INNOVATIVE GEOPHYSICAL TECHNOLOGIES FOR THE EXPLORATION OF FAULTS, KARSTIC STRUCTURES AND CAVITIES IN TUNNELING

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Abstract

The geophysical engineering company Bo-Ra-tec provides problem oriented solutions through the development of innovative surveying technologies. Thanks to their high specialization the application of geophysical methods (ground penetrating radar, borehole radar, microgravimetry and geoelectric tomography) has made an unprecedented contribution to the successful detection of faults, cavities and karstic structures in both conventional and TBM tunneling.
Especially in rock formations prone to karstification there are no or only limited geological/ hydrological principles that allow a safe prognosis of the existence and location of karstic and fault structures. Thus the application of geophysical methods offers a high efficiency in the detection and localization of faults, cavities and karstic structures as they, when combined with targeted verification drillings, provide an extensive three-dimensional structural investigation of rock formations. Four examples of geophysical karst and fault investigations in German tunneling are presented here to demonstrate the innovative technologies and their respective survey results that in all cases contributed to the safe excavation process and later operation of the tunnels.

Key words
tunneling, karst, exploration, geophysics, radar, gravimetry

1 Introduction

The company Bo-Ra-tec GmbH Weimar offers extensive geophysical services in conventional prospecting and monitoring. For this purpose the company has specialized in different geophysical methods, most importantly in

- radar and borehole radar technology (BH technology),
- gravimetry and
- geoelectrics.

The main focus of the geophysical engineering company Bo-Ra-tec is to provide problem oriented solutions through the development of innovative surveying concepts and technologies. The development of new and continuous improvement of existing technologies and methods are a major part of that process. Thanks to their high specialization the application of geophysical methods has made an unprecedented contribution to the successful detection of faults, cavities and karstic structures in both conventional and TBM tunnelling and has since been successfully introduced into tunneling practice.

Especially in rock formations prone to karstification there are no or only limited geological/hydrological concepts that allow a safe prognosis of the existence and three-dimensional location of karstic and fault structures. For tunneling projects in karst prone rock formations discrete investigation drillings or geological mappings based on only selected spots do not offer the spatially comprehensive information on karst structures and faults that is needed

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for a safe excavation process and operation of a tunnel. Thus the application of specialized geophysical methods offers a high efficiency in the detection and localization of faults, cavities and karstic structures as they, when combined with targeted verification drillings, provide an extensive three-dimensional structural investigation of rock formations.

Four examples of geophysical karst and fault investigations in German tunnelling are presented here to demonstrate the innovatively adapted technologies and concepts and their respective survey results.

2 Katzenberg Tunnel (railway line Karlsruhe - Basel)

As part of the expansion and new construction of the railway line Karlsruhe – Basel by the Deutsche Bahn AG the Katzenberg Tunnel was constructed in the section of the planning approval 9.1 Schliengen – Eimeldingen between Efring-Kirchen to the south and Bad Bellingen to the north. The 9.38 km long tunnel was excavated from 2005 till 2007 with two tunnel boring machines with earth pressure balance shields (EPB-TBM).

The geological setting of the projected tunnel path was determined via core drillings, dynamic probing, borehole probing and digging. Rocks of the White Jurassic (Oxfordian limestone complex) and of the Early Tertiary were found to be covered by Pleistocenic and Holocenic unconsolidated rocks. The rock formation of the White Jurassic were drilled through by the TBM between tunnel meter (TM) 744 and TM 1268 (Fig. 1) and showed clear signs of erosion and karstification processes.

The certain determination of larger hollow and/or filled karstic cavities in the rock formation of the White Jurassic is an essential condition for the safe excavation process and especially the later operation of the tunnel. Thus geophysical prospecting was used in addition to geological probing via selected drillings and systematic geological tunnel face inspections.

The geophysical prospecting was conducted simultaneously to the excavation of the Late Jurassic formations in the Katzenberg Tunnel with the following goals:

- detection of faults and karstified zones as well as open cavities ahead and around the tunnel,
- detection of open cavities in the direct vicinity of the tunnel face,
- characterization of the bedding conditions around and most importantly beneath the tunnel.

BH technology is perfectly suited for all three of these goals and thus was selected as the preferred measurement method. This was the first application of BH technology in world-wide TBM tunneling history. As an additional innovation the prospecting was conducted simultaneously to the excavation process as an online measurement from the earth pressure balance shield of the TBM.

Ground penetrating radar is an impulse reflection method. A transmitting antenna emits short electromagnetic impulses that penetrate the surrounding rock and are reflected by stratigraphic boundaries between layers of different dielectric properties (complex dielectric constant, electric conductivity). The reflected waves are then recorded by a receiving antenna. Through the measured travel time of the radar wave between transmitting and receiving antenna the distance of an identified reflector can be calculated if the mean radar wave velocity in the medium is known. Reflections are indicative of layer boundaries, fissures, cavities and karstified or eroded zones. The measurement method can be used during the active excavation process both in reflection (RX mode) and crosshole mode (CH) mode, as shown in Fig. 2.

