

- Construction: from design of the cavern until construction (drilling) and handover to production
- Production: the active phase of leaching brine including WO's and other maintenance activities
- Optional Storage phase: phase during which material is stored within the cavern, either by Nobian or the storage operator
- Post-leaching: phase where cavern is not actively used for production to get the temperature of the brine within an acceptable temperature range compared to surrounding rock, and//or backfilling to decrease the risk of salt creep/lower the height and volume of the cavern, with the aim to ensure a safe post-mining phase
- Abandonment: permanent closure of the cavern (physical activity to install permanent barriers)
- Post-mining: period after permanent closure of the cavern, in which effects of the cavern on the surroundings (surface) are monitored and acted upon if needed

In general, the overall corporate policy of Nobian is based on 4 key values: Care, Ownership, Safety and Excellence (see also the figure below). These values guide Nobian's behaviour and are a crucial part of the strong identity and company culture. They demonstrate what Nobian stand for as a corporate citizen, as a business partner and as an employer. The values guide our relationships with our partners, suppliers, and stakeholders. In the context of cavern stability, the values mean that Nobian is a prudent mining operator, doing everything that can reasonably be required to ensure the safe operation of caverns during all its lifecycle phases.

Figure 2 Nobian's 4 key company values

Meeting legal and regulatory requirements is an absolute must for all sites and employees. In the Dutch legislation Nobian has a duty of care (“zorgplicht”). This means that Nobian has a legal obligation to (within reason): prevent adverse consequences for humans and the environment; prevent damage due to ground motion; prevent lowering safety levels and; prevent that the systemic management of reservoirs/minerals is damaged. The ambitions of Nobian go beyond these external requirements and are based on their vision on “zero incidents and accidents”. Nobian strives for an operation which causes no harm to people or the environment. This ambition is supported by a process of continuous improvement. Moreover, Nobian recognizes the need for an open continuous dialog with the local community.

In line with the company values, Nobian is committed to continuously build up knowledge and experience on cavern stability and integrity. As a result, Nobian uses state-of-the-art scientific approaches and actively shares knowledge through multiple channels, from academic journals (e.g., Baumann et al., 2022) to professional organisations (such as the Solution Mining Research Institute: SMRI), but also community outreach such as local information meetings and Nobian’s website. Using this approach Nobian is able to continuously re-assess risks and possible mitigation associated to solution mining.

1.2. Cavern stability & integrity strategy

The Nobian HSES Standard Procedure is a core process of Nobian. It contains Standard Procedure 6: Process Safety and Asset Integrity which is a structured process to assess, understand, and manage risk associated with industrial operations to eliminate injuries and incidents related to hazardous substances and processes.
The Nobian Process Safety Management (PSM) framework must be used to secure proper design, construction, operation and decommissioning of pipelines as well as design, drilling, operation and abandonment of wells and caverns.

To ensure correct implementation of the PSM framework on the brine fields the pipelines, wells and caverns should meet the requirements associated with the 21 building blocks provided by the PSM framework. See figure below and this link. This document focusses on the process safety elements for caverns in the five development phases.

BB1 – Leadership Management and Commitment
BB2 – Organizational and Operational Experience
BB3 – Competence Matrix
BB4 – Training Matrix
BB5 – Employee Involvement
BB6 – Contractor Management
BB7 – PSI Substance Register
BB8 – PSI Process Technology
BB9 – PSI Asset Register
BB10 - Major Hazards & Catastrophic Events
BB11 – Maintenance and Inspections Plans and Procedures
BB12 – Standards and Tools
BB13 – Management of Change
BB14 – Hazard Studies
BB15 – Pre-Start-Up Safety Reviews
BB16 – Investigations of Incidents
BB17 – PSM Audits
BB18 – Stakeholder Outreach
BB19 – Safe Work Practices
BB20 – Standard Operating Procedures
BB21 – Emergency Response Planning

Figure 3 Process Safety Management building blocks

Nobian also has an Emergency & Incident management process, which is HSE Operational Procedure 5. It describes the plan of action in case of an emergency, as well at what level the Nobian Emergency Team will be involved, or if it remains at the level of local responders (incident level 0, only local impact). Figure 4 below details the emergency response workflow in the event the NET is involved (incident levels 1, 2 and 3). In case site-specific cavern-related problems occur, both the Manager of Brinefield Technology and the Director Mining Development & Compliance are informed and can help sites to evaluate if the NET should be informed in case this is not clear already. Further information specifically on mitigation actions related to cavern stability events can be found in section 7.4.

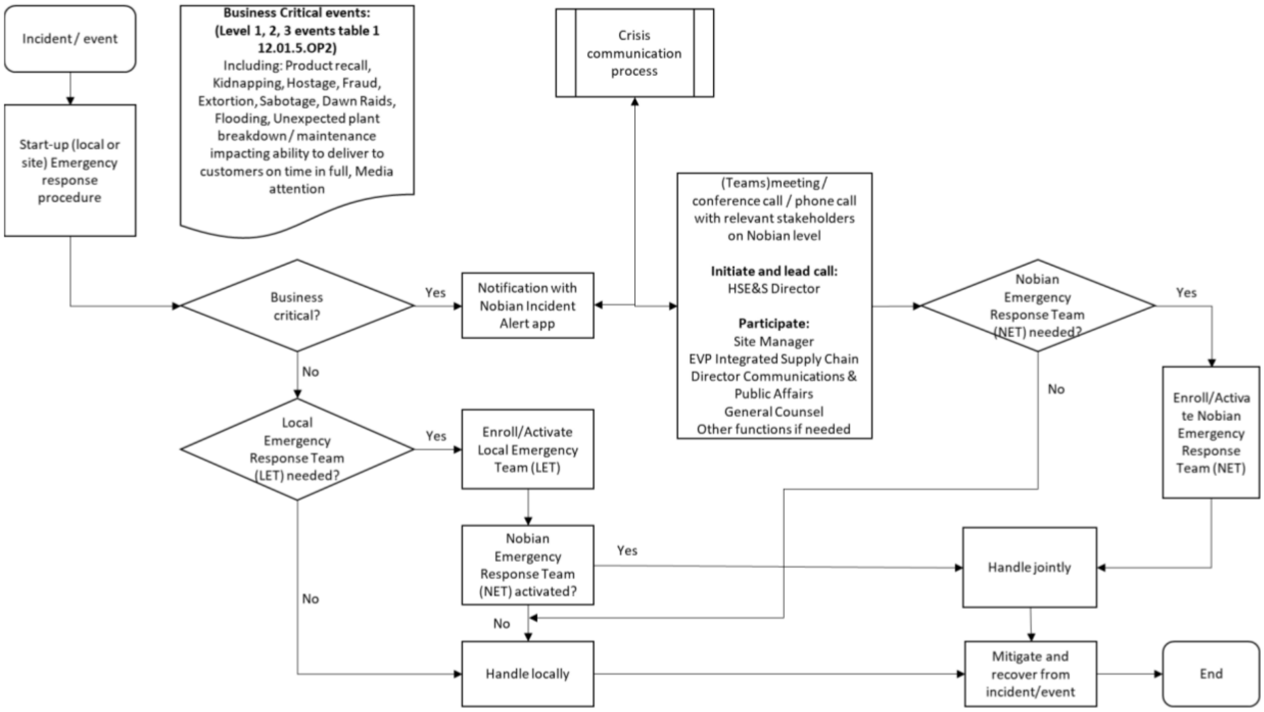

Figure 4 Incident notification and emergency response workflow from HSE Operational Procedure 5

1.3. Legal status CSIMS

1.3.1. Netherlands

For any mining at depths below 100 m in the Netherlands, a mining license ("winningsvergunning") is required, and the Minister of economic affairs needs to have consented to the extraction plan ("winningsplan"). The legal procedures and prerequisites are described in the Dutch mining law (a translated version to English can be found here). Note that there have been updates to the mining law, but these are only available in Dutch). The mining law stipulates that extraction needs to be done following the extraction plan, thus Nobian is held to that. The extraction plan holds technical details on how the caverns are developed and the stability and integrity are managed, from development to post mining. This is usually done in a general sense, as the technical details were considered of minor importance for permitting purposes. Note that in cases where Nobian is the last holder of the mining licence, Nobian remains responsible for the post-mining phase (until legislation decides otherwise).
The cavern stability and integrity management system, the current documentation, should be read as an internal standard on how Nobian manages cavern stability and integrity throughout the lifecycle of a cavern (i.e., from development to post-mining) and also a cavern field. As such this document has no strict legal status, meaning there is no direct link to the mining law. However, it can be seen as completion of the general guidelines that are listed in the extraction plans of the different fields that Nobian operates in. Nobian implements CSIMS as implementation of Article 33 in the Dutch mining law, also known as the duty of care ("zorgplicht")-article, thereby making explicit what may be expected from Nobian as mining operator. Of course, this is from Nobian's perspective, and can be seen as Nobian's specific measures on the generally formulated legal requirements. CSIMS may be updated if legal requirements change, when directed to do so by the regulatory agency or if scientific or practical insights change.

1.3.2. Denmark

For any mining activities in Denmark, the Danish Subsoil Act states rules and regulations for the appropriate use and exploration of the Danish subsoil and its natural resources (a translated version to English can be found here). Any company who wants to explore and produce needs a mining license, granted by the Minister of Climate, Energy and Utilities. Separate licences are need for preliminary Investigations, exploration, and production. The minister may lay down specific terms & conditions to each of the licenses. A company needs to submit a proper activity plan for each of these licenses and needs to show the capacity to be a proper mining operator. The license is submitted for an approval to a committee set up by the Danish Parliament. The Danish Subsoil Act gives more details on what to submit and which legislation is involved. However, the major focus in this legislation is on offshore oil and gas, the area of salt solution mining still has less detailed focus and guidance in this legislation. Nobian takes the responsibility of going further than this legislation as a prudent mining operator.

2. Resources, roles, responsibilities, and authority levels

2.1. Organizational structure

The production site has primary responsibility for brine and salt production and is supported by, amongst others, the Mining Development & Compliance department (MDC).

The production site is built on the core activities:

- Production management
- Asset Management and Technology

The Mining development & Compliance department is built on two legs at a functional level:

- Well Life Cycle Engineering (WLE), *Well Life Cycle Engineering* is responsible for the design and supervision of all new wells, workovers and final well plug and abandonment
- Brinefield Technology (BFT), *Brinefield Technology* is responsible for the long- and short-term production planning, cavern field development, cavern abandonment and short term cavern development

The managers of each section report to the Director Mining Development and Compliance, who in turn reports to the Mining Director.

The *Salt Production departments* - which oversee the entire day-to-day process from brine production to end-products - report directly into the different sites. The plant managers of the salt production plants are the asset owners of the brine production facilities, including the caverns. The Asset Owner is responsible for asset integrity at the owner's site. The overall process for Asset Integrity with respect to cavern integrity is driven by CSIMS. The asset owners are accountable for implementation of CSIMS on their brine production sites. This includes the post-mining phase. An exception exists when the site is no longer active: in this case the responsibility lies with MDC. MDC is responsible for providing the knowledge and know-how how to ensure cavern stability and integrity through the lifecycle of the cavern. This document shall therefore serve as the foundation for indicating the control measures to ensure cavern stability and integrity throughout its lifecycle.

Each production site contributes to the CSIMS by monitoring the caverns which are part of their asset base. The relevant data is recorded and shared with the technical experts of the MDC department to secure adherence to the principles of CSIMS. Figure 5, below, is an illustration of the above-mentioned organizational structure, the interactive organogram can also be found on the Nobian intranet (KNOWBIAN).

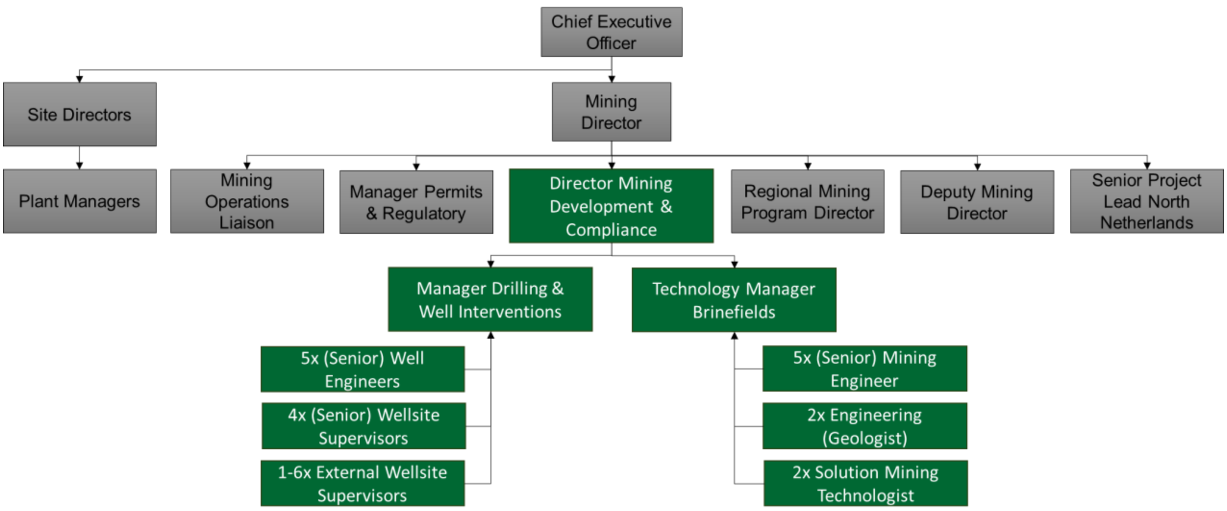

Figure 5 Nobian CSIMS organogram

The asset owner can utilize additional resources for the implementation and improvement of the CSIMS.

2.2. Competency

Nobian possesses a broad range of expertise to allow for effective implementation of the CSIMS process as highlighted in section 2.1, above. Table 1 stipulates the competency level based on role within the company, while table 2 contains competencies based on specific activities. The BFT group within MDC is the repository of cavern engineering expertise within Nobian (see table 2 below). This expertise is a result of formal education (including post graduate level studies and research), industry approved training courses and practical work experience.
Nobian also makes use of external experts where an assessment concludes that additional expertise is required.

The competency level as used in the tables below is defined as follows:

- **Skill**:
  - Role competency: Can evaluate and/or contribute to the improvement of CSIMS, content holder
  - Activity competency: The person must be able to perform the activity with no (or very limited) supervision or guidance.
- **Knowledge:**
  - Role competency: Can reproduce/apply the content of CSIMS, active user
  - Activity competency: The person must understand the principle of the activity but is generally not required to perform the activity. If needed, execution of the activity will be done under the supervision of a skilled person.
- **Awareness:**
  - Role competency: aware of CSIMS as a framework and can refer within the company to the knowledge holders
  - Activity competency: This person only needs to understand how said activity interacts with their role. They should not perform the activity, even under direct supervision of a skilled person.

If not mentioned in table 1 below, no level of informed on the existence and content is assumed.

Role within company	Competency level
Nobian organization wide (and subsequent teams)	
CEO	Awareness
Site directors	Awareness
Plant managers	Awareness
R&D Technology and Sustainability	Awareness
Legal	Awareness
Asset management	Knowledge
HSE	Knowledge
Mining branch specific	
Mining Director	Knowledge
Manager Permits & Regulatory	Knowledge
Senior Project Lead North Netherlands	Awareness
Mining Operations Liaison	Awareness
Deputy Mining Director	Knowledge
Regional Mining Program Director	Awareness
Director Mining Development & Compliance	Knowledge
Manager BFT	Knowledge
Mining Engineer	Skill
(Engineering) Geologist	Skill
Solution Mining Technologist	Skill
Manager WLE	Knowledge
Well Engineer	Knowledge
Wellsite Supervisor	Knowledge
External Wellsite Supervisor	Awareness
Brine production	Awareness

Table 1 CSIMS competency related to organogram

No.	Activity	MDC		Site	
		WLE	BFT	Asset Management	Production
1	Cavern barrier assessment as constructed	Skill	Knowledge	Awareness	Knowledge
2	Calculate & set MAASP	Skill	Skill	Awareness	Awareness
3	Monitor cavern pressures within barrier envelope	Skill	Skill	Awareness	Skill
4	Monitor annulus pressure	Skill	Skill	Knowledge	Skill
5	Assess cavern operating envelope	Skill	Skill	Awareness	Awareness
6	Sonar logs (run & interpretation)	Knowledge	Skill	Awareness	Skill
7	Interpret / process sonar log	Awareness	Skill	Awareness	Knowledge
8	Well control	Skill	Knowledge	Skill	Awareness
9	Assess well barrier schematic	Skill	Knowledge	Knowledge	Knowledge
10	Risk-assess & process deviations	Skill	Skill	Awareness	Awareness
11	Site specific Geology	Knowledge	Skill	Awareness	Awareness
12	Geomechanics	Skill	Skill	Awareness	Awareness
13	Rock strength / salt rheology	Knowledge	Skill	Awareness	Awareness
14	Subsidence monitoring / Geodesy	Awareness	Skill	Knowledge	Awareness
15	Mining damage expertise	Awareness	Skill	Knowledge	Awareness
16	Microseismic monitoring	Awareness	Skill	Knowledge	Awareness
17	Leaching Technology	Knowledge	Skill	Skill	Skill
18	GIS knowledge	Awareness	Skill	Awareness	Awareness
19	FEM cavern field design modelling interpretation	Awareness	Skill	Awareness	Awareness
20	Rock Mechanics (tensile, compressive strength, stress characterisation)	Awareness	Skill	n.a.	Awareness
21	Define cavern test criteria (POT, LOT, etc)	Knowledge	Skill	Awareness	Awareness
22	Determine Cavern Operating Parameters (Safety Factors, MAAPS, etc)	Knowledge	Skill	Awareness	Awareness
23	Determine basis of cavern	Awareness	Skill	Awareness	Awareness
24	Risk assessment throughout lifecycle	Knowledge	Skill	Knowledge	Skill
25	Storage related processes	Knowledge	Skill	n.a.	n.a.

Table 2 Nobian Mining competency matrix

Each department is responsible for ensuring that they have appropriate competency management in place to comply with the levels specified in table 2, above.

3. Risk assessment aspects of cavern integrity management

3.1. General

Nobian's HSE&S policy statement forms the basis of all health and safety related matters. As a risk-based management system, CSIMS, is built on Nobian's comprehensive risk management systems. The HSE&S management system comprises nine elements arranged in a pyramid and is housed in an online SharePoint directory. In the figure below, an illustration of the HSE&S management system is shown.

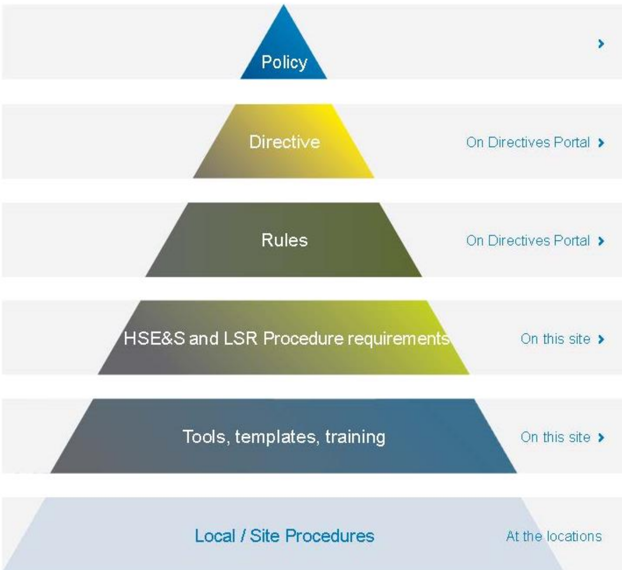

Figure 6 illustration of the Nobian HSE&S management system

- Directives are mandatory documents with "must-do's". These are high-level documents containing the most important, but basic instructions which guide actions and planning within Nobian.
- Rules specify the mandatory requirements to comply with the related Directives of Nobian.
- Procedures, requirements, and related documents provide additional and/or explanatory information to implement and elaborate Directives and Rules.

All can be found in Nobian-HSE&S portals.

3.2. Risk assessment process

3.2.1. Risk assessment based on HSE&S methodology

CSIMS risk management is derived from the *Procedure requirements 6 Process Safety and Asset Integrity* document which forms part of the *HSE&S and LSR Procedure requirement* layer in the pyramid (Figure 6). Procedure 6 is further supported by a range of related documents.

The risk assessment process consists of:

1. Identify the hazard (more on this in 3.3)
2. Define the level of unmitigated risk by assigning a likely frequency (F) and severity (S)
3. Identify appropriate mitigation measures to reduce the risk ("barriers", see 3.3)
4. Re-evaluate the residual risk by assigning new frequency and severity

Table 3, below, illustrates the outcomes of assigning frequency and severity to a particular hazard based on Nobian risk assessment criteria. The position in the risk matrix is defined by one of the three colours of the matrix.

- At positions in the risk matrix that are indicated green, no specific action for follow up is required.

- At positions in the risk matrix that are indicated red, risk reduction measures or redesign is required.
- At positions in the risk matrix that are indicated yellow, the residual risk of the situation under study is assessed as being tolerable under conditions (ALARP). For this situation it must be demonstrated that risk reduction that is or will be achieved, is as low as reasonably practicable (ALARP).

A more detailed description is available under *Nobian HSE&S rules Procedure 6.*

Nobian has internally defined categories in order to allocate the severity of a particular hazard, along five categories: "People", "Environment", "Assets", "Reputation" and "Security". In this document we assess risks according to the categories "People", "Environment" and "Reputation", as "Security" is not considered applicable, and "Assets" are of minor importance compared to safety considerations in the context of cavern stability. The specific categories are described in the table below, these form the vertical axis of the risk assessment matrix.

Severity level	Assets	People	Environment	Reputation
S5	**>** 25 million €: major damage	**One** or more off-site fatalities, or several fatalities on-site, or several severe injuries off-site.	**Catastrophic** escape with major off-site impact	**Damage** to Nobian stakeholders; International media attention.
S4	**<** 25 million €: significant damage	**One** fatality on-site, or several severe injuries on-site, or one severe injury off-site	**Significant** escape which has to be reported to the authorities with off-site impact	Damage to business stakeholders; National media attention.
S3	< 5 million €: important damage	One severe injury (potential life changing consequences) on-site	Escape that is observable or has impact off-site; permit violation (with regard to permitted emission points)	Damage to local stakeholders (such as local suppliers or neighbours); Local media attention.
S2	< 1 million €: medium damage	Reportable injury (medical treatment, restricted work, or lost time)	Escape almost certainly contained on-site, not readily controlled, with no observable impact off-site	External complaint, affects local company reputation.
S1	< 100k €: small damage	First Aid treatment	Escape readily controlled, contained on-site with no off-site impacts	No damage to company reputation.

Table 3 Nobian severity ranking matrix

Frequency of events, describing the horizontal position in the risk assessment matrix is described using the table below. Note that these are used in a general sense, as not all cavern integrity related risks can be described to have a frequency. For example, a catastrophic event such as sinkhole formation can only occur once (a phased collapse is considered a single event here). The interpretation for frequency is therefore discussed for each of the identified risks.

F0	F1	F2	F3	F4	F5	F6
Extremely unlikely; very unlikely event in area with low occupancy	Very unlikely; credible to occur, but requires the failure of several layers of protection	Improbable; foreseeable to occur, but requires the failure of more than one layer of protection	Remote; a singular incident in industry on similar technology has occurred	Occasional; not expected to occur during remaining plant lifetime	Probable; could occur during remaining lifetime of plant	Frequent; has occurred during lifetime of plant

Table 4 Nobian frequency ranking matrix

The two axes make up the risk assessment matrix, with 3 colour codes: green, yellow and red. These denote non-critical, important and critical. Mitigated risks that remain within red fields are not accepted within Nobian. For those that end up in yellow fields additional mitigation measures or research must take place in order to further reduce the risk. Green fields are considered acceptable.

S5 Catastrophic	**6**	**7**	**8**	**9**	**10**	**11**	**12**
S4 Major	**4**	**6**	**7**	**8**	**9**	**10**	**11**
S3 High	**3**	**4**	**5**	**6**	**8**	**9**	**10**
S2 Moderate	**2**	**3**	**4**	**5**	**6**	**8**	**9**
S1 Negligible / Slight	**1**	**2**	**3**	**4**	**5**	**6**	**8**
	F0	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**

Table 5 Nobian risk assessment matrix.

The individual scores listed in Table 5 can be used to differentiate risks within the colour fields. For all codes within the green field (scores up to 5) the risk is classified as "low", and within the red field (all scores above 9) as "very high". Within the yellow field some differentiation is possible, with scores 6 to 8. Here 6 is considered "Low ALARP", 7 "Medium ALARP" and 8 "High ALARP" (ALARP stands for As Low as Reasonably Practicable).

When it is not possible to eliminate hazards entirely with mitigating measures the principle of as-low-as-reasonably-practicable (ALARP) needs to be applied (i.e., with risk scores of 6 to 8). Figure 7, below, illustrates the principle of ALARP.

