The paper was published in the proceedings of 10th International Symposium on Field Measurements in Geomechanics and was organized by Prof. Pedricto Rocha Filho.

The conference was held in Rio de Janeiro, Brazil, on July 16-20 2018.

FMGM 2018
INTERNATIONAL SYMPOSIUM ON FIELD MEASUREMENTS IN GEOMECHANICS
Rio de Janeiro - PUC-Rio, 16-20. July | 2018

Detection of Cavities in Karst Subsoil Affecting Civil Engineering Structures by Means of Geophysical Measurements

Regina Kauther
Federal Waterways Engineering and Research Institute, Karlsruhe, Germany,
regina.kauther@baw.de

Cornelia Wolf
Federal Waterways Engineering and Research Institute, Karlsruhe, Germany,
cornelia.wolf@baw.de

SUMMARY: The Hessigheim navigation lock is located in a karst region where the underlying rock formation is locally dissolved by groundwater flow, converting the rock into soil or causing cavities and occasionally also leading to sinkholes. Geodetic surveys, undertaken on a regular schedule, meanwhile indicate unacceptable displacements for considerable parts of the civil engineering structure as a consequence of the leaching processes. These deformations are expected to be progressive. Typically for karst topography the stratigraphy changes with time thus re-investigation of the ground is required occasionally. To explore the current state of stratigraphy and to improve understanding of the soil-structure interaction a large ground investigation program has been carried out recently. Besides using conventional field investigation tools like drillings and probings the program was particularly designed to determine the properties of the subsoil near the boreholes by geophysical measurements (gamma-gamma, gamma ray, full wave sonic log) and in-between the boreholes by classic and tomographic crosshole seismic measurements. By analyzing a total of 46 vertical wave velocity profiles, the main objectives were to localize existing cavities and to determine their size and filling. In this paper the scope of the investigation program as well as selected results are presented. Difficulties and benefits of the additional geophysical measurements are discussed. It is also intended to use these measurements for future monitoring of (potential) subsoil changes.

KEYWORDS: karst, crosshole seismic measurements, geophysical measurements

1 INTRODUCTION

Geotechnical investigations shall be planned in such a way as to ensure that relevant geotechnical information and data are available at various stages of a project. Geotechnical information shall be adequate to manage identified and anticipated project risks (according to EN 1997-2:2007). To meet these requirements, the site investigation needs to be configured according to the specifics of the site.

In this case study, an extensive investigation program in difficult karst subsoil conditions is presented. The program comprises direct and indirect investigation methods as well as geophysical and seismic measurements. Geotechnical engineers as well as geophysicists are engaged in the study. It is shown that no single method will provide answers to all the questions associated with localizing existing cavities, determining their size, extension and filling but considerable improvement can be achieved by applying several methods and by combining their results.

2 HESSIGHEIM NAVIGATION LOCK

The Hessigheim lock structure is situated on the river Neckar north of Stuttgart, Germany. Lock #1, weir and powerhouse were constructed in 1950/51. Lock #2 was added about ten years later. The community of Hessigheim at the right bank of the river is located directly adjacent to the locks. Each lock chamber's usable length is 110 m with a clear width of 12 m and lifting height of 6.2 m. A powerhouse, a small residential area and several greenhouses can be recognized on the left bank of the river in Fig. 1.

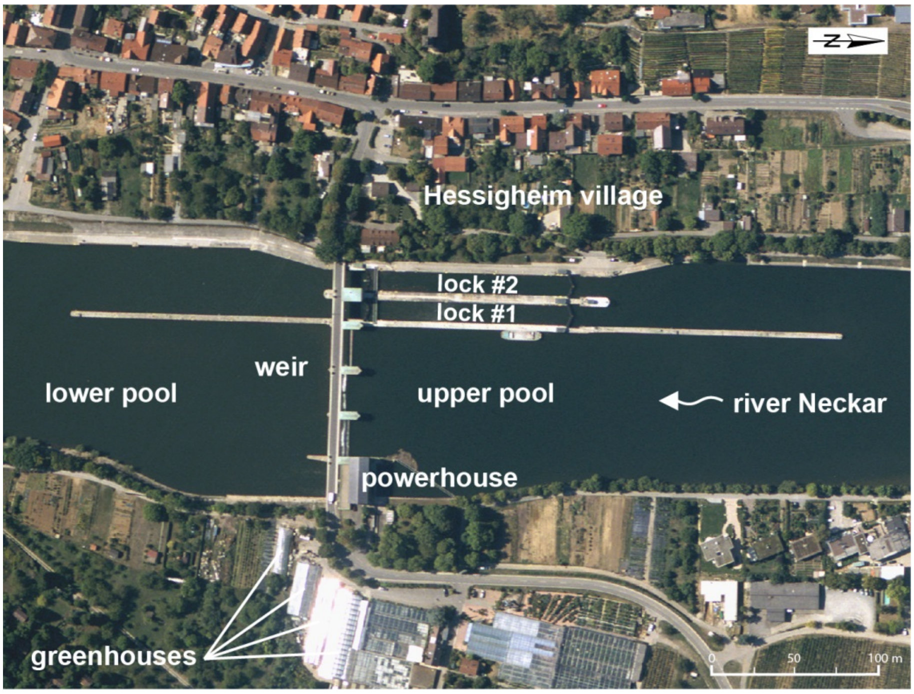

Figure 1. Aerial view of the Hessigheim lock structure and vicinity.

Rocks of the so-called Middle Muschelkalk (mm, shell-bearing limestone) are found in the Neckar basin in the Hessigheim area. A simplified cross-section (together with the structure of the upper gate of the second lock) showing the local subsoil conditions is depicted in Fig. 2. From bottom to top a lower sulphate layer and a lower dolomite layer can be differentiated, which is overlain by a rock salt deposit. The following upper sulphate layer is composed of an upper and lower clay anhydrite layer, divided by a distinctive layer of intermediate dolomite of only a few metres of thickness. Above the rock, soil layers exist, consisting of river gravel ("Neckar gravel") and fill. According to lab tests the upper clay anhydrite consists of 87 % to 99 % $CaSO_4 \cdot 2H_2O$ (gypsum) and the lower clay anhydrite of 67 % $CaSO_4 \cdot 2H_2O$ on average. As a consequence, because of the solubility of gypsum in water the upper clay anhydrite is strongly weathered in large parts, leached and comprises numerous cavities. The weathered upper clay anhydrite consists of cohesive material with soft to stiff consistency resting on the leached karst base level and is called residual clay. Such underground conditions are prone to form sinkholes, which occasionally occured in the Hessigheim area before, during and after the installation of the lock structures. Such sinkholes tend to develop over many years until final breakdown.