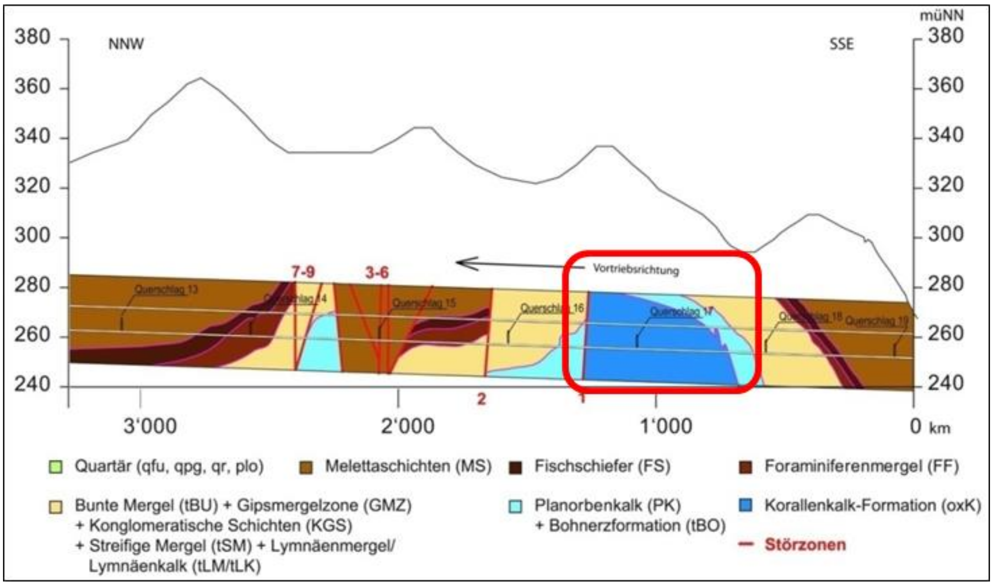

Fig. 1 Geological cross section of the lithological rock formations of the Katzenberg Tunnel in the area of White Jurassic.

During a RX measurement both transmitter and receiver are placed behind each other in the same borehole. The whole set of antennas are moved continuously along the hole (Fig. 2, top). The recorded radargram represents the geological/tectonic rock structure surrounding the borehole. CH measurements facilitate the comprehensive investigation of petrophysical parameters of the rock formations between transmitting and receiving antenna. During a CH measurement transmitter and receiver are placed in different boreholes and are continuously moved along their respective boreholes in sync (Fig. 2, bottom). The measured travel time and amplitude of the recorded radar signal facilitates the deduction of inhomogeneities like cavities or clay/debris-filled karstic structures along or close to the irradiated plane, thus delivering direct proof of cavernous structures filled with air, water or clay.

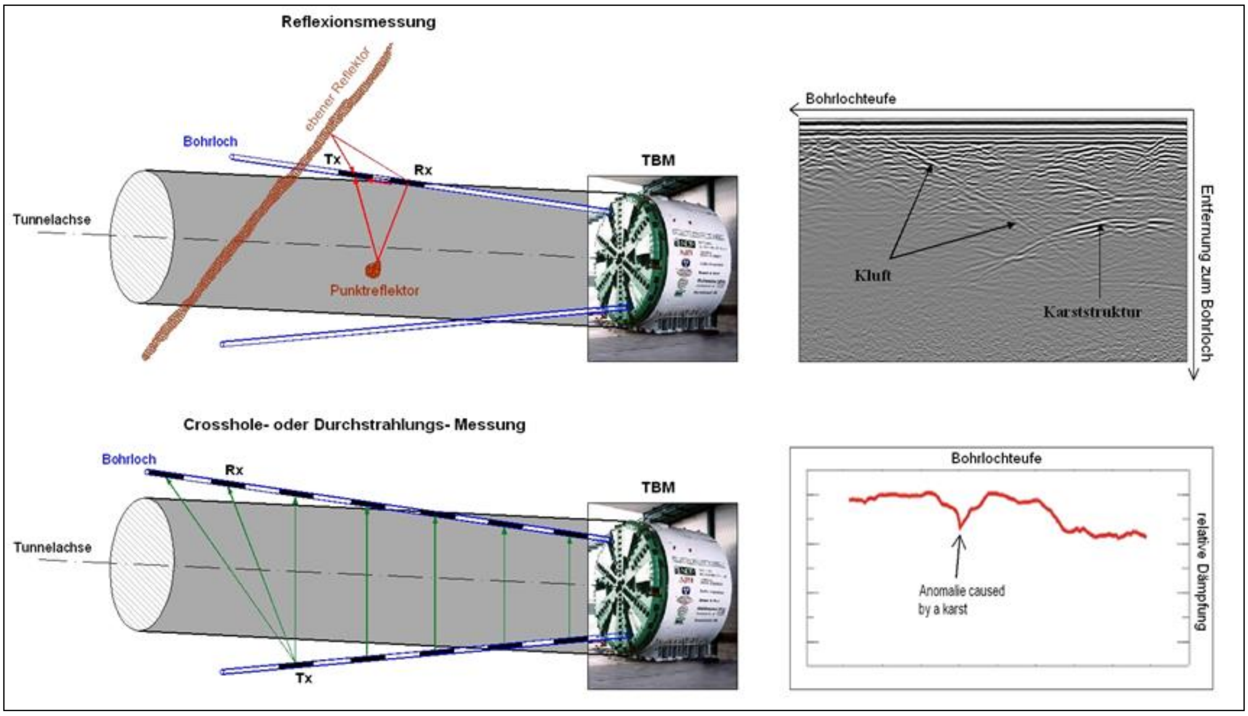

Fig. 2 Measurement principles of borehole radar: RX measurement (top) and CH measurement (bottom).