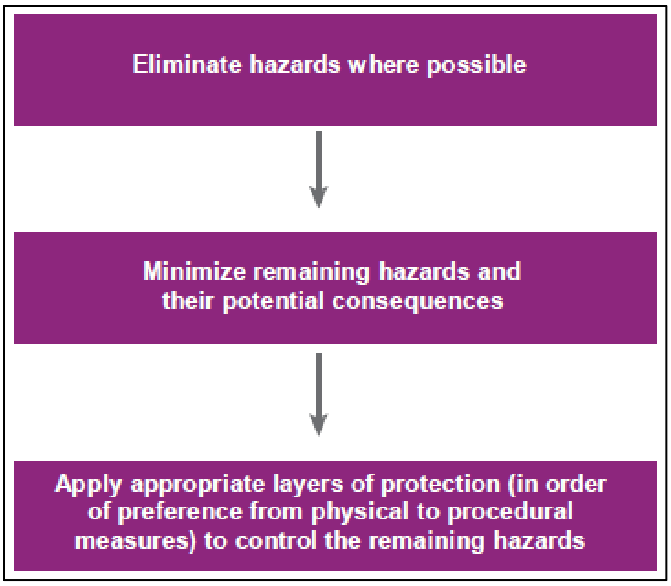

Figure 7 ALARP principle

For each identified risk, the risk is classified for severity (S) considering the three subdivisions (People, Environment, Reputation), and frequency (F). Each risk is described first as unmitigated, followed by the mitigated risk, whereby all mitigation measures that Nobian takes are discussed. As a rule with this methodology, for each independent mitigation measure (or safeguard) the frequency range may be reduced. In some cases, the severity classification is reduced when mitigation measures are such that the risk becomes nearly physically impossible to take place. A clear motivation is provided in these cases.

3.2.2. Risk assessment based on Fine and Kinney

Nobian's internal risk assessment matrix, described above, was developed with a focus on process safety. The result is that the likely frequency of an event occurring is not that applicable to mining related risks. For example: subsidence is a gradual process and cannot be captured as an event with a frequency of occurrence. Nobian therefore also allows the Fine and Kinney methodology to be used when more applicable. Mining related risks can be best described using a combination of the two methodologies.

The Fine & Kinney's methodology calculates the risk based on the product of three scores in reference to the categories "probability" (P), "exposure" (E) and "severity" (S), (see scoring tables below). Thus, the overall risk score (R) is calculated as R = P x E x S. For example, consider a risk that is unlikely, happens rarely but can have severe consequences. This would score 0.5 on Probability, 1 on Exposure and 7 on Severity. The overall score would be 3.5.

The score classification is listed below. Note that the severity scale (S, table 8) focuses mainly on the risks associated to "people" in the previous chapter. To check for consistency between the two approaches it is therefore only done for the risks in the category "people".

Probability (P)	
Description	score
Next to impossible / unthinkable	0.1
Almost unimaginable	0.2
Highly unlikely but conceivable	0.5
Unlikely, but possible in the long term	1
Unusual (but possible)	3
Possible	6
To be expected	10

Table 6 Fine & Kinney risk model probability classification and scoring

Exposure (E)	
Description	score
Very rarely (less than 1x a year)	0.5
Rarely (approx. 1x a year)	1
Sometimes (multiple times a year)	2
Occasionally (weekly)	3
Frequently (daily)	6
Constantly (Multiple times per day)	10

Table 7 Fine & Kinney risk model exposure classification and scoring

Severity (S)	
Description	score
Slight effect, injury without absence through illness	1
Important, injury with absence	3
Severe, lasting injury with absence	7
Very severe, a fatal casualty	15
Disaster, multiple fatal casualties	40

Table 8 Fine & Kinney risk model Severity classification and scoring

In terms of risk acceptance Fine and Kinney propose the following:

Rank	R score bounds	Description
1	R ≤ 21	Slight risk, acceptable
2	21 < R ≤ 71	Little risk, attention required
3	71 < R ≤ 201	Moderate risk, apply simple measures
4	201 < R ≤ 401	High risk, apply large measures immediately
5	R > 401	Risk is too high, stop activities/operation

Table 9 Fine & Kinney risk model Risk ranking scoring

In principle, Nobian takes into account all risk levels as defined by the Fine and Kinney method, and acts accordingly. The risk rank itself is used to prioritize actions and research (if applicable).

3.3. Hazard identification, the bow tie approach

To identify potential hazards (the first step in the risk identification process), a team of specialists from Nobian (potentially appended with externals) identify hazards and risks in “HAZID and HAZOP”- type sessions (resp. “Hazard identification” and “hazard and operability” study). In such sessions the bow-tie methodology is used where the main hazard is listed as “top event” which lies at the centre of the bow tie. Using this method an assessment is made on what can be done to prevent potential hazards (left side of the bow tie, named “barriers”), and what can be done as remediation in case the event has happened (right-hand side, disregarding any effectiveness on the preventive side). Note that at this point the potential impact of a specific hazard has not been considered yet. As a second step the impact of hazards is identified, and where needed backed by scientific literature or research. Thereby the risks are identified and classified using the methodology as presented in table 3.

In the following chapter a general framework is laid out in terms of the physics of salt caverns, as well as the typical timeline of events of a cavern (chapter 4.5). With knowledge of the processes and effects in various stages of a project in mind, the identified risks can be described in a Cavern Failure Model (chapter 5). In this chapter the actions taken to prevent or remediate top events are discussed. Based on this risk assessment design limits and operational limits are set in place and are discussed in chapter 6.

4. Cavern (field) stability & integrity elements

4.1. Cavern types

Cavern types depend on the geology and on their intended use. Regarding geology, Twenthe-Rijn caverns in bedded salt have a different cavern and field design compared to Heiligerlee, Zuidwending and Hvornum caverns in domal salt. Regarding the intended use, salt production is the primary goal of Nobian. In most of our production sites, caverns are leached for production purposes only. However, salt caverns are great for storing gases, and therefore Nobian has identified the opportunity to provide subsurface storage space to the energy market as a secondary business case. Therefore, it is important to mention potential differences between production and storage caverns in relation to stability and integrity. Where applicable, specific information related to storage caverns is mentioned.

Storage caverns currently under development are designed following storage operator requirements, who will take responsibility for the caverns after salt production has finished. Nobian is also in the process of designing some of its own production caverns with the secondary use of energy storage in mind. This is done to comply with the requirement for ‘planmatig beheer’, one of the extraction plan approval requirements. The design of these caverns follows that of the storage caverns already in development.

In principle many caverns can be used for storage of gas/fluids regardless of the geological history of the salt formation (e.g., storage phase, 4.5.3.). As long as the cavern is developed in such a way that the cavern is stable and tight, meaning in practice no hydraulic connection to other layers exists or can be expected to occur, the cavern can be used for storage purposes. However, in the past caverns have been developed for brine production only, resulting in shapes, sizes and depth ranges that are not optimal for storage.

Energy storage not only requires suitable geology but also the presence of the required energy infrastructure. At this point, Zuidwending is the most important Nobian production location where these elements come together (with natural gas storage caverns operated by Gasunie). A nitrogen storage facility is operated by Gasunie in Heiligerlee. Finally, a smaller diesel storage facility is operated by Nobian in the Twente-Rijn field.

4.2. Cavern (field) stability & integrity philosophy

Nobian operates according to its four company key values: care, ownership, safety and excellence (see also chapter one). In the context of cavern stability this means being a prudent mining operator, meeting regulatory requirements, implementing industry best practices, and complying with internal HSE&S standards and objectives. The philosophy is based on a risk management approach which mitigates risks from identified hazards through engineering, operational and human controls. Nobian considers the following definition for a safe cavern: A cavern is a void space within rock salt formations resulting from solution mining processes. This space is in principle filled with brine (saturated except during active leaching) and minor component of mining auxiliary products, such as blanketing fluid (particularly during leaching). A safe cavern is considered safe throughout its lifecycle (design to post mining) if it does (and will) not leak, such that fluids largely remain within the cavern and to a stricter degree within the rock salt formation, isolated from other potential aquifers in the subsurface. Moreover, a cavern that is considered safe does not cause negative consequences at surface, such as harm to people, to the environment or Nobian’s reputation. A cavern (field) can still be considered safe when it eventually causes an acceptable amount of subsidence (a gradual bowl-like shape of several km width and several cm at its deepest point). A safe cavern does not cause damage at surface through seismicity or ground collapse events (sinkholes).

In principle, Nobian strives to develop caverns according to the latest scientific and professional insights and therefore has developed a framework for cavern design and control measures. It is noted that Nobian carries a legacy of older caverns that do not meet current design standards. For these caverns tailor-made solutions are used. Note also that new insights into cavern stability resulting from science or updated field knowledge may cause that some caverns that were previously considered safe are no longer so, and further mitigation of risks is required as per the framework of this document, CSIMS.

As described earlier, Nobian produces brine from the subsurface using solution mining techniques, which is later refined to salt products. The technique results in a residual cavern within the rock salt. Some techniques rely on this cavern to converge already during the operation timescale. Nobian chooses to not use this technique (called squeeze mining) in order to limit both subsidence as well as subsidence rates, and thereby cause the least impact on the built and natural environment and stay within acceptable effects for people and the environment for a timespan of a hunderd years (from the start of mining). It is noted that some post-mining effects take place beyond this timespan. However, if potential negative effects (described in chapter 5) were to happen, they most likely occur during operation of the cavern or relatively shortly after abandonment, in the post-leaching phase (see more in section 4.5. for definitions). Also here, in case scientific insights or lessons learned within the salt mining community change this perspective, Nobian will reassess the timespan and update CSIMS.

The framework of cavern integrity and stability described in this paragraph only focusses on solution mining techniques where a cavern is developed in the subsurface. Other techniques to extract rock salt (such as squeeze mining or excavation mining) are not incorporated as these methods are currently not used by Nobian.

4.3. Definitions of physical parameters in the context of cavern integrity

This paragraph explains the most important definitions, and how they are used within Nobian. Where possible the parameter units are given as SI-units (International standards, such as Pascals), SI-derived (such as bars or MPa's) or otherwise specified. This section (along with 4.4) provides the framework needed to evaluate the risks associated with solution mining.

4.3.1. Cavern depth

Cavern depth is expressed in meters with reference to either ground level or national standards such as "NAP" (Normaal Amsterdams Peil) for the Netherlands. Cavern depth can refer to different points of the cavern itself. These include cavern roof (shortest distance to surface), cavern base (largest distance to surface), and LCC depth (last cemented casing). Note that all the listed depth-values in this document are considered "true vertical"-values, whereas in some cases boreholes can be deviated such that differences between along hole distance and true vertical can arise. If this is the case with respect to a cavern, then the convention is explicitly listed.

4.3.2. Cavern dimensions

A cavern is typically simplified to the shape of a cylinder, with a diameter and a height. The cavern diameter is typically listed as maximum observed diameter (or average diameter in case of near cylindrical shape of the cavern). Cavern height is the difference between the deepest point of the cavern and the shallowest point (i.e., the roof).

4.3.3. Cavern pressure

The pressure of the fluid (typically brine or blanket oil, in some cases gas or stored oil) within the cavern, which is given in units bar (1 bar = 10^5 Pascal) or MPa (1 MPa = 10^6 Pascal). Because the cavern has a depth range and pressure increases with depth, it is needed that a reference point (depth) is given. This can be the cavern roof or LCCS (see above). Fluid pressure increases with depth at approximately 0.12 bar/m for saturated brine (more on the gradient below). Note that this pressure has no directional component and is essentially a scalar property. Note that depending on the context a distinction between absolute pressure (often denoted as bar_a or bara) and gauge pressure (bar_g or barg) can be made. For absolute pressure the atmospheric pressure is considered (roughly 1 bar at surface), and gauge pressure corrects for it (0 bar at surface). Within this document only bar_g values are considered, but often the distinction can be ignored all together as pressures that are compared will have the same definition, thus the added 1 bar drops out (i.e., pressure differences).

4.3.4. Pressure gradient

A value that describes the increase of cavern pressure with depth. The rate of increase is generally due to the weight of the overlying fluid and are therefore directly related to the density of the gas or fluid within the cavern. The gradient can be calculated by density (in kg/m^3) multiplied by the gravitational constant (9.81 m/s^2) and results in a unit equivalent to Pascals per meter [Pa/m] (or [bar/m] if divided by a factor 10^5). Typical values are 0.70-0,90 bar/m for blanket material, 0.10 bar/m for fresh water and 0.12 bar/m for brine. A gas gradient is steeper, as the density of gas is low.
In some cases, a pressure gradient is used to show limits of cavern pressure in a general sense, such that it may be applied to multiple caverns, each with specific reference depths. This can be used to calculate a maximum pressure at the well head given the gradient of the fluid inside the borehole. For example, consider the case where a gradient of 0.18 bar/m is not to be exceeded at an LCCS-depth of 500 m. This implies that at 500 m the maximum pressure is 500 * 0.18 = 90 bar. A 500 m column of brine would result in 500 * 0.12 = 60 bar. Therefore, in this specific case the maximum wellhead pressure would be 90 – 60 = 30 bar.

4.3.5. Temperature

Can be subdivided in the temperature outside of the cavern and/or within the cavern and, units °C (Celsius) or K (Kelvin). Note that as with pressure, this value requires a reference depth. For intact rocks (i.e., without considering a cavern) the temperature generally increases linearly with depth as a result of a constant heat flux from within the earth and is known as the geothermal gradient. For the Netherlands, this value is typically 30-31 °C/km but can vary depending on the local geology (e.g., Bonté et al., 2012, Békési et al., 2020). Within the cavern the temperature is generally lower as a result of brine production using fresh surface water or local ground-water sources. The temperature inside the cavern depends on the caverns size (considering the heat flux remains the same, and a higher volume is heated up, it takes longer) and the temperature of the water that enters the cavern and is somewhere between the upper bound (the geothermal gradient) and the temperature of the inflowing water. Given enough time the temperature heats up to the upper bound due to geothermal heat influx.

Temperature development with cavern storage
In case a cavern is planned to be used as a storage facility after removing salt by solution mining, it could be filled with gas or fluids. The temperature may be different as a result of the initial fluid/gas temperature as well as compression and decompression effects (adiabatic heating and cooling) of the gas itself. If left non-disturbed the temperature within the cavern will equilibrate with the geothermal gradient by means of conduction and advection (flow) of heat. In the case of advection, thermally induced flow (flow cells) can develop within the cavern. This can potentially cause that the temperature inside the cavern deviates from a linear trend with respect to depth and sharp or stepwise changes with depth are observed.

4.3.6. Cavern compressibility

The value that relates the volume of fluids within the cavern that need to be added or removed to change the cavern pressure by 1 MPa (up or down). The value depends on the total volume of the cavern and is related to the compressibility of the fluid itself along with that of the cavern walls, and hence there is a dependency on the caverns' geometry (e.g., Bérest et al., 1998). Typical values of the factor are in the order of 4 x 10^{-4} /MPa. To put this into context, to drop the pressure by 10 bar (1 MPa) in a cavern with a volume of 1 million cubic meters some 400 m^3 of brine need to be expelled for the pressure reduction to occur.

4.3.7. Flow rate

The flux of fluids (liquid or gas) into or out of the cavern, in units m^3/h (cubic meters per hour) or l/s (litres per second). Note that this is a volume flux. In the case of gasses often the mass-flux (mass per time unit) is used, as the volume changes substantially on with different operating pressures due to the high compressibility of gas compared to liquids.

4.3.8. Stress-state

The amount of mechanical load which depends on the orientation. Typical units are bar or MPa. Unlike pressure, with stress there is a directional component. The number of differences in stress values can vary depending on orientation. For example: A horizontal plane in the subsurface is mechanically loaded by the weight of the overlying layers (the load in the same direction as the plane's normal). A vertical plane at the same depth would have a lower load normal to this plane in case of a normal faulting tectonic regime (common in the Netherlands). For areas where mountain formation takes place the horizontal stresses may be higher than the vertical stresses.

4.3.9. Stress gradient

The increase of stress with depth in a particular orientation. Multiplying the stress gradient with a depth gives the stress value at a specific depth. Common values include the vertical stress gradient, which is the result of the weight of the overlying layers (typically 0.22 bar/m for sedimentary basins, e.g., Bérest et al 2020, but note that variation with depth is possible due to denser/lighter layers). Much like the pressure gradient this can be calculated by the density multiplied by the gravitational constant. Using general approaches horizontal stress gradients can be evaluated too. For the Netherlands this is typically around 0.16 bar/m (e.g., Orlic 2016) but can vary locally as shown by leak-off tests gathered within the Netherlands (van Wees et al., 2014). The gradient itself can also change with lithology depending on the rock-mechanical behaviour from layer to layer. For salt layers the horizontal stress gradient can generally be as high as the vertical stress gradient, Due to the salt's plastic deformation abilities under subsurface pressure/temperature conditions it will act much like a fluid where stresses are hydrostatic.

4.3.10. Differential stress

The difference between the maximum stress level and minimum stress level (in different directions) at a certain point. For salt solution mining the difference is generally assumed as equal to that of the stress-state within rock salt (far away from the cavern wall) and the fluid-pressure inside the cavern acting as a boundary load normal to the wall.

4.3.11. Strain rate

The amount of strain per time unit, where strain is often defined as a length compared to an initial length (known as "engineering strain"). Strain is dimensionless and therefore does not carry a unit. The amount of change in a certain time period is the strain rate and has a unit per second (SI) or per day if strain rates are slow. In other words, the strain rate is a definition of how fast something is changing shape. Just like the stress state, the strain-rate can be different for different orientations in a single point. Often the strain rate is highest in the direction where the differential stress is highest (co-axial deformation). In terms of caverns the strain rate relates directly to the inward movement of the cavern walls.

4.3.12. Permeability

The ability of fluids to percolate through a solid medium, given in units of Darcy or m^2 (SI, 1 Darcy $\approx 10^{-12}$ m^2). High permeability means that fluids can flow through the connected pore space of rocks at low pressure differences, low permeability means high pressure differences are required to reach the same flowrate. Low permeability is therefore also known as "tight", meaning that it can hold fluids inside, above or below the formation without flowing through the formation itself. This is generally the case for salt formations, but also low porous rocks such as clay formations. The pore space itself is made up out of the space between grains or crystals, as well as potential cracks that have formed within the material. For salt formations the permeability can be as low as 10^{-22} m^2. To put this into context consider a column of water of 1-meter height that drains (vertically only) through a street tile of 5 cm thickness. For a general sandstone tile (permeability assumed at 10^{-12} m^2 or one Darcy), the column would drop to 0.5 meters in about an hour. For salt (permeability of 10^{-22} m^2) this would take over 1.12 million years (i.e., 10 orders of magnitude longer).
The relevance of permeability seems low due to the sealing nature of rock salts. However, considering long term abandonment the permeability of other layers adjacent to the rock salt formation are of importance too. This is often referred to as leak-off potential.

4.3.13. Strength of the rock salt

The maximum level of differential stress without permanent deformation, such as forming cracks. More precisely this is the dilatation criterion and depends on the depth (confining pressure) and the temperature. Cracks can potentially coalesce to form a crack-network through which fluids could percolate (see more below). In some cases, the failure envelope is used as the maximum strength, which lies above (higher differential stresses) compared to the dilatation criterion (e.g., Heap and Faulkner, 2008). Note that this is the case for the laboratory under known stress conditions. In the context of borehole stability, and by extension cavern stability the rock salt strength may also refer to a combination of the local stress and the intrinsic formation's strength. This is because often the stress itself at depth is not exactly known, nor is the laboratory-rock strength. The observed strength of a formation by means of a pressure test is than the result of overcoming the local minimum in-situ stress in combination with the rock strength (e.g., White et al., 2002).

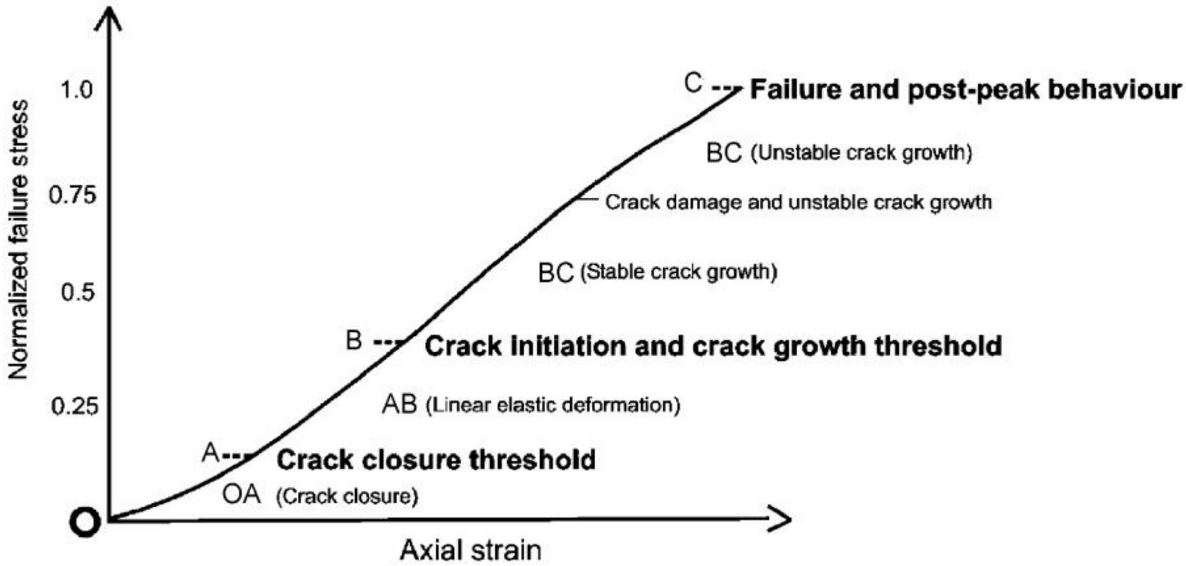

Figure 8 Illustrative stress/strain curve showing different levels of crack mechanisms with respect to failure stress, adapted from Heap and Faulkner 2008.

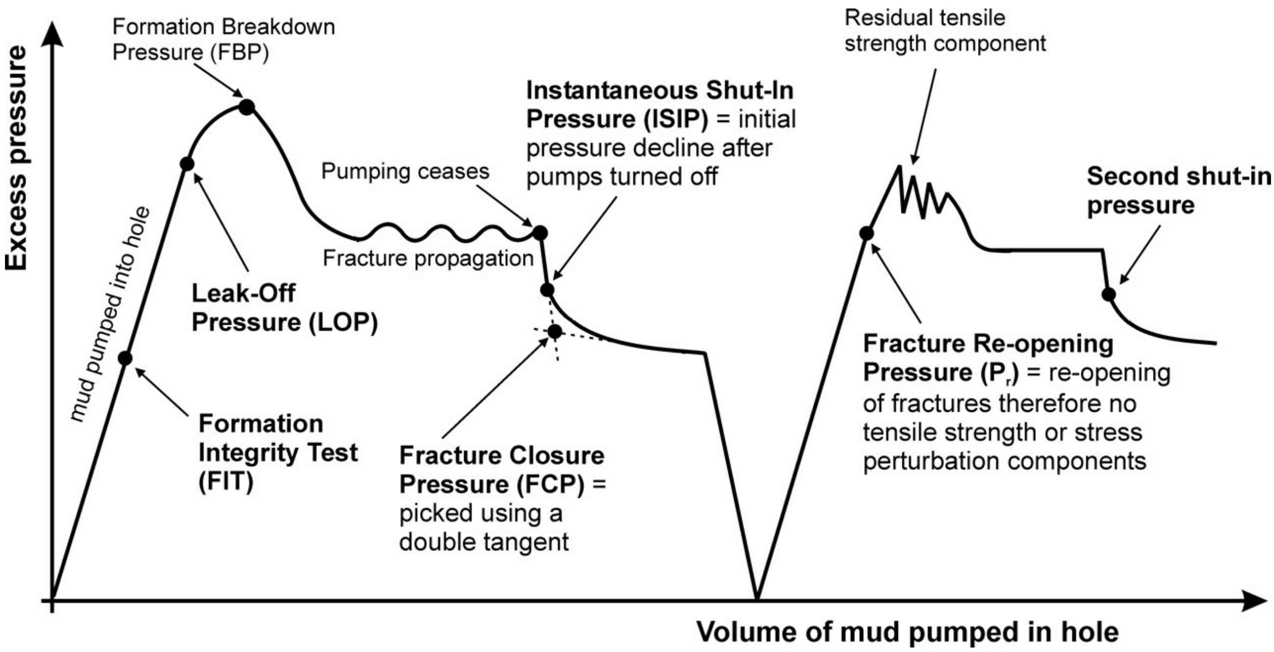

Figure 9 Schematic overview of rock strength in combination with the local stress on the field-scale as determined by leak-off tests. Figure adapted from White et al., 2002.

4.4. Physical processes affecting cavern stability

4.4.1. Cavern pressure control

By regulating the pressure at the surface, the pressure in the cavern can be changed. If the pressure at the wellhead is set to zero (bar_g), the pressure within the cavern is as low as that caused by the pressure gradient (i.e., density of the fluid, for saturated brine 0,12 bar/m). For steady-state conditions (no-flow through the well), the pressure in the cavern is that what is measured at surface, plus the pressure gradient. During flow there may be a pressure decrease due to friction effects along the borehole, resulting in a higher cavern pressure than estimated considering no-flow conditions (but above the 0 bar at surface estimate). If a cavern pressure exceeds a certain upper limit for any reason, the pressure may be reduced by outflow through the wellhead or through damaging the last cemented casing shoe (LCCS). Naturally, an exception exists for abandoned caverns where there is no longer a hydraulic connection through the wellhead and no pressure is registered. Reasons for pressure limits may include fracturing limits but also limits discussed in the WIMS (wellhead rating, max. pressure tests). Outflow of cavern fluids essentially reduces the volume of the fluid in the borehole + cavern system.

Pressure control during storage phase
The pressure regime of an energy storage cavern during the storage phase is fundamentally different to that during or after leaching. The storage operator will be operating the cavern at much higher pressures than occur during and after leaching. A pressure range is determined whereby the maximum pressure is defined by the strength of the LCCS (last cemented casing shoe). The minimum pressure is set so that the cavern is not allowed to contract too much as a result of the lithostatic pressure of the rock salt around it.
For the planned hydrogen storage caverns in Zuidwending (both HyStock and Nobian caverns following the same design), the pressure range is 90 - 198 bar at the LCCS during the storage phase.
To ensure smooth operation of multiple storage caverns within a field, similar cavern design like depth and volume is desirable, as this results in similar pressure ranges.

