Geophysical structural exploration in civil engineering, tunneling and mining

Paul Lehmann, *Bo-Ra-tec GmbH, Weimar, Germany, paul.lehmann@boratec.net*

Markus Schmidt, *Bo-Ra-tec GmbH, Weimar, Germany, markus.schmidt@boratec.net*

Thomas Richter, *Bo-Ra-tec GmbH, Weimar, Germany, thomas.richter@boratec.net*

Michael Eidner, *Bo-Ra-tec GmbH, Weimar, Germany, michael.eidner@boratec.net*

ABSTRACT: Geophysics can be a powerful tool to get an understanding of the subsurface structure, conditions and material properties. However, many engineers are unaware of its realistic advantages or are disillusioned by false promises.

While the interpretation of measured geophysical parameters are not unambiguous and cannot substitute the commonly used direct ground sampling through boreholes and excavations, they can however deliver indirect evidence of the area between discrete spots, thus yielding comprehensive information on the 3D space with non-invasive and increasingly faster and more feasible methods.

We present selected examples of the application of innovative geophysical technologies that were developed for specific surveying goals, including the detection of karstic structures, cavities and faults ahead of/after the tunnel boring machine or conventional drill-and-blast excavation of tunnels, the detailed mapping of a congestion in a production shaft of a limestone quarry and the exploration of salt and limestone deposits.

Keywords: geophysics, radar, karst, mining, tunneling

1. Introduction

Any construction project starts with planning on the grounds of most comprehensive and accurate information on the building ground that the construction will be based on. One of the most important parameters of interest is ground stability which is majorly affected by geological or also anthropogenic structures in the underground. This could include hollow or partially sediment-filled karstic cavities but also relics of historic mining structures like old drives and shafts.

The usual and most direct way to check for any structural weaknesses of that kind would be probing via excavation or drilling, which is costly both in time and effort and will cover only discrete spots across the building area and is likely to overlook small-scale structures. For the monitoring of existing infrastructures e.g. mines and quarries there is also an increased interest in knowing the conditions of the bedding rock. For instance the efficient planning of remaining deposit volumes in the mining industry presumes detailed knowledge of layer boundaries and tectonic structures beyond or above the actual mine or quarry.

Geophysical technologies can provide a fast and powerful tool to gain access to information on the whole underground between these discrete probing points and can in many cases be applied without disturbing the underground by measuring from the surface or boreholes, despite existing infrastructure on the surface.

As some geophysical methods may not be suitable under certain underground conditions, the deliberate planning by experienced experts and in some cases preceding test measurements are necessary to assess if the result will solve the goal of the investigation. While the interpretation of measured geophysical data might be ambiguous and cannot substitute direct ground sampling through boreholes and excavations they can, however, deliver indirect evidence about the underground situation.

The following selection of example projects will show how Bo-Ra-tec GmbH has successfully contributed to the implementation of geophysical technologies, especially radar, in geotechnical applications like tunneling, mining and construction. These projects represent how common geophysical surveying methods can meet the specific investigation goals of customers from these branches. They are step stones on geophysic's mission to approaching the greatest challenge of descriptively presenting geophysical data to planners and technical responsibles in an understandable way so they can make the best use of the technology's capabilities.

2. Exemplary projects

We present selected project results of the application of innovative geophysical technologies. These results provided either safety relevant information on the stability of the bedding rock of a tunnel excavation or helped optimize the mining operation of an underground salt mine and a limestone quarry.

2.1. Karst detection in tunneling

Bo-Ra-tec was involved in several tunneling projects where the projected tunnel path passed through limestone strata of the White Jurassic which are prone to intermediate to severe karstification. The detection of larger open or partially filled karstic cavities and the following stabilization through backfilling was a decisive precondition for the safety of the tunnel excavation and especially for the later operation of the tunnel.

Hence the objective was to

- determine the location and approximate dimension of fault and karst zones as well as open cavities ahead of the tunnel face and/or in the vicinity (of up to 15 m) around the tunnel tube
- characterize the bedding rock conditions around the tunnel, especially the ground beneath the tubes.