The applied measurement concept for exploring the projected tunnel path and its direct surrounding in the section of the Oxford limestone comprised a combination of RX measurements in one or two inclined horizontal boreholes as well as CH measurements between two boreholes. The boreholes were drilled from openings in the shield of the TBM. They were drilled at a lateral angle of 8° towards the outside (in relation to the tunnel axis) and had a mean length of about 30 m. Fig. 3 shows the schematic depiction of a TBM shield as seen from the direction of drilling. The boreholes were drilled alternatingly at the 1 and 7 o'clock (Fig. 3, green) or 5 and 11 o'clock positions (Fig. 3, red). The measurements took place during the excavation process in the Late Jurassic thus facilitating a complete investigation of the area directly ahead of the TBM. As data analysis and interpretation happened right after the completion of the measurements the drilling team was aware of what lay ahead only few hours after the measurements.

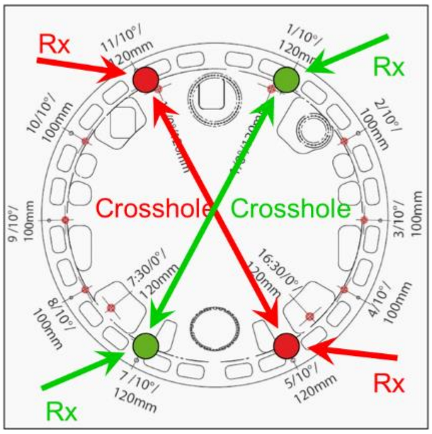

Fig. 3 Schematic front view of the TBM shield. The borehole positions and respective measurements at 1 and 7 o'clock are marked in green, the ones at 5 and 11 o'clock are marked in red.

The following selected example will show the geophysical proof of a fault zone in the karstified rock around the Katzenberg Tunnel, representatively documenting the great achievement of this prospecting technology. Fault zones within an intact rock mass always produce areas of strong erosion and are bound to lithological changes in the rock. The radargram in Fig. 4 shows such a tectonic fault. The radar signal is almost entirely cancelled within the zone surrounding the fault. Beginning and end of the fault are marked by strong linear reflections. Analysis of the radar data from both horizontal boreholes provided an accurate location as well as extent and strike of the fault in the rock mass ahead even before it was encountered with the TBM. Later inspection of the tunnel face confirmed the fault to the meter.

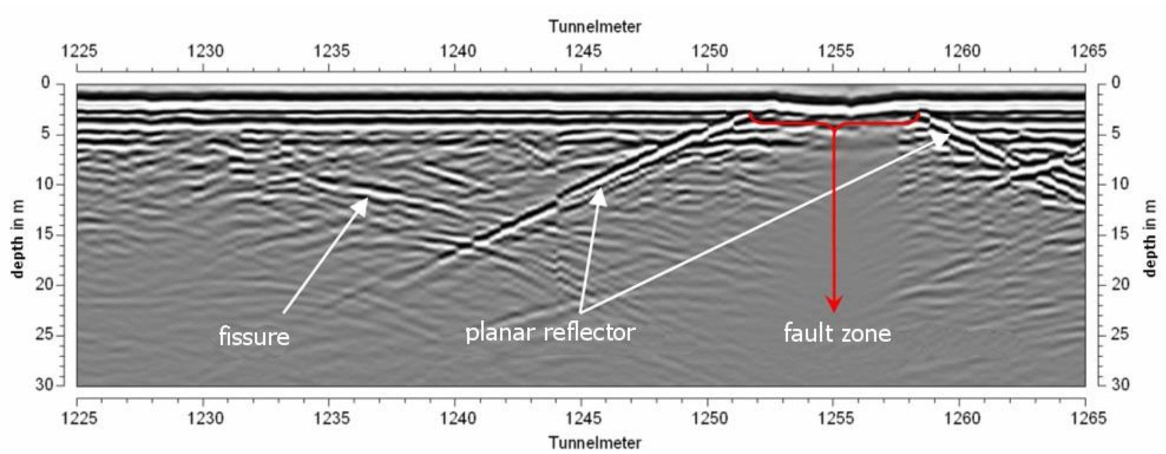

Fig. 4 Detecting a fault zone in the data of a RX measurement.

The following results could be deduced from the insights gathered from the geophysical prospecting and subsequent geological/geophysical data analysis at the Katzenberg Tunnel:

- immediate information on the karstification grade of a rock mass ahead of the tunnel excavation is possible,
- identification and resolution of fissure, fault and karst zones, including assessment of extent and distance to the tunnel axis are possible if the structure has a decimeter dimension,
- accurate assessment of an identified structure's location is possible thanks to the combination of RX and CH measurements in several boreholes,
- detailed structural assessment of the karstification grade of the rock mass surrounding the tunnel up to 20 m is possible.

Through the completion of the borehole radar measurements in the Katzenberg Tunnel it could be shown that even during a machine based tunnel excavation process geophysical measurements can be accommodated despite strictly limited time windows. The results of the data analysis prove that a comprehensive picture of the possible dangers through karstification, faults and fissure systems within the rock mass can be provided even before the TBM encounters them.

3 Osterberg Tunnel (railway line Erfurt - Halle/Leipzig)

The expert assessment „Additional elaboration of the karst zone problem and of tunneling classes" on the railway line Erfurt – Leipzig/Halle – Osterberg Tunnel (Kirschke, 2007) reports that the geophysically and geotechnically detected sinkhole structure along the path of the tunnel tubes had not been sufficiently accurately explored. That is why the exact three-dimensional structure of the sinkhole and its effect on the tunnel excavation process were determined through an additional geoelectric survey which will be presented here. The previous exploration had provided a rough estimation of the sinkhole's dimensions, so the complementary geoelectric measurement scheme in 2008 and 2009 could be adapted optimally to meet the criteria of a detailed 3D survey. Fig. 5 shows the anomaly detected during the previous exploration with an extent of 80 m to 100 m parallel and about 60 m to 80 m perpendicular to the tunnel axis.