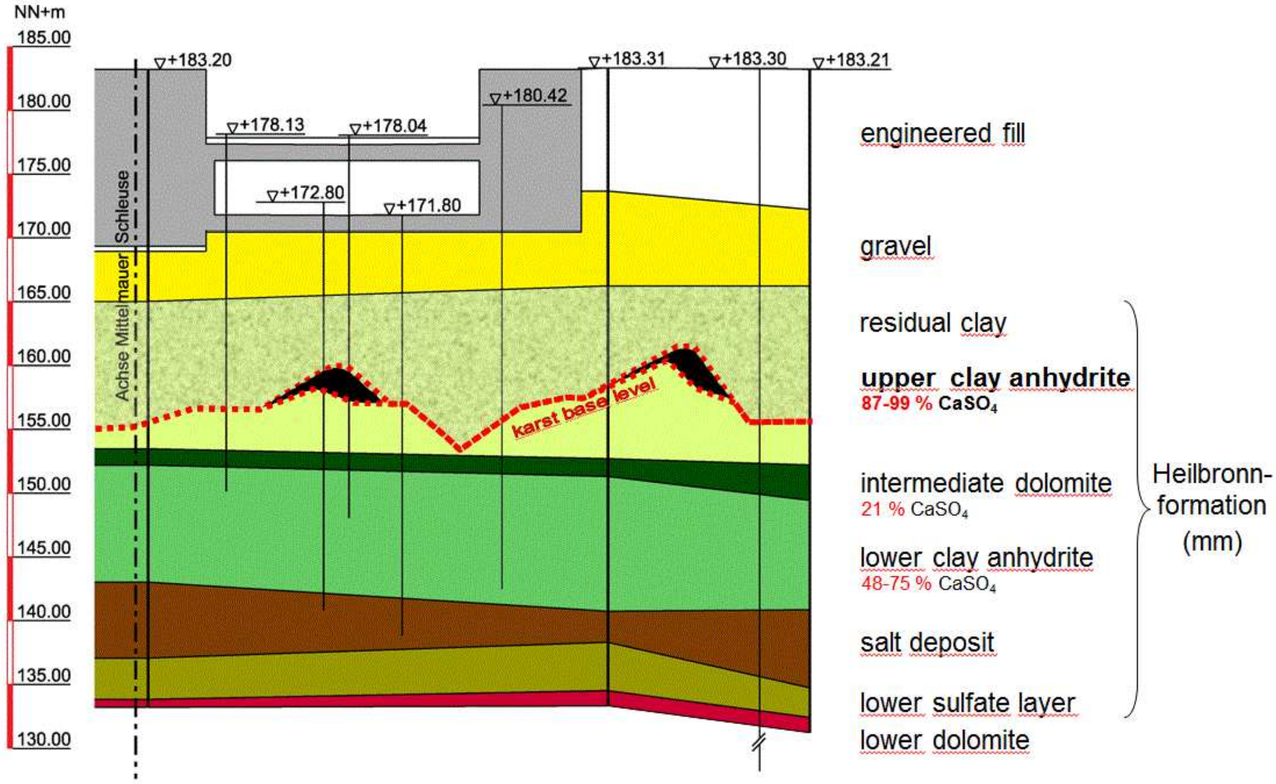

Figure 2. Characteristic geological cross-section.

Since construction, the leaching processes in the subsoil have led to considerable displacements of the lock structure. In the 1980s the lock structure was eventually completely rehabilitated by grouting the underground cavities with cement slurry underneath the locks, weir and powerhouse. Background information on the entire project is provided in Bergholz et al. 2011.

As a consequence of the leaching processes the civil engineering structure has been extensively monitored since 1970. The monitoring program consists of groundwater observations, vertical and horizontal geodetic measurements as well as extensometer measurements, all performed at least at yearly intervals. While potentially damaging displacements stopped directly underneath the lock structures due to the rehabilitation measures, continuous leaching seems to progress in the proximity of the grouted areas. In 2005 irregular displacements were detected at the landward walls of the right upper head of lock #2. Analysis of all available geodetic data revealed further parts of the lock with ongoing deformations such as a settlement trough landwards of the chamber wall of lock #2, continuous settlement and tilting of the concrete wall upstream of the upper head and continuous settlement and tilting of the powerhouse. Despite of the fact that the displacements are still in the range of millimeters further investigation seemed to be necessary.

Since considerable settlements and small sinkholes are also being observed in the vicinity of the lock structure where no geodetic data was available, the InSAR (Interferometric Synthetic Aperture Radar) technique as a proven remote sensing tool was used additionally for the detection of extent and development of possibly forming leaching zones and sinkholes. As a result InSAR information yielded the extent of a further presumed leaching zone at the greenhouses and at the sheet pile wall on the western side of the upper pool. InSAR data processing and evaluation is described in detail by Kauther & Schulze (2015).

After localization of the areas, where further site investigation was required, a comprehensive ground investigation program was set up. The main objectives of the soil investigation program were to:

- explore the current state of stratigraphy
- compare the current state with that based on previous drilling campaigns
- detect possible cavities in the subsoil
- get an estimation of their extent and filling.

Based on the findings the engineering questions to be answered were to:

- improve understanding of the soil-structure interaction, in particular the risk for the development of sinkholes
- be able to design ground improvement measures to maintain operational areas (where necessary)
- be able to design geotechnical and geohydraulic countermeasures to minimize further leaching processes
- derive (integral) elasticity parameters of the intact rock in the lower clay anhydrite layer, because lab tests are not feasible.

3 SOIL INVESTIGATION PROGRAM

In order to provide best information about the karst subsoil, geophysical and seismic testing was applied in addition to conventional site investigation tools such as drillings and cone penetration tests. The advantages of geophysical measurements are that they are nondestructive and less expensive than direct drilling. As they also capture the ground integrally, it is possible to overcome the random sample characteristic of the direct methods. Discussing options concerning the site in Hessigheim it turned out that only seismic and geophysical borehole measurements would be promising. Other geophysical methods had to be excluded due to site conditions as well as the assumed size and depth of the cavities. Structures like sheet pile walls adjacent to the area of interest eliminate all kinds of electromagnetic methods. Microgravity and electrical resistivity measurements lack the required resolution. The ground penetration radar is limited by its penetration depth. Detailed information about the methods and their selection can be found in McCann et al. (1987) and GGU (2011).

3.1 Conventional investigation program

The conventional ground investigation program consists of 59 drillings and 15 CPT tests. Investigation points were basically located where noticeable displacements had been detected by geodetic levelling and/or using the InSAR technique or could be verified by observation in the area of the lock structure and its vicinity.

In areas where the boreholes are planned to be used for seismic testing, the spacing between two boreholes was 5 m to 16 m in order to get suitable results (Butler & Curro, 1981). For the purpose of sampling, a percussive core drilling technique with a percussion clay cutter with cutting edge inside is used in the soil layers. The outer diameter of the casing was 219 mm. Rock samples are gained by applying the wireline core drilling method with triple tube core barrel, where the inner barrel is extractable and the outer barrel remains in the borehole as casing. The outer diameter of the outer barrel was 146 mm. Using the wireline core drilling technique a flushing medium (here water) was used. The depth of most of the drillings was 45 m and the diameter of the soil and rock samples was 100 mm. The selected drilling tools allow an achievable sampling quality category "A" according to EN ISO 22475-1:2006 (characterized by no or only slight disturbance of soil or rock structure). Most of the CPT-tests were not able to penetrate deep enough into the gravel layer; therefore the depths of the tests are limited to a maximum of approximately 10 m. A ground plan of the site (Fig. 3) shows the investigation points marked with black dots and also indicates four areas where geophysical and seismic testing took place as well. In these areas drillings are concentrated to meet the requirements for seismic testing.