Borehole radar is optimally suitable for this surveying task since the emitted radar wave is reflected at material boundaries facilitating the detection of cavities, faults or different rock types. When used in crosshole mode, placing transmitting and receiving antenna in different boreholes, the recorded radar wave velocity and signal attenuation can give direct evidence of air- or sediment-filled structures in the 3D space between the boreholes (Fig. 1 below).

Radar can yield high penetration depths of several tens of meters in limestone thus providing 3D information of the rock area around single boreholes and between pairs of boreholes.

This high-resolution borehole method provides fast measurement progress without the need for tight coupling of the equipment to the borehole walls (unlike seismics) and is independent of the existence of water or air in the borehole.

2.1.1. Detection ahead of the TBM

Between 2005 and 2007 the over 9 km long Katzenberg Tunnel was excavated during the railway renovation of the line between Karlsruhe and Basel (Germany/Switzerland) using a tunnel boring machine (TBM).

The unprecedented application of borehole radar provided essential information of the rock material and the existence and location of karstic cavities, sediment filled structures or faults ahead of the tunnel face, thus enabling the engineers to react to possibly dangerous areas before the TBM actually met them [1, 2]. A combination of inline (reflection) and crosshole measurements was used in two to four boreholes that were drilled at slight angles from the tunnel face into the direction of the tunnel excavation (Fig. 1). The boreholes were up to 50 m deep and were drilled at a slight outward angle so an area of at least 40 m ahead of the tunnel face could be surveyed and analyzed. Analysis could be delivered within few hours after the measurement. The excavation progress suffered minimal downtimes for the borehole drilling and measurements but in turn received a clear picture of the 3D space ahead and around the tunnel tube, providing an advantage over discrete investigation drillings which could easily have missed local karstic structures. Fig. 2 shows an exemplary radargram of a fault structure that crossed the projected path of the tunnel at a potentially dangerous angle so protective measures could be taken before the excavation met the structure.

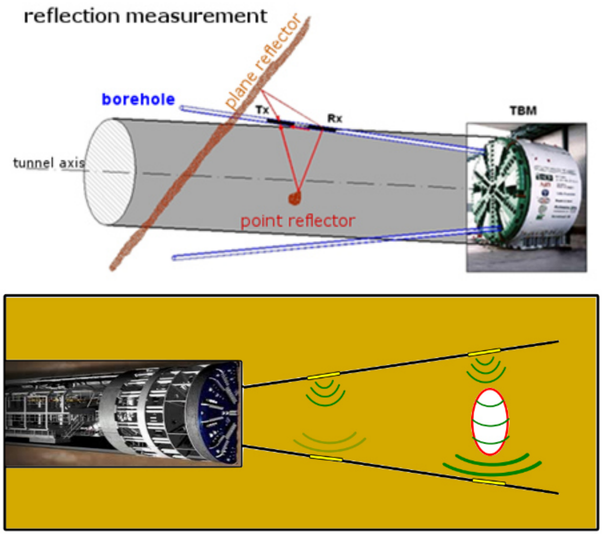

Figure 1: Principles of reflection (inline) radar measurement (above) and crosshole radar measurement (below) ahead of a TBM.