The geoelectric survey was planned as a combination of 2D tomographic profiles along and across the tunnel axis. Geoelectric measurements are perfectly suited for the solution of this survey challenge as the anomaly contrast between intact non-karstified or non-eroded limestone and a large scale karst zone (sinkhole) is large and can thus be measured with great certainty. The geoelectric survey routine simultaneously records profiling and sounding measurements along profile lines so the subsequent data analysis and inversion routines produce a detailed map of the resistivity distribution of the investigated subsurface.

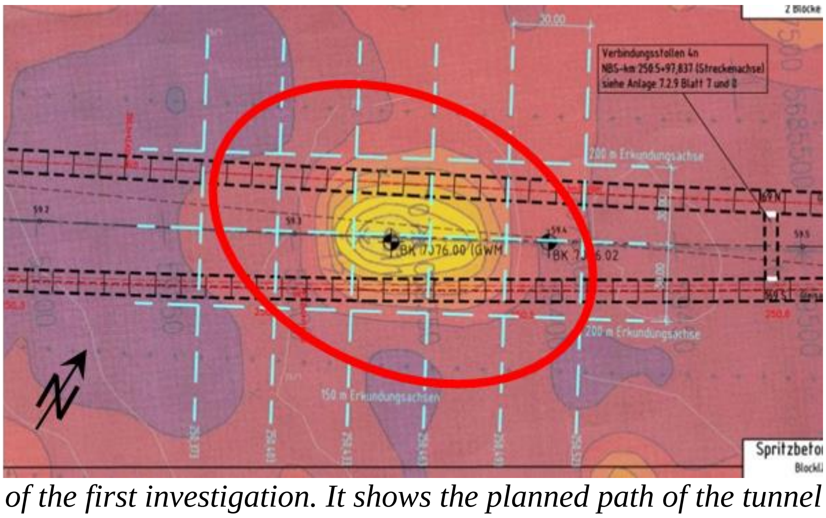

Fig. 5 Results of the first investigation. It shows the planned path of the tunnel tubes (black dashed lines), the geoelectric low resistivity anomaly (yellow), the location of two core drillings (black circles) and the planned geoelectric profiles (cyan dashed lines).

At the Osterberg Tunnel the planned number of three profiles along and six profiles perpendicular to the tunnel axis was carried out. The profile lines were spaced 30 m from each other. The placement of the electrodes was chosen in a way that assured the coverage of an area of 200 m (NE-SW) by 150 m (NW-SE) at a survey depth of 50 m below the terrain. For an optimal resolution of the (nearly) vertical boundaries of the sinkhole an electrode configuration after Schlumberger was chosen. The results of the first measurements gave cause for two additional crossing profiles, reducing the lateral distance between profiles from 30 m to 15 m. The aim of these complementary profiles was to detect the exact boundaries of the sinkhole at the level of the two tunnel tubes at the demanded accuracy of 5 x 5 m.
Fig. 6 (left) shows the resulting resistivity distribution along the 2D cross profiles. The sinkhole features a much lower electric resistivity (blue to green areas) compared to the surrounding rock. The spatial dimension of the sinkhole has a relatively small extent as seen in the geoelectric data between TM 504 and 564.

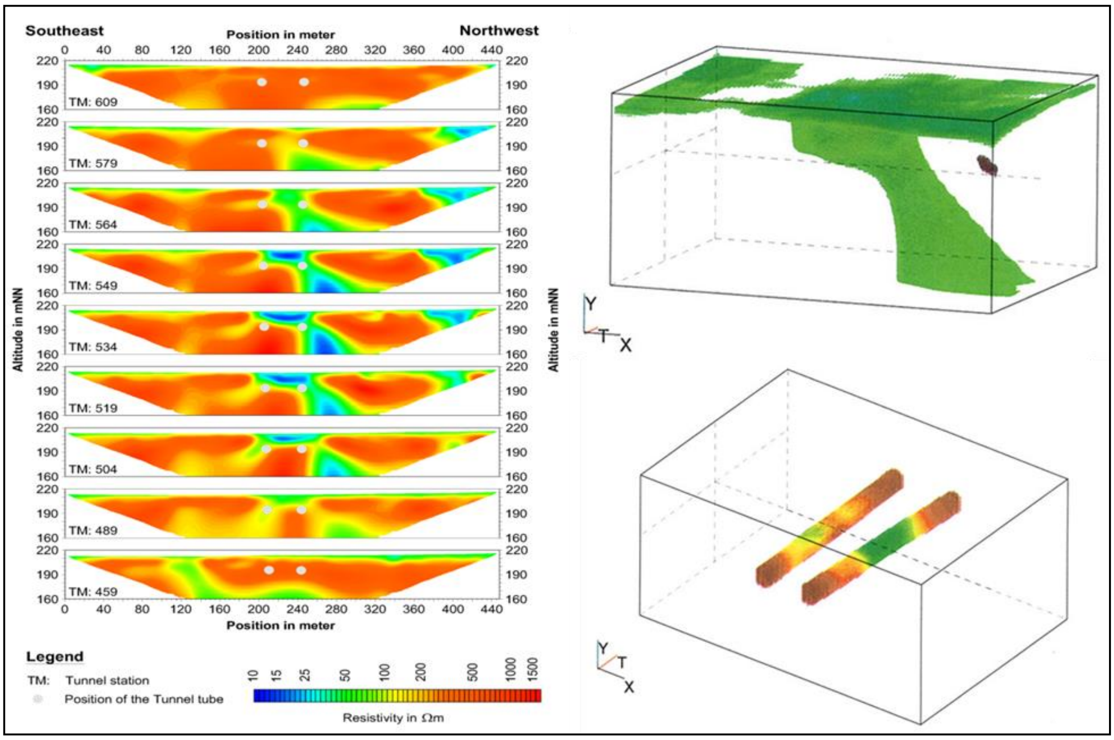

Fig. 6 Inversion results along the geoelectric tomography profiles perpendicular to the tunnel axis (left) with lightly colored circles representing the path of the tunnel tubes. The calculated three dimensional extent of the sinkhole is seen on the right.