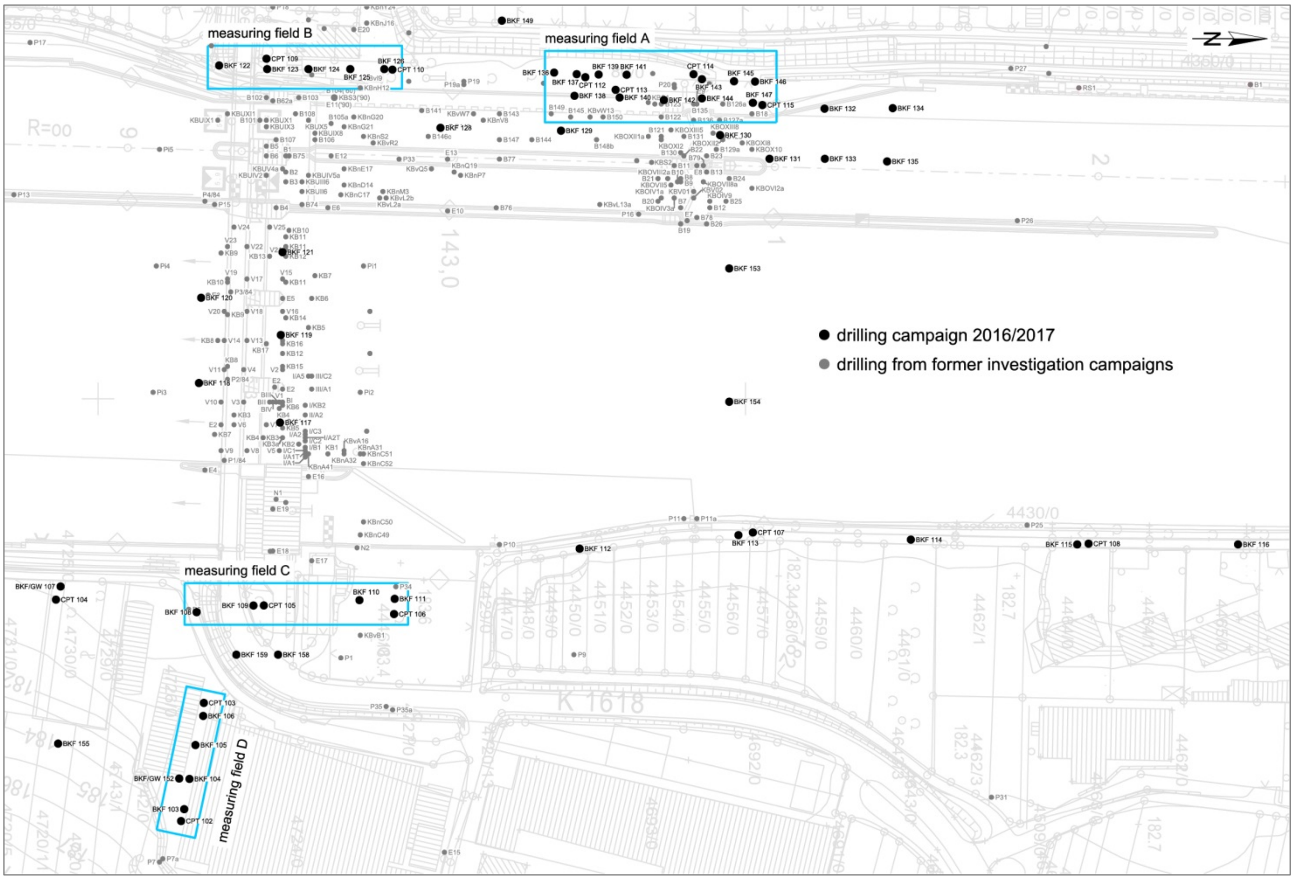

Figure 3. Ground plan of the site with measuring fields for geophysical investigation, marked with a turquoise frame.

As a result of the drilling campaign, it was possible to generally verify the soil stratigraphy depicted in Fig. 2, but it had to be noticed that the rock has almost dissolved in the layer of the upper clay anhydrite. Meaning that the karst base level in the areas of measuring fields "A", "C" and "D" has lowered significantly, partly down to the intermediate dolomite layer. Observing sections of "no resistance" while lowering the core barrel, hardly any soil could be extracted and substantial core losses were logged in this layer. Additionally, drilling records also mention a total loss of the flushing water in most of the drillings when reaching this layer. Both observations indicate a system of greater and/or smaller cavities in a range from 1 to 10 m (accumulated loss of cores) in one borehole. Neckar Gravel and remaining rock boulders that migrated from above were found in the cores down to the depth of the intermediate dolomite layer, indicating that most of the cavities are also connected. Furthermore the intermediate dolomite layer was detected in a reduced thickness particularly in the area of measuring field "A", but relevant leaching of the lower anhydrite layer has not started yet. Areas where cavities were detected are identical to areas where displacements at the structures or in their proximity had been measured, showing a direct and strong soil-structure-interaction. The same is valid for the drilling results in the area of measuring field "B". In areas where no settlements had been identified, almost no core losses had occurred during drilling.

An attempt to inspect the ground in situ was also made by scanning the borehole wall using an optical and acoustical televiewer after completing the drillings and extracting the core barrel. Borehole televiewing can provide a picture of the subsurface where all structural features of the rock formation are still in their original position. Using this technique a stable borehole wall is required and the borehole must be filled with clear water. In spite of great effort, these conditions existed only in few locations. In most of the inspected drillings, the borehole wall collapsed, subsequently filling the borehole with soft ground material up to 20 m. Caliper measurements down to this depth show that the borehole has considerably widened in the leached rock layer above. In Fig. 4 an image of a borehole wall is provided. The remaining gypsum rock and a cavity filled with silty material can easily be recognized.

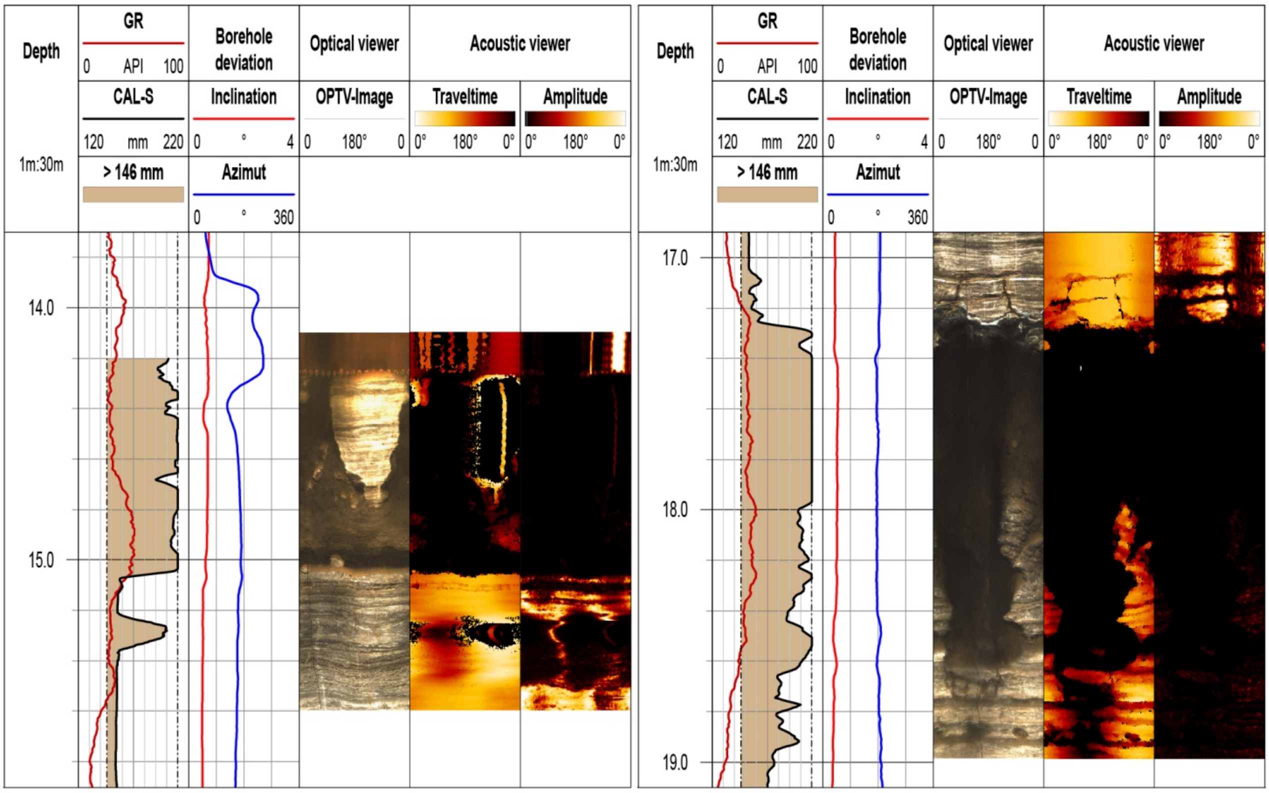

Figure 4. Scan of borehole wall representing a cavity and silty filling in the layer of the upper clay anhydrite (depth 14.1 to 18.9 m below ground surface), source: BLM report, 2017.

As drillings, can be regarded as random samples, crosshole seismic measurements were carried out to explore the ground in between the drillings. The primary purpose of obtaining crosshole data is to get the most detailed in situ seismic velocity profile for additional material characterization. For this site, crosshole testing is also performed to detect anomalies in the soil and rock layers, which could be interpreted as cavities and possibly get an estimation of their distribution and their horizontal extent.

3.2 Geophysical investigation program

All seismic and geophysical measurements were performed in boreholes stabilized by casings. The boreholes are prepared for seismic testing by widening the diameter of the drilling to 219 mm down to the bottom of the borehole. After the drilling is completed a 100 mm PVC pipe is inserted. The annular space between the borehole wall and the pipe is then filled flush with grout. Measurements of the inclination (2-axis) of the borehole were carried out to determine the actual horizontal distance between the boreholes to be used with the crosshole and tomographic measurements.

3.2.1 Classic crosshole seismic measurements

For crosshole seismic measurements the seismic source and receiver are lowered to the same depth in two adjacent boreholes. Therefore the crosshole seismic measurement is assumed as a horizontal transmission of the subsoil. The source generates seismic waves that travel through the material in between and are then recorded by the receiver in the other borehole. From the picked first arrival times of the waves, the depth dependent profile of the mean seismic velocities in between the drillings can be determined. Since the seismic wave velocities are affected by the elastic properties and the density of the soil, their values reflect the material of the geological stratigraphy and provide information about the structure of the underground. Anomalies such as cavities in rock material cause the ray path to travel around the cavity resulting in lower apparent wave velocities (Fig. 5).