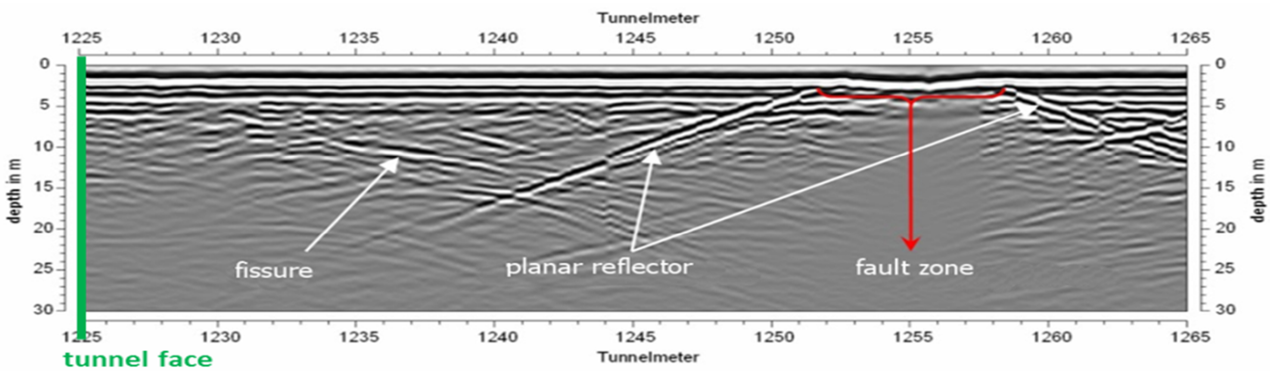

Figure 2: Detection of a fault zone crossing the tunnel path 30 m ahead of the tunnel face.

2.1.2. Detection after NATM excavation

A different karst investigation approach was chosen during the excavation of the Steinbühl Tunnel tubes along the railway line Wendlingen – Ulm (Germany) [3]. Here radar measurements followed the conventional drill and blast excavation (New Austrian Tunneling Method) and were used to detect any remaining karstic structures or cavities in the radius of 15 m around the excavated tubes before the tunnel lining was installed. The optimized borehole arrangement used star shaped borehole raster at discrete intervals along the tunnel tubes as shown in Fig. 3. This setup guaranteed a comprehensive coverage of the entire area around the tubes thus facilitating the detection of cavities down to a size of 1 m³. Borehole radar was again applied in a combination of reflection and crosshole measurements along a total of over 9 km of the tunnel track. Additional microgravimetric measurements were performed to investigate the bedding rock below the tunnelfloor along the tunneltrack.

Fig. 4 shows a

Over 500 karstic structures were identified from the radar data. Almost 200 of these were explored with verification drillings as their dimensions and distances were relevant to the tunnel's safety and stability. Over 90% of the structures interpreted from the radar data were found at the predicted location and could subsequently be successfully backfilled.

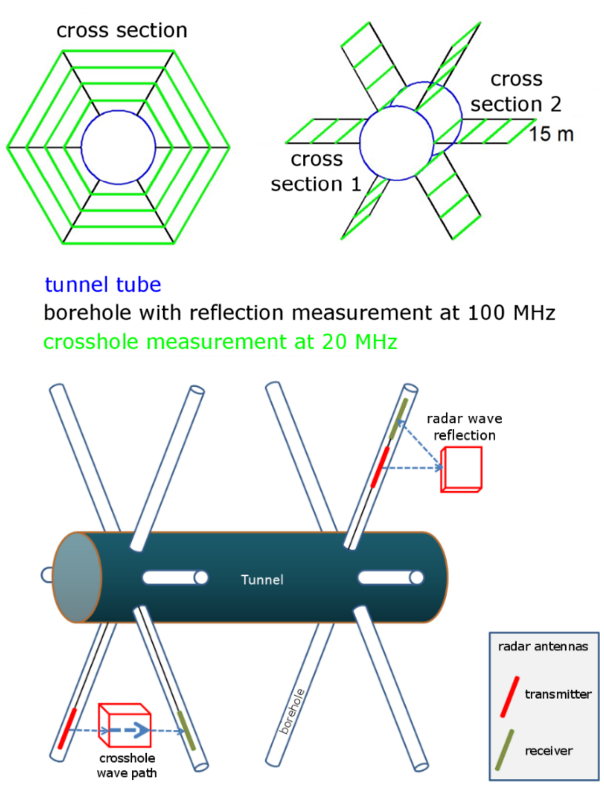

Figure 3: Principle of the radar investigation using reflection and crosshole measurements to cover the bedding rock surrounding the already excavated tunnel tube.

