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Technical Conference Paper

1965 – 2025

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SMRI Spring 2025 Technical Conference
27-29 April 2025
Wilhelmshaven, Germany

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Concept and implementation of seismic monitoring in salt and potash cavern fields

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Abstract:
When working in subsurface operations, e.g. in underground mining or in cavern fields, the safety of the working environment, i.e. the subsurface rock mass, has the highest priority. As the geomechanical parameters change with every intervention, the reactions of the bedrock must be monitored and, if necessary, linked to alarms for short-term reactions. One component of this surveillance is seismic monitoring. This technique provides the option of monitoring the 3D rock mass remotely over time, hence 4D. For meaningful and successful monitoring of the seismicity of a cavern field, the monitoring objectives must first be defined.
The release of seismic energy is always the result of a geomechanical/geotechnical process. The seismic events can result from the storage level in the cavern, from the over-burden (the protective layer) or from fault activation nearby due to stress redistribution. We will show examples of how the sensitivity and localisation accuracy of the monitoring system changes for different sensor setups. Each seismic monitoring network is an individually customised tool that develops its full information value best in conjunction with other monitoring systems.

Key words: seismic monitoring, microseismic monitoring, salt caverns, cavern stability, safety, monitoring technology

1. Introduction
For meaningful and successful monitoring of the seismicity of a cavern field, the monitoring objectives must first be defined. These objectives can be for example:

- Recording changes in geomechanical properties to optimize production
- Safety of property, employees and residents
- Compliance with laws and regulations
- Advertising effectiveness of safe operation for the public

The release of seismic energy is always the result of a geomechanical/geotechnical process. The seismic events can result from the storage level in the cavern, from the overburden (the protective layer) or from fault activation nearby due to stress redistribution. Several criteria must be met, in order to be able to monitor these areas with a high degree of localisation accuracy:

- The geological subsurface model, and thus the velocity model of the seismic waves, should be well known.
- The required horizontal and vertical localisation accuracy should be calculated.
- The area to be monitored should be spatially well defined.
- The sensors on the surface, in boreholes or in the caverns should have a high signal to noise ratio.
- The sensitivity of the sensor system must be adequate.

We will show examples of how the sensitivity and localisation accuracy of the monitoring system

changes for different sensor setups. We will discuss which options exist and which developments can be expected in the future.

The technology currently in use is:

- 3 axial (three component) surface seismometers
- Borehole seismometers
- Hydrophones
- Hydrophone chains

These sensors are a comprehensive set of seismic measurement instruments for monitoring. More recent developments based on fibre optic cables laid on the surface or directly in the pipes of the cavern boreholes can generate even denser measurement networks in the future. All these seismic sensors can be combined with the data from surveying and with the response of the caverns (e.g. pressure changes at the head) to provide a more robust picture.

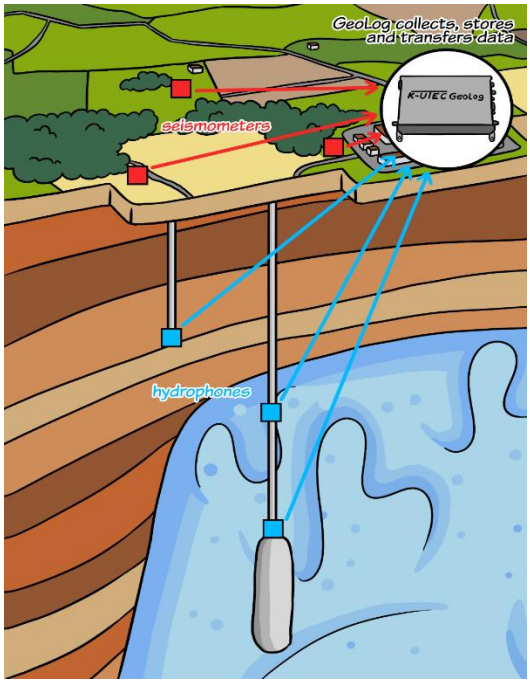

Figure 1: Scheme of a seismic monitoring system of a cavern field.

The seismic measurement results help to identify the cause of the seismic events. Calculations and measurements in the literature have already shown that different frequency characteristics indicate different causes of seismic events. Examples of stress redistribution in the area of the safety pillars, material collapse from the salt cavern roof or rock reaction from geological fault zones in the vicinity of the cavern field will be presented.

Other studies, such as work on seismic interferometry, suggest that long-term analyses (depending on the project) can provide indications of an increased seismicity and, therefore, rock mechanical risk. However, these analyses require a project-specific time series of data in order to determine the correct parameters. Finally, the moment tensor provides information about the focal mechanism and thus about the type of the rupture. Each seismic monitoring network is an individually customised tool that develops its full information value best in conjunction with other monitoring systems.

2. Definition of the seismic network effort

As all caverns and the areas to be monitored are different, a preliminary study with modelling or estimated parameters for the seismic parameters in the underground should analyse the risk of seismicity. Based on this study, threshold values for detection and, if necessary, alarm criteria must be defined. These threshold values are in turn parameters for the sensitivity calculations for the installation locations of the sensors.