4.4.2. Cavern convergence

A process whereby the cavern-walls move relatively slowly inward to the cavern, thereby reducing the cavern's volume. The walls close in due to creep mechanisms. For creep to occur there needs to be a differential stress, a stress difference between the stress-state outside of the cavern (also known as far field stress), and the fluid-pressure inside the cavern. This pressure acts as a boundary load on the cavern wall and is generally lower in magnitude than the load that of the far-field stress state. At low cavern pressure the differential stress is high and thus the speed at which the cavern closes is high. If pressure is not controlled, the decrease of volume will cause the pressure of the fluid inside the cavern to go up (thereby slowing creep down again). The speed at which a cavern closes due to creep is faster if the cavern is in an environment with a higher lithostatic pressure and higher temperature. Therefore, deeper caverns decrease faster in volume by creep than shallower caverns.

For creep, there are two mechanisms that play an important role, dislocation creep and pressure solution creep (e.g., Bérest et al., 2019). They both contribute to the overall deformation behaviour of the cavern. However, depending on the differential stress and temperature, their relative contributions may differ. At relatively high levels of differential stress (a low cavern pressure), dislocation creep is dominant. This means that the observed deformation rate (or strain rate) is largely due to dislocation creep and to a far lesser extend due to pressure solution/precipitation creep. The effectiveness of the dislocation creep mechanism can be shown by an outflow test, where the borehole is left open at surface and the amount of volume that comes out of the borehole is tracked over time (e.g., Brouard et al., 2013).

At low differential stress (high cavern pressure), the thermodynamical setting is such that the effectiveness of dislocation creep is limited, and pressure solution and precipitation creep becomes dominant. The dislocation creep mechanism is still active but results in a relatively low strain rate compared to that of pressure solution and precipitation. If only dislocation creep is considered, then creep induced pressure increases should almost disappear if the cavern pressure is high, and this seems not to be the case (KEM17 Cavern Scale report, Brouard consulting). Therefore, caverns continue to creep to a close also at high brine pressures in the cavern over very long time.

The micro-mechanics of dislocation creep involve crystal plastic deformation by migrating defects in the crystal structure. Pressure solution creep and precipitation involves the dissolution of locally stressed salt crystal edges in micro-films of water between grains, and precipitation in places where the stress is low. Hence there is a grain size dependency as the mechanism is active at the crystal edges, faster deformation rates are expected at lower grain sizes (higher ratio of surface to volume). The mechanism requires water to be present between salt-crystals in the subsurface. In case of brine within the cavern this is the case, but not necessarily if a cavern is used for gas storage (at least not for the cavern wall-gas interface). The effects thereof are not known now and are topic of scientific research. In addition, some studies suggests that the pressure solution creep mechanism is no longer effective if the differential stress is below a certain threshold. These include the theoretical approach of Oosterhout et al., 2022 which suggests a lower value of the threshold at 0.7 bar. The work of Hunfeld et al., (2022) uses this approach to explain the measured subsidence pattern using numerical models where the threshold is implemented. The general idea behind the existence of the threshold is that the stresses at the crystal edges are not high enough to favour the dissolution process. Because there is no consensus from scientific research yet, Nobian takes the conservative approach assuming the micro-scale mechanism prevails also at such low differential stresses (i.e., high cavern pressures). As a consequence, it is assumed that pressure solution creep is still active at high brine pressure in the cavern, which may lead to an overestimate of the creep effect after abandonment. Nobian sees this as a conservative approach. Recent CCC-research has taken the threshold (assumed at 0.7 bar) into account to investigate its possible influence through numerical models. The research found a slight retarding effect on the cavern pressure development after abandonment, but no substantial changes in the evolving cavern pressure.

Cavern convergence during the storage phase

The impact of cavern convergence is larger in the case of a storage cavern as a result of two factors:

1. With a typical storage phase of 40 years, the longevity of a storage cavern is much longer than that of a modern production cavern. This means that the geomechanical processes leading to convergence have a longer time to act on the cavern. However, it should be noted that some of the older production caverns in the Nobian portfolio have also been active for decades.
2. Cyclic loading of the storage medium: During production and injection of the storage cavern the pressure decreases and increases cyclically. There are pressure windows defined for storage caverns with associated maximum times a cavern can be at a certain pressure. In periods of low pressure (production of the storage medium), cavern convergence increases due to the difference between the pressure in the cavern and the lithostatic pressure. While in periods of higher-pressure cavern convergence due to creep is lower. As the effect of the lower pressure periods on accelerating cavern convergence is higher than the effect of higher-pressure periods on decelerating cavern convergence (transient creep state), overall, cavern convergence is faster when there is cyclic loading when compared to constant pressure. This difference is caused by the non-linear behaviour of the salt, more information on this can be found in the paper written by Bérest, P., Karimi-Jafari, M., & Brouard, B. (2017). The cyclicity timescale depends on the storage medium, for natural gas this can be yearly (production in the winter and injection in the summer), for hydrogen this can be once every two weeks and for CAES this can be in the range of daily or several days.

4.4.3. Thermo-elastic effects

An intrinsic property of all materials and fluids is that they expand (greater length or greater volume) when their temperature increases and contract when temperature decreases. This leads to a certain amount of thermal strain. If this expansion or strain is somehow confined, the stress or pressure will increase via elastic behaviour. The amount of strain is then proportional to the stress or pressure change needed to get the same amount of strain by elasticity. In the cavern context, this means that during warming (when the cavern temperature with depth-line is lower than that of the geothermal gradient) the cavern's pressure will increase. The elastic response of the cavern is the same as with cavern compressibility and is a function of both the fluid properties inside the cavern as well as the cavern shape. The rate at which the pressure increases is then directly linked to the rate at which the cavern warms up. This is a function of the temperature difference between the cavern's fluid and the geothermal gradient outside of the cavern and depends on the effectiveness of heat conduction into the cavern. When the cavern temperature is near the geothermal gradient, the thermally induced pressure increase effect is negligible. For details on heat exchange in and around caverns see Bérest 2019 and Durup et al., 2007 for a field example.

4.4.4. Permeation

The distributed outflow of cavern-fluids into the salt formation through percolation between salt grains. This is essentially the same as permeability, with the caveat that the flow / infiltration is distributed over the interface where the infiltration takes place, and not concentrated in a permeable structure such as a permeable layer or fault. In essence the fluid seeps out through the cavern walls and is considered a volume loss. Thus, the pressure is reduced within the cavern (or rather, stays the same and there is a volume loss within the cavern). The process typically occurs when the cavern pressure is close to the mean stress in the host rock, the cavern walls. In this case, at a relatively high cavern pressure (brine pressure in the cavern), the stress that essentially pushes two grains of salt (or salt crystals) together is overcome by the fluid pressure pushing the two grains apart at the boundary of the two crystals. The effectiveness depends on where the fluid is able to build up a fluid pressure inside the salt body, or how the pressure inside the cavern dissipates into the rock salt formation. This can either be distributed all along the cavern walls but might also be localized in an area where the natural permeability is somewhat higher (i.e., the amount of fluid that can flow through an area given the same driving forces). This is possible due to impurities within the salt dome at various scales, from trapped sand-grains between salt crystals to left-over banks of anhydrite layers that have moved along with the salt during tectonically active phases. For more information see Bérest et al., 2001; 2007.

<u>Effective stress reduction through increased cavern pressure</u>
Note that permeation has the effect to lower the effective stress inside the cavern walls where the fluid pressure is increased (e.g., Fokker 1995). Thereby the rock salt at the cavern walls has a higher risk of forming microfractures, as the stress state is closer to the failure line (or strength) of the material. However, it is debatable to what extent the fluid pressure reduces the effective stress-levels. Nobian has commissioned research to investigate this effect and study permeation in more detail through laboratory and numerical efforts (CCC research, see Baumann et al., 2022). The thought is that due to the low porosity/permeability of the rock salt, not all pore spaces may be connected such that the local pressure can rise. Thus, locally fluid pressures between grains of salt may stay the same as when they are isolated. In case of a “perfectly connected” network, the fluid pressure reduces the stress as stress minus the pore pressure. If the network is not perfect and not all grain boundaries are reached, a factor between 0 and 1 can be introduced to describe the effectiveness of the pore pressure. This factor is related to the poro-elastic effects inside the rock and is often linked to Biot’s coefficient. This coefficient relates to the elastic parameters of the dry bulk rock (including pores, fractures etc.) to that of the constituents (minerals and grains) it’s made up of. For rock salt there is no consensus within scientific literature on what an appropriate Biot’s coefficient would be. Nobian therefore assumes the simple effective stress law, i.e., a Biot’s coefficient of 1, when stresses around caverns are evaluated. This yields a conservative approach as with a lower Biot’s coefficient the stresses will be higher, and likely further away from failure criteria (see strength of rock salt in previous section).

Laboratory research within the CCC framework has been conducted by IfG Leipzig, and an investigation of the microstructure is carried out by MaP (Schmatz et al., 2024 in prep). Experiments follow the test procedure of Popp et al., (2015), with the adaption that the gas is replaced by saturated brine. In a nutshell the test involves a standard cylindrical sample subjected to a triaxial stress state. From the top part of the sample a small borehole is cemented in, with a cm-scale open hole in the bottom, which forms a mini-cavern within the sample. Fluid pressure inside the mini-cavern is increased until leak-off is observed. Brine can flow out of the sample space through pathways in the sample jacket. Furthermore, tests were carried out under a low deviatoric stress of 1 MPa to allow for a non-isotropic stress state that is expected at the cavern wall in the abandonment scenario. Tests were conducted on various rock-salt samples such that the influence of impurity content and grain-size could be assessed in a qualitative sense. The number of tests was not large enough for a quantitative approach.

Initial results do not provide a conclusive answer, meaning that there was not a consistent test response which would allow for a quantitative description of when permeation behaviour may be expected, and how the resulting permeability varies with effective stress. Microstructural evidence does hint at possible leak-off paths at halite-impurity boundaries or even through micro-porous impurities (anhydrite for example). However, upscaling these results to a larger scale (field scale) remain challenging. Subsequent laboratory tests are pending to increase the number of tests and aim for the possibility of a statistical approach. However, the effectiveness of small-scale laboratory tests is likely not effective enough. Also, in light of the upscaling problem developments for field-scale tests to measure permeation in-situ in a borehole are taking place. Results of such tests can likely be incorporated in future versions of this document.

4.4.5. Fracturing/faulting

A sudden event where a new discontinuity is created within the host rock. Relatively large bodies of salt (and potentially also over- or side burden) are displaced relative to each other along a certain plane: the fault plane. Fracturing can occur in two “modes”. Mode 1 is considered an opening fracture, where the two rock faces slightly move away normal to the newly created fracture plane. This process also known as fracturing. In mode 2, shear faults, the two sides of the fault move along the fault plane and is known as faulting. Thus, technically speaking the distinguishing feature is if there is lateral movement along the discontinuity. A third mode is also recognized, as relative rotation around an axis that is normal to the fault plane, but this can be considered a special case of mode 2. Often faults are created as a mixed mode, meaning there is an opening (fracturing) component as well as a shear (faulting) component. The fracture mode that is observed (most) depends on the stress state at which the fracture or fault was formed. Tensile stress states favour opening fractures and compressive stress state faults.

An important parameter in terms of cavern stability is the permeability of resulting opening fractures. Regardless of the fracture mode, the fracture plane has some roughness (unevenness, it is not a perfectly straight plane), which causes some voids to open, along which fluids may flow out, through a permeable channel (if the pressure is lower outside of the cavern. Opening fractures tend to have a higher fracture aperture, meaning more space for fluids to flow out: a higher fracture permeability. The amount of fluid that can potentially flow out of the cavern is determined by the pressure difference within the cavern and that of the medium where it flows into and can be estimated using the cavern compressibility. To assess the flowrate (leakage per time unit) assumptions need to be made on the permeability of the fault as well. This is non-trivial to solve for as the permeability is directly linked to the fracture aperture, which itself depends on the pressure level inside the fracture. The fracture is therefore assumed to be highly permeable, which works as a worst-case estimate.

4.4.6. Seismicity

Seismicity can be used in two contexts here: as an external cause (external seismicity that affects the cavern stability), or an internal effect (a seismic signal that can be used to identify physical processes in and around cavern). An example of external seismicity is from the Groningen gas field to the Heiligerlee and Zuidwending caverns. Research has shown that the energy needed to cause stability problems at the caverns are not reached by these seismic events (ARUP 2021).
As for internal effects: Fracturing can lead to seismic events, which can be measured at the surface if the energy release is large enough (and the network sensitive enough). By using a network of seismic stations, fracturing in the subsurface may be detected and localised, such that it can be linked to a specific cavern. Trends in terms of depth, horizontal position and magnitude changes give indications of what is happening in and around a cavern. Note that some level of fracturing already takes place within the subsurface without human interference, although generally below the level where humans feel them. Monitoring of seismicity is more sensitive than humans and thus provides tools to assess cavern stability. However, it should be carefully compared to natural background levels which unfortunately have not always been measured beforehand.

Seismicity during the storage phase
For storage caverns, it is suspected that, during the relatively long lifetime, more seismic events occur when compared to production caverns. Seismicity is not expected to have an additional effect related to storage alone, other than the beforementioned longevity of the cavern and resulting longer period during which seismic monitoring is required.
It should be noted that fast leaching of storage caverns, for example to meet storage-operator demands, has in the past resulted in irregular cavern geometries. Without frequent checks on the evolving cavern shape during the leaching phase (sonar logs), interventions in the leaching strategy may be too late to avoid irregular shapes. This is particularly the case if the local geology in the planned cavern volume consists of anhydrite layers/banks or other insoluble content. This overall has not impacted cavern integrity but may lead to an increased risk of rock fall events. These in turn require investigation and may lead to down time of the storage cavern to ascertain the continued integrity. With the current microseismic monitoring as Nobian uses it for the brine caverns, a higher frequency of rockfall events imply more frequent sonar measurements. However, site

and storage specific traffic light systems should be developed to relate microseismic activity to possible integrity risks.

4.4.7. Stress redistribution, cavern shape, arch design cavern roofs etc.

The shape of a cavern, particularly the cavern's roof defines how well the stress of the overburden (due to the weight of the overlying layers) is distributed. It's been long established that arch- or dome-shapes are well equipped to handle the stress of the overburden, as evidenced by arch-bridges and domal structures in buildings. The same holds for cavern roofs. Much like the arch-bridge design, where the pillars carry the weight of the bridge, "pillars" or an area around the caverns, including the cavern walls are subjected to an increased level of stress to carry the weight of the overburden above the cavern. In case of a field with multiple caverns, the distance between caverns is chosen such that the minimal distance between caverns (defined as the pillar width) is more than enough including safety factors, such that the pillar itself can handle the added overburden weight of both caverns without exceeding the strength criteria. More on this can be found in section 5.3.2.

In cases where the salt deposit is relatively thin (e.g., bedded salts), the roof may comprise of another lithological unit instead of a salt-dome roof. If this is the case the overlying layer should be competent (strong) enough to handle the overburden pressure. This does put a limit on the lateral extend a cavern can be and requires a tailored geomechanical assessment.

4.5. Cavern lifecycle phases

Nobian recognizes five phases of the cavern during its lifecycle. These are: 1) Exploration and Construction, 2) Production, 3) Post-leaching 4) Abandonment and finally 5) Post-mining. The phases are discussed below, as well as what marks the changeover. An optional storage phase is also possible after the production phase, which will also be described in this document.

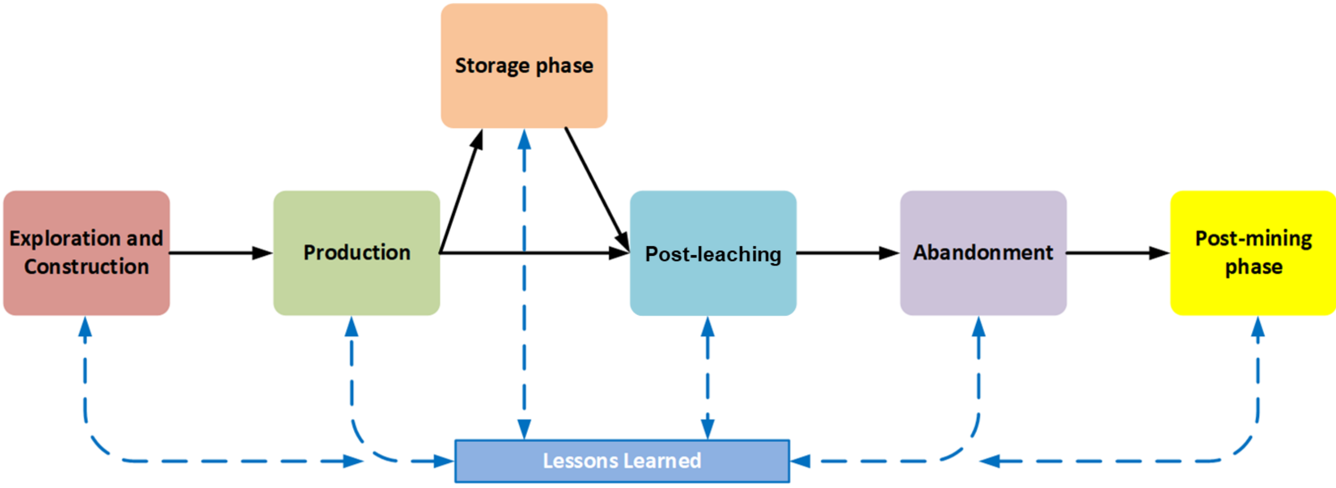

Figure 10 The Cavern Stability and Integrity Management System (CSIMS)

4.5.1. Design phase

In this phase the actual cavern does not exist yet. All potential safety-concerns are still theoretical and can be taken into account by optimizing the field design. As such the cavern(-field) can be developed such that unwanted effects (see chapter 5) are absent by design, or at least mitigated as much as reasonably possible. Thereby potential scenarios where aftercare is needed at the end of the lifecycle (4.5.4. and onwards) are not foreseen but cannot be excluded due to the uncertain nature of geology.

Certain actions are taken to evaluate a safe cavern during all subsequent phases (design limits are discussed below). For example, parameters such as cavern depth, height, distance to other caverns (field design), specific leaching technology per field, etc. are used to evaluate a safe design using state of the art numerical modeling techniques. In this phase some assumptions need to be made, for example on the geological structure or the mechanical behaviour of the salt in the subsurface (strength, far field stresses, creep behaviour). These can be made on the basis of Nobian's experience within the different fields, but additionally through data in the public domain (e.g., via the Dutch "Oil and Gas portal", nlog.nl; or the Dutch Geological service, TNO-GDN, dinoloket.nl). In terms of data quality there is expertise within MDC that can evaluate the usability of the data (see skill matrix section 2.2). Moreover Nobian can hire external experts to help out in the design phase, get a second opinion or audit designs.

These can potentially be further constrained by drilling an evaluation well, which provides representative data for the entire field (this assumes lateral variability on the length scale of 1-2 kilometers (at most) within the same salt structure is negligible, which can only be confirmed once two wells are drilled). An evaluation well provides access to the overburden and salt formation, and well-logging techniques can be used to measure several in-situ properties, depending on either the "well delivery process" (Link) or upon request by BFT. Additionally during the drilling process testing phases can be scheduled in order to assess the formation integrity through (extended) leak off tests. This gives information on the local stresses at test depth, and the mechanical strength of the tested formation. In case the evaluation well is (partly) drilled using a coring drill bit, the borehole-core can be extracted to surface. Samples from this core can be used for laboratory tests to further explore mechanical behaviour and permeability under controlled conditions.

The caverns main access will be its central borehole (in some special cases an additional borehole is required). The principles of designing a safe borehole is described in the Well Integrity Management System (WIMS) documentation. Potential changes in stresses on the borehole due to emergence of a cavern below are taken into account during this phase as well. As such the approaches within the WIMS and this document are integrated.

In a field-design approach a local seismometer-network is installed prior to drilling the wells. This allows a measurement of natural background seismicity, and provides a baseline to which future measurements of seismicity can be compared, in terms of an increased event rate (for example, a number of events per month) and / or statistically significant changes in the magnitude of events. Note that a local dedicated seismometer network can measure lower levels of seismicity compared to country-wide networks. Typically local networks are able to pick up on seismic activity that is far below the threshold for nuisance (i.e., being felt), and even further from thresholds where damage could occur. It is therefore important to establish a baseline using the same setup. A local network is also better suited to pin-point source location of the seismic events, which allows to check if the activity is clustered around a certain cavern or a particular lithological interface. Note that Nobians main goal for microsesismic monitoring is cavern stability monitoring. Generally the energy of these signals is orders of magnitude lower than those associated to seismically induced damage.

The design phase changes to the production phase once the borehole is drilled and completed. Drilling the borehole itself could be considered another phase based on the amount of technical details, safety considerations, expertise and skills required. For this the reader is referred to the WIMS documentation and the well delivery process. It is not included here.

General guidelines for the design of a salt production cavern

- The design is an optimum between maximum amount of extractable salt, minimal energy use and minimal surface effects (where only manageable effects to water household are acceptable).
- This optimum translates in different designs depending on the local geology. It is different for production caverns in bedded salt versus domal salt or pillow salt.
    - In shallow bedded salt, cavern stability is the safety parameter that controls maximum cavern dimension and field design. Creep and pressure increase after abandonment are limited and slow.
    - In domal and pillow salt, stability is given when following the guidelines of ABVO (Allgemeine Bergverordnung über Untertagebetriebe, Tagebaue und Salinen, 1966) on salt roof and dome flank thickness. The safety parameters controlling maximum dimensions of caverns and the cavern field are either the upper limit to the equilibrium pressure after abandonment or the long-term subsidence effects. Per field a field specific proof of the stability will given before the design phase is concluded.
- The depth interval of a cavern is controlled by the need for a sufficiently thick salt roof at the top and limited convergence at the base of the cavern. The latter increases with depth, thereby limiting the maximum depth of a potential storage cavern. The height of the cavern also plays a vital role during abandonment and is therefore also important during the design phase.

Design of a storage cavern

Storage caverns require slightly different parameters and have specific design elements, however the guidelines for salt production caverns also apply for storage caverns. The design of a storage cavern is primarily controlled by the requirement for efficient fill and empty cycles.
The specific design elements are mentioned below:

- For efficient filling and emptying, gas and hydrogen storage caverns typically have a volume of 0,5-1 mln m^3. This volume represents an operational optimum whereby a sufficiently large gas volume can be stored and accessed without the need for excessive amounts of cushion gas (which cannot be extracted and used during the storage phase). This volume is lower than the average production cavern. Another advantage of a smaller cavern is that it takes less time to leach the cavern and start the storage phase and limits subsidence which is expected to be slightly more in storage caverns than production caverns.
- When designing a storage cavern field, care is taken to maintain sufficient distance between caverns to limit neighbouring storage caverns geomechanically influencing each other. There is usually a

larger distance between storage caverns than production caverns, to limit subsidence (which is expected to be slightly higher in comparison to production caverns due to the long duration of a storage phase during which the caverns are filled with gas at variable pressures). This is specified in section 5.3.2.

- The depth range at which a storage cavern is operated depends mainly on the pressure range the storage cavern is to be operated (which is directly related to the storage capacity of the cavern). To prevent different caverns having to be operated at different pressure ranges (leading to unnecessarily complicated pumping infrastructure), all storage caverns in a field have the same vertical range (i.e., similar LCCS depths).
- The speed at which the cavern is leached, or rather, the timing of when the storage cavern is to be complete. This can be either at “normal” production speeds or increased speeds, depending on when the storage needs to be available. Leaching speed has implications on cavern shape, which are explained further in 4.4.6. The speed of leaching is set during the design phase, and considered final after surface facilities are in place, as it is difficult (or costly) to change this at a later stage. This means that there should be a carefully laid out plan. Logistically, there also needs to be enough time to process the (unsaturated) brine, through a saturation cavern or directly to the plant.

4.5.2. Production phase

During the production phase the borehole is in place and the cavern is growing in volume, up to it’s maximum dimensions as defined by the design and confirmed in permits. During leaching there are regular checks on the geometry of the developing cavern by means of sonar measurements. This is done at regular intervals, defined by a certain amount / tonnes of produced salt or every 5 years, which ever comes first. These sonar logs enable Nobian to see if the cavern is developing according to plan. If this is not the case there are remediation measures such as changing the specific leaching technique and sonar logs can be taken more frequently to track the cavern development at a higher resolution. More details on this can be found in chapter 5. Both during production of brine as well as periods in between where production is suspended, the pressure in the cavern is regulated via the borehole. This ensures that the cavern pressure does not go above a certain limit (avoiding permeation and fracturing by some margin), more details on these limits in chapter 5).

In principle the production phase ends when the cavern reaches it’s maximum size, or if there is some other reason to stop producing brine from the specific cavern permanantly. Reasons may vary from commercial reasons to unexpected amounts of clustered seismic activity near the cavern.

Leaching phase of a storage cavern
The leaching phase of storage cavern is not fundamentally different to that of a primary production cavern. However, there is often a market requirement to deliver the storage cavern early. This results in faster leaching rates that need to be incorporated in the production infrastructure of the field. In particular, this requires the availability of other caverns to resaturate the produced brine. Also, faster leaching rates may lead to irregular cavern shapes (see 4.4.6).