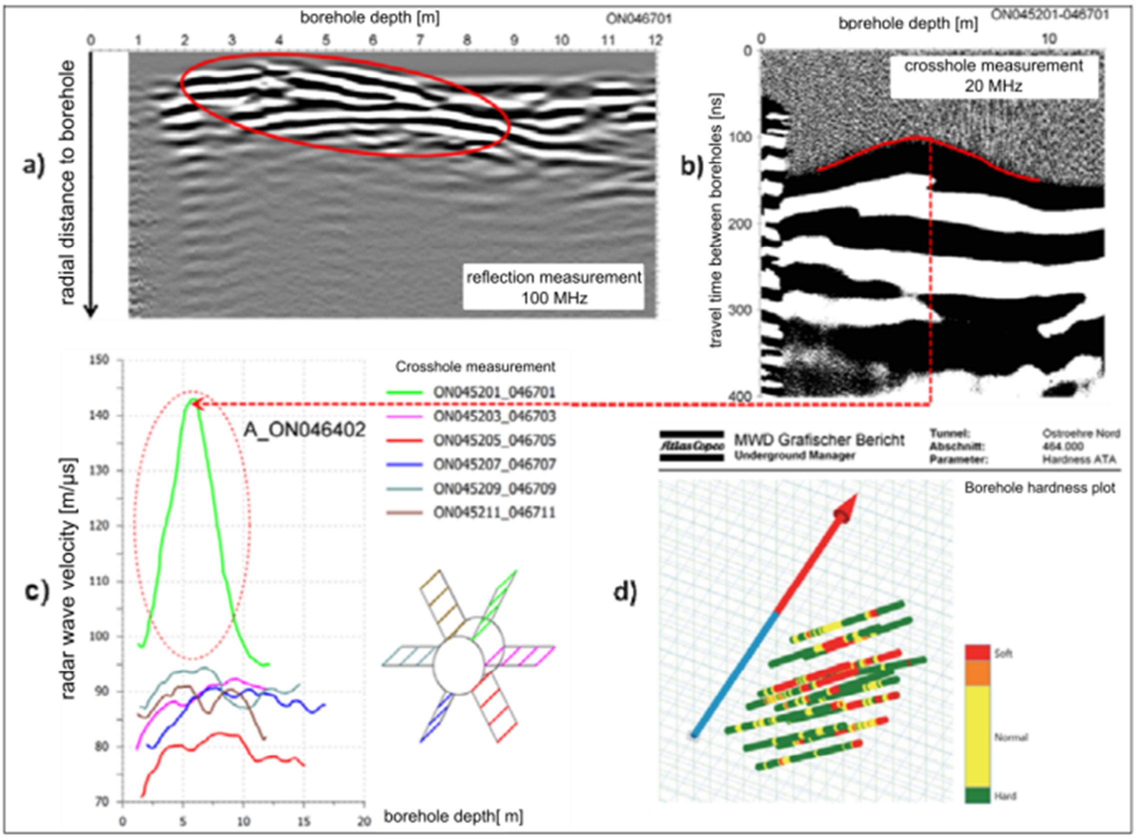

Figure 4: Exemplary result from the Steinbühl-Tunnel investigation shows a significant reflector in the reflection measurements (a), which was correlated with a reduced radar wave travel time in the crosshole measurements between neighboring boreholes (b) and the resulting radar wave velocity curve (c). The anomaly was later found to be related to a significant cavity represented by the red parts of the borehole hardness plot in the verification drillings (d).

2.2. Detection of a shaft congestion in a limestone quarry

Between 2017 and 2019 an Austrian limestone quarry frequently suffered production disturbances in the main shaft they used for transporting quarried limestone from the mountain down to the valley. The 120 m deep shaft leads to a horizontal gallery at the level of the valley where a conveyor belt moves the material to dump trucks for further transport. The shaft is usually filled to the brim with shattered rock so the material can be withdrawn at the bottom in controlled amounts. However, especially in winter there were frequent occurences of a congestion of the material somewhere along the length of the shaft, which was only noticed since the filling level at the top did not decrease as material was withdrawn at the bottom. Thus an air-filled cavity must have formed beneath the congestion. Fig. 5 shows a schematic of the situation. An uncontrolled sagging of thousands of tons of loose material over tens of meters could have destroyed the withdrawing mechanism at the bottom of the shaft. Hence the mining company stopped withdrawing material and intended to inject a brine solution to the location of the material congestion, since it was thought to be related to partial freezing of water penetrating the shaft from faults and cracks in the surrounding rock. However, they did not have any information on the depth of the congested area.