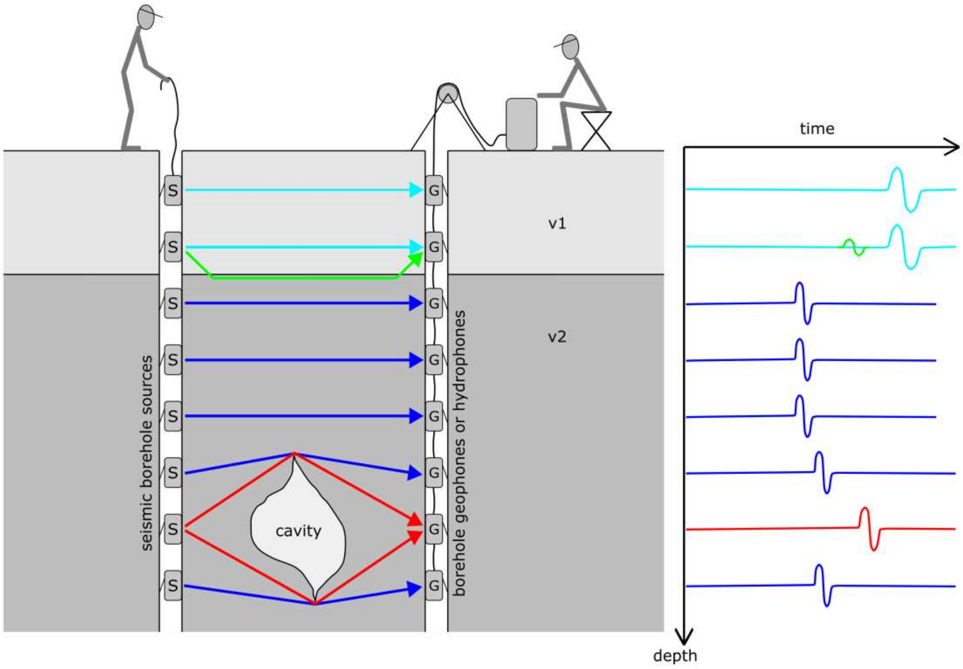

Figure 5. Principle of crosshole seismic measurements, according to GGU.

The crosshole seismic measurements were carried out for both compressional and shear waves (P- and S-waves) in all four measuring fields “A”, “B”, “C” and “D” which results in a total of 36 vertical measuring planes. In most cases, the distance between the drillings is smaller than 15 m. The vertical measuring interval is 1 m. A sketch of the measuring planes in measuring field “A” is given in Fig.6.

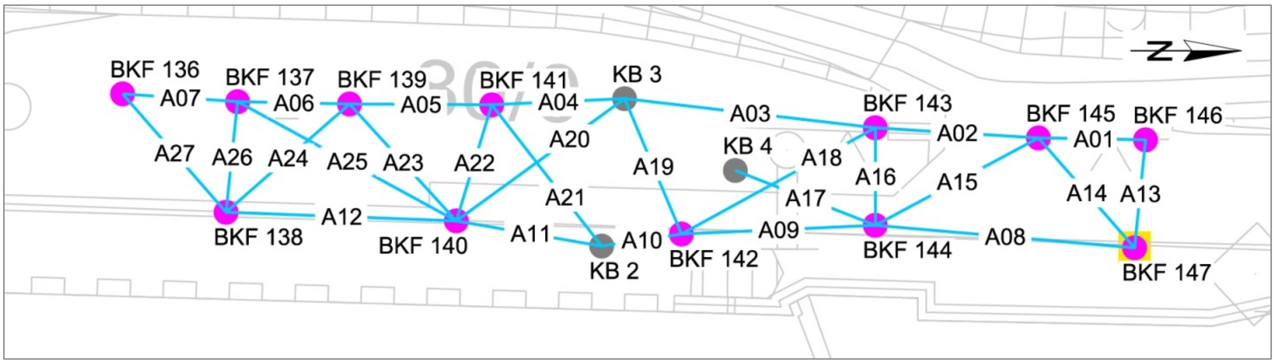

Figure 6. Sketch of measuring planes (measuring field "A").

An electromagnetical borehole source (type BIS-SH by Geotomographie GmbH) that generates horizontally polarized shear waves as well as compressional waves with frequencies up to 4 kHz was used. The applied borehole geophones (10 and 15 Hz resonance frequency) consist of one vertical component and 4 or 6 (semi-) circular arranged horizontal components respectively. The signals were recorded with a sampling rate of 32 kHz and a digital resolution of 24 bit.

In order to determine the seismic wave velocities the first arrival times of both wave types have to be picked manually for each recorded signal. A seismogram section of classic crosshole measurements in field "A" can be found in Fig. 7.

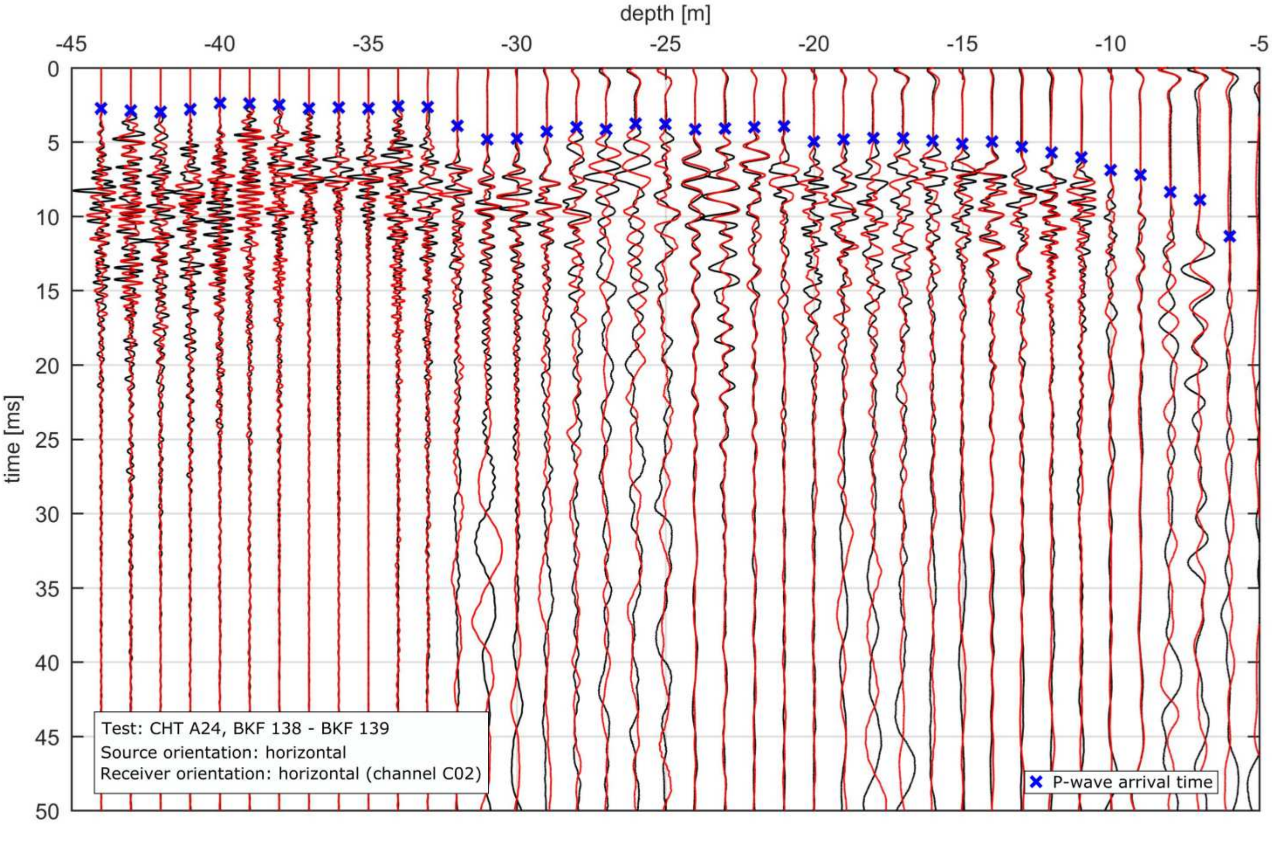

Figure 7. Example of seismic signals recorded in measuring field "A" with picked P-wave arrival times.