4.5.3. Storage phase (optional)

After production, when a cavern has reached its maximum designed size, the cavern could potentially be used for other purposes instead of (being prepared for) abandonment. This phase generally lies outside of Nobian’s responsibility as the cavern’s exploitation is handed over to a third party, and thereby the mining license as well. Storage products include; hydrocarbons (Nobian’s GOME caverns); Nitrogen gas (Gasunie, Heiligerlee); Methane (Gasunie, Zuidwending); Compressed air energy storage (or CAES, in development by Corre Energy, Zuidwending) and Hydrogen (in development by EnergyStock B.V., Zuidwending).
In terms of cavern stability, it is of importance that the pressure inside the cavern remains within pre-defined limits such that the integrity is ensured, at least to the best practises and current knowledge. Limits primarily involve pressure but may also include limits on flowrates / volume flux related to borehole integrity. When the cavern is filled with storage material like a gas, instead of brine, the pressure within the cavern is based on a gas gradient instead of a water gradient, resulting in a lower pressure and higher differential pressure with the lithostatic pressure. If it is foreseen that a cavern will have a subsequent use after salt mining, design limits may be different such that the cavern is at an optimal depth and has an optimal geometry for storage. During the storage phase the cavern will most likely shrink in size due to creep effects (see 4.4.2.) and have associated subsidence. After a storage phase, caverns need to be abandoned similar to caverns that come

out of production. The subsequent phases are therefore the same, and the responsibility of these phases are with the storage operator.

Storage caverns not operated by Nobian
In the case Nobian is not the storage operator, all cavern-related responsibilities are handed over to the storage operator when the storage licence comes into effect (and Nobian's salt mining license is terminated). Even though Nobian is not the operator of the storage cavern, debrining of the cavern is conducted with both Nobian and the storage party, as debrining and filling with storage media is simultaneous. Produced brine is then processed by Nobian.

From a legal point of view, in this case Nobian is no longer the (last) holder of the mining license. Therefore Responsibility for subsequent phases to the storage phase, including post-mining (i.e., post-storage in this context) lies with the third-party operator.

Nobian takes care of proper handover to third party operators by means of knowledge transfer, cavern history etc. More on handover procedures can be found in chapter 8. The philosophy is that even though Nobian is no longer responsible in a legal sense, care is taken that also in the long-term the cavern use and abandonment is considered safe. This is in line with the general policy and company values (see 1.1.). Nobian therefore strives to establish the life-cycle philosophy with third parties, and when possible, work together on joint permit applications (albeit for different stages), and sharing research efforts.

End of storage
Where Nobian is operator of the storage caverns (e.g. GOME), care is taken to prepare the cavern for the post-leaching (and post-storage) phase. As mentioned earlier, the storage caverns are to be abandoned in similar fashion to caverns that come out of production. This means the cavern must be filled with brine or water. This process of preparing the cavern for the post-leaching phase is called rebrining (or rewatering), replacing the storage medium with brine/water which will become brine.

When end of storage occurs for caverns not operated by Nobian, there might be the need for large amounts of brine or water to rebrine the cavern, for which Nobian can be of help. There is uncertainty involved in the availability of the brine or water, as the life cycle of a storage cavern is relatively long (up to 40 years) when compared to modern production caverns.

4.5.4. Post-leaching phase

When leaching from a cavern is stopped, and the cavern will not, or no longer be used for storage purposes, the post-leaching phase starts. This phase is designated for the necessary actions and time to create circumstances for safe cavern abandonment. There are two important aspects that are considered in this phase: thermal equilibrium and backfiling.

In the case of storage caverns, the phases described in this chapter occur much later due to the prolonged (typically decades) storage operations phase. Although this does not impact the required actions, care is taken to consider larger uncertainties regarding the presence of brine and infrastructure required at a more distant point in the future. If, for some reason, the salt mining industry is no longer active in the region, there should still be a possibility to abandon storage caverns safely. Alternative options such as filling the cavern with fresh water instead of rebrining, are therefore also investigated.

Thermal equilibrium
In the previous phase, the injected water had a lower temperature compared to the initial geothermal temperature gradient within the salt rock. Note that this varies per field because of the different approaches and field situations. For the Hengelo caverns the injected fresh water temperature is often warmer than or has equal temperature when compared to the in-situ temperatures due to the shallow depths of the caverns (low temperature) in combinaton with that the fresh-water is at elevated temperatures as some of the water is a return-flow from the factory. However, considering the situation in Hvornum, the temperature difference is relatively high due to the low temperature of the fresh water input in combination with deeper caverns.

For cases where the injected fresh water has a lower temperature, due to heat flux from below and beside the cavern, the brine within the cavern will heat up. Since the cavern is a closed volume there is no room for thermal expansion and as a result the pressure within the cavern will go up. If the cavern pressure exceeds the maximum pressure integrity may be lost (fracturing + leakage). Therefore the pressure is reduced by bleeding off brine from the cavern. The effect drops out when the temperaturegradient within the cavern is equal to that of the initial geothermal gradient, or is low enough. The approporiate waiting time depends on the cavern depth and shape. For this numerical models are in development, pressure development + bleed off events may be useful to assess whether the thermal effect is still relevant.

The rate at which the temperature changes is expected to decrease over time, as the temperature difference becomes smaller. At some point (definition to follow), the temperature difference is small enough such that pressure changes due to the thermal expansion effect can be considered negligible. At that point it is assumed that bleed-off moments are no longer necessary. If additional information also indicates that the cavern is stable (for example a total lack or deminishing rate of microsesimic events, subsidence monitoring) the well can be plugged and abandoned and the well goes into the abandonment phase.

Since the well is no longer actively used for production, care must be taken that the well does not clog up due to crystallization of salt from brine cooling in the well. This would cause that pressure control (bleed-off) can no longer take place. This is discussed in WIMS.

Backfilling
Backfilling is a preventive measure to reduce cavern related risks discussed in the next chapter. During this stage the brine volume in the cavern will be partially replaced by solids that will be injected into the cavern in a stream of saturated brine. In this stage the backfilling return brine will be produced from the cavern, but the cavern will not become larger, because active leaching of rock salt is not taking place. Backfilling as a preventive measure is described in paragraph 5.3.9. Whether a backfilling stage is required for a cavern depends on site specific conditions, abandonment plans and local acceptance of possible mining effects after abandonment.

Compensation of damages
Effects and/or damages relating to the potential long-term effects of subsidence are to be compensated. More on this compensation is discussed in 4.5.6., the post-mining phase, as that is when the effects are more likely to occur.

4.5.5. Abandonment

In terms of cavern stability this phase is of minor importance, and is relatively short. During the previous phase it was established that the cavern can be abandoned in a safe manner, meaning that there is sufficient confidence that the equilibrium pressure within the cavern is such that pressure control using the borehole is no longer required, and potential subsequent subsidence is limited. Abandonment in this sense is alternatively termed as “hard shut in”. During the abandonment phase there can be a final check of the cavern shape by means of a sonar measurement, such that the final shape before closing the cavern is known. If this shows irregularities that change the assessment that the cavern can be abandoned safely, the cavern is dropped back in the previous phase where monitoring is taking place.The abandonment phase is listed seperately from the previous phase to align phases with the WIMS.

4.5.6. Post-mining

Caverns are abandoned in a safe manner when it can be assumed with as much confidence as reasonably possible that the pressure within the cavern remains within set limits, such that substantial leakage out of the salt formation is avoided (low leakage rates in the order of liters per day due to permeation are not considered here). Note that 100% confidence is not possible with current state-of-the-art methods due to the uncertain nature of geology, for example due to lateral variation within the salt deposit or overburden. Field evidence over the years is eventually the only way that the safety can be demonstrated. The well abandonment is designed such that it can handle the expected maximum cavern pressure. The pressure within the cavern will no longer be regulated by means of bleeding off at the surface, and can no longer be monitored. Processes that change pressure within the cavern thus have to form an equilibrium cavern pressure that can be considered safe. Monitoring of subsidence and seismicity remain active to check if the cavern remains safe. If this is not the case mitigative actions can be taken. From a legal point of view Nobian has a requirement to monitor for 30 years after the production has stopped in the Netherlands. However, Nobian considers all phases prior to abandonment as relevant for monitoring, thus the post-leaching phase (with variable duration depending on field specific parameters) is added to the 30 years monitoring period. Note that technically the relatively small volumes of brine (compared to production phase) that are bled off are still used for production. From that point of view the post-leaching phase can be considered as production. In effect, if the post-leaching phase takes for example 20 years (reaching thermal equilibrium), Nobian will monitor for a number of years during thermal equilibrium (or other post-leaching measures) depending on the abandonment plan + 30 years after abandonment (which can be adjusted based on the criteria that there is a stable situation). Nobian or its successor remains liable for damages caused by its activities.

Compensation of damages

During this phase, necessary actions are taken to mitigate potential long term effects. Long term expected subsidence is modelled, and if the prognosis of these models is that damages are expected, Nobian will help the parties involved. In most cases the prognosed subsidence will affect water management, which is the domain of the water authorities. There are discussions with water authorities to come to agreements. To a lesser extent, minimal effects can be expected on municipal sewers. There is also the possibility to report damages to the Mining Damage Committee (Commissie Mijnbouwschade). (waterschappen, lange termijn en van te voren).

4.6. Geology / Field specific approaches

Nobian operates caverns in different fields that vary in their geological structure. This results in differences in risk assessment. The following fields are described here.

- Bedded salt formations
- Pillow salt formations
- Domal salt formations

In the figure below, the different salt formations are shown:

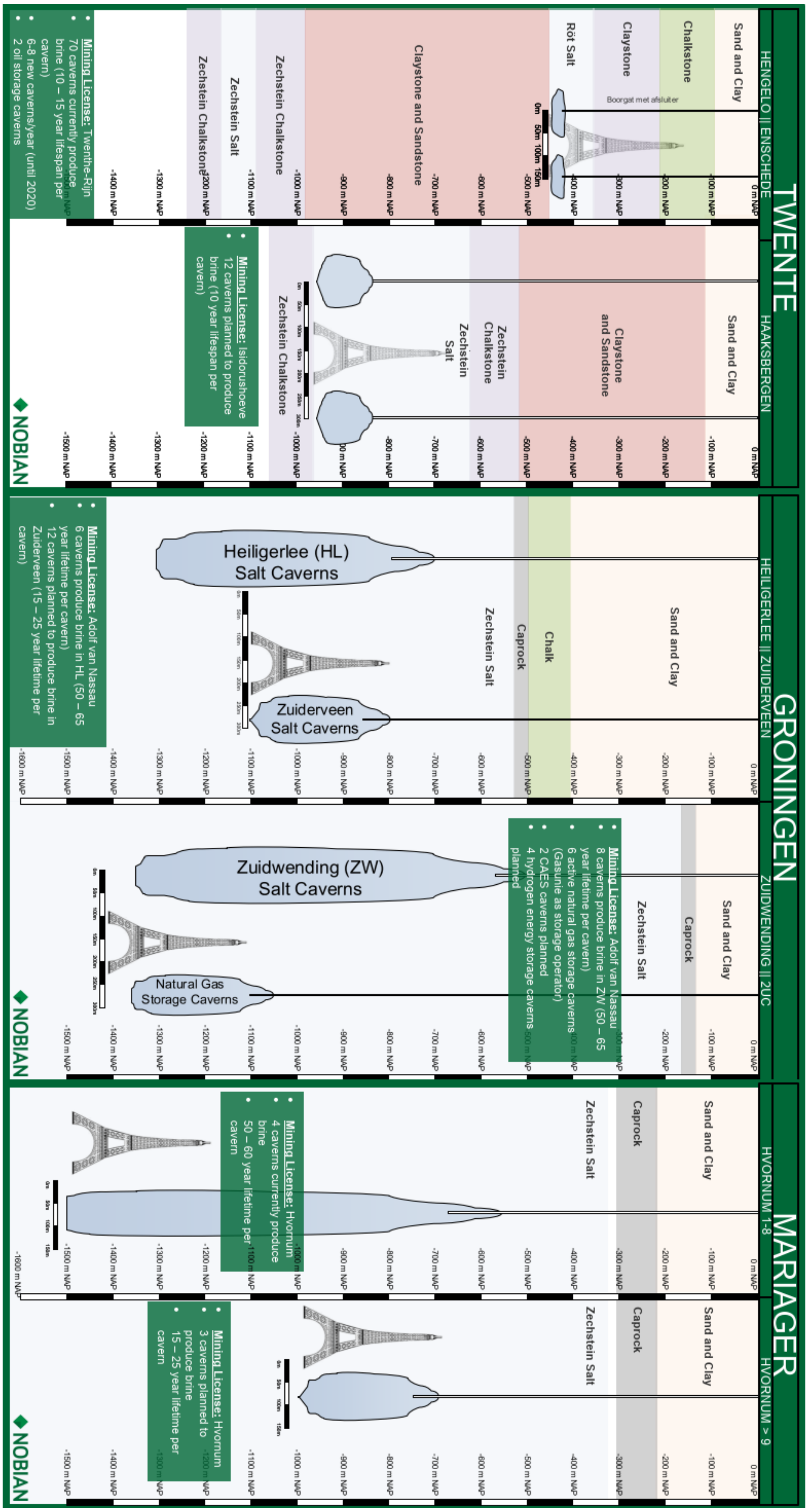

Figure 11 different salt formations

4.6.1. Bedded salt formations

The Hengelo field lies in a bedded salt formation. In such a formation the salt lies (close to) horizontal (dip 0-15°) and are at relatively shallow depths (300-600 m). At these depths, the temperature is approx. 20 - 30 °C, resulting in creep mechanisms being slow. Pressure increase due to creep is relatively low such that it is hardly detectable. The likely cause is the low temperature and low pressure (caused by the shallow depth), such that also the generally faster creep mechanism of pressure solution creep is low to the extent that pressure increase inside the cavern can be considered negligible. This may also explain why the layers have remained in place at the same thickness, as intra-layer flow has remained insignificant. Note that within the salt formations other lithologies can be present, for example anhydrite layers.

While creep is considered of minor importance, the shallow cavern depth does lead to other hazards which are more pronounced, as there is less overburden there is less overall overburden strength. These field specific hazards for the Hengelo field are outlined in the document “Hengelo Uitloog Techniek”, or HUT. The risks have been incorporated in the following chapters.

In the Hengelo field, the GOME (diesel) storage cavern is operated by Nobian, in bedded salt. The storage plan for the GOME is available in-house (*20130418 Opslagplan Gasolieopslag De Marssteden*), which was approved by the Ministry of Economic Affairs and Climate (Reference: DGETM-EM/13148427).

4.6.2. Pillow salt formations

In contrast to the bedded salt formations, pillow salt formations do show significant variation in the thickness of the salt layers. But not (yet) to the extent that a salt dome or diapir has formed. The pillow structure can be considered a transitional structure. Within these formations creep mechanisms are expected to play a role. Caverns are typically developed in the thicker part of the formation, such that there is ample space for a spherical roof and distance between the salt roof and the top of the salt formation. Nobian has plans to develop the pillow salt formation at Haaksbergen.

4.6.3. Domal salt formations

These formations are the result of salt layers flowing to shallower levels by means of tectonically induced diapirism. In essence domal salt formations are developed as follows: Initially flat (bedded) salt layers have been buried deep enough such that they are hot enough for creep mechanisms to be relatively fast and the stresses are high. The salt is effectively squeezed out to shallower levels, thereby a dome is formed. This is the case for the Heiligerlee and Zuidwending fields. In some cases (such as the Mariager field in Denmark), a chimney like structure is formed from the dome further upward whereby a tall mushroom-like structure is developed: a salt diapir.

Both domal and salt diapir structures enable (several) tall caverns to be formed within the salt structure, enabling a relatively large extraction volume using a single well. However, Nobian is moving away from this technique as recent insights have shown that caverns with a large height prove challenging with regards to safe abandonment, in the post-mining phase. Due to the large height, pressure increase at the bottom of the cavern (where creep is generally faster) may cause the pressure at the top of the cavern to exceed hydraulic fracturing limits. In the future Nobian will use a design with a lower height to avoid these challenges completely.

Most storage caverns in the Netherlands are operated in domal salt formations, these are in the Zuidwending and Heiligerlee domes. Nobian has provided caverns in these domes for storage by third parties and has plans to develop more storage caverns (e.g., Nitrogen gas (Gasunie, Heiligerlee); Methane (Gasunie, Zuidwending); Compressed air energy storage (or CAES, in developed by Corre Energy) and Hydrogen (in development by EnergyStock BV)).

5. Cavern Failure model

5.1. Top Events

Nobian has identified the following main risks (or top events) using the procedure described in chapter 3. Note that these are not in order of severity. Moreover, these risks have different likelihood of occurring at different lifecycle phases, which is discussed in chapter 6. This list does not include risks regarding the well integrity, as those are described in the WIMS.

1. Subsidence by creep above acceptance limits
2. Sinkhole formation
3. Liquefaction
4. Damage to buildings or infrastructure due to seismic events
5. Groundwater (fresh) contamination
6. Contamination of other (non-freshwater) aquifers.
7. Hydraulic connections to other caverns

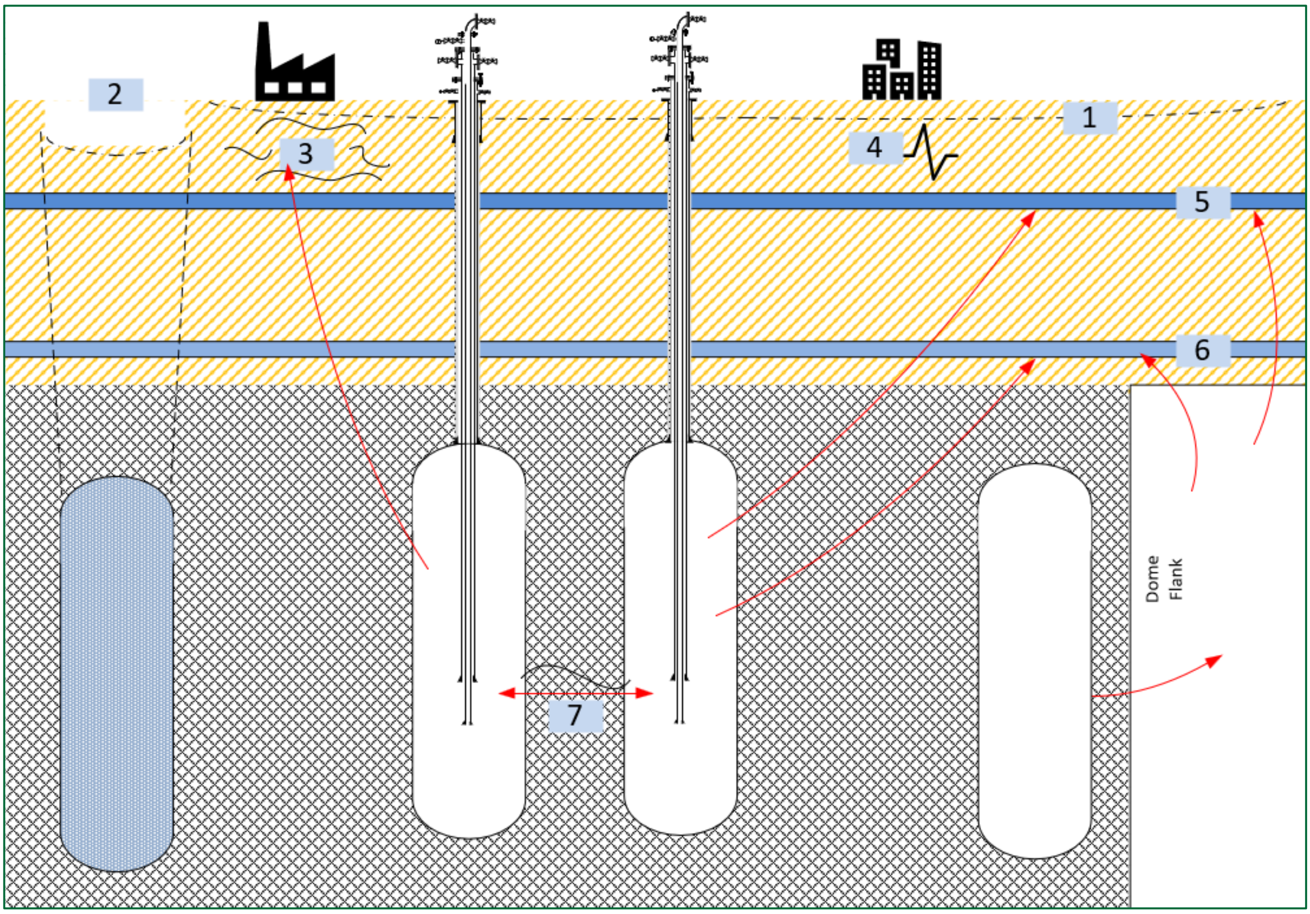

Figure 12 Nobian Cavern Failure Model: Top Events

5.1.1. Subsidence by creep above acceptance limits

This risk describes particularly an event where the amount of subsidence (defined as the difference in elevation between that before salt mining and the present / predicted future) reaches values that are above pre-approved acceptance limits. At surface subsidence can cause buildings to be tilted and/or tensile stresses to emerge in buildings. For safety limits building specifications have been taken as input. Moreover, subsidence can potentially cause integrity issues with shallow underground structures (sewer lines etc.) and on a larger scale adverse effects on the water management are possible.

Some subsidence is already expected to result from the solution mining practise and is described in the extraction plan. By means of consent from authorities, after careful consideration of the predicted effects and minimizing measures, this amount is considered as accepted. In the definition used here, subsidence is a gradual change of altitude over time, typically a timespan of multiple years. Sudden events, such as sinkhole formation, cavern collapse and associated cavern migration, could technically be listed as subsidence above acceptance limits, but it is caused by a different mechanism. Therefore, likelihood and effects are different, making it logical to treat this risk separately (see 5.1.2).

As touched upon earlier (section 4.2.), subsidence at Nobian's caverns is usually observed as a gradual bowl-like shape that develops over several decades and spans several hundreds of meters across horizontally and is in the decimetre scale at its deepest point in the middle (above the centre of the cavern field). Note that these values can vary per field and should be taken as indicative. In addition, the surface-subsidence region caused by two or more caverns within the same field can overlap which each other, causing higher subsidence in the overlapping part. In a general sense, subsidence is the result of convergence of the cavern volume where salt has been extracted from the subsurface by mining. Due to creep processes and assuming a constant volume of rock salt, the salt plastically deforms in the subsurface in the direction of the caverns, leading to cavern convergence (cavern volume reduction). This translates via the gradual deflecting overburden layers to the surface in the form of gradual subsidence in an area around the cavern location. In this simplified view, any delamination effects (where layers decouple from each other along their interface) and strength of the overlying layers is ignored, but these would dampen the amount of subsidence observed at the surface.

The largest amount of subsidence that can potentially occur is when the entire cavern is "squeeze closed", meaning that the cavern walls move inward such that they touch each other in the central axis, and no cavity is left behind. In essence the volume of the subsidence bowl is equal to the size of the caverns, not considering potential bulking effects in the overburden. On the basis of current scientific insights this is expected to happen on a timescale of a hundred thousand years or more as Nobian's caverns are situated at depths where creep rates are relatively low. More research is being done to better evaluate the long-term effects (e.g., Baumann et al., 2022). Note that on these long timescales other natural geological effects that influence subsidence may also play a role, such as tectonic movement and sediment influx. This makes long term subsidence hard to forecast. In addition, Nobian takes other mining activities that could cause subsidence into account as well (e.g., due to gas extraction in the North of the Netherlands, see KEM-19 report TNO/Deltares).

5.1.2. Sinkhole formation

When the structural elements above a cavern fail (meaning a loss of load bearing capacity), the material above the cavern might fall into the cavern-space much like a plug or piston (e.g., Bérest 2017). Such collapse might happen at once (the plug or piston) or can happen due to gradual collapse of overlying layers, termed cavern migration.

As a measure to prevent sinkhole formation Nobian designs new caverns such that there is an arch-shape roof at the top of the cavern and makes sure that the top of the cavern is far enough away from the top of the salt formation. Thereby the "salt roof" (the distance between these two) is thick enough to support the overlying layers (see also 4.4.7.). In addition, caverns are situated far enough from a dome/diapir edge. Moreover, other sub-surface activities in the over- or underburden (e.g., geothermal heat extraction, natural gas extraction) near the salt deposit are avoided, although it is up to the authorities to decide whether this additional risk is acceptable for which further study is required.

The spherical roof design generally does not work for bedded salt formations as the layers are often not thick enough. Caverns in the Hengelo field (bedded salts) do not have spherical roofs but rather overlying layers that are competent enough to act as a roof formation at pre-determined maximum cavern diameters. During the first decades of salt mining in the Hengelo field, this rock mechanical design concept was not yet developed and applied. For several caverns that were developed in these decades there is a risk that the process of cavern migration can result in the formation of a sinkhole. The risk assessment for the Hengelo field is treated in a separate document (available in Dutch only): "Beleid Monitoren en Vullen Cavernes Twente". This document is updated when new insights are obtained. Preventive and mitigating measures are derived from the most recent version of the document.

Cavern migration does not always lead to a sinkhole and could also end up in a more concentrated form of subsidence (spatially). The bulking effect of material falling into a cavern, causes a reduction in cavern size when a cavern is migrating upwards because the rubble from the collapsed material takes up more volume than the original material. When there is still a sufficiently thick layer of competent rock above a cavern when it is filled with bulked overburden, migration stops in the subsurface and a sinkhole will not occur. There will however be some subsidence as a consequence of the compaction of the bulked material. For a sinkhole to occur the cavern needs to be relatively high and located at shallow depth, such that the bulking effect does not sufficiently reduce the cavern size and the process therefore does not stop timely.

5.1.3. Liquefaction

In case cavern integrity is lost by means of a fracture to the surface, brine from the cavern can ingress into porous soil layers and potentially cause liquefaction. During liquefaction, the capacity of soil layers to withstand shear stresses is greatly reduced, and the soil behaves much like a fluid. Thereby the capacity to carry the weight of overlying structures is reduced, and they may essentially sink into the soil. However, a recent study (Witteveen & Bos 2022) has shown that for this to happen, the volumes of brine that need to be expelled out of the cavern exceed the maximum estimates of cavern leakage volumes. Theoretically it would be possible if all leakage happened only into the shallow layers, where multiple barriers (casings) are present. These estimates themselves are based on worst case scenarios, such as a high cavern compressibility, a large cavern volume and a large pressure drop (from high cavern pressure up to the pore pressure within the soil). Therefore, this risk is considered purely theoretical. Field specific studies will be done to validate this.