Two boreholes were drilled on each side of the shaft and have been used for crosshole radar measurements. During the crosshole measurement transmitter and receiver antennas are moved simultaneously along the same depth range to obtain a velocity profile of the direct wave between them. The observed velocity of the radar wave propagation between the antennas in the two opposing boreholes would yield information on the location of the hollow part of the shaft beneath the congestion. Fig. 6 and Fig. 7 show the resulting radargrams and velocity curves of the measurements between the boreholes. Since a congestion occurred several times over the span of a year different curves can be seen. The data shows that each of the three observed congestions must have happened at more or less the same depth. The green curve in Fig. 7 shows a reference measurement before the congestion occurred.
The data showed a rise of the radar wave velocity by 15 m/µs from a mean level of 95 m/µs, giving a clear indication of the depth of the hollow beneath the congested area. Additionally to the crosshole radar measurements a tomographic radar survey was executed to determine a more accurate shape of the roof and the floor of the hollow. The results showed that the hollow was shaped non-symmetrically, especially at the roof.

Owing to the accurate determination of the depth of the congestion the quarry operator was able to direct the injection drillings optimally for the dissolution of the congestion with brine. The connection of the location to existing fault and fissure systems which were also detected and analysed from the radar data is currently being investigated to reduce the risk of further congestions in the future.

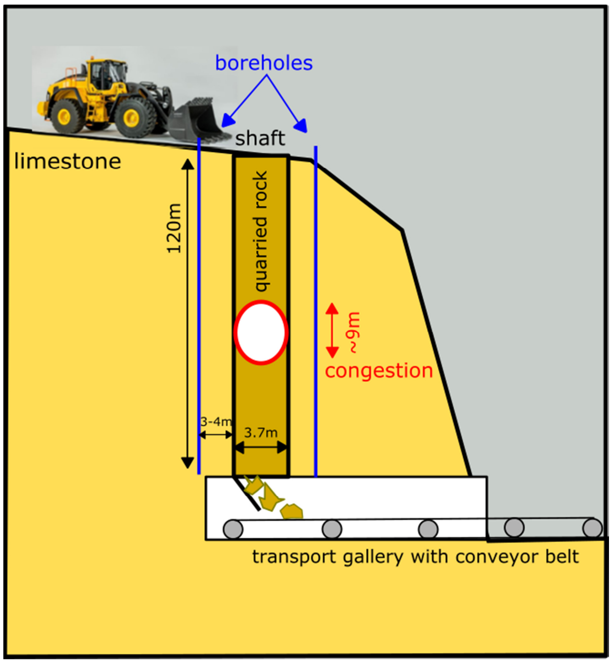

Figure 5: Schematic of the congested transport shaft and transport gallery in the limestone quarry.

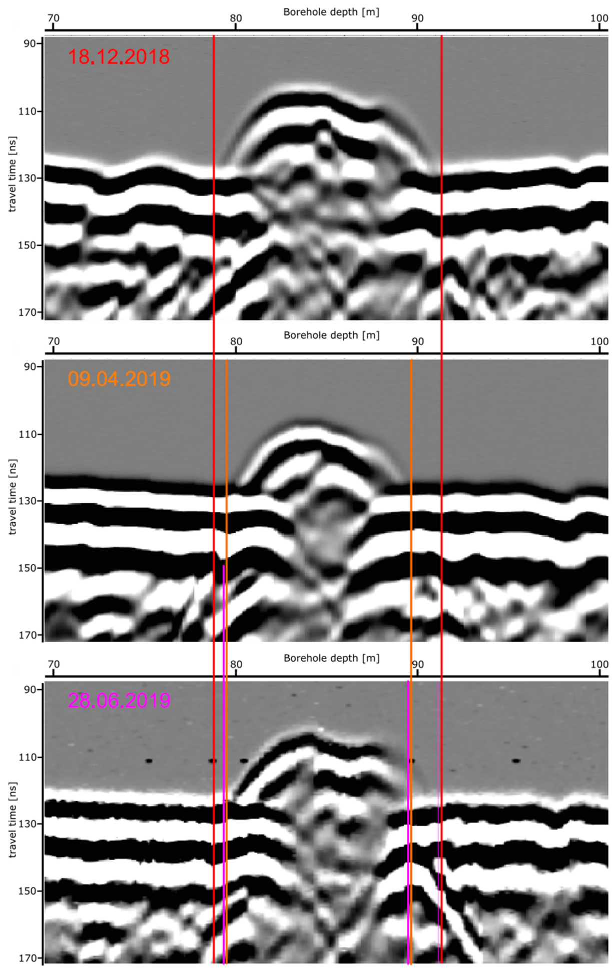

Figure 6: The Radargrams of the different crosshole measurements show a reduced travel time at approximately the same depth area of the shaft. Minor differences in the depth range are marked by the differently colored vertical lines according to the respective dates of the measurements.