Considering measurements in the deeper areas where rock is expected, a good data quality was observed in most cases, which allowed clear wave identification. However, in the upper measuring depths, sometimes poor signal quality was found, which made the accurate picking of the arrival time or actually the identification of the shear wave difficult and even failed in some cases.

Several factors may cause poor data quality and hence affect the reliable shear wave picking and identification:

- In contrast to the primarily arriving P-waves, the S-waves arrive considerably later. Therefore the first arrival of the S-wave is covered by disturbing waves and much more filtering has to be done.
- For long distances between source and receiver the seismic energy is highly attenuated and scattered, which leads to smaller amplitudes in the recorded signal and hence to a poor signal to noise ratio. This specifically applies to the wave propagation in loose sediments where the attenuation and scattering is the highest.
- The correct coupling of the seismic source as well as the receiver to the surrounding material is very important to ensure the transfer of the whole energy from the source into the soil and then from the soil to the receiver. Therefore, the correct grouting of the boreholes is important when a PVC pipe is inserted.
- Another factor leading to difficult shear wave identification is the structure of the underground. Inhomogeneities such as boundary surfaces, cracks and/or cavities lead to reflection and refraction of the seismic waves which results in a complex wave field where it is extremely difficult to distinguish the different wave types.

Since the first arrival of the compressional wave corresponds to the first significant amplitude of the signal, its clear identification is much easier and could be determined for all classic and tomographic crosshole measurements. The only difficulties occurred above the groundwater table where damping is extremely high.

As an example Fig. 8 shows the shear and compressional wave velocities measured between the drillings BKF 138 and 139 as well as the detailed information about the drilling cores. Missing data points result from poor signal quality where the reliable identification of the shear wave amplitude was not accomplished. The distance between the two drillings was 12.6 m.

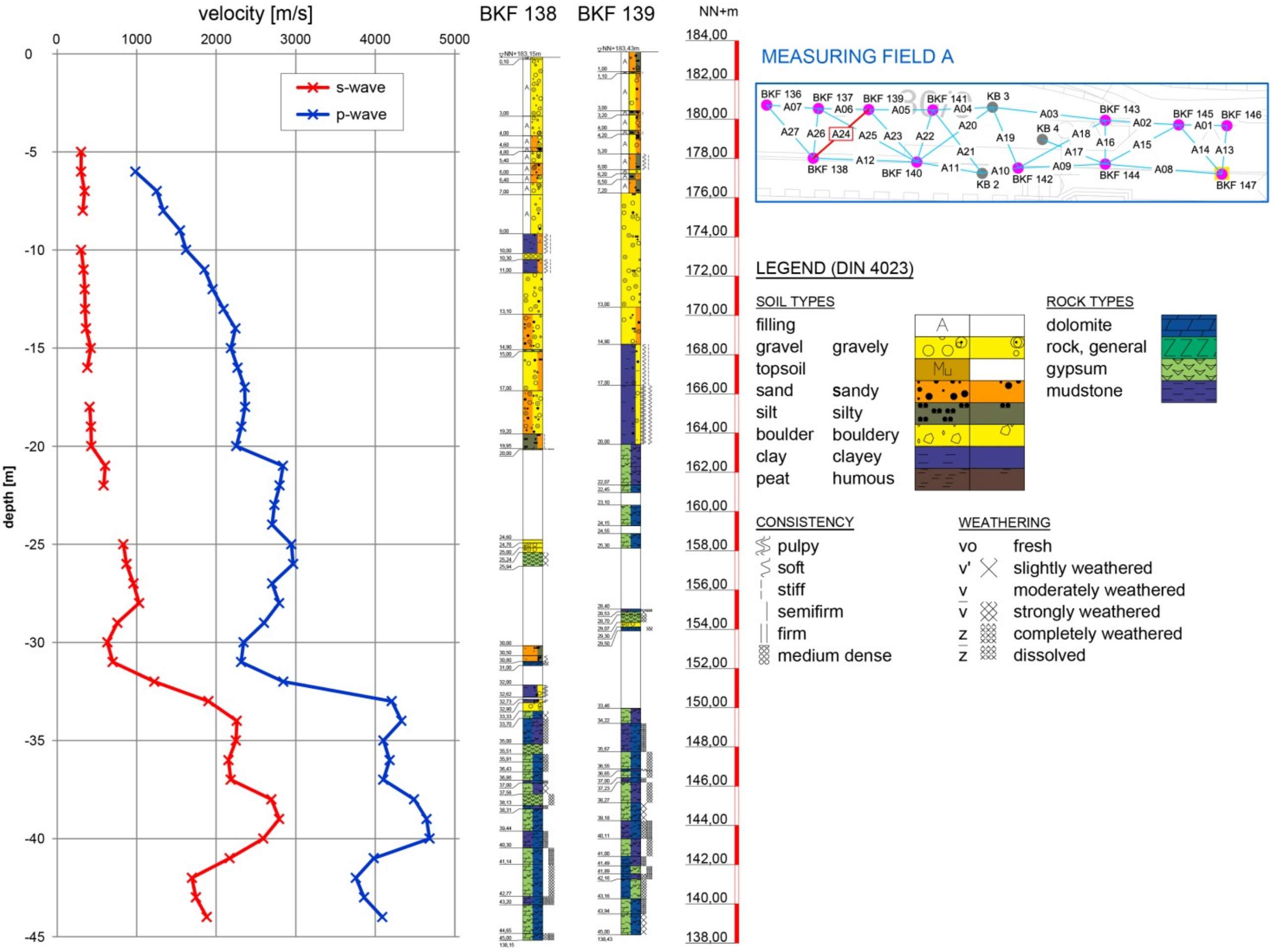

Figure 8. Measured shear and compressional wave velocities between drillings BKF 138 and 139.

Based on the seismic wave velocities together with information from the drilling core, the subsoil can be divided into three sections.

The upper section ranges from the surface to a depth approximately 20 m where loose sediments (such as sand, gravel, silt and clay) were found in the borehole. The value for the compressional wave velocity ranges from 1000 – 2300 m/s and increases with depth. The shear wave velocity ranges from 300 – 500 m/s.

The middle section (20 – 33 m) mainly consists of leached rock characterized by alternating thin layers of gypsum rock with cavities of variable extent. In this section, the seismic wave velocities first show increased values compared to the upper section (up to 1000 m/s for v_S and up to 3000 m/s for v_P) that is followed by a significant decrease.

The lower section ranges from 33 m to 44 m where rock (dolomite, claystone and gypsum) can be found. This is reflected in a significant increase of both the shear and compressional wave velocity to values >2000 m/s (v_S) and >4000 m/s (v_P), which correspond to intact rock mass. Beneath 40 m decreasing velocities can be observed, possibly associated to a decreasing density of the rock in this depth.

It is essential to be aware that cavities of the observed size of a few meters and their horizontal extent in the leached rock layer cannot be distinguished by the classic crosshole measurements in a direct manner, because mean values of the ground between the two boreholes are measured. This could be demonstrated by additionally measuring the compressional wave velocities on rock samples in the laboratory by means of ultrasonic measurements. Intact rock pieces that remained in the leached upper anhydrite layer were collected from the cores of some drillings which had also been used for crosshole and tomographic measurements in the field. Fig. 9 presents the results in comparison. In the layer of the lower clay anhydrite the measured values on the rock samples in the laboratory were slightly higher than the values measured in the field, which can be attributed to the discontinuities in the rock material in situ. In the layer of the upper clay anhydrite the measurements in situ show significantly lower values (depth 20 to 33 m). This can be explained by the existence of cavities and leached rock to a considerable degree also in between the boreholes.