The geoelectric data were processed and presented with a 3D visualization software that was particularly developed for this project, so the coordinating construction syndicate of the tunnel was able to assess the influence of the sinkhole on tunnel excavation at all times and to subsequently reduce risks and hazards by appropriate safety and stabilization measures. Fig. 6 (right) shows two 3D visualization examples of the sinkhole. The upper image presents the spatial shape of the whole sinkhole structure. The lower image shows the location and extent of the anomalous zone of the sinkhole within the projected path of the tunnel tubes. For both tubes the boundaries between intact rock and karstified, partly unconsolidated rock of the sinkhole could be estimated with great certainty. According to the data the northern tube was affected much more by the sinkhole than the southern tube.

During the following excavation of the Osterberg Tunnel the results of the geophysical survey were confirmed by detailed geological tunnel face investigations which showed a high conformity with the predicted location and extent of the sinkhole structure in both tubes, as documented in the official construction report of the project. The remarkable advantage of this geophysical prospecting technology was that the survey was executed and completed before and entirely decoupled from the tunnel excavation and thus posed no negative influence or restriction to the tunnel construction process.

4 Expansion and new construction of the railway line Augsburg - Ulm

As part of the expansion and new construction project of the railway line Stuttgart – Augsburg two new tunnels are being built on the railway line segment Wendlingen – Ulm in the area of the steep climb up the Swabian Mountains (Schwäbische Alb), namely the Steinbühl Tunnel and the Boßler Tunnel. Both tunnels cross the geological formation of the White Jurassic which is prone to variable grades of karstification (Fig. 7). Both tunneling projects involved geophysical surveys with different objectives.

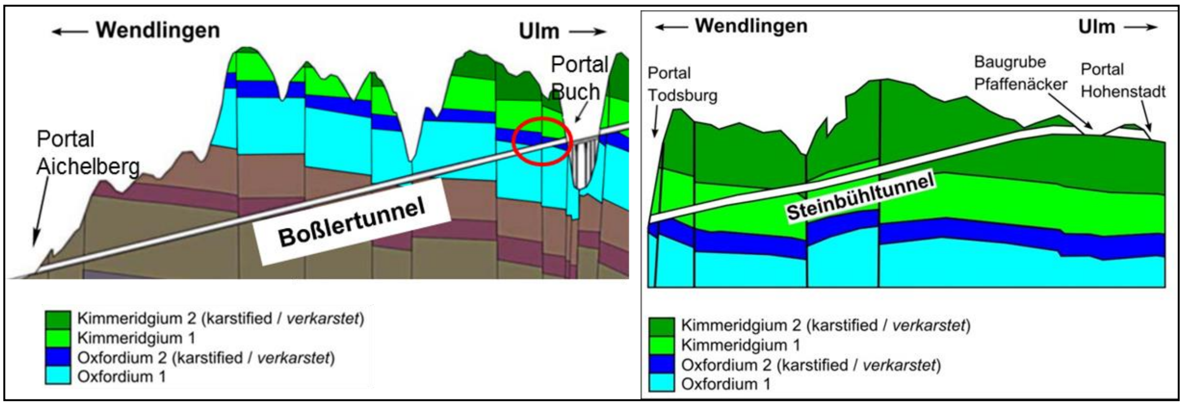

Fig. 7 Geological situation in the area of the Boßler Tunnel (left) and Steinbühl Tunnel (right, adapted after Kirschke, 2007).

4.1 Steinbühl Tunnel

As part of the excavation process of the two tubes of the 4.8 km long Steinbühl Tunnel a comprehensive karst investigation of the geological formation of the White Jurassic (Kimmeridgian 2, lower reef limestone, Kimmeridgian 1 and Oxfordian 2) was demanded. Especially the geological strata of the Kimmeridgian 2 (ki2) and Oxfordian 2 (ox2) are classified as prone to karstification (Breidenstein, 2013; Koslowski, 2014).

The karst exploration of the Steinbühl Tunnel included two investigation phases. Phase 1 featured an investigation by drilling during the excavation process, led by the construction syndicate. Phase 2 happened after the excavation of roof, bench and floor but before placement of the tunnel lining, and included both a systematic drilling investigation and a comprehensive geophysical survey of the rock mass around the excavated tunnel. Goal of the survey was to detect air-filled or clay/debris-filled karstic cavities larger than 1 m³ in the direct vicinity of the tunnel tube. For that purpose survey depths of 15 m were demanded between and below the tubes. Above and beyond the outer sidewalls of the tubes 10 m were demanded.

The geophysical survey combined both RX and CH measurements with borehole radar (compare chapter 2) with microgravimetry measurements in an unprecedented innovative exploration concept. Borehole radar measurements were used for the detailed investigation of the whole rock area surrounding the tubes, while the microgravimetry measurements served as an additional method to investigate the rock mass underneath the floor of the tunnel.