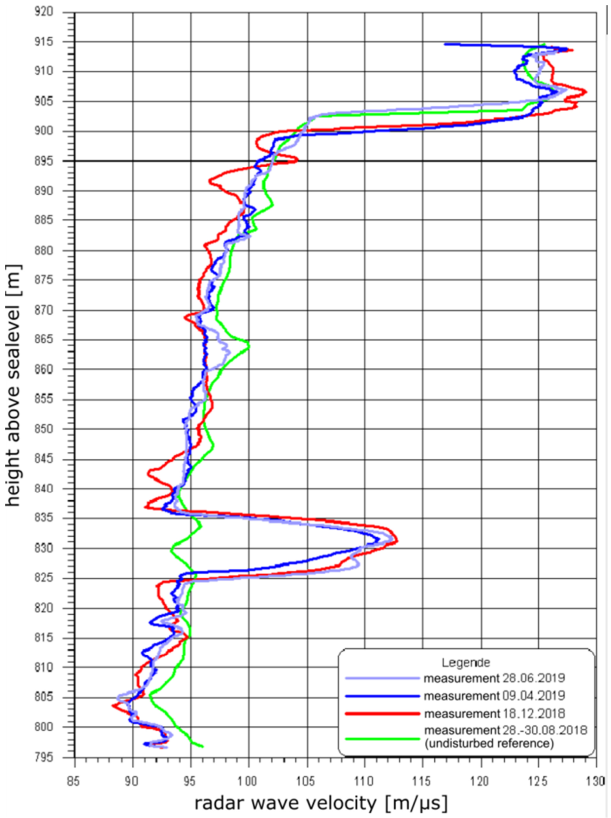

Figure 7: Velocity curves over the depth of the shaft resulting from the crosshole measurements during three separate instances of the shaft congestion (grey, blue and red) and the reference measurement (green) before the congestions had occurred.

2.3. Determination of the thickness of a salt deposit

The information of the remaining deposit thickness in horizontal drift mining is important not only for economical reasons but in some cases also for safety

reasons, especially when the resource is also mined from the back of a drift. If the remaining thickness of the mined material becomes too thin the risk of a collapse of the back of the mining drift increases significantly posing a huge risk to both personnel and equipment.

In a salt mine in the South of Germany the shallow layering of rock salt strata of the Zechstein age (Zwickelsalz) is wedged between layers of anhydrite. For reasons of drift stability and to reduce equipment wear the goal is to keep a safe distance of several decimeters to meters from the anhydritic layers in the hanging and the lying walls. The conventional way of the salt mine operator was to drill into the salt at discrete distances along the drift to determine the remaining deposit thickness. Due to quite significant undulations in the layer thickness the interpolation of the thickness between these measured spots can sometimes be inaccurate.

Moreover the Zwickelsalz rock salt stratum is riddled with local anhydritic inclusions that, when hit with the discrete investigation drilling, suggest that the remaining thickness of the layer would be much lower than it actually is. It is not possible for the operator to distinguish between hitting the layer boundary to the anhydrite or merely drilling into a spatially limited anhydritic inclusion.

A ground penetrating radar (GPR) survey conducted along the back and the floor of the mining drifts was to clarify the depth of the layer boundary and thus the real remaining thickness of the salt deposit along exemplary profiles in the underground salt mine.

GPR antennas of center frequencies between 100 and 250 MHz were used as an optimal compromise between penetration depth and resolution. The profiles were up to 250 m long. Fig. 8 shows an exemplary radargram of a 250 MHz antenna along the floor of the drift (with the central part omitted due to lack of space – orange line).