5.1.4. Damage to buildings or infrastructure due to seismic events

Seismic events can possibly emerge from multiple mechanisms. The first is by stress redistribution in the overlying layers of the salt dome, and at pre-existing faults. For this to happen there isn't necessarily any leakage out of the cavern required, but it could also happen if there is leakage. Due to extraction and subsidence, stresses can change, such that the stress-state at previously existing faults is no longer stable (i.e., exceeds the frictional strength criteria). Note that also in-tact material (without pre-existing faults) can potentially be in an unstable state and create new fractures, which might generate seismicity. But generally, the strength of existing faults is substantially less compared to that of in-tact rock.

A second mechanism is due to leakage out of the cavern, where fluids at relatively high pressure compared to the pressure within the overburden infiltrate existing faults and increase the pore pressure at the fault. This causes the effective stress to reduce, which can push the stress state into the unstable field, much as the previous mechanism.

A third mechanism involves the cavern itself. Within the salt structure some layers can exist that are not as soluble as halite layers. During leaching or storage these can break off and fall downward within the cavern. The cracking of potential break-off events can be detected if enough energy is involved and the sensitivity of the micro seismic measurement network.

Seismic events can lead to damage at surface. The amount of energy at the source is transferred to the surface as a shockwave. The extend of surface movement is typically listed as Peak Ground Velocity (PGV, usually in cm/s or mm/s) or Peak Ground Acceleration (as %g, a percentage of the gravitational acceleration). The amount of PGV or PGA is the result of the energy-level at the source and the distance from the source. The further away from the source you are, the lower the amplitude at that point is. Thereby a relatively low-magnitude event close to the surface could still generate damage. Moreover, the site-specific properties of the layers from source to surface can cause an amplification effect. Mathematical relationships between magnitude and distance are therefore largely based on empirical data (such as Ground Motion Prediction Equations), such as Bommer et al., (2017, 2019) and Ruigrok and Dost (2020). Nobian currently uses the approach from Ruigrok and Dost (2020), as this includes a depth dependence. Damage thresholds in terms of PGV and PGA exist in the form of building-standards (for the Netherlands: SBR Trillingsrichtlijn A, 2017). These imply that a building should for example be able to withstand the movement generated by trucks driving in the nearby street.

Nobian operates seismic monitoring networks around all her active cavern fields and has protocols in place which describe what actions are taken if seismicity in a certain area exceeds specifically set thresholds. More on this is listed in chapters 6 and 7.

5.1.5. Groundwater (fresh) contamination

An opening fracture has formed that reaches all the way to near-surface, causing a fluid pathway to exist between the cavern and groundwater reserves. The contaminant can be brine (observable as increase in chlorine content or conductivity less than 3.00 mS/cm), but also blanketing material (oil/diesel) that is used to limit upward leaching of salt caverns or storage media. Maximum tolerable values for the Netherlands are 50 mg/kg in soil, and 50 mu g/l for groundwater (based on appendix 1 from the regulation "Circulaire bodemsanering per 1 juli 2013, "BWBR0033592 (overheid.nl)).

Link to fracture propagation studies: leak-off into permeable structures that are within the path of the fracture. Note that the fracture advance is the result of the pressure inside the fracture itself. For non-porous/permeable rocks the pressure can be maintained and thus the fracture can grow. But for porous/permeable layers some or all of the fluids inside the fracture infiltrate these layers, and some or all of the pressure inside the fracture is bled off (e.g., Koning, 1989).

5.1.6. Contamination of other (non-freshwater) aquifers.

Similar as above, in terms of consequences considered less dramatic compared to the previous, as the hazard to health and environment is reduced. This top event is also applicable to layers below cavern (if there is sufficient porosity/permeability) and beside the cavern outside the cavern dome (not applicable or bedded salt formations).

The top event is also listed as the Dutch mining regulation lists that after abandonment flow of gasses or fluids through a barrier formation to other rock layers should be prevented (Mijnbouw Regeling, article 8.5.1.3). Considering that for solution mining, the salt formation itself forms both the reservoir-body as well as the seal (unless leaching has gone up to the top of the salt formation), leakage to other layers would technically violate this law at the moment the wellbore is closed off. Currently, there is no technical solution to seal a fracture, although lab-data do suggest healing of salt formations to some degree. For example, Fuenkajorn and Phueakphum, (2011) show that the permeability of mode 1 fractures drops two to four orders of magnitude within a timescale of days to weeks. Such effects have also been seen in preliminary results from laboratory tests on core material of Nobian's fields (research commissioned by Nobian by CCC team, in prep). In addition, creating a deliberate hydraulic connection between a cavern and permeable layer outside the salt formation may form part of an abandonment strategy, ensuring there is a leak off potential (e.g., Nieland and Skaug, 2011). Note that for the Dutch situation such bleed off efforts require a legal exemption to be granted, in which case it needs to be shown that this is the best option considering all stakeholders (long-term) as well as the environment.

5.1.7. Hydraulic connections to other caverns

If a fracture is formed to another cavern, this could potentially lead to pressure changes in the other cavern. There are multiple scenarios grouped into this top event, depending on the status (and cavern lifecycle phase) of the caverns involved. The different scenarios also change the mitigation that can be done. For example, if cavern A is abandoned and unexpectedly a fracture is formed to cavern B which is in production (or worst-case, in the storage phase), pressure maintenance can be done at cavern B. However, in the case where cavern B is also closed off, the mitigation options are limited, and it is up to debate if follow-up actions are even required.

5.1.8. Other top-events cavern/well integrity

Some effects that take place at the cavern could influence the well integrity. During well design such effects are considered. For completion they are also mentioned here. The full risk assessment can be found in the WIMS. Cavern/Well integrity elements are:

- The well loses its sealing capacity due to a cavern pressure that is too high
- The well integrity is lost due to salt-flow around the borehole / cement (fracturing /delamination / tension caused by creep)
- Loss of hydraulic connection due to crystallization

5.2. Possible (root) causes

Starting from the physics, root causes can be grouped together in two categories: either the pressure inside the cavern is too high or too low. The reason why the pressure has changed to that can be a combination of physical processes that are discussed in chapter 4.4. Additionally, subsequent events may happen, which themselves may be classified as a cause for a top event. For example: when the cavern pressure exceeds the pressure limit (strength at the roof), a fracture may form through which leakage of cavern fluids may occur. That in turn could potentially cause fluid pressures outside the salt-formation to increase, thereby lowering effective stresses which may in turn cause slip on pre-existing faults.

5.2.1. Cavern pressure too high

If the pressure inside a cavern exceeds the local minimum principal stress a tensile fracture may form. This may be compared to a water balloon that is overfilled: the balloon surface cracks open and the water escapes. In the cavern situation this is less dramatic as the cavern's walls are much thicker. However, if a fracture forms, fluids can escape the cavern through the fracture until the pressure is balanced to outside the cavern, such that there is no longer a driving force for flow. If this balance is not reached the fracture will continue to grow outward as well as develop larger fracture aperture. This in turn makes predicting the overall fracture permeability and thereby the leak-off potential difficult to predict. Note that the tensile strength is considered negligible, but most rocks do have some capacity to handle tensile stresses without fracturing: tensile strength. However, this value is generally relatively low compared to the in-situ stress and perhaps there are pre-existing fractures within the subsurface which are likely not to have a tensile strength. Therefore, tensile strength is neglected (considered to be zero) until it can be quantified.

Pressure inside a cavern can go up if there are no (sufficiently effective) mechanisms leading to a decrease of pressure. For example, if the cavern pressure is not "bled off" at appropriate times through brine flux in the borehole during standstill phases. Creep effects can cause the pressure inside the cavern to rise above the fracturing limit. Note that at high cavern pressure creep effects are relatively slow thus might not be observable on a timescale of a week or even longer, although they may have been underestimated in the first place. For example, Bérest et al., (2019) have shown that creep effects can be faster than expected if pressure solution creep is not considered. Creep effects depends on the cavern depth, and more importantly the temperature at depth. Long term pressures can theoretically go above lithostatic conditions, up to fracturing limits.

Note that for relatively high caverns, creep effects at the bottom of the cavern can push the fluid pressure up for the entire cavern. Consider the following as an example: If originally the pressure is controlled at surface, the pressure at depth will be that of the surface level plus the pressure gradient multiplied by the depth. If the cavern is shut in from this point in time, thermal expansion and creep effects can cause the pressure to rise for the entire cavern, theoretically up to the point where the pressure at the bottom of the cavern is equal to the confining stress caused by the lithostatic load. However, the pressure gradient (linked to the density of the fluid inside the cavern) remains constant. This situation causes that in the upper part of the cavern the fluid pressure exceeds the lithostatic stress. This favours fracturing, and possibly permeation/percolation should a fluid pathway exist. Note that lateral fractures could form at lower levels if the stress within the salt-dome does not follow the common assumption of hydrostatic (isotropic) stress at the level of lithostatic load. Such situations may occur at the salt dome edge or within the sidewall burden (non-salt sediments, typically not creeping such that the stress state is not isotropic).

Fracturing itself can be detected by seismic monitoring stations, even though the energy release for opening fractures (mode 1) is relatively low compared to shear fractures (mode 2). Permeation effects are unlikely to be detectable with seismic monitoring but may be detected through (deep) groundwater monitoring when permeation is pervasive enough to elevate salinity locally.

5.2.2. Subsequent effects too high cavern pressure

If a pathway / fracture is formed, it will likely grow upward as the confining stresses there are lower. The height at which the cavern grows upward depends on the "leak off potential"; if permeable layers are crossed by the fracture where the excess cavern pressure can bleed off. This does mean that saturated brine infiltrates aquifers where the salt content is generally lower. In a worst case, the fracture forms all the way up to the freshwater / brine contact.

If the pore pressure front reaches a fault in the subsurface it may cause the effective stress state at the fault to change to an unstable situation and might trigger seismicity. Fluid pressure at the fault may be elevated either through a connection of the fracture to a pre-existing fault or by elevated pore pressures in an aquifer in the overburden that is bound by a fault.

5.2.3. Cavern pressure too low

Low cavern pressures lead to relatively high creep rates (high differential stresses) and thereby cause subsidence.

A low cavern pressure can result if the gas/fluid within the cavern has a path that is permeable enough to leak out in a relatively short timescale (such that longer term creep effects do not play a role to increase the pressure). Permeable paths include:

- the borehole (except after abandonment), where free outflow could take place due to human error.
- fractures that have formed from the cavern wall for any reason (see previous)
- wormhole features (preferential fingering effects) caused by permeation (observed at lab scale, but has not been demonstrated at field scale yet)
- connections to the overburden or basement due to improper leaching strategy (minimum distance of cavern to top salt / base salt not observed).

The limit for a too low cavern pressure is closely linked to the amount of allowable (or permitted) subsidence, and therefore depends on the effectiveness (or speed) of creep effects. The possibility exists that these are underestimated, in the sense that the creep is faster than expected. This can occur if the constitutive equations that are derived (or when applicable assumed) in the design phase are not precise enough. It is noted here again that at low cavern pressures the differential stress is high, and thereby dislocation creep mechanism is likely to be dominant.

5.2.4. Subsequent effects too low cavern pressure

A cavern pressure that is too low might generate too large stress differences in the roof of the cavern, such that roof collapses. Or alternatively if a cavern was leached out such that there is no spherical roof within the salt formation (for example in bedded salt formations), the overlying layers may form the roof and could potentially collapse if the stresses exceed the formations strength. This in turn may lead to layers above the salt roof (or other roofing formation) to collapse as well. This could trigger an upward chain reaction, but one that generally dies out before reaching the surface. This “migration of caverns” is limited by the fact that the rubble from the collapsed layers takes up more volume than that of the original material. This process is known as bulking. If, however, a cavern is situated shallow enough the migration could go all the way to the surface, causing a sinkhole at surface. Collapse of layers can be measured by micro seismic monitoring if enough energy is involved. These events are known as rock-fall events. Prior movement within the vicinity of the potentially unstable cavern (typically listed as shear events) can be picked up too, and can be used as an early warning (see more on seismicity monitoring)

5.3. Preventing top events: preventive barriers

Nobian has the responsibility to assure cavern stability and integrity throughout the cavern (field) lifecycle as (last) holder of the mining license. Therefore, several actions are set in place throughout the lifecycle of a cavern (field) to prevent the top events described in the previous paragraph to happen. A number of these are applicable to various top events and are therefore grouped here.

5.3.1. Cavern design phase

The basis for a safe cavern starts at the drawing board. Usually, several caverns are developed in a field, therefore a field approach is taken. Caverns design determines the leaching strategy (depth of casing strings, blanketing fluid etc.), such that the evolving shape can be considered safe both on short and long term. In order to assess this, numerical models can be employed to evaluate the stress field around the caverns within the field and compared to the strength of the rock salt.

For new salt caverns, a cavern and field design has been defined as standard within Nobian, applying scientific insights from recent years and the most recent best practices in the industry. At the moment, the design for pillow and domal salt caverns is derived from the design for gas storage caverns in pillow or domal salts structures (i.e., *Rokahr et al., 1997*). It should be noted that, gas storage caverns generally have a lower height compared to brine production caverns. Because of the low density of stored gas compared to brine, the pressure gradient within the cavern is almost flat (see 4.3.4), meaning that the pressure at the top of the cavern is nearly the same as at the bottom. Having a larger depth range can potentially lead to overpressures at the top of the cavern, due to creep effects in the deeper parts. In addition to available literature and industry best practices, the design of gas storage caverns can also be translated into a safe design for caverns intended for brine production / salt extraction *(e.g., Bérest et al., 2020)*. For bedded salts like in the Twenthe-Rijn field, the Good Salt Mining Practice (GSMP) contains the cavern design guidelines.

The model salt cavern has the following features:

- A maximum cavern diameter, which depends on the depth of the cavern and properties of the salt (creep, permeation). The diameter is one of the key factors defining cavern stability during the operation phase and afterwards and has a major influence on the amount of subsidence.
- A spherical roof within the salt formation (for reasoning see 4.4.7.), note that a spherical roof is a current industry standard (Rokahr et al., 1997).
- A maximum height of the cavern itself, which depends on the depth of the cavern and the properties of the salt (creep, permeation, fracturing behavior).
- A maximum height of the sump is based on leaching techniques, which are described in Nobian standards.
- A minimum thickness of the salt roof (defined as the distance between the top of the salt deposit and the shallowest part of the cavern roof). This minimum thickness depends on the formation type, as well as the cavern's depth.
- A minimum thickness between the bottom of the cavern and base of the salt deposit. This distance is built in to prevent possible influences on the cavern pressure from the underlying layers. For example: if cavern pressure leaks off to the underburden, this might lead to more creep effects and thereby more subsidence.
- A spacing of the caverns, enough space (centre to centre) based on ratios between the pillar width (minimum wall to wall distance between caverns) and cavern diameters. Threshold values depend on the mechanical behaviour of the salt, and thereby also the depth.
- A configuration that limits the spatial extent of subsidence. This could be done by developing caverns in a zig-zag pattern in two rows, with equal spacing between caverns (leading to a semi-hexagonal setup). Another option is a line configuration, comparable to room and pillar mining in conventional rock salt mining. In all cases, the surface configuration also has a large influence on where well pads and caverns can be placed.

5.3.2. Pillar-diameter ratios (B/d) (all phases)

The pillar-diameter ratio gives the required minimum thickness (B) of the pier (or pillar) at a given cavern diameter (d) to ensure the stability of the caverns indirectly. More directly the factor limits the amount of overburden weight that areas between two caverns have to handle.The B/d factor is particularly usefull in limiting the potential magnitude of subsidence due to salt creep mechanisms.
Figure 13 below assumes a field with a hexagonal grid: a cavern in the middle with 6 caverns around it with equal distances. The reference depth of the cavern is defined as the depth at 2/3 of the depth of the cavern (i.e., ground level to salt roof plus 2/3 of the cavern height). This reference depth is needed to determine the B/d ratio.

In a hexagonal cavern grid, the minimum salt pillar between the caverns should be as follows:

- B/d from 0.7 to 0.9 for cavern reference depth between 500 and 700 m
- B/d from 0.9 to 1.15 for cavern reference depth between 700 to 1,000 m
- B/d from 1.15 to 1.5 for cavern reference depth between 1,000 to 1,500 m
- B/d from 1.5 to 1.82 for cavern reference depth between 1,500 to 2,000 m

Figure 13 Pillar-diameter ratios (B/d) per reference depth

Example application B/d ratios:
Table 10 below shows the calculation of the desired B/d ratios, where as an example the mutual distance between wells (the centre of the caverns) is 250 m. For the cavern model, Nobian uses 110 m as the safe diameter. This mutual distance between boreholes of 250 m and a max cavern diameter of 110 m results in a calculated B/d ratio of 1.27. For a cavern with a reference depth of less than 1000 meters, according to figure 13, the minimum B/d ratio should be 0.90 – 1.15. Since this value is higher than the minimum 1.15, Nobian considers this as a safe approach (DEEP.KBB 2019).

Distance between boreholes (m)	250	250	250	250
Max diameter cavern (m)	110	115	120	125
Pillar minimum thickness (m)	140	135	130	125
B/d ratio (-)	1.27	1.17	1.08	1.00

Table 10: B/d ratios, with reference depth 700-1000 m

Note that these B/d ratios are applicable for pillow and domal salt formations. For bedded salts (i.e., Hengelo field), case specific evaluations need to be made where the overlying strata (and thus the strength of the overburden) are considered too (for example: BGR, 2004 (available in German only)

Storage caverns
In addition to the factors described above, the pillar-diameter ratio of storage caverns is also controlled by the requirement to safely store gases at variable pressures during a decade long storage phase. For this reason, a B/d range of 2.1 to 2.5 for a cavern reference depth of 1500 m is advised (DEEP-KBB, 2022).

5.3.3. Cavern geometry height (all phases) / monitoring through sonar techniques

The depth and height of the cavern largely determine the behavior of the cavern after abandonment (salt creep, see 4.4.), but also play a role during production and post-leaching phases. Caverns are therefore regularly checked through sonar measurements, to see if the geometry remains within pre-defined safety contours. Note that sonar measurements can have a relatively large error, where individual measurements of distance from logging tool to cavern wall can vary by 5 meters. However, if there are anomalies in the cavern shape, or if the cavern dimension has unexpectingly exceeded safety contours production is stopped. Subsequent actions are then assessed on a case by case basis.

5.3.4. Cavern types / field specific approaches

Nobian operates different cavern types, dependent on the geological parameters, salt deposit, field design, etc. (see section 4.6.). For each cavern type, a standard is described and available in Nobian's Manual Master documentation system. Note that all of Nobians cavern types are based on solution mining techniques.

5.3.5. Leaching technique

For the leaching of the cavern, a number of parameters can be controlled by the leaching technique. The following parameters are adhered to:

- A safety factor is used for the pressure (injection, production, blanket fluid). This means that the pressure is kept below a maximum value that includes a safety margin.
- When leaching, a diameter is maintained that is smaller than the max diameter, to prevent the max diameter from being exceeded.
- The salt roof is controlled by the correct amount (and depth level) of blanket fluid.

- Height is controlled on the basis of simulation and subsequently selecting the correct suspension depth for the production casing.

There are different leaching techniques for the different fields, for example the HUT (Hengelo Uitloog Techniek), which is a field specific approach to leaching of caverns in the Twenthe-Rijn field.

5.3.6. Maximum allowable annular surface pressure (MAASP)

The cavern and well are designed for a certain maximum allowable pressure. The design is made in such a way that the maximum allowable pressure is calculated, considering the weakest link in the cavern & well system. This weakest link should always be the casing shoe, meaning that all other parts in the cavern (and well) should be able to withstand a higher pressure than that. Generally, the strength of the casing shoe is equivalent to the fracture pressure at the depth, meaning that is given by the local geology (and horizontal stress) and cannot be externally controlled. The maximum pressure can be lower due to well completion or for example if the wellhead has not been tested to high pressures. The MAASP procedure takes all this in consideration.

The MAASP of all wells is calculated based on the well's particular situation (LCCS depth, density of fluids, formation strength, etc.). The values are recorded in the appropriate database and is readily available to relevant parties (drilling and well intervention, brine field technology or production operations).

See MAASP procedures for more information about MAASP (via ManualMaster, link)

5.3.7. Seismicity

For seismicity Nobian has dedicated measuring networks and associated traffic light systems in place. These act as early warning systems and define actions that Nobian takes to further assess the nature of the seismicity and whether there is a cause for concern / other preventive actions. These are described in the following documents / files:

- Hengelo field TLS and communication protocol (available in-house)
- Heiligerlee and Zuidwending TLS and communication protocol (available in-house)
- Communication protocol (via ManualMaster, Communicatieprotocol Microseismisch Meetnetwerk HL-ZW, link)

5.3.8. Stability criteria for abandonment

Caverns will only be abandoned if the following criteria are met:

- The risks resulting from fracturing (leakage, potential seismicity, instability) are reduced sufficiently. Top events such as liquefaction and contamination of aquifers in the overburden are associated to this mechanism. In effect this means that the expected equilibrium pressure after abandonment (resulting from thermal equilibration and creep effects) lies below the fracture propagation pressure (the safety limit during production phase where no leakage outside of the cavern is expected). Potentially a higher threshold value can be used if this can be considered safe (see also the KEM-17 research project). This requires the site specific (or even cavern specific) assessment of:
    - Creep rates (at various cavern pressure levels, particularly high pressure, low differential stress)
    - Leak off potential or permeation through the cavern wall (pressure dependent / effective stress dependent) can be done through field-scale tests or in lesser extend laboratory tests on core material. To this end evaluation wells are preferred prior to the development of caverns, if possible.
    - Assess the risk of localized fracturing / leakage to shallow layers. (note that KEM-17 report, page 13, recommendation 4, suggests depth to be important here: *"In shallow caverns (less than 1000 m), when thermal equilibrium is reached, several in situ tests performed in various geological conditions strongly suggest that, in the long term, an equilibrium pressure, significantly smaller than geostatic pressure, will be reached. Slow brine rates will permeate to the salt formation. Safe abandonment is possible."*
    - If a higher pressure than the fracture propagation pressure is considered, cavern specific research is needed to show that this is considered safe in the long term.
- The amount of expected subsidence is acceptable, this requires the following:

- A physics-based model of the expected subsidence based on creep rates and equilibrium pressure
- Acceptence from authorities and other stakeholders (i.e., water boards etc.)
- Potential financial reservations to deal with contingencies
- The risk of sinkhole formation is considered extremely unlikely (F0, see chapter 3)

5.3.9. Backfilling caverns

If the need emerges, caverns can be filled up with solids. This is an extensive measure with technical challenges considering the volume that needs to be filled up, and the relatively small access through a borehole. Filling up caverns serves two purposes: limiting the total volume of the cavern (in case of collapsing overburden) and limiting the total creep closure. In the latter case the backfill material essentially builds up a skeleton within lower part of the cavern space that withstands cavern closure due to its material strength (for granular material, this can be thought of as the coefficient of internal friction).
For the Hengelo field (bedded salts) this is in place (see “Final Beleid Monitoren en Vullen Cavernes Twente 2022” (Nobian, 2022). This document describes how the risk of sinkhole formation as a result of cavern migration is managed. In this case the purpose of backfilling is to reduce the cavern size such that cavern migration will not lead to a sinkhole.
For other fields (domal salts), the criteria and potential filling scenarios are under development. In these cases backfilling caverns implies a reduction of effects of creep closure. Thereby the “driving force” for pressure increase is reduced, and leak off via permeation may be fast enough to reduce the maximum cavern pressure that could theoretically occur after abandonment. Research by Brouard Consulting within the CCC-team has shown that this strategy has indeed a limiting effect on the overall maximum observed cavern pressure after abandonment of a (partially) backfilled cavern (CCC study, in prep). Moreover, as the effective size of the cavern is reduced the potential outflow volume in case of integrity loss is reduced as well (Fenix Consulting, in prep). At the time of this CSIMS update, research efforts are done to evaluate what material may be available, and to what extend compaction effects of the backfill itself and internal friction coefficients develop. Further development of numerical models (2D and 3D) which include backfilling scenarios will become part of site-specific abandonment plans.

5.4. Remediation barriers

The following points describe the remediation barriers in case that a top event has taken place despite all preventive actions. Note that if such an event has taken place Nobian is responsible to remediate the situation, and communication protocols are activated. Moreover, for the Dutch fields Nobian has an agreement with the Dutch Ministry of Economic Affairs and Climate policy to handle any mining related damage through the commission mining related damage (link: Homepage | Commissie Mijnbouwschade). This includes fields where Nobian is no longer actively producing (post-mining), as last holder of the mining license. The commission independently researches the causal link between damage and (historical) mining activities and advices on compensation. For more information, the reader is referred to their website (in Dutch).

5.4.1. Subsidence by creep above acceptance limits

If subsidence exceeds limits, Nobian will take the following actions.

- Financial compensation of associated physical damage to buildings, sewer installations etc. (potentially through the Commission Mining related damage).
- Financial compensation of associated environmental damage (natural areas or farmlands below water table etc.)
- Build water-management structures (dikes, pumps etc.) to deal with increased flooding risk or higher groundwater.
- In cases where the subsidence’s lateral extent is small enough: fill up the area.