Borehole radar measurements were taken along six boreholes drilled radially around the tube at equidistant cross sections along the tunnel as seen in Fig. 8 (left). In accordance with the demanded investigation depth the boreholes were over 10 m and 15 m long respectively. The distance between the cross sections was 15 m. RX measurements were taken in each borehole (6 per cross section), while CH measurements were taken between all neighboring boreholes within one cross section as well as between one and the next cross section (12 per cross section). This concept ensured the complete spatial coverage of the tunnel bedding that had to be investigated with radar. Localization of karstic structures was possible through the combined analysis of radar wave travel time or velocity anomalies in the CH data and identified reflections in the RX data.

Microgravimetry measurements (Fig. 8, right) were taken on the tunnel floor along four equidistant profiles parallel to the tunnel axis at a station interval of 2 m. Distance between the profiles was 2 m, as well. The gravimetric survey served as an additional coverage of the rock mass beneath the floor of the tunnel tubes.

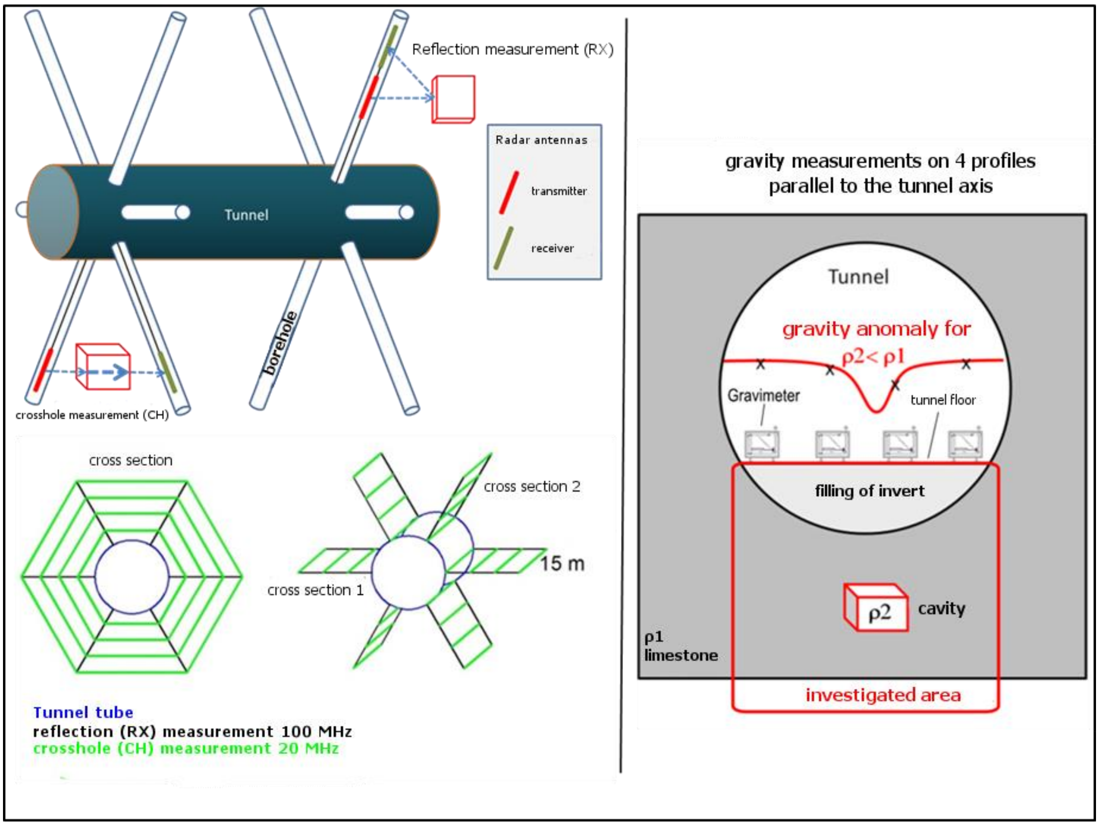

Fig. 8 Exploration concept in the Steinbühl Tunnel with schematic of the cross section investigated via radar measurements from radial boreholes (left). Measurement and exploration concept of the microgravimetric measurements (right).

A gravimeter records minute differences in the Earth's gravitational pull using a sophisticated system of a mass suspended on a spring. The measured differences of this force between different locations allow an estimation of the distribution of masses in the subsurface and thus the distribution of the petrophysical parameter density ρ. Generally microgravimetry has been successfully applied in structural investigations, mineral exploration (preferably salt deposits) and possible air-or clay/debris-filled cavities in areas prone to subrosion. In tunneling areas of unconsolidated rock below the tunnel floor (like hollow or partly filled cavities) cause gravitational minima in the microgravimetric data (Fig. 8, right).

In the karst prone rock formations ki2 and ox2 along both tubes of the Steinbühl Tunnel a total of 443 tunnel cross sections were investigated via borehole radar and 5496 m were covered with microgravimetric measurements.

Complex three-dimensional data analysis of the recorded borehole radar measurements (radar wave velocity anomalies and reflections) facilitated the identification of a great number of karstic structures, while air-filled and clay/debris-filled structures could be differentiated clearly. Microgravimetric data provided a map of the local gravity field where negative gravity anomalies indicated an area of lower density below the tunnel floor. These anomalies served as the basis for further modelling of location, size and density of karstic structures.