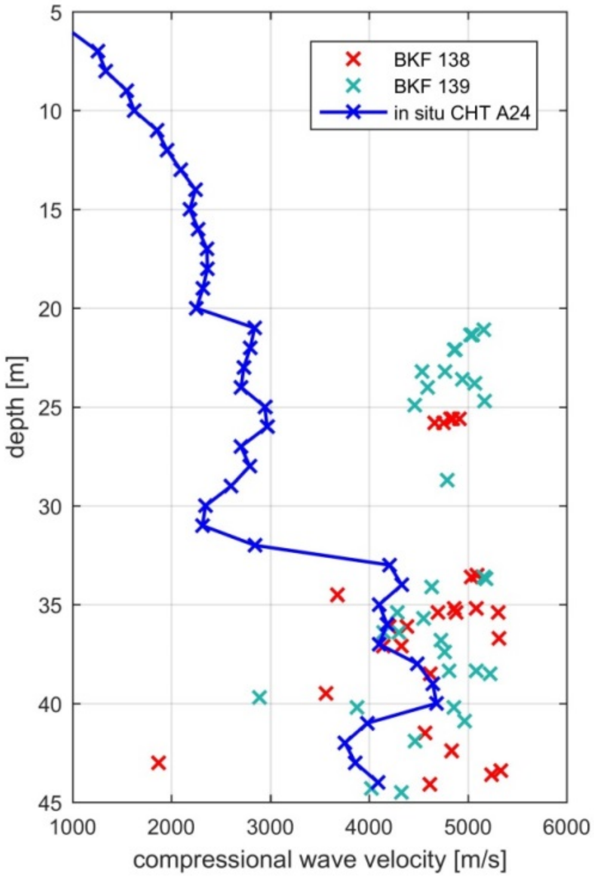

Figure 9. Comparison between measured P-wave velocities in situ and in the laboratory.

In Fig. 10, the compressional wave velocities of all 27 crosshole measurements in field “A” are displayed. They all show a very similar shape as described before, with few discrepancies in the velocity values. Particularly noticeable appears to be the range between 22 – 32 m where all measurements show a significant decrease in seismic velocities right above the transition to the highest values.

Fig. 10 also shows a comparison with the measured data in field “B”. As it can easily be seen, the wave velocities in the same depth are much higher. Since intact rock material was extracted from the boreholes in the related depth, the lower velocity values between 22 – 32 m in field “A” were assigned to the existence of a very weak layer consisting of remaining rock, residual clay or silt, and cavities, which has to be assumed to spread about the whole measuring field “A”.

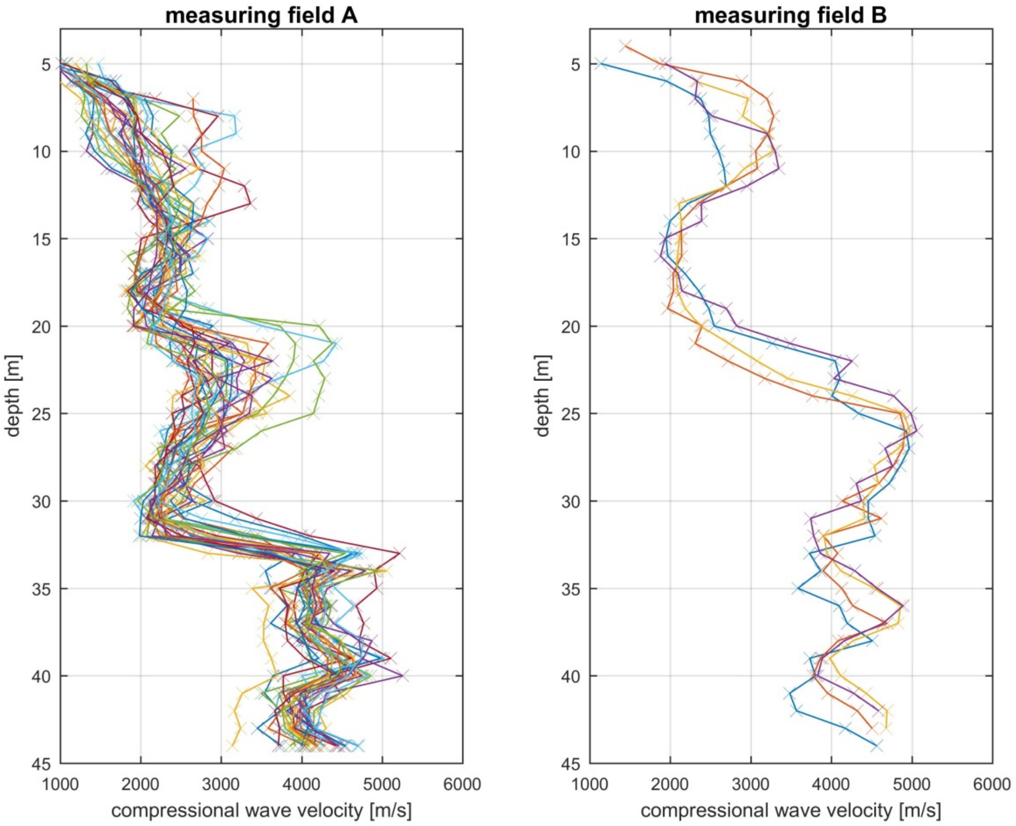

Figure 10. Compressional wave velocities measured in measuring field “A” (left) and “B” (right).

3.2.2 Tomographic crosshole seismic measurements

In addition to the crosshole seismic measurements, 10 tomographic measurements were carried out within and in between the measuring field “C” and “D” (Fig. 11).

The aim of seismic tomography measurements is to sustain 2D (and 3D) images of the spatial distribution of the seismic velocities. Therefore, tomographic measurements are particularly suitable to identify the location of inhomogeneities of the subsurface. In addition to the depth, which can also be estimated by classic crosshole seismic measurements, the thickness and lateral extent of the inhomogeneity can be determined as well.

The principle of this technique is similar to the classic crosshole seismic procedure. Instead of merely one seismic receiver, an array of equidistant receivers is located in one borehole while the source is lowered down into an adjacent borehole, generating seismic pulses in multiple depths. By using this source receiver configuration, many ray paths overlap in various angles, which results in a high resolution image. The pulses are recorded by the complete receiver array respectively.

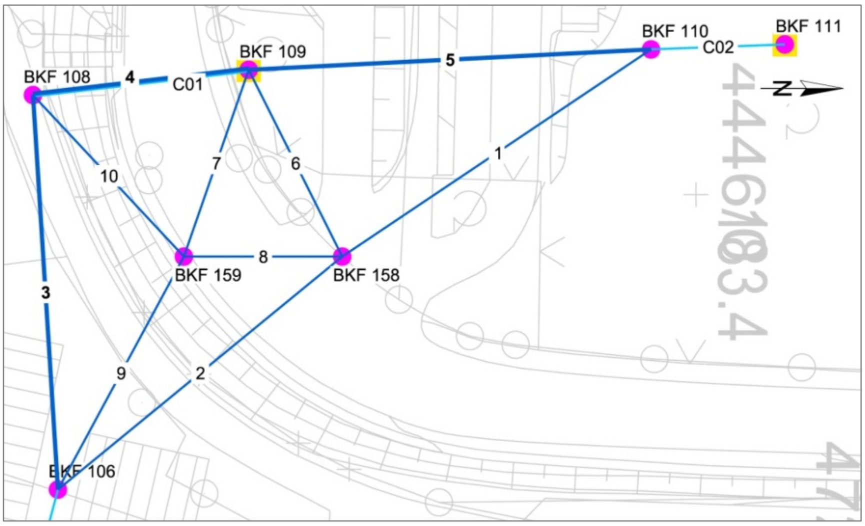

Figure 11. Sketch of the layout for tomographic crosshole measurements within and in between measuring field ”C” and “D”.

Since the ray paths in between the boreholes are not only horizontal and the distance between source and receiver is greater (up to 35 m) as in classic crosshole measurements, the recorded wave field is quite complex, which makes the identification of shear waves extremely difficult and in many cases impossible. Therefore, only P-wave tomography was performed.

For the tomographic measurements a different type of borehole source was used. The sparker source (type SBS42 by Geotomographie GmbH) only generates compressional waves with frequencies up to 5 kHz. As receiver, two arrays of each 24 hydrophones with a vertical spacing of 1 m were used. As for crosshole seismic measurements, the signals were recorded with a sampling rate of 32 kHz and a digital resolution of 24 bit. An exemplary result based on the tomographic crosshole seismic measurements of the vertical measuring planes 5-4-3 are displayed in Fig. 12.

With the 2D image of the compressional wave velocity along various drillings the lateral variation in the velocity distribution is revealed as well.