5.4.2. Sinkhole formation

If a sinkhole becomes unavoidable, Nobian will take the following actions:

- Evacuation of potential unstable area around sinkhole

- Financial compensation of associated physical damage to buildings
- Financial compensation of associated environmental damage (natural areas or farmlands below water table etc.)
- If the sinkholes lateral extent and depth is small enough: fill up the area.
- In case of groundwater contamination: see 5.4.5.

Evacuation

If an increased rate of seismicity (e.g., number of events above a certain magnitude per day or seismic event(s) that can be felt) is observed, in combination with an upward migration pattern of events, this may suggest that the formation of a sinkhole is happening. Nobian deems it highly unlikely for this to happen, as it is a stacking of worst-case scenarios (for detailed risk analysis see 6.1.2. during production and 6.3.2. during the abandonment / post-mining phase). It is difficult to clearly define thresholds values for this (as is done within the traffic light systems that Nobian already uses) and requires a case-by-case evaluation to understand the mechanisms of the seismic event(s). It is important to understand the nature of the observed seismicity (both the source and the cause) and place this within the context of the different Nobian sites when there is sufficient time to respond. If time allows, sonar measurements will give insight on what is happening (e.g., migration of the cavern). Depending on this, it can be preferred to start preventive actions like extra measurements or effectuate the ERP and potentially start backfilling. However, should there be too much seismicity suggesting the unlikely event of sinkhole formation, the area above a cavern can be evacuated via contact with the proper authorities.

The emergency response plans (ERP) are location-specific and can be found in the following documentation:

- For the Hengelo field the documentation (HSE Proces 9.6 BNP) can be found internally on SharePoint, link.
- For Heiligerlee the documentation can be found via ManualMaster (Link)
- For Zuidwending the documentation can be found via ManualMaster (Link)
- For Mariager: To be found in the database of Mariager (link to be added)

5.4.3. Liquefaction

If liquefaction has occurred, Nobian will take the following actions:

- Financial compensation of associated physical damage to buildings
- Financial compensation of associated environmental damage (natural areas or farmlands below water table etc.)
- Evacuation is a possibility in the event that liquefaction is highly likely or unavoidable, although this is deemed a theoretical risk.

5.4.4. Damage caused by seismic events

When damage due to seismic events has emerged, Nobian will take the following action

- Financial compensation of associated physical damage to buildings (potentially through the Commission Mining related damage)
- Financial compensation of associated environmental damage (natural areas or farmlands below water table etc.)

5.4.5. Fresh- / Groundwater contamination

In case of a brine/oil spill up to fresh- or ground water levels, Nobian will take the following actions:

- Sanitation / large scale clean up (for example, add high amounts of fresh water to dilute the brine)
- Financial compensation for loss of income (for farms etc, companies which rely on the groundwater)
- Financial compensation of associated environmental damage

5.4.6. Contamination of other aquifers

In case of a brine/oil spill up other aquifers, Nobian will first assess the possibility of remediation. After that Nobian can take the following actions:

- If applicable: Sanitation / large scale clean up (for example, add high amounts of fresh water to dilute the brine)
- If applicable: Financial compensation of associated environmental damage.

5.4.7. Hydraulic connections other caverns

Should a hydraulic connection to another cavern have formed, Nobian will take the following actions:

- Pressure control in active cavern(s)
- Operate connected caverns as a single system
- In case both caverns are closed off and subsequent problems are expected: drill access to one or both of the caverns
- Compensation in the case that the hydraulic connection is to a storage cavern in which storage is then no longer possible.

5.5. Bow-tie diagrams

The cavern failure model is built up based on the bow-tie diagram. This diagram is subdivided into the following potential steps of an incident:

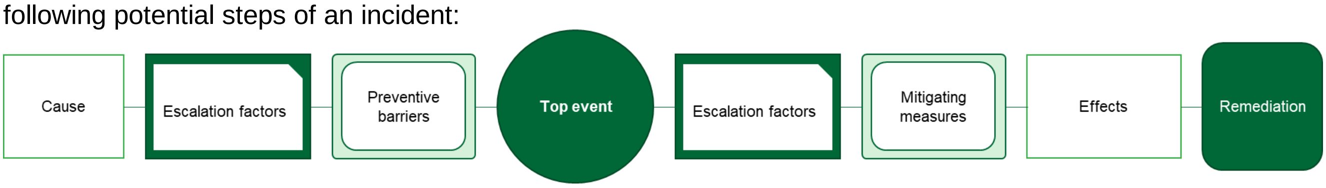

Figure 14 Bow-tie diagram

For each of the top events the bow-tie diagrams are displayed on the following pages.

5.5.1. CFM 1 Subsidence by creep above acceptance limits bow-tie

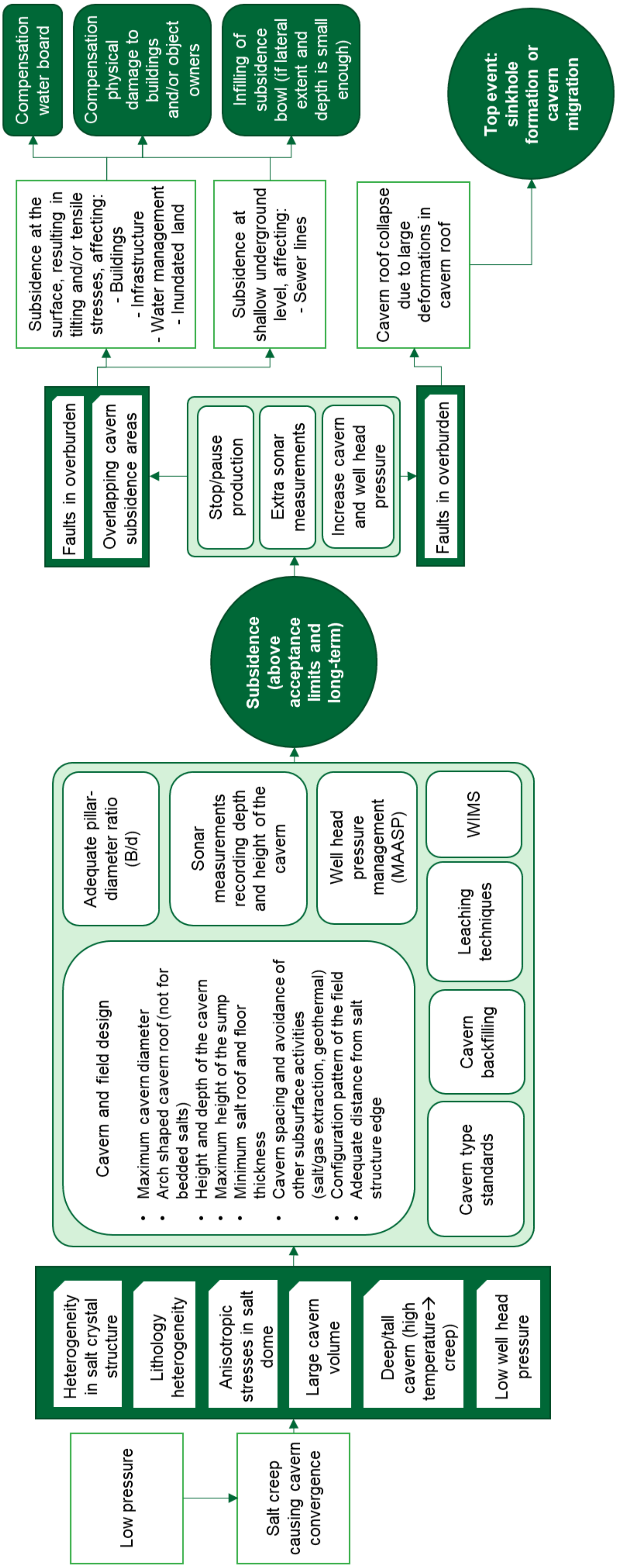

Figure 15 CFM 1 Subsidence top event bow-tie

5.5.2. CFM 2 Sinkhole bow-tie

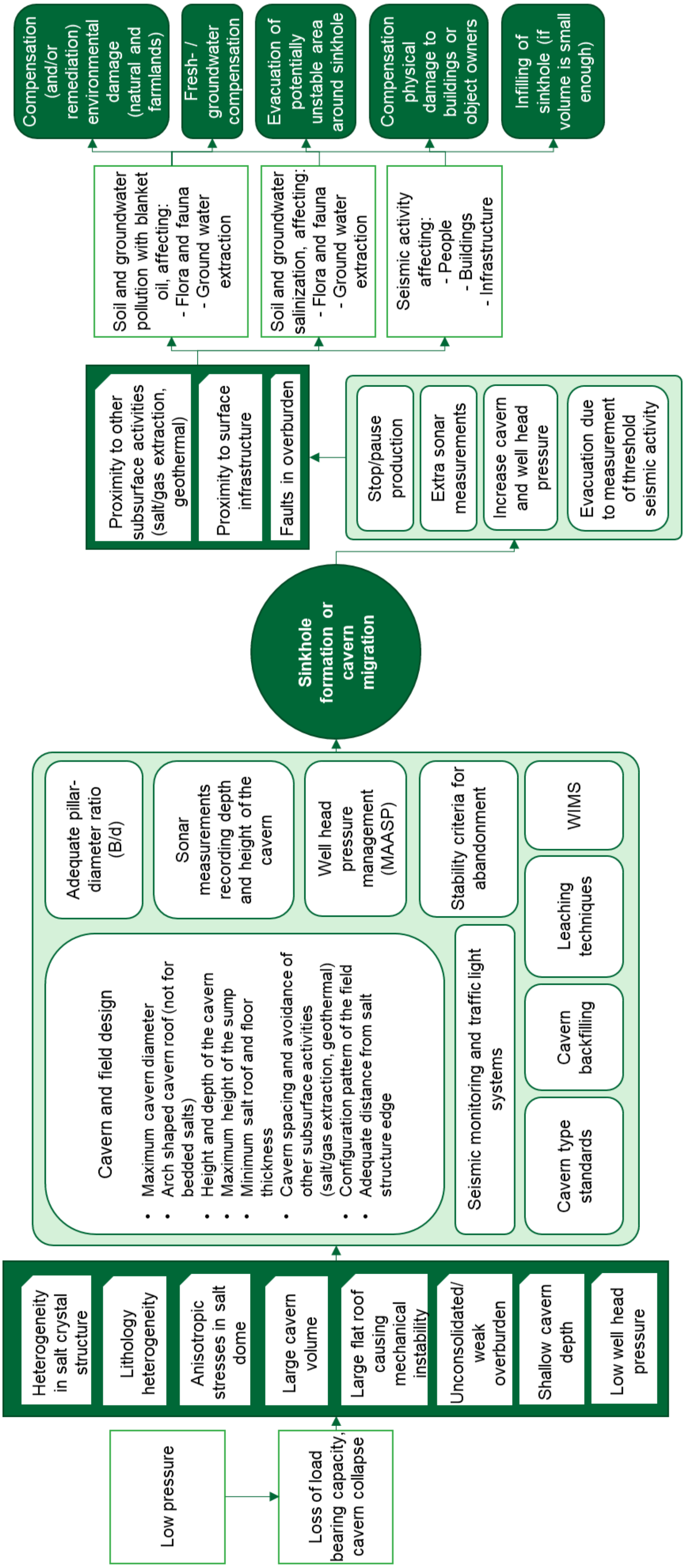

Figure 16 CFM 2 Sinkhole top event bow-tie

5.5.3. CFM 3 Liquefaction bow-tie

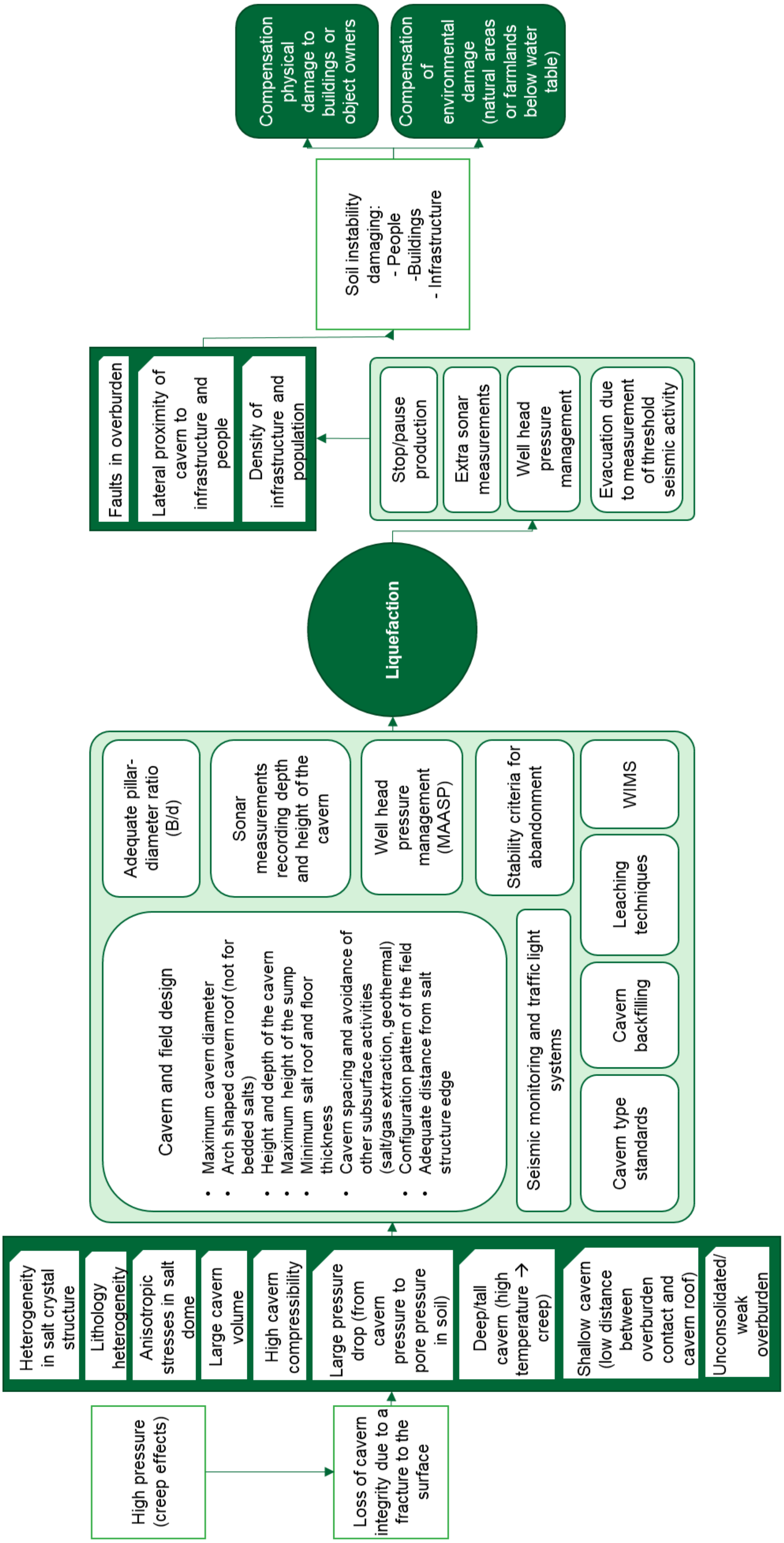

Figure 17 CFM 3 Liquefaction top event bow-tie

5.5.4. CFM 4 Damage to buildings or infrastructure due to seismic events bow-tie

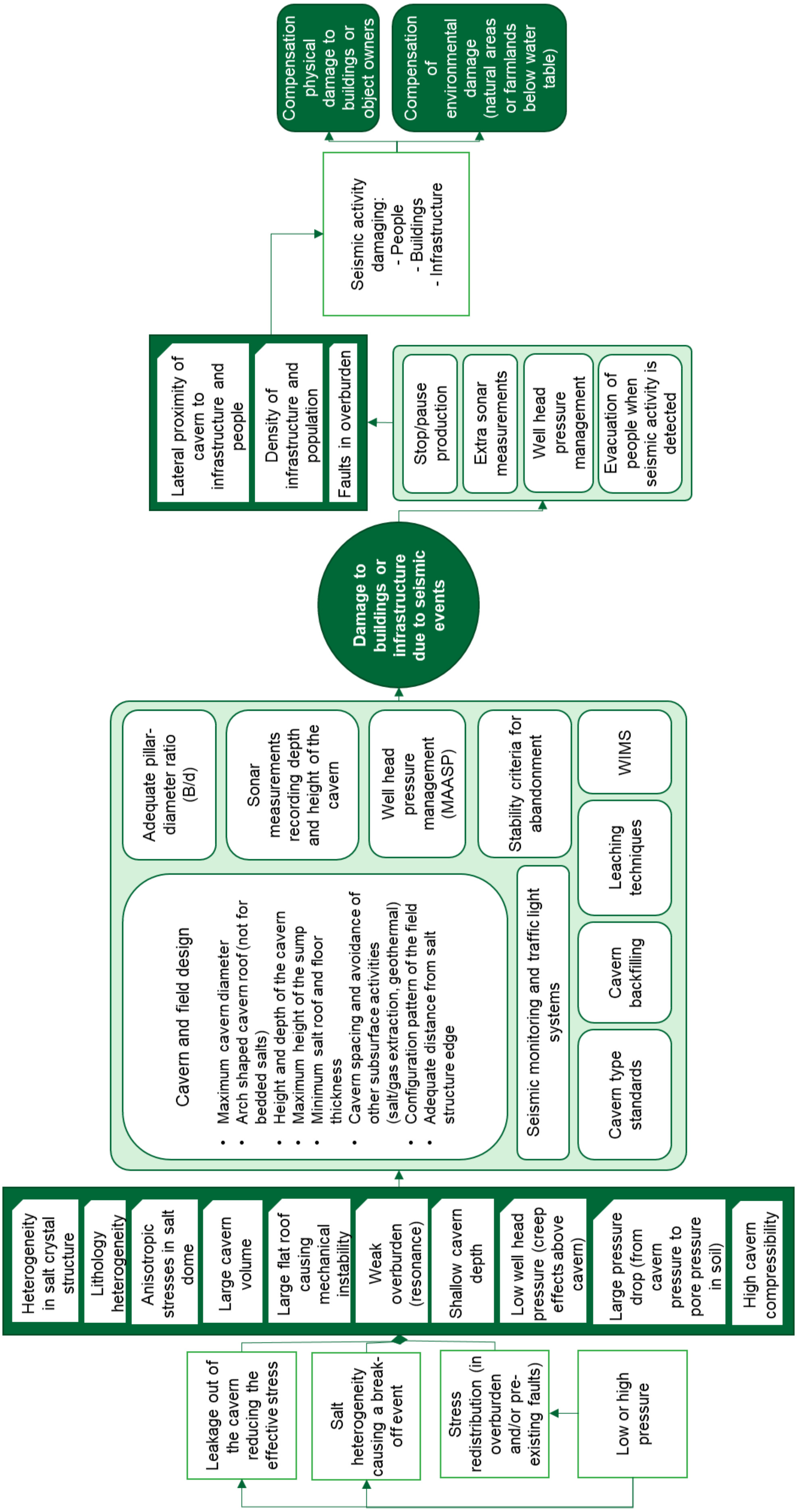

Figure 18 CFM 4 Damage to buildings or infrastructure due to seismic events top event bow-tie

5.5.5. CFM 5 Groundwater (fresh) contamination bow-tie

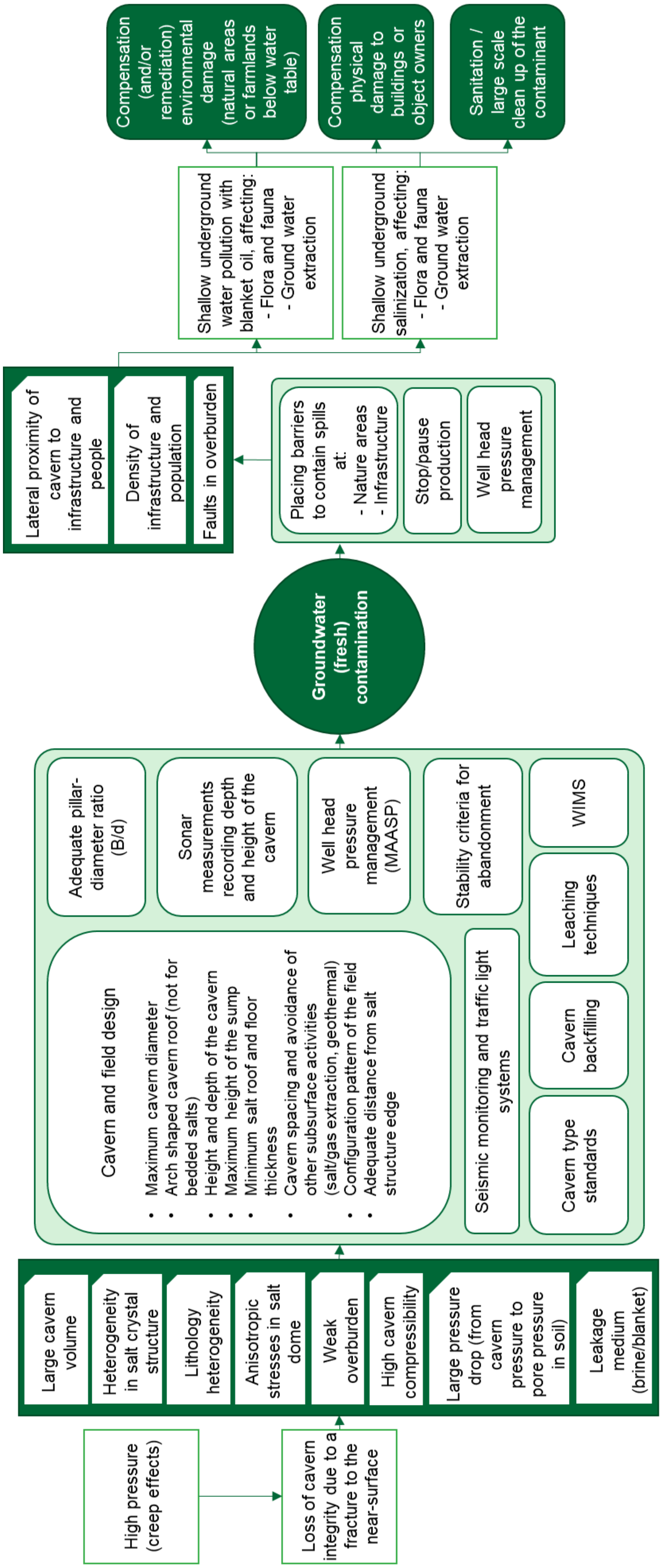

Figure 19 CFM 5 Groundwater (fresh) contamination top event bow-tie

5.5.6. CFM 6 Contamination of other (non-freshwater) aquifers bow-tie

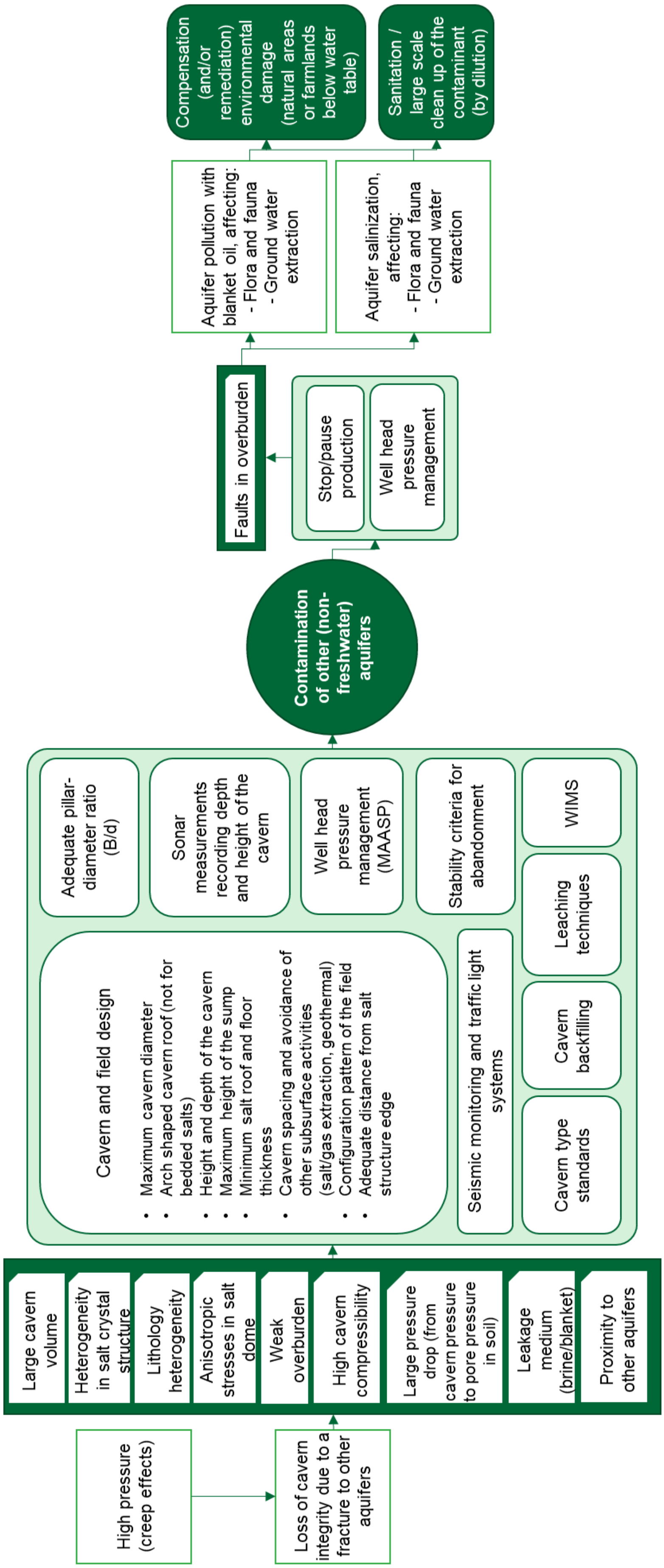

Figure 20 CFM 6 Contamination of other (non-freshwater) aquifers top event bow-tie