The sensitivity calculation results offer different options for the accuracy of the localization results for different parameters. This includes information about the seismic velocity model, the localization algorithm and the noise/source ratio. For many issues relating to deep monitoring targets, borehole probes are finally suitable for qualitatively capturing the low energy releases. Many geomechanical reactions of the rock mass occur with stress changes, either with many small energy releases, or fewer but larger energy releases.
Based on knowledge of the optimal distribution for the sensor location, field work with noise measurement can start. The noise measurements are carried out in accordance with the guidelines of the FKPE paper, which specify limit criteria for seismological sensor locations of 95% of the noise level below 2 micrometres/second over a test period of 7 days. Furthermore, any conditions imposed by the authorities regarding vibration measurements must be observed as an obligation to provide evidence. DIN vibration measuring stations can be integrated into these networks and PGV sensors can be installed to assess the vibration impact areas.

3. Sensor options

There are several sensor options available on the market.

- 1 axial and 3 axial (three component – velocity proportional) surface seismometers
- Borehole seismometers (three component – velocity proportional)
- Hydrophones and Hydrophone chains
- Fibre optic sensor system (DAS – distributed acoustic sensing)

Each of the sensor types is useful for different situations.

Figure 2: Example for a 3 axial seismometer

Surface sensors are generally the easiest to install. The cost of such an installation is particularly low when the seismometers are installed in buildings, on solid ground in protected areas or in easily erected seismometer bunkers. For such purposes, the data loggers and peripheral devices can often be integrated into these protected areas. The data loggers with integrated sensors available on the market are usually equivalent for these purposes. A disadvantage in some cases can be the routing of cables to integrate power, time and mobile data connections.
Borehole sensors can be placed closer to the monitored areas. This requires a borehole, which, if not already available, is a cost factor. Nevertheless, the advantages usually predominate, as lower energy releases, which can either be suppressed in the surface noise or attenuated, can be recognised at the sensor.

Hydrophones can be integrated into the cavern, but only if they are not in use anymore. In the case of active inlets and outlets of oil, gases or saline liquids, the noise is too high for meaningful operation of such a sensor.
Fibre optic sensor systems can be installed at the surface or in boreholes. The fibre optic sensor system enables a close-meshed network of 1 axial sensors to be generated. This means that a significantly

higher density of measuring sensors can be realised. Ideally, even pre-existing telecom cables can be used sometimes. This requires a strong connection with the cable to the ground. If using the so-called DAS, a huge amount of data can be generated. The necessary interrogator for such systems are currently the highest hardware cost factor, since the equipment is still a “new” development. The fibre cable can also be integrated in borehole cementing which is more challenging compared to the surface installation.

4 Seismic events

Since every seismic monitoring task has different parameters, it is necessary to get used to the local circumstances.

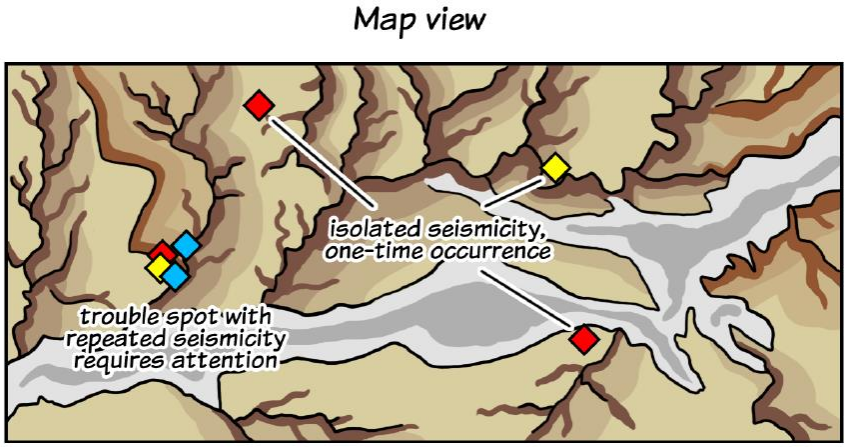

Figure 3: Example distribution of seismic events over time

The different geomechanical causes for the seismic events can be distinguished by the character of the seismic event. The parameters for such events can differ in terms of frequency, energy release, the properties of the hearth surface solutions, duration and also the dispersion characteristics. It is important that sufficient high-quality data is available for such a characterisation. For the characterisation of such a seismic event, several articles were published in the past ([1],[2],[3]). Furthermore, own experiences and examples lead to classifications, which are the base of the evaluation of the events. Examples are so-called geomechanical events (the source is in-between of the caverns) in the safety pillars. The seismic frequencies are in a medium range.