The general division into three sections, as found in the results of the classic crosshole measurements in measuring field “A” and “B” can also be found here. The main difference lies in the middle section where instead of increasing compressional wave velocities followed by a significant decrease, lower velocities were observed in general. The low velocity values also range into greater depths. The rock formation in the lower section shows many (some) areas with significantly decreased compressional wave velocities. This leads to the assumption that the leaching on this side of the river has progressed further than in area A.

Fig. 12 also reveals that cavities (whether filled or unfilled) can spread horizontally in a range of approximately ten meters.

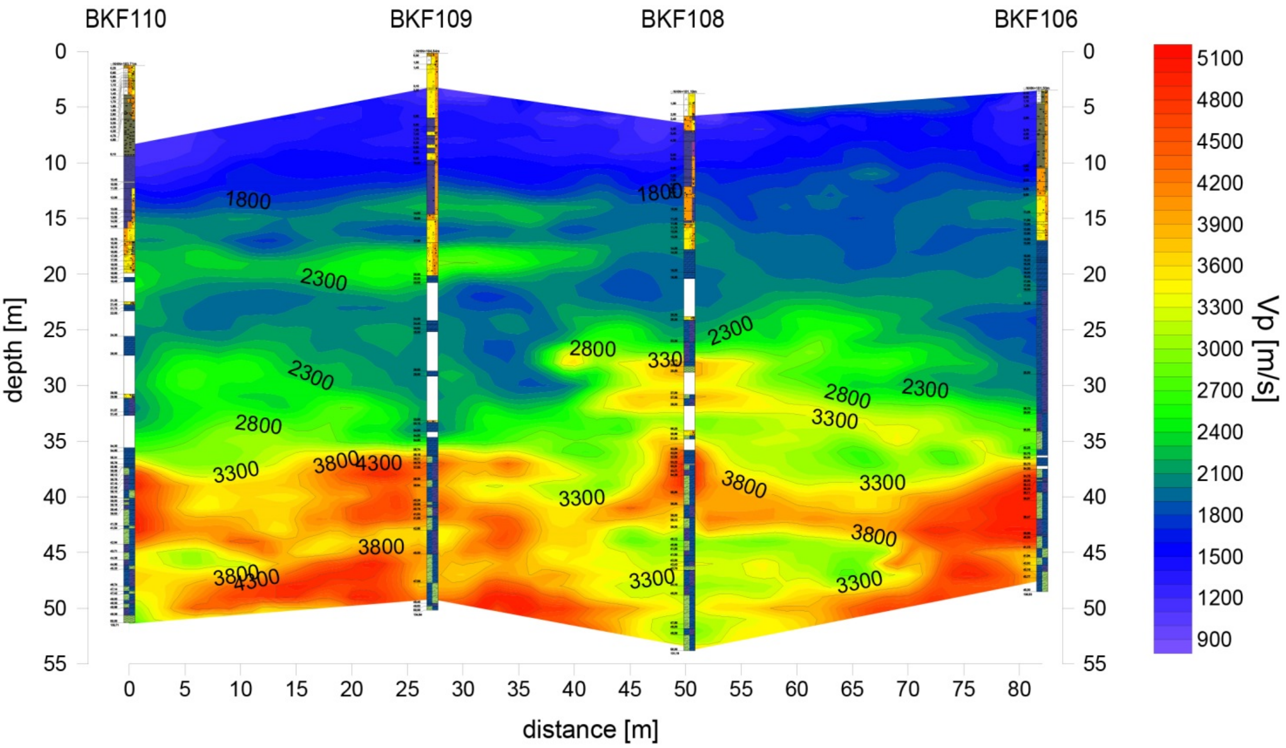

Figure 12. Exemplary result of tomographic crosshole measurements (measuring planes 5-4-3).

3.2.3 Geophysical borehole measurements

With geophysical borehole measurements, information about the area directly surrounding the borehole can be determined. A measuring probe is moved in the borehole with constant velocity delivering continuous signals over the whole depth of the borehole.

Table 1 gives an overview over the geophysical measurements that were carried out in all boreholes of measuring field “A” and “B” as well as in all boreholes used for tomographic measurements. The table also contains some information about the measured parameters, their correlation with different soil properties and the different penetration depths that can be achieved depending on the method applied.

Table 1. Geophysical borehole measurements.

Method	Measured parameter	Correlation with	Penetration depth
Full Wave Sonic Log	P-wave velocity; wave field	Lithology, quality of cementation and coupling to surrounding material	Several dm
Gamma Ray (GR)	Natural radioactivity	Lithology; Clay content	30 – 50 cm
Gamma-Gamma (RHOB)	Gamma quantum rate after interaction with material	Density	20 – 40 cm
Neutron-Neutron (NN)	Neutron rate after interaction with material	Water content; porosity	20 – 30 cm

According to the penetration depths given in table 1, it can be assessed that signals can also be obtained from the area beyond the grouting around the PVC pipe. It can be assumed that ambiguities in the interpretation of measured wave velocities decrease due to minor penetration depths in comparison to the crosshole date.

Interpretation is only reasonable where the connection between the plastic pipe, the cement suspension of the annular space and the surrounding ground could be verified by the full wave sonic log.

Assigning the measured signals to natural fill material the following soil density parameters are applied:

Table 2. Characteristic values for some soil parameters (according to Kolymbas, 2011).

Soil type	dry unit weight γ_d [kN/m³]	Porosity n	Void ratio e	Water content w_{max}	saturated unit weight γ_r [kN/m³]
Clay, soft	12	0.54	1.17	0.45	17
Clay, stiff	17	0.35	0.53	0.20	20
Silt (quartz)	16-19	0.27-0.38	0.37-0.62	0.14-0.24	20-22
Sand, loose	14	0.46	0.86	0.33	19
Sand, dense	19	0.27	0.37	0.14	22
Coarse Gravel	16-19	0.27-0.38	0.37-0.62	0.14-0.24	20-22

Geophysical borehole data was interpreted using following guidelines based on density values (range), P-and S-wave-velocities (calibrated) and identification of clay minerals based on γ-Ray-measurements:

- A cavity filled with water or any kind of slurry should have a density less than 1.3 g/cm³ and a P-wave velocity around 1500 m/s (P-wave velocity in water). Shear waves don't propagate in fluids.
- Densities less than 1.5 g/cm³ can be interpreted as partly or completely unfilled cavities.
- A cavity filled with clay and/or clayey silt should have a density in a range of 1.7 – 2.0 g/cm³, the γ-Ray-signal indicating a clayey material. P-wave velocities and S-wave velocities are low in comparison.
- A cavity filled with gravel possesses densities in a range of 2.0 to 2.2 g/cm³. P- and S-wave velocities are higher in comparison.
- Intact layers of claystone, dolomite and gypsum rock could be easily distinguished with P-wave velocities greater than 3500 m/s and S-wave velocities greater than 2000 m/s and densities around 2.2 g/cm³.

All drillings configured for seismic and geophysical testing were analyzed in detail in conjunction with their surrounding according to the guidelines mentioned above. Fig. 13 provides an example.

According to the guidelines given above, the following findings can be stated for this example:

- Full wave sonic log shows that the spacing around the PVC pipe is fully cemented.
- From 12 to 16 meters below ground level γ–γ-density-Log as well as neutron-neutron-Log indicates high values, which is consistent with lower γ-Ray signals and with the coarse gravel found in the borehole in this section.
- From 18 to 24 meters below ground level, γ–γ-density-Log shows lower values in a magnitude of 1.8 g/cm³ and γ-Ray indicate clay mineral, which leads to the conclusion that the cavity is filled with residual clay. Also P-wave velocity values are very low in comparison.
- In the area of the cavity below (26 – 30 m), the γ–γ-density-signal is higher and γ-Ray is lower. The P-wave velocity value decreases again. As a consequence, a silty or gravelly filling is derived. The higher value in between the cavities is assigned to the thin rock layer in this depth.