5.5.7. CFM 7 Hydraulic connections to other caverns bow-tie

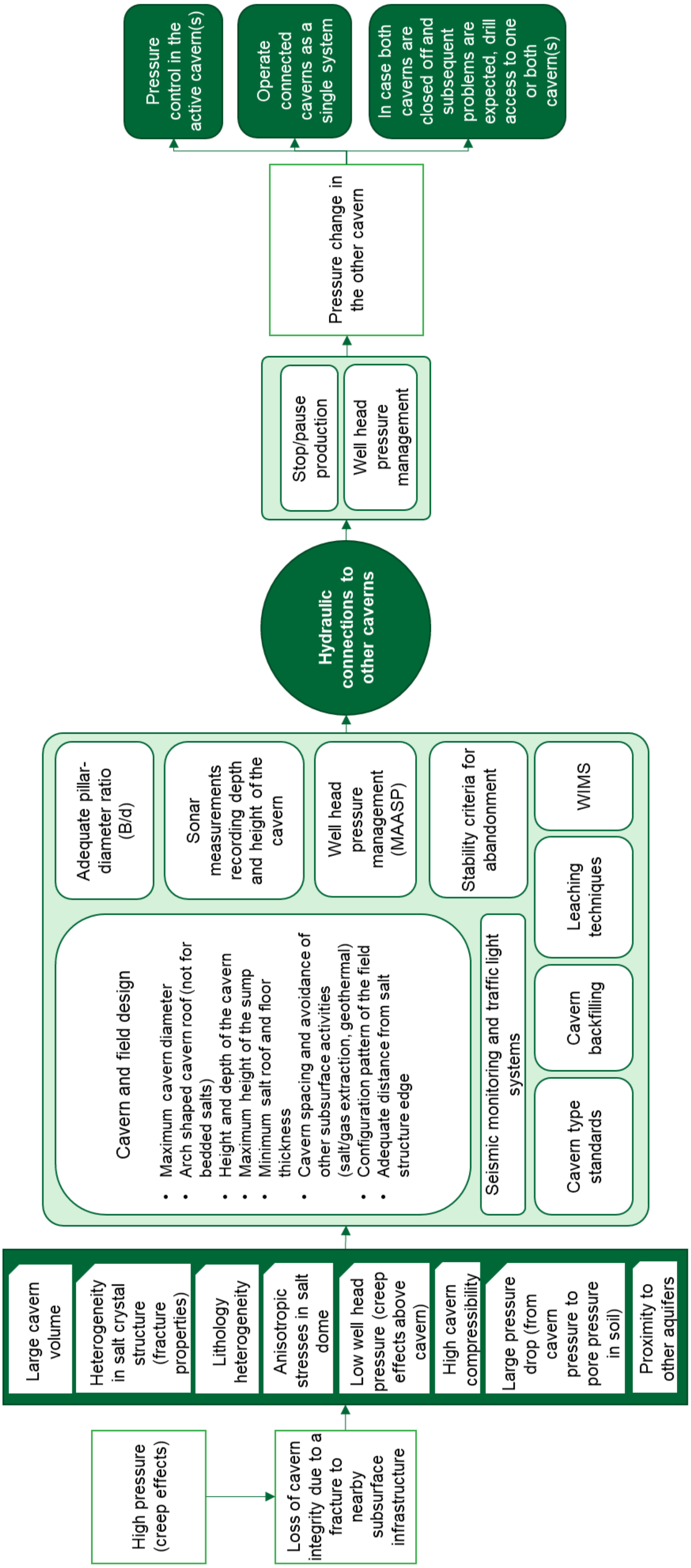

Figure 21 CFM 7 Hydraulic connections to other caverns top event bow-tie

6. Risk assessment: Hazard and Impact of top events

In this Chapter, the result of risk assessment on hazard and impact of top events is presented, using the table with severity and frequency axes as defined in chapter 2 from the Nobian HSE&S standards. For all identified top events we discuss the unmitigated and mitigated risks, for each of the three subdivisions of severity (People, Environment and Reputation). As risks change during the lifetime of the project, we discuss it for the production and post-leaching phases first (when pressure control is in place, section 6.1), followed by the abandonment and post-mining phases (section 6.3.). Section 6.2 has some information on the storage phase. Additionally, the Fine and Kinney method scores are used as a comparison to the Nobian HSE&S standards for the unmitigated risk scenarios. This is done to evaluate if the unmitigated (e.g., “starting point”) is placed correctly in the risk matrix.

Note that these top events are placed if no preventive barriers or remediation actions are in place: the unmitigated risk. In practise, safeguards and additional risk mitigations are in place to prevent the top event from happening, and/or prevent the impact in the highly unlikely event the top event is happening.

6.1. During Production and Post-Leaching Phase

6.1.1. Subsidence caused by creep beyond acceptance limits

The following assessment is done based on the caverns in the Netherlands. In the Danish fields elevation differences on the scale of the width of an expected subsidence bowl are in the order of several meters and situated above mean sea level. Thus, an expected subsidence of some decimetres may be looked upon differently in Denmark compared to the Dutch fields. We therefore discuss the Dutch fields here and consider it a worst-case scenario for Denmark field.

S5 Catastrophic							
S4 Major							
S3 High						**E, R**	
S2 Moderate				**E, R**			
S1 Negligible / Slight			**P**				
	F0	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**

Figure 22 Risk matrix: Subsidence caused by creep beyond acceptance limits during production and post-leaching phase

Unmitigated:
If left unmitigated, subsidence is considered as an unlikely source to cause a (reportable) injury. The score for People is therefore listed as S1, F2. Here also psychological aspects are considered. People may feel uncomfortable and can potentially even develop psychologically induced illnesses just by the idea that their house is exposed to subsidence (extrapolating from health-assessments in the Groningen-field gas extraction area). For mitigating this risk, proper information sharing, and communication plans are essential.
As for environmental impact, the unmitigated risk is considered to have an off-site impact and could form a permit violation and is considered probable to occur. The score for Environment is therefore S3, F5. For Reputation, it is expected that this will lead to local media attention, and is therefore scored S3, F5 too. Since the subsidence is rather local, news on national media scale is not expected.

The score according to the Fine and Kinney method puts the unmitigated risk in the slight risk category, with a score of 3.5. The sub-category scores are 0.5 for probability (highly unlikely), exposure 1 (Rarely), and

Severity 7 (Severe, lasting injury with absence). The fact that this method scores relatively low compared to the assessment for Environment and Reputation in the figure above (based on Nobian's risk assessment procedure) has to do with the fact that in the Fine and Kinney method the probability and exposure categories are tailored to injury/fatality reasons at severity, and thus coincide mostly with the People-risk of Nobian's internal risk assessment method. In that regard the scores are comparable.

Mitigated

For the mitigated risks, the People score has remained the same, as no actions or safeguards are formally required to further reduce this specific risk. However, Nobian sees transparent information and communication plans as a vital mitigating action for People score. Thus, mitigation actions will remain in place.
Environment and Reputation risks are reduced by the following preventive mitigation actions: design/leaching technique (limiting maximum cavern size, thereby limiting subsidence), tracking of subsidence (and adapting leaching based on the result), and keeping the pressure at the cavern relatively high to reduce the creep velocity (and thereby cavern convergence and subsidence).
This places the Environment and Reputation risk at S2, F3, as despite the safeguards Nobian still expects a remote chance of subsidence at higher values than permitted. This means that Nobian will continuously reassess subsidence for all fields, including the abandonment phase.

Note that the Severity-level is not dropped, but arguments can be made that it should. Due to subsidence, there can theoretically be slight rotations buildings if either side of the building experiences more subsidence than the other side, and there by some tension within the edifice. A recent study by TNO and TU Delft has shown that for gas-extraction and storage projects (where similar or more subsidence is expected compared to salt mining both in spatial as vertical sense), the effects on building integrity is negligible. The expected horizontal strain (tensional) and relative rotation of the buildings lie well within the stable field where no esthetical damage is expected (see Geurts et al., 2021, TNO-rapport R10325B). Similar conclusions have been recently drawn in a computational study on masonry buildings (Rots et al., 2021).

6.1.2. Sinkholes

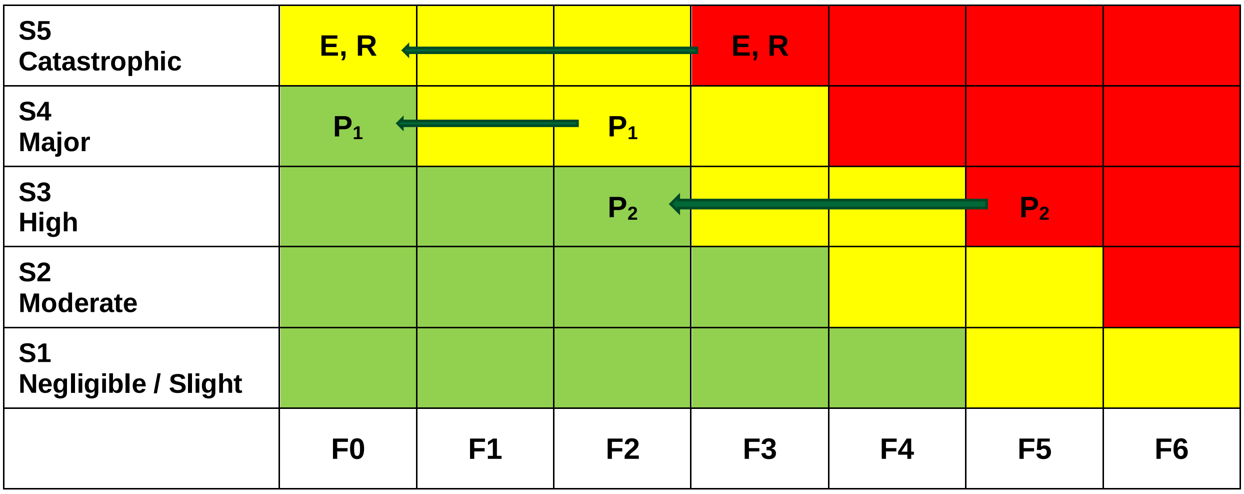

Figure 23 Risk matrix: Sinkholes during production and post-leaching phase

Unmitigated

The unmitigated risk considers takes the approach that the sinkhole will happen at an unexpected moment. This is based on the unexpected sinkhole formation in the Hengelo area in 1991. However, during that event there were no associated injuries. Here injuries are considered for the unmitigated risk, as in some cases there are buildings and public infrastructure above Nobian's caverns. For other fields, the risk may be lower. For example, caverns situated in domal salt structures have a salt roof, whereas in bedded salt this can be an insoluble layer only. In this risk matrix the highest value for frequency is used and projected to other fields as well, even though the cavern (-field) has different characteristics. A subdivision has been made for two "People" scenarios: one considering a fatality (P_2), implying that this person is within the surface contour of the emerging sinkhole forms and; one where a severe injury (non-fatal) takes place (P_2) implying a person is at or around the emerging sinkhole and is injured. Also, here psychological effects are included, as described under the subsidence paragraph.

Based on the Fine and Kinney method the risk is scored at 20 points, with the sub-category scores of 0.5 for probability (highly unlikely), exposure 1 (Rarely), and Severity 40 (disaster, multiple fatal casualties). This score the P_1 scenario (one fatality) is comparable but considers the risk to be lower (category "slight risk"). Here the change in different methodologies becomes apparent. While the severity of the risk is comparable, due to the combination of probability of occurrence and exposure factor, the risk categorisation is lower for the Fine and Kinney method. Nevertheless, Nobian has taken mitigation actions to prevent the formation of sinkholes.

Mitigated
Environment, Reputation, and the fatality scenario (People 1 / P_1): due to improved design it is as good as physically impossible to create a sinkhole, therefore considered extremely unlikely to occur. Note that this holds for Nobian's newer caverns, some older (legacy) design caverns in the Hengelo field do not fall into this category. These require special attention for which a tailor-made cavern specific plan is available and in effect, therefore not discussed here (see section 5.1.2 for documentation). In a more general sense, the risk reducing factors here are the design (in combination with leaching plan), pressure control and monitoring of seismicity (as early warning system). It is important to note that sinkhole formation can, as a worst-case approach, be as good as instantaneous. In practise there is a good chance that there is some time (often several years) between early-warning signals and the eventual collapse. Such a time to evacuate the area is not captured well within the scoring method.

6.1.3. Liquefaction

S5 Catastrophic	**E, R**						
S4 Major	**P, E, R**						
S3 High							
S2 Moderate							
S1 Negligible / Slight							
	F0	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**

Figure 24 Risk matrix: Liquefaction during production and post-leaching phase

Unmitigated
Should this risk occur, Nobian considers it an event of severity classification S5 for reputation and environment, but ranks the severity somewhat lower for people, as it is regarded that several injuries will happen at most. Nobian has recently had the likelihood of liquefaction assessed by an external expertise. The resulting report (Witteveen and Bos, 2022) regards liquefaction effects to have a high impact but very low frequency. The works suggests that large amounts of brine need to leak to surface in order to have this effect, but amounts are not quantified. Liquefaction may also happen as a result of seismic events. However, the associated ground shaking is in the order of 10% that of the gravitational acceleration. The risk of this happening is discussed below, along with seismic events.
As safeguards, Nobian has seismic monitoring combined with traffic light systems in place. Moreover, there is pressure control in place, limiting the chance that a fracture forms to surface leading to a sufficient volume of brine to cause liquefaction. Other top events that can occur due to fracturing are further discussed below too. Note that above the salt deposits, there can be other layers where the brine could leak off to. This natural barrier is not considered as it is unclear what the effective leak off potential per field is. It is however a topic of further study per field and could be included in later versions of this document.

The Fine and Kinney-method scores 0.5 on probability (highly unlikely), 1 on exposure (rarely), and 40 on severity (disaster), leading to an overall score of 20. This score implies no further actions are required according to this method and is in agreeance to Nobian's risk assessment.

Mitigated
Using the mitigation actions (or safeguards) described above, the risk can be reduced. As the frequency cannot go lower, scores for Environment and Reputation are reduced in severity, thereby reflecting the reduced risk.

6.1.4. Damage due to seismic events

S5 Catastrophic	**P_1, R_1**						
S4 Major	**P_1, R_1, E_1**						
S3 High		**R_2**		**R_2**			
S2 Moderate		**E_2, P_2**		**E_2, P_2**			
S1 Negligible / Slight							
	F0	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**

Figure 25 Risk matrix: Damage due to seismic events during production and post-leaching phase

Unmitigated
Seismicity has the potential to cause (irreparable) damage to houses and infrastructural works. However, such events typically occur when large faults (or sections thereof) slip at the same time. The energy release based on such events can happen in oil/gas extraction fields due to differences in compaction around bounding faults. For salt solution mining, the mechanism for large earthquakes is different. Seismicity can occur due to stress redistribution around and above the cavern, perhaps indicating collapse events. Seismicity has been measured by Nobian around the fields, and typically is well below a magnitude where the seismicity is detected (by humans) at surface. Due to the other mechanisms causing seismicity (compared to oil/gas extraction), and the fact that the observed magnitudes are relatively low Nobian considers the 0.1g scenario required for liquefaction to be extremely unlikely. Nonetheless, two Environment-scenarios are considered: E_1 where buildings are damaged beyond repair (liquefaction could fall in this sub-category too), and E_2, non-structural cosmetic damage.

Note that damage to Nobian's caverns due to external seismicity is not listed here but has been discussed in section 4.4.6. Should external seismicity trigger something within Nobian's cavern fields it is captured by the other top events discussed in this chapter.

Comparative scores are defined using the Fine and Kinney method for the scenarios of crashing buildings and cosmetic, non-structural damage. For the first scenario Nobian considers the probability unlikely (0.5), exposure very rarely (0.5), but severity at the level of a disaster (40), leading to an overall score of 10: low risk. The scenario of non-structural but cosmetic damage leads to a different assessment: a probability of possible (6), exposure of occasional (3), and a severity of lasting injuries (7), leading to an overall score of 84, requesting simple measures for this moderate risk. For the E_2 risk, the Fine and Kinney-method leads to more actions required by Nobian, which are in place.

Mitigated

There are two safeguards are in place to limit the effects: Pressure control and the TLS as early warning system. Note that there are implicit safeguards in the design of the field, such as the minimum distance between caverns. Moreover, experience from decades of operating salt solution mining fields has shown no case of damage through seismicity due to salt mining. This is backed up by recent years where seismic events have been monitored by local networks.
With the safeguards in place, all risks are reduced to within the green/acceptable fields.

6.1.5. Contamination fresh- or groundwater aquifers

S5 Catastrophic							
S4 Major	**E, R** ←			**E, R**			
S3 High							
S2 Moderate	**P_2** ←	**P_2**					
S1 Negligible / Slight		**P_1** ←	**P_1**				
	F0	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**

Figure 26 Risk matrix: Contamination fresh- or groundwater aquifers during production and post-leaching phase

Unmitigated
The risk of fresh- or groundwater contamination requires that a fracture forms from the cavern and leads toward the surface. Depending on the depth of the cavern, and the occurrence of permeable layers in the overburden the risk may vary. Here the risk of a fracture forming all the way to surface and brine and / or blanketing fluids (or storage media) leaking into groundwater of freshwater layers is considered. For all risks categories Nobian considers the risk frequency to be “remote” (F3), as it is known that such an incident has occurred within the industry, even though the leaching method was different. The incident shows that it can happen if left unmitigated. The severity for both Environment and Reputation is classified as S4. For environment we consider the leakage to groundwater as a significant escape that has to be reported, but not catastrophic. The cause is that leakage is finite (the cavern will only leak off the amount of brine needed until a new equilibrium is reached). Another reason for not considering the leakage catastrophic is that the volume of the leaked brine (or blanketing fluid) is limited in comparison to the groundwater supply. Note that dilution can further reduce the impact in case of a brine leakage. As for reputation, we consider this to lead to national attention in the media at best. The risk in the people category is considered to have a low severity, based on the thought that at best some first aid treatment is needed if someone ingests the brine-polluted water (scenario P_1). If blanketing fluid is leaked out, and ingested the severity may be higher, but the likelihood is further reduced (scenario P_2). Note that not all fresh water is drinking water. The likelihood of contamination of drinking water is therefore lower than contamination of fresh water.

Using the Fine and Kinney methodology, scores of 3 (probability unusual but possible), 2 (exposure sometimes), and 1 (slight effect) emerge. The combined risk is then 6, which is largely due to the fact that contamination of fresh water is likely to be detected early enough such that injury through the subsequent effects of groundwater pollution are limited.

Mitigated
There are two safeguards are in place to limit the effects: Pressure control and the TLS as early warning system. Note that there are implicit safeguards in the design of the field, such as the minimum distance between caverns, limitation in height of caverns, distance to dome flank and the thickness of the cavern roof. Additionally monitoring of groundwater quality is done as well.
With the safeguards in place, all risks are reduced to within the green/acceptable fields.

6.1.6. Contamination other aquifers

S5 Catastrophic							
S4 Major							
S3 High			**E, R** ←	**E, R**			
S2 Moderate							
S1 Negligible / Slight		**P** ←	**P**				
	F0	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**

Figure 27 Risk matrix: Contamination other aquifers during production and post-leaching phase

Unmitigated
This risk is similar to above in terms of the driving mechanism, but the severity is considered lower as it is unlikely that there are direct negative effects. This is unless the contaminated aquifers are used for other purposes, such as geothermal heat production, thermal storage, or gas extraction. Note that these layers are somewhat deeper compared to the shallow ground- or freshwater layers, thereby the chance that a fracture reaches these layers is higher compared to shallower layers. In terms of Environment and Reputation categories the severity levels are considered to be reduced to S3, but should remain there, because technically it is a permit violation (see section 5.1.6). For the category People the risk is negligible (S1), as there is no direct impact on humans conceivable.
This is also reflected by the assessment based on the Fine and Kinney methodology. Here a score of 6 is listed for probability (possible), 2 for exposure (sometimes), but 1 for severity (slight effect), leading to an overall score of 12 (acceptable risk).

Mitigated
There are two safeguards are in place to limit the effects: Pressure control and the TLS as early warning system. Note that there are implicit safeguards in the design of the field, such as the minimum distance between caverns, limitation in height of caverns, thickness of cavern roof and distance to the salt dome flank. With the safeguards in place, all risks are reduced to within the green/acceptable fields.

6.1.7. Hydraulic connections to other caverns

S5 Catastrophic							
S4 Major	**E_3, R_3** ←	**E_3, R_3**					
S3 High			**E_2, R_2** ←	**E_2, R_2**			
S2 Moderate		**E_1, R_1** ←	**E_1, R_1**				
S1 Negligible / Slight	**P**						
	F0	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**

Figure 28 Risk matrix: Hydraulic connections to other caverns during production and post-leaching phase

Unmitigated
Here three environmental scenarios are taken into account: E_1 / R_1, where the other cavern is in production (or storage), and E_2 / R_2, where the other cavern is closed off, and E_3 / R_3 where the other cavern is used for storage purposes. Risks in the category People is considered equivalent for all these scenarios.
Note that this top event itself can potentially lead to other top events which can potentially cascade into other top events, all of which are discussed above. For example, if a fracture is formed between two caverns that are at different depths, the higher pressure at the deeper cavern could lead to an increase of pressure in the shallower cavern which goes above the fracturing limit of the shallow cavern. A pressure that is too high may lead to fracturing, which is associated to the top events of seismic events, contamination of other aquifers and indirectly also subsidence and sinkhole formations. Leakage leads to low pressure in the cavern, thereby high creep rates and more subsidence, and integrity loss may lead to collapse of the cavern thereby leading to sinkhole formation. Such a cascade of events is highly unlikely to occur due to several safety barriers in place.

If a hydraulic connection is formed between another active cavern or an abandoned cavern, it is considered a permit violation and therefore for severity the unmitigated risks are placed in S2 for the E_1 / R_1, and S3 for the E_2 / R_2. Finally, the severity of a connection to a storage cavern is deemed higher (S4) as this would likely lead to the storage cavern to be suspended or abandoned. For frequency Nobian regards the frequency of a hydraulic connection forming between two producing caverns as improbable (with the exception of the Hengelo field, where connected leaching is geomechanically stable if caverns are connected in a row), as there is pressure control in both caverns. If the second cavern is closed off, the frequency is one level higher. This is because when there is active pressure management in both caverns, the chance of a fracture occurring is lower. Currently, there is no way to precisely know the pressure in the closed off cavern.

Using the Fine and Kinney method, scores for probability, exposure and severity are 3, 0.5 and 1 respectively (unusual, vary rarely and slight effect), leading to a score of 1.5. This is the same for both scenarios (active → closed cavern and active → active cavern).

Mitigated

Safeguards in place are pressure control and potentially the monitoring of seismicity (note that tracking opening fractures is difficult due to the relatively low amount of energy release).

6.2. During storage phase

The majority of (planned) energy storage caverns is not operated by Nobian. However, Nobian works closely together with the (potential) storage operators to ensure that the cavern design and built infrastructure allows safe storage operations. Risk analysis and bow-ties for the diesel storage (GOME) are available in house (storage plan with attachments 11, 12a and 12b on risk assessment and attachments 14 and 15 on bow ties). An overview of risks associated with storage caverns is presented in *"Risk analysis of worldwide salt cavern storage and its implications for the Dutch cavern storage industry"* (Eising, 2021). The results of this study are also consulted for the risk assessment and bow ties presented in this CSIMS document. It also serves as an extensive reference for incidents which have been reported during storage in salt caverns.

6.3. During abandonment and post-mining phase

In this section we no longer consider mitigated versus unmitigated risks, as these are considered the same after abandonment. The locations in the risk-matrices should be considered a residual risk. The philosophy here is that caverns are not abandoned if the (expected) long term risk lies within an unacceptable field (i.e., red and most yellow fields). This follows from dedicated measures, where needed, that will be described in detail in removal plans per (part of a) cavern field. Moreover, after abandonment there is no mitigation possible (in the sense of section 5.3) as the borehole is no longer accessible. Some remediation actions (in the sense of 5.4) are possible. These are discussed per top event below. Given enough time creep-effects will change the geometry of the cavern(s) and salt dome. This may have caused substantial stress distribution within the subsurface, such that the risk-assessment has changed. Such effects are currently researched and may result in rewriting this part of this document in later versions.

6.3.1. Subsidence by creep beyond acceptable limits

S5 **Catastrophic**							
S4 **Major**							
S3 **High**			**E, R**				
S2 **Moderate**							
S1 **Negligible / Slight**				**P**			
	F0	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**

Figure 29 Risk matrix: Subsidence during abandonment and post-mining phase

If a cavern is abandoned, Nobian considers the expected amount of subsidence to be within acceptance limits (i.e., as agreed with authorities). The risk considered here is the subsidence exceeding that limit. While some caverns have already been successfully abandoned and have not shown problems in terms of accelerated subsidence rates or total subsidence above limits, it is not known for all cases if this can be met in the long term. Thus, it requires further research on the abandonment strategy. To this end Nobian has a team of external scientists working on the site-specific characteristics (in the Cavern Closure Consortium, see also Baumann et al., 2022). Only the caverns that are considered safe in the long-term are abandoned. If caverns cannot be considered safe Nobian will work to find tailor-made cavern specific solutions that are agreed upon by the authorities, to the extent that may be reasonably expected from a mining operator. Pressures in the cavern as a result of a hard shut-in are expected to be higher than when the cavern is in production, this in turn limits subsidence.