The red line marks the layer boundary between rock salt and the underlying middle anhydrite which can mostly be consecutively followed. Green arrows mark the local anhydritic inclusions which are occuring so frequently at shallower depths than the real layer boundary that the discrete investigation drillings falsely interpreted the inclusions to represent the layer boundary (short vertical magenta lines on the right side of the radargram). The real rock salt thickness, however, was up to 3 m greater than the drilling interpretation would have suggested since the borehole accidentally hit anhydritic inclusions.

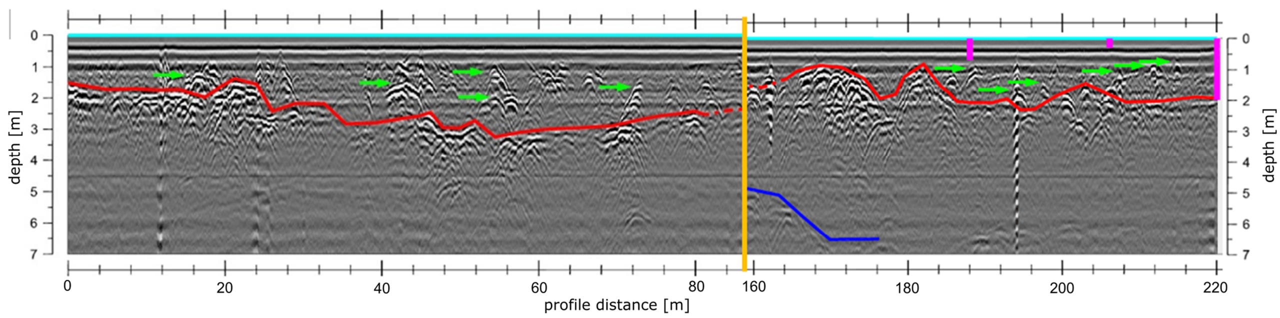

Figure 8: Radargrams of two stretches of a GPR measurement (250 MHz) on the floor of a rock salt mine (attached at the yellow line). Anhydritic inclusions are marked with green arrows, the layer boundary of the middle anhydrite is marked in red. The vertical magenta colored bars show salt rock thickness interpreted from discrete drillings. The blue line in the second half of the radargram represents the base anhydrite below.

This represents how geophysical surveys can cover whole areas, providing comprehensive 2D or 3D information on the subsurface as opposed to discrete drillings or excavations.

3. Conclusion

The previously shown examples are a representation of some very clear and easily graspable ways of using geophysical data for a more comprehensive picture of the geological or geotechnical situation beneath the ground. In all the presented cases geophysics provided an insight into the ground conditions that could not have been achieved at the same speed and financial efficiency with conventional methods of direct probing through drilling or excavation.

This way geophysical methods have successfully contributed to either the construction safety for both personnel and equipment or to the unhindered continuation or optimization of an ongoing mining operation.

Engineers need to be aware that geophysical methods can be an important part in geotechnical planning when ground conditions and the investigation goal are suitable, but at the same time they only measure certain physical parameters which can be ambiguous in their interpretation and hence always should be verified by different geophysical or geotechnical methods and calibrated by real on site direct probing and observation, if the prediction proved correct.

References

[1] Richter, T., Weh, M., Boll, S., 2008. Geophysical Investigation in Advance of Karstified Structures and Disturbance Zones during the Excavation of the "Katzenbergtunnel" in Germany. *Geotechnics and Tunneling 1, Vol. 5,* pp. 450 - 459.

[2] Kirschke, D., Lorenz, K., Richter, T., Seidel, K., 2011. Geophysical Prospection Technology in Advance of Disturbance Zones, Cavities and Karstified Structures. *Tunnelbau 2011, Special edition of the DGGT - German Society of Geotechnics, VGE Verlag GmbH* Essen/Germany, pp. 9 - 76.

[3] Schmidt, M., Richter, T., Lehmann, P., 2017. Innovative geophysical technologies for the exploration of faults, karstic structures and cavities in tunnelling. *Geomechanics and Tunnelling 4, Vol. 10*, pp. 380 - 394.