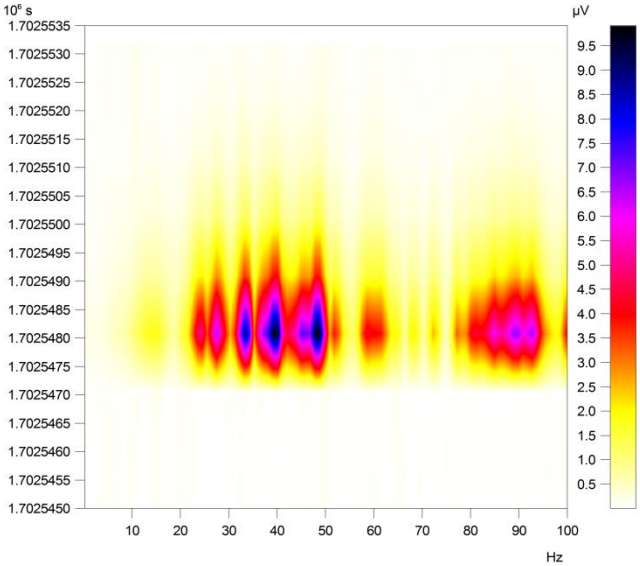

Figure 4: Examples of a geomechanical event in pillars – main amplitude in lower frequency range

Other examples are roof falls. In that case it is possible that two seismic recordings can be registered (detachment of the rock and impact at the bottom of the cavern in the sump). The frequency is higher, but the events are shorter in time.

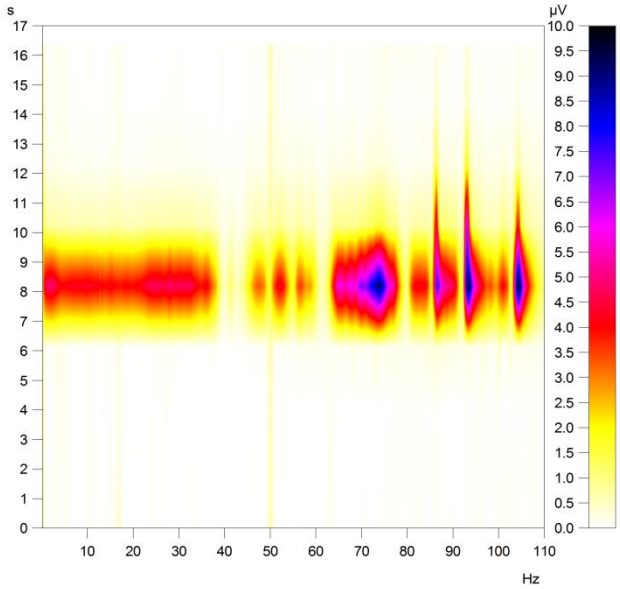

Figure 5: Examples of a roof fall – main amplitude in higher frequency range

The figure 5 show an example of seismic events in the overburden, in the protection layer. The parameters are depending on the stiffness of the geological layers above the cavern. The localization results show the positions. In combination with a roof fall event followed by several seismic events, it could be a hint of a raised quarry.
Other Examples can show “tectonic” event below the cavern field area. The reasons are normally preformed structures that react subsequently to relief, loads and stresses in the rock mass or just natural seismicity. These events often occur with higher energy releases and usually have the lowest frequency ranges in their seismic amplitudes.

5 Further seismic statements and research areas

Other seismic performances are still part of R&D efforts. For example, seismic interferometry can be used for long term monitoring of the rock stress changes. Some R&D results indicate that the rock stress can be shown in a ratio of the seismic velocity change in the underground. In such case the permanent ratio of the performance of the noise wave through the monitored area can be measured. Such measurements show, that the ratio of the seismic wave velocity to the change of the seismic wave velocity increases until the stress release. With enough data for a monitored area in combination with other data from the observation of the cavern, like pressure in the caverns, surface subsidence monitoring and other it might be possible to get better indications of the geomechanically behave of the rock in the underground.

Summary

Release of seismic energy is always the result of a geomechanical/geotechnical process. The results of seismic monitoring of a cavern field always provide indications of the integrity of the caverns.
The seismic monitoring should be designed following a risk assessment and the identified requirements. With sensors surrounding the monitoring area in all dimensions, the accuracy of the monitoring target will be enhanced. Since there are several options for the sensors, the positioning of the sensors, the data transmission chain and the resulting reaction chain available, the risk study should cover different scenarios.
In combination with additional data from geomechanics, surveying and cavern parameter monitoring, seismic monitoring can complete the overall picture of the condition of the cavern field with little effort. In some cases, seismic monitoring is already being used to specifically check caverns, e.g. with sonar surveys, which have shown conspicuous results. Other caverns that have not shown any seismic reactions can be put on the back line with the cavity surveys.

We show several options of seismic monitoring in our presentation. The performance of seismic monitoring and the specific experience in the monitoring area allow statistical statements to be made. In addition, the seismic events that have occurred can also be assigned to their probable cause through a detailed analysis. This usually requires a start-up phase in which a statistically relevant number of seismic events have been analyzed. After this, it is possible to make a classification based on the experience of the cavern operators.

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