6.3.2. Sinkholes

S5 **Catastrophic**	**E, R**						
S4 **Major**	**P_1**						
S3 **High**			**P_2**				
S2 **Moderate**							
S1 **Negligible / Slight**							
	F0	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**

Figure 30 Risk matrix: Sinkholes during abandonment and post-mining phase

Environment, Reputation and the fatality scenario (People 1 / P_1): due to improved design it is as good as physically impossible to create a sinkhole, therefore considered extremely unlikely to occur. Note that this is true for Nobian's newer caverns, some older (legacy) design caverns in the Hengelo field do not fall into this category. These require special attention for which a tailor-made cavern specific plan is available and in effect, therefore not discussed here (see "Beleid Monitoren en Vullen Cavernes Twente 2022", available inhouse).

Nobian employs microseismic monitoring techniques at all fields to indirectly monitor stability, also in the post-mining phase. Such a system could be used as an early-warning system. In the context of sinkholes, areas may be evacuated in case of an increase of event rate in combination with a shallowing of seismic event depths and increasing surface PGV's per event. Procedures are defined in the Traffic Light systems, or TLS (see also 5.3.7), which in turn can lead to the site-specific ERP to come into effect.

6.3.3. Liquefaction

S5 Catastrophic							
S4 Major	**P, E, R**						
S3 High							
S2 Moderate							
S1 Negligible / Slight							
	F0	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**

Figure 31 Risk matrix: Liquefaction during abandonment and post-mining phase

For post-mining phase it has been established that the equilibrium pressure is below the "safe"-threshold, thus the pressure control safeguard is no longer required.

6.3.4. Damage due to seismic events

S5 Catastrophic							
S4 Major	**P_1, E_1, R_1**						
S3 High			**R_2**				
S2 Moderate			**P_2, E_2**				
S1 Negligible / Slight							
	F0	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**

Figure 32 Risk matrix: Damage due to seismic events during abandonment and post-mining phase

Here, two Environment-scenarios are considered: E1 where buildings are damaged beyond repair, and E2, non-structural cosmetic damage.
Also here, the stable cavern pressure is such that the risk of fracturing is physically impossible. However, due to cavern creep, stresses in the overburden may change causing some low magnitude seismicity.

6.3.5. Contamination fresh- or groundwater aquifers

S5 Catastrophic							
S4 Major	**E, R**						
S3 High							
S2 Moderate							
S1 Negligible / Slight			**P**				
	F0	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**

Figure 33 Risk matrix: Contamination fresh- or groundwater aquifers during abandonment and post-mining phase

For post-mining phase it has been established that the equilibrium pressure is below the "safe"-threshold, thus the pressure control safeguard is no longer required.
Note that a TLS is in place at all fields to monitor if fracturing does occur. In the most extreme case, a cavern has to be reopened as a mitigating measure.

6.3.6. Contamination other aquifers

S5 Catastrophic							
S4 Major							
S3 High			**E, R**				
S2 Moderate							
S1 Negligible / Slight			**P**				
	F0	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**

Figure 34 Risk matrix: Contamination other aquifers during abandonment and post-mining phase

For post-mining phase it has been established that the equilibrium pressure is below the "safe"-threshold, thus the pressure control safeguard is no longer required.
Note that a TLS is in place at all fields to monitor if fracturing does occur.

6.3.7. Hydraulic connections to other caverns

S5 Catastrophic							
S4 Major	**E_3, R_3**						
S3 High			**R_2, E_1**				
S2 Moderate		**R_2, E_2**					
S1 Negligible / Slight	**P**						
	F0	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**

Figure 35 Risk matrix: Hydraulic connections to other caverns during abandonment and post-mining phase

Here three environmental scenarios are taken into account: E_1/R_1, where the other cavern is in production, E_2/ R_2 where the other cavern is abandoned/closed off, and E_3/R_3 where the other cavern is a storage cavern. Risks in the categories People and Reputation are considered equivalent for these two scenarios. In the most extreme case, a cavern has to be reopened as a mitigating measure.

7. Cavern PDCA: operating limits, monitoring and surveillance

7.1. Control measures

To actively monitor the caverns, a monitoring system with proportional control measures is set up, based on Plan-Do-Check-Act (PDCA) cycles. These PDCA cycles are known from quality management and show a clear connection between:

- **Plan:** write down which activity, calculation or forecast you will perform
- **Do:** performing the activity
- **Check:** check whether the measured value corresponds to the expected value, forecast or calculation.
- **Act:** if necessary, adjusting the process to ensure a controlled situation

The processes and post-mining effects are presented in the CSIMS database and CSIMS Dashboard (see also 7.3). In the table the processes and post-mining effects are classified per period, and in each period it is indicated which tests & measures are carried out to keep the processes and post-mining effects under control.

This table is the basis for the monitoring and surveillance system, which is made visual via the CSIMS Dashboard as explained in 7.3. Table and monitoring surveillance system form a dynamic document, which are periodically updated and discussed. For this, operating limits must first be defined, as decribed in the next paragraph.

Responsibilities:
Cavern monitoring and surveillance is the responsibility of the site production organization. Each site is responsible to ensure the monitoring and surveillance conform CSIMS. MDC supports the sites by defining what is considered anomalous and requires reporting. The frequency of monitoring and surveillance is dependent on the status of the cavern and the parameter to be monitored, as further described in the CSIMS database & dashboard (see also Table 11).

Monitoring: stop when needed:
Production is halted and a cavern is taken out of service when:

- A sonar measurement indicates the cavern has reached its design limit.
- Sonar measurements and simulations indicate that further leaching will result in cavern instability – even if the original dimensions have not been reached.
- Monitoring indicates issues with well integrity or cavern stability and/or integrity. This means that the risk of one of the cavern failure modes would reach an unacceptable level in case of continuation of the production from that specific cavern.

Connection to WIMS:
Also here, the connection to WIMS for cavern monitoring is important:

- The well location of caverns that are producing or in thermal equilibration are visually inspected daily by a production operator. During the inspection, the wells are checked for obvious signs of leakage and all pressure readings are checked for anomalous readings.
- Caverns/wells that are closed in (not actively producing but may be brought back into production later)) are visually inspected at least once per or once per month by a production operator. The frequency depends on a risk assessment of the situation.
- Suspended (including pre-abandoned) wells have reached the end of their safe production limit, are plugged and logged and are placed on the list for future final abandonment. It is only required to visually inspect these wells once per month. Note that active caverns in Heiligerlee, Zuidwending and Mariager are monitored (for pressure) continuously.

The monitoring frequency of wells can be adjusted based on the advice of WLE. For more information about WIMS, see WIMS procedure.

7.2. Operating limits

For all caverns, operating limits are defined in such a way that processes and effects in the subsurface are not exceeding limits. Limits are set for all measures described in Table 11 below. These limits are set in each phase of the cavern (construction, operation, post-leaching, abandonment, post-mining), including the way of controlling these values. For these operating limits, there is a close connection between cavern and well elements. Therefore, WIMS is also a vital link to safe operating limits for caverns (see WIMS procedure, well operating limits for more info).

Life cycle phase	Control measure: process or effect	Responsible	Frequency	Limit (if applicable)
Design and preparation	Cavern design	BFT	One off	
	Field design	BFT	One off	
	Subsidence calculations – base line levelling	BFT	Per 5 years	
	Stability calculations	BFT	One off	
	Closure plans	BFT	One off*	
	Seismic interpretation of overburden	BFT	One off	
	Seismicity risk analysis - base line	BFT	One off	
	Groundwater measurements (starting point)	HSE	One off	
	Tests to rock samples (cores) – Field design	BFT	One off	
	Field design modelling for pressure build up (permeation/fracturing)	BFT	One off	
Execution (aanleg put)	Temperature log of the rock salt and overburden	BFT	One off	
	Pressure tests on formation and well: (X)LOT (Leak Off Test), FIT (Formation Integrity Test), P(L)OT (pressure observation test)	BFT	One off	
	Geologische logs (gesteente druk ter plaatse last cemented casing shoe)	BFT	One off	
	Werkprogramma	WLE	One off	
Operation	Waterpassing	BFT	1-5 year	Subsidence prognosis as per permit
	SONAR data incl. temperature	BFT	1-5 year	Cavern within designed rock mechanical envelope
	Microseismicity monitoring + TLS	BFT	Continuous	Event rate/max magnitude/clustering compared to background
	MIT (Mechanical Integrity Test) in WIMS	WLE	One off	Casing pressure limits
	Pressure measurement data	Brine production	Depends per field	MAASP per cavern
	PIMS – controle rondes lekkages	Asset Management	Day-month	Varies per pipe section
	Groundwater and surface water samples (peilbuizen)	Brine production	Week – year	Standards from (Circulaire bodemsanering 2013, bijlage 1)
	Blanketing fluid level	Brine production	Depends per field	Varies per cavern and leaching phases
	Blanketing fluid pressure	Brine production	Continuous	Varies per cavern
	USIT data	WLE	One off	

Life cycle phase	Control measure: process or effect	Responsible	Frequency	Limit (if applicable)
Storage phase (responsibility is with the storage operator)	Waterpassing	BFT	1-5 year	Subsidence prognosis as per permit
	SONAR data incl. temperature	BFT	1-5 year	Cavern within designed rock mechanical envelope
	Microseismicity monitoring + TLS	BFT	Continuous	Event rate/max magnitude/clustering compared to background
Post-leaching	All above mentioned at operation	See above		
	Outflow test	BFT	One off / at every bleed off moment	Bleed off: reduction of 10 bar at surface.
	Monitoring of pressure increase by cavern convergence	BFT	One off, if possible	0.18 bar/m (MAASP / Bérest et al., 2022)
	VSP (vertical seismic profile) measurement (where applicable)	BFT	One off, if needed	
Abandonment	Design & Work program	WLE	One off	
	End of Well report/EOWR	MDC	One off	
	Waterpassing	BFT	One off	
	Seismic data + TLS	BFT	Continuous	
	Groundwater and surface water samples (peilbuizen)	Brine production	One off	
	Abandonment program (based on removal plan)	WLE	One off	
Post-Mining	Waterpassing	BFT	1-5 year	Subsidence prognosis as per permit
	Seismic data + TLS	BFT	Continuous	Event rate/max magnitude/clustering compared to background

*Table 11 Cavern operating limits. (*updated on the basis of scientific insights, and checked if still up to date at each lifecycle phase, particularly abandonment phase)*

7.3. CSIMS Dashboard

As indicated in the introduction of this document, CSIMS is considered a document that requires to be amended and updated where new information can lead to improvements in managing cavern integrity. The annual performance review of CSIMS is a cornerstone of this continuous improvement. The effective performance of CSIMS at the site can be determined by measuring compliance with prescribed maintenance, reviewing reports & documents and the cavern failure model.

Cavern integrity elements are first defined and documented in the cavern design. These documents are saved on the MDC drive in the specific cavern folder. During the lifecycle of the cavern, changes to the cavern are documented via a Management of Change procedure. Documents are saved on the MDC drive.

The cavern is added to Nobian's cavern dashboard that is used to illustrate the status of a cavern stability and integrity elements. This Nobian's cavern dashboard is used to monitor progress during the year on all monitoring actions for stability and integrity elements. Pictures of the dashboard are shown below (Figure 36 and 37).

For each individual cavern, the dashboard shows the following information from the underlaying database:

- The current lifecycle phase status of the cavern
- The cavern failure codes per lifecycle phase to indicate which cavern failure code could happen in that phase, following the colour coding from the risk matrix (see chapter 3.2.1, table 5, green, yellow and red)
- Maximum pressure is shown which is correlated to MAASP

- Subsidence contours are shown (interpolation of subsidence status of 2020), for both salt extraction as well as all mining related activities
- Other maps that are displayed are cavern contours, projected maximum distance between caverns and water levelling
- Microseismic events are shown including the date, location, magnitude, depth and PGV

To clarify: legacy caverns that do not follow current CSIMS strategy (special cases) will be flagged as such in the dashboard, and will show mitigation actions where needed, timing of the actions, etc. More detailed approach per case will be available in separate documents or in the underlying database, depending on the case. The CSIMS dashboard will act as a performance monitoring tool for follow up. This implies that for caverns such as HL-H cavern specific actions are taken, which are described in individual memorandums.

BFT is responsible for reviewing and providing quality of the information contained in the dashboard. It is the responsibility of the production site to provide relevant information in a timely manner so that the dashboard can be kept up to date. This information can be delivered via official daily operations reports or memorandums.

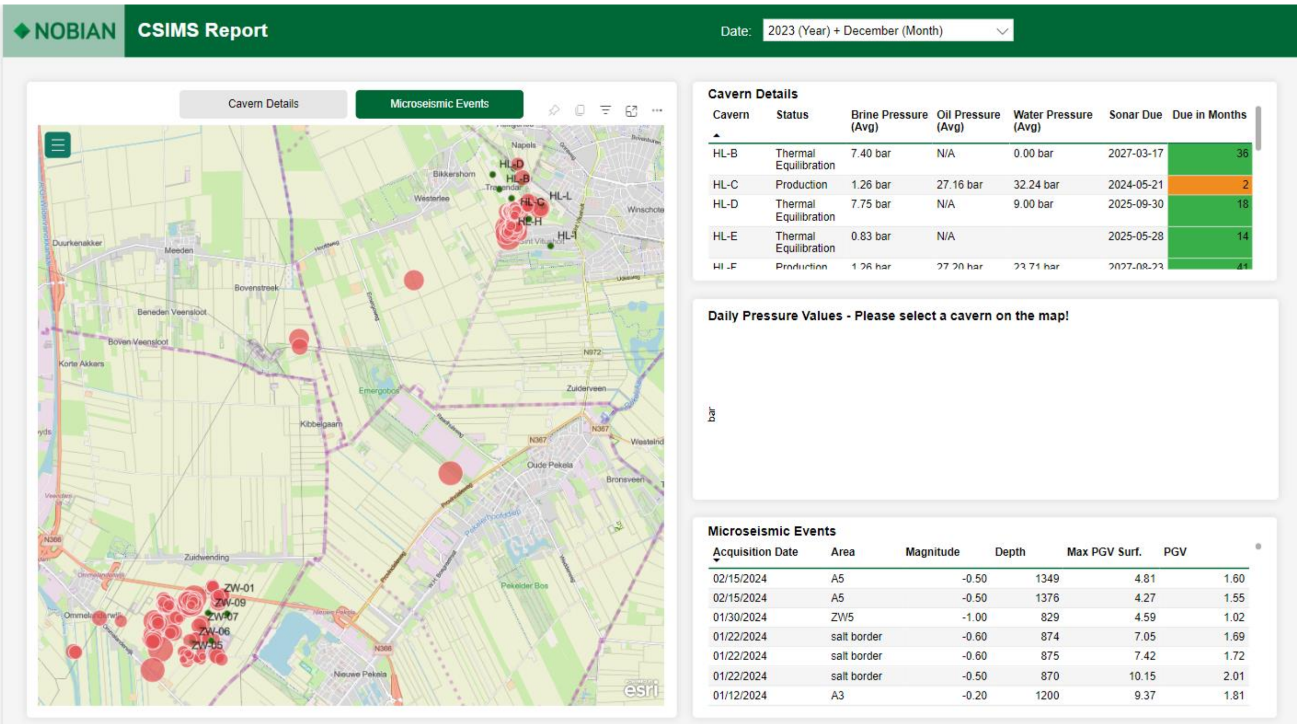

Figure 36 Cavern Dashboard online environment (example for the Groningen fields of Zuidwending and Heiligerlee, showing the microseismicity page)

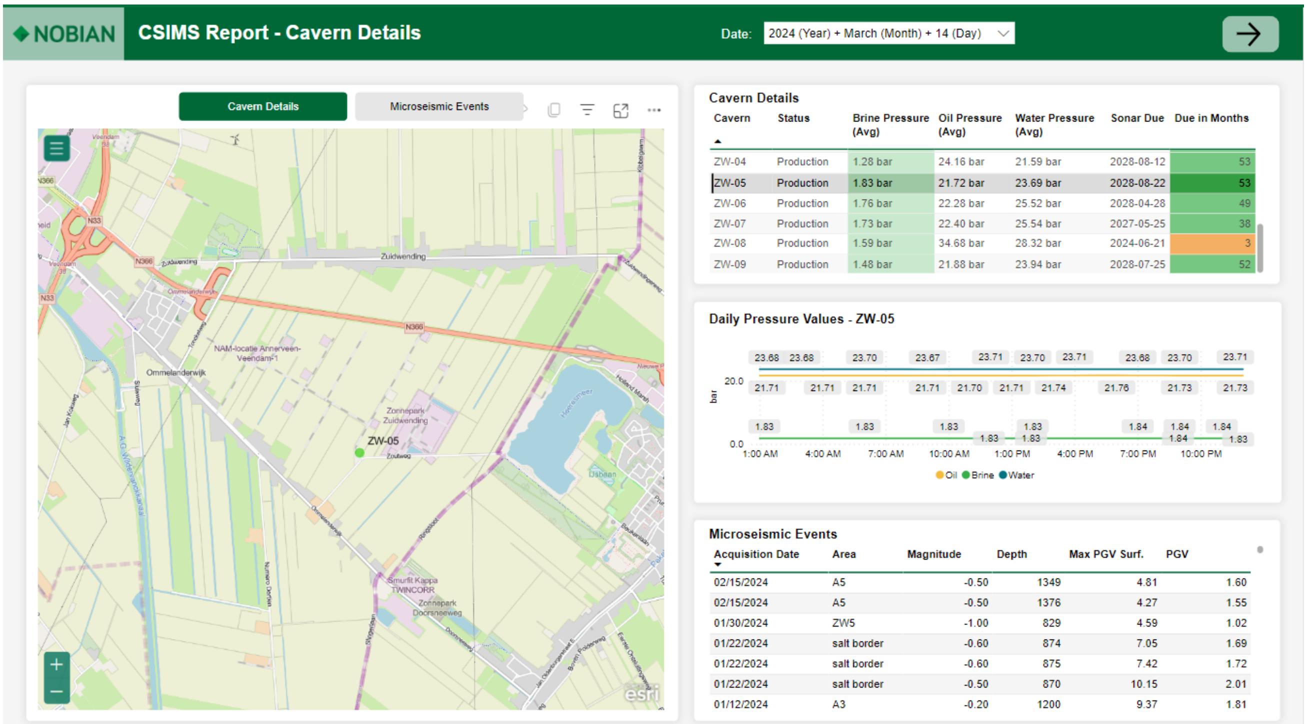

Figure 37 Cavern Dashboard online environment (example for the Groningen fields of Zuidwending and Heiligerlee, showing the cavern details page, with daily pressure values)

7.4. Contingency plans

Contingency plans (or emergency response plans, ERP) are in place if operating limits are exceeded and/or effects are occurring. These plans are described in a structure of documents that will be executed in sequence the moment operating limits are exceeded and/or effects are occurring. Due to differences in short-term or long term risks, the plans fall into two categories labelled “level 1” and “level 2”. Depending on the cavern field such plans may be generic or cavern specific. For the latter cavern specific plans are available.

The workflow would be as follows:

- A certain threshold is suprassed which triggers follow-up action. Triggers may be the magnitude of seismic events, an increased event rate within a pre-defined time window, or an upwards migrating trend (see TLS for further details). Triggers may also arise from anomalies in production data, such as unexpected changes in cavern pressure. Follow-up actions include an investigation on what happened at surface (e.g., was a valve opened when it shouldn’t have?) but can also mean a cavern specific investigation such as a sonar survey. Follow-up actions are defined by this verification step. After verification it can be determined if the cavern risks have changed (i.e., following the framework of CSIMS using the cavern failure modes.).
- If needed (high risk) site- or cavern specific preventive plans can be set in motion. This would be a “level 1”, where there is no immediate risk of injury, environmental spills etc, but cannot be reasonably excluded in the long term. Examples are cavern-specific backfilling plans (i.e., section 5.3.9).
- In case there is an immediate risk, the “level 2” comes into play and the BNP is used. Where CSIMS is always consulted after a trigger, Level 1 and Level 2 documents are site- or cavern-specific preventive or mitigation actions. Further links to available documentation can be found below.

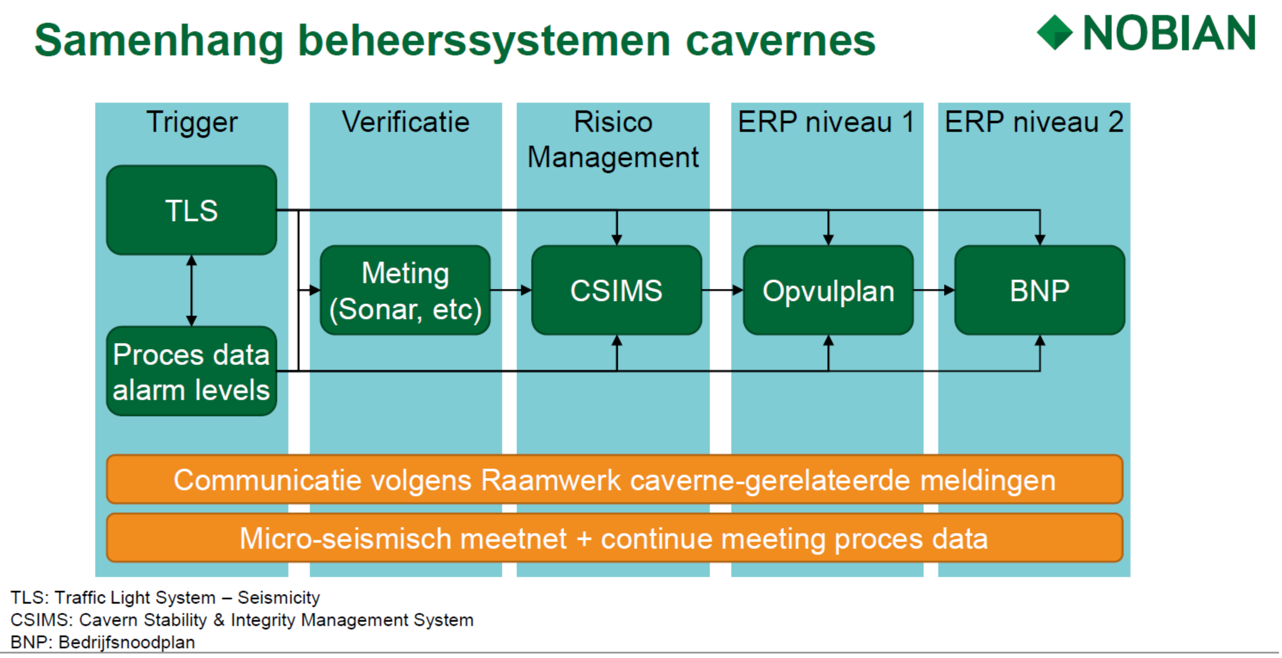

Figure 38 Overview of how site-specific plans interact with CSIMS (English version to follow in yearly document update)

7.4.1. Main documents / links

- Nobian HSE portal (via SharePoint, link)
- Emergency response and community awareness (Rule 12.01.5, link)
- Cavern related reports to state supervision of mines (only relevant for Dutch fields): available through Manual Master: Raamwerk caverne gerelateerde meldingen, link

7.4.2. TLS and communication protocols

Traffic Light Systems and related communication protocols (see also 5.3.7):

- Hengelo field TLS and communication protocol: "20220105_Communicatieprotocol en TLS MSM TWR" (available in house)
- Heiligerlee and Zuidwending TLS and communication protocol (available in house)
- Communication protocol (via ManualMaster, Communicatieprotocol Microseismisch Meetnetwerk HL-ZW, link)

7.4.3. Emergency response plans

Emergency response plans are related to the sites and can be found here:

- For the Hengelo field: "bedrijfsnoodplan (BNP) is available through SharePoint (link)
- For Heiligerlee the documentation can be found via ManualMaster (Link): Salt Bedrijfsnoodplan Heiligerlee (BNP)
- For Zuidwending the documentation can be found via ManualMaster (Link): Salt Bedrijfsnoodplan Zuidwending (BNP)
- For Mariager: see database Mariager (link to follow)

8. Cavern handover

In simple terms the purpose of the cavern handover process is to clearly indicate who is responsible for the cavern integrity at any point in time. A list of requirements and documentation is described in the Cavern Delivery Process (CDP) documentation. The CDP follows Nobian Project Management internal guidelines. As described in section 2.1, above, ownership of the asset (cavern) falls with the site production organization whilst the site Asset Management group are responsible for creating, maintaining, and decommissioning said assets. The responsibility for the integrity of the asset therefore changes hands between these two groups throughout its lifecycle.

The cavern handover process is identical to the well handover process, as described in WIMS. To know more about the cavern handover process, see WIMS procedures.

9. Cavern maintenance / connection with well maintenance

Connected to caverns is well maintenance and testing. Well maintenance and testing are described in WIMS. Aspects from the well, which relate directly to cavern stability and integrity elements, are described in WIMS. Cavern and well maintenance are often combined. Cavern maintenance normally consists of sonar measurements followed by simulation and if needed adaptation of blanket level, injection- and production pipe depths and flow ranges.

10. Management of change

The purpose of Nobian's MOC process is identify and mitigate risks (HSE, cost, compliance, etc) that result from a changes or deviations to an agreed upon work programs, designs, or processes.

A MOC process for all mining related activities has been created. The main elements of the document:

- Defines changes and deviations
- Explains the link to individual site MOC processes and systems
- Clarifies the classification of changes or deviations
- Designates level of approvals required
- Risk assessment process to be followed

The document is a controlled document and available via Nobian's Manual Master system (link).

11. Compliance audit

Nobian internal audit policy states that all elements within a process are audited within a three-year period. The frequency of auditing for specific elements can be adjusted if they are identified as critical elements. The mining department and QA&C group determine the criticality based on technical evaluation and outcomes of previous audits. In line with its compliance mandate, MDC, provides technical assistance in the auditing of CSIMS.

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CSIMS

NOBIAN’S CAVERN STABILITY and INTEGRITY MANAGEMENT SYSTEM

Chemistry
you can count on