Fig. 9 shows the positive radar wave velocity anomalies in several CH measurements (upper graphs) and the negative gravity anomaly (lower left gravity map) that led to the identification of a karstic cavity beneath the tunnel floor around TM 305 close to the southern tube of the Steinbühl Tunnel. Targeted verification drillings confirmed the existence and exact location of a hollow karst structure in great concordance with the geophysical prediction, as seen in the drilling log data (lower right).

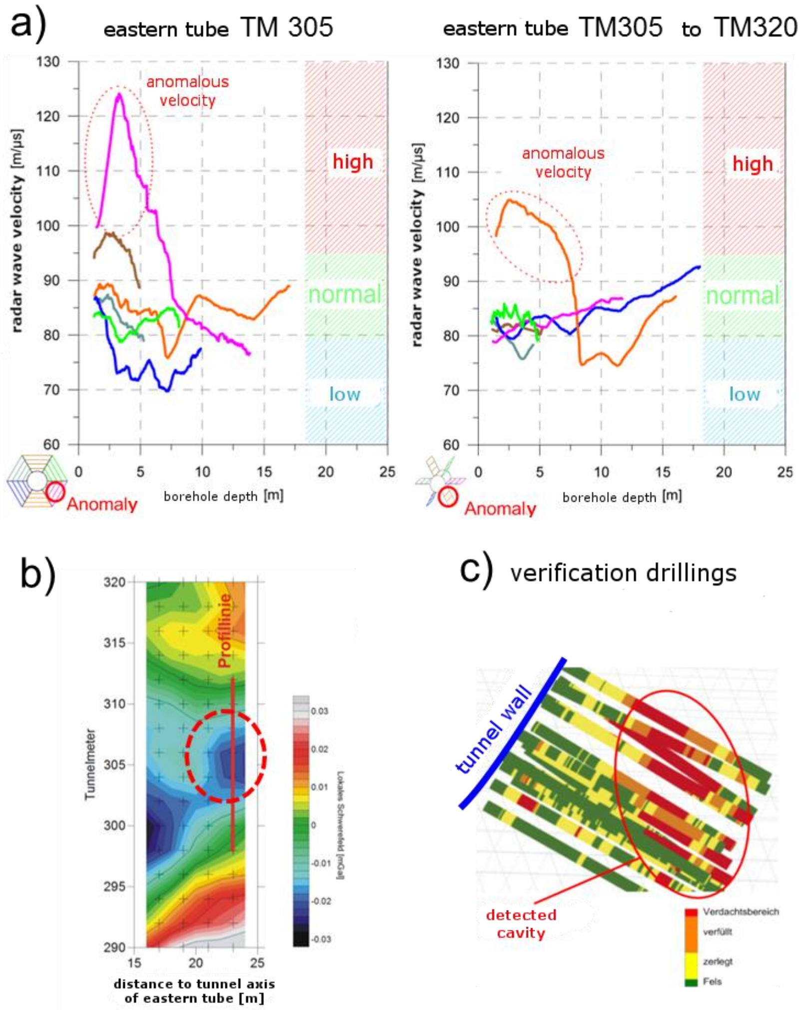

Fig. 9 Exemplary results of the geophysical measurements in the Steinbühl Tunnel. a) shows the radar wave velocities of different crosshole radar measurements at one cross section (TM 305) and between two cross sections (TM305 – 320), with the anomalously high velocities marked. b) shows the local gravity field obtained from microgravimetric measurements with the negative gravity anomaly circled. c) shows the results of the ensuing verification drillings that confirmed existence and location of the karstic cavity.

Along the length of the two tubes of the Steinbühl Tunnel a total of 522 karstic structures were identified by geophysical exploration. Of the 284 structures classified as air-filled 191 had to be verified by drillings and filled with concrete for static reasons. 170 of the karstic structures were confirmed in approximate size and location, while 21 structures were not encountered, most likely due to their small dimension. This translates to a success ratio of about 89 %.

The results of this innovatively comprehensive geophysical survey at the Steinbühl Tunnel attest to the great insight that can be gained by an efficiently adapted measurement concept combining borehole radar and gravimetry. In addition to fully covering the rock mass surrounding the tubes as demanded, karstic structures were accurately predicted in location, approximate dimension and filling.

4.2 Boßler Tunnel

The Boßler Tunnel featuring a full length of 8.8 km crosses the rock formations ki1 and ox2 on the first 350 m starting from the portal Buch (Fig. 10, red marking at the lower left). In order to decide if the tunnel can be safely excavated with a TBM a geophysical survey was to determine the karstification grade of the respective strata. Objective of the investigation was the assessment of the surrounding rock with respect to the existence and extent of possible fault zones and karstic structures. The investigation was to be conducted before the tunnel excavation began.

For this purpose two nearly horizontal boreholes were drilled from the portal Buch to a length of 350 m in the direction of the projected tunnel tubes. Besides drill core analysis RX and CH radar measurements were taken. This exploration concept of a radar investigation from a portal and thus decoupled from the excavation process has been unprecedented. Drill core analysis provided a rough glimpse into the lithology to be encountered by the projected tunnel tubes.

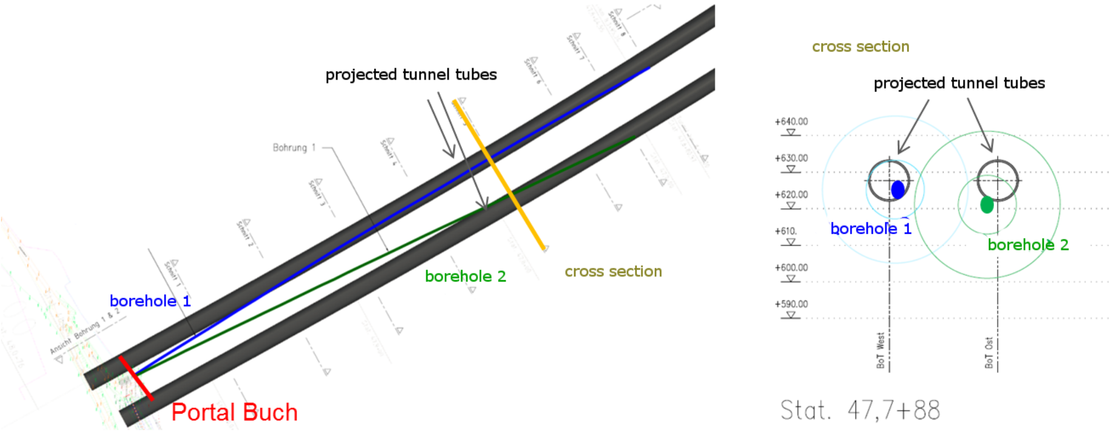

Fig. 10 Schematic of the boreholes along the path of the tunnel tubes of the Boßler Tunnel, topview (left) and front view (right).

Both boreholes were used for RX measurements and a CH measurement between the two. Analysis of the geophysical data and drill cores showed that no large karstic structures had to be expected in the bedding of the tunnel tubes within the rock formations ox2 and ki1. However, several fault zones were encountered along the 350 m drill paths. The section between a depth of 175 m and 295 m showed a greater number of reflections in the RX data indicating a more severely disturbed rock zone. Fig. 11 shows an example radargram of the RX measurement in borehole 2 with markings around areas of stronger radar reflectivity. The results of the CH measurements between both boreholes showed no radar wave velocity anomalies that would indicate air-filled karstic cavities within the covered rock mass.

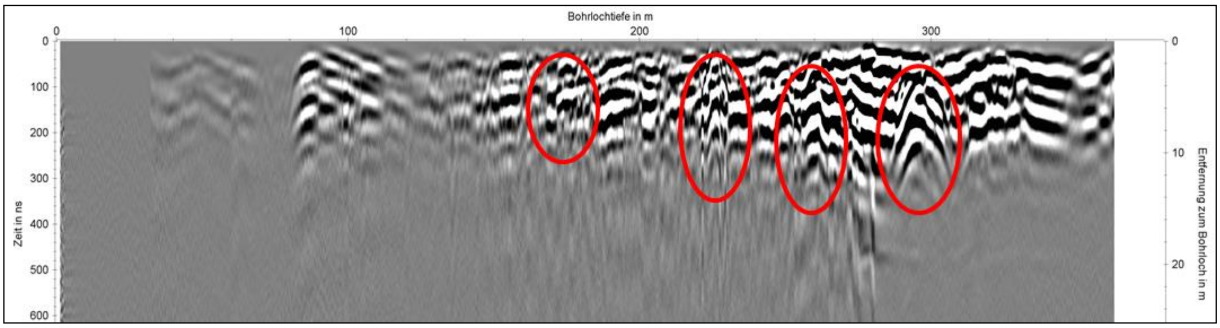

Fig. 11 Radargram of a RX measurement in borehole 2 as part of the geophysical karst exploration at the Boßler Tunnel

5 Conclusion

Through several tunneling projects the company Bo-Ra-tec GmbH has successfully introduced innovative geophysical survey concepts for the detection of karstic structures into tunneling practice. Geophysical methods offer a high efficiency in the detection of fault and karst zones in tunneling as they provide an extensive three dimensional structural investigation of rock formations when combined with targeted verification drillings.

At the Katzenberg Tunnel, part of the railway line Karlsruhe – Basel, borehole radar technology was applied for the first time in world-wide TBM tunneling history as an online measurement from the earth pressure balance shield simultaneously to the excavation process. The results of the geophysical data allowed an almost immediate assessment of the karstification grade of the rock mass ahead of the tunnel excavation already during the measurement. Fissures, faults and karstic structures could be accurately located up to a distance of 20 m around the tunnel tubes.

At the Osterberg Tunnel, part of the railway line Erfurt – Halle/Leipzig, a detailed 3D geoelectric survey of a sinkhole was conducted independently of the tunnel excavation process. The geophysical data delivered an accurate account of the sinkhole's location and its boundaries so its influence on the tunnel tubes could be assessed. Detailed geololgical tunnel face analysis during the following excavation process confirmed the geophysical results with high concordance.

At the Steinbühl Tunnel, part of the railway line Wendlingen – Ulm, an unprecedented, innovatively comprehensive karst exploration survey was conducted to investigate the rock mass surrounding the tunnel tubes up to a radial distance of 15 m. A combination of radar reflection and crosshole measurements with microgravimetry measurements facilitated the accurate detection of karstic structures larger than 1 m^3 within the covered investigation area. Especially the identified air-filled karstic cavities were later verified by targeted drillings and showed a high concordance of about 90 % in predicted location and dimension.

The unprecedented karst exploration concept at the Boßler Tunnel, part of the railway line Wendlingen – Ulm, featured a radar investigation from two horizontal boreholes drilled from a portal before the excavation process. An accurate assessment of the rock mass with respect to existence and extent of possible fault zones and karstic structures was possible based on the geophysical data.

The application of innovative and particularly adapted geophysical exploration concepts has in all cases contributed significantly to a safe excavation process and subsequent operation of the tunnels presented.

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