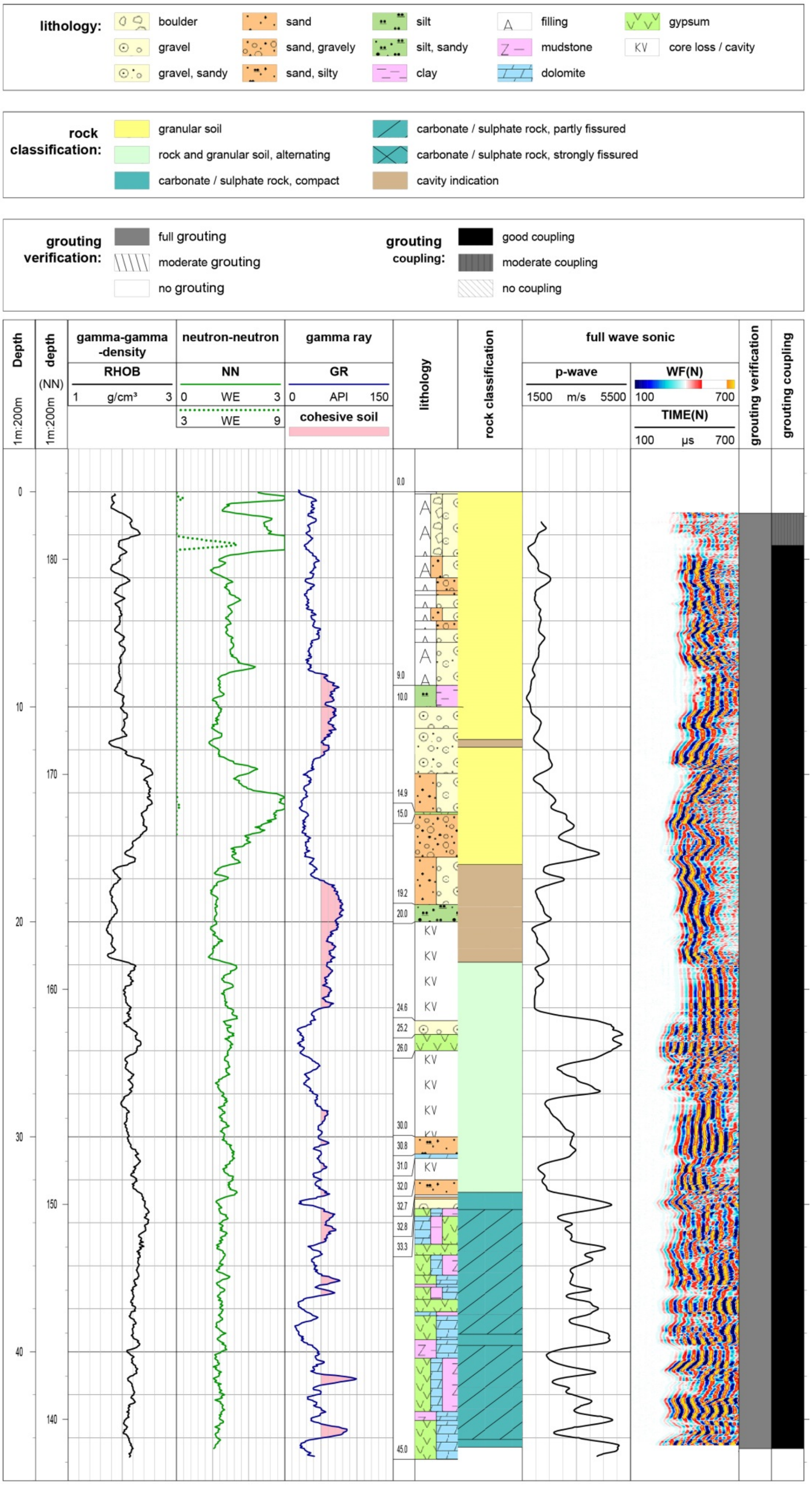

Figure 13. Results of borehole geophysical measurements in drilling BKF 138 (source: BLM – Gesellschaft für Bohrlochmessungen mbH).

Summarizing the results of the investigation program the following can be stated:

- Re-investigation of the subsoil using drillings allowed direct inspection of core samples. The existence of even very coarse Neckar gravel down to depths of 30 m below ground level indicates a system of smaller and greater cavities which allows migration of the material. In some drillings, significant losses of core material and flushing medium occurred. These drillings are all located in areas where settlements have been observed as well.
- The size of possible cavities was investigated by classic crosshole measurements. Significantly lower velocities in a depth between 22 to 32 m below ground level in a total of 27 measurements in between 15 adjacent drillings (measuring field "A") leads to the conclusion that the cavities (filled or unfilled) spread about the whole area. Tomographic measurements in measuring field "C" and "D" support the assumption that single cavities may reach a lateral extent of about 10 m.
- As drillings reveal, the filling of the cavities is very heterogeneous und can consist of remaining rock pieces, residual clay and silt or sand and gravel having migrated from above.
- Borehole geophysical measurements provide additional information particularly in the areas where the core losses had occurred. Cavities without filling material are detected only to a minor degree. Often a clayey material is indicated but also silty and gravelly fillings have to be anticipated concerning the design of ground improvement measures.

4 CONCLUSION AND OUTLOOK

By analyzing a total of 46 shear and compressional wave velocity profiles, the main objectives were to localize existing cavities, to determine their size and filling material. Describing methods and results from a user´s point of view, it could be demonstrated that none of the applied methods alone provided answers to all subjects in question. It was illustrated that some limitations and shortcoming of the respective method could be overcome by combining several methods.

From an engineer´s point of view it cannot be postulated that even in the case of filled cavities external loads can be transferred through the filled cavity down into the intact rock layers. This refers to the fact, that partial fillings of the cavities may not be detected and a mechanical sound contact between cavity ceiling and filling material cannot be assumed.

Based on the soil investigation program described herein it was decided that rehabilitation work needs to be carried out for a start in the area of measuring field "A". The type of measures has to be selected by considering all kind of material that could be verified as cavity filling by coring and borehole geophysical methods.

Almost no core losses had been observed in the boreholes in measuring field "B". Seismic testing indicates that intact rock seems to be in place also in between the drillings. As a result there is currently no need for ground improvement in the area of measuring field "B".

With seismic methods it is also possible to monitor further leaching processes by comparing future measurements with the current velocity values and to evaluate the result of ground improvement measures.

ACKNOWLEDGEMENTS

We would like to thank Waterways and Shipping Office Stuttgart (Wasser- und Schifffahrtsamt), Amt für Neckarausbau Heidelberg, BLM – Gesellschaft für Bohrlochmessungen mbH, Geotomographie GmbH, GGU Gesellschaft für Geophysikalische Untersuchungen mbH for their enthusiasm, discussion and assistance.

REFERENCES

Bergholz, K., Kauther, R., Montenegro, H., Strasser, D. (2011): Grundwasserinduzierte Veränderungen im lösungsempfindlichen Baugrund unterhalb der Schleusenanlage Hessigheim am Neckar, *Proceedings BAW-Kolloquium "Aktuelle geotechnische Fragestellungen bei Baumaßnahmen an Bundeswasserstraßen",* pp.13-26, Karlsruhe, Oktober 2011 https://izw.baw.de/publikationen/kolloquien/0/Tagungsband_Aktuelle%20geotechn%20Fragestellungen_2011_Grundwasserinduzierte_Ver%C3%A4nderungen_loesempfindlichen_Baugrund_Schleusenanlage_Hessigheim_Neckar.pdf

BLM, Gesellschaft für Bohrlochmessungen mbH (2017): Geophysikalische Bohrlochmessung Messfeld A und B, unpublished report

Butler, D. K., Curro., J. R., Jr. (1981): Crosshole seismic testing – Procedures and pitfalls, *Geophysics*, vol. 46, no. 1, p. 23-29.

DIN 4023:2004-09, Geotechnische Erkundung und Untersuchungen – Zeichnerische Darstellung der Ergebnisse von Bohrungen und sonstigen direkten Aufschlüssen

DIN EN ISO 22475-1, Geotechnical investigation and testing – Sampling methods and groundwater measurements – Part 1: Technical principles for execution (ISO 22475-1:2006)

DIN EN 1997-2:2007, Eurocode 7: Entwurf, Berechnung und Bemessung in der Geotechnik – Teil 2: Erkundung und Untersuchung des Baugrunds

Geotomographie GmbH (2016): Crosshole Messungen Neckarschleuse Hessigheim, Messfeld C+D, unpublished report

Geotomographie GmbH (2017): Crosshole Messungen Neckarschleuse Hessigheim, Messfeld A, B, unpublished report

Geotomographie GmbH (2017): Seismische P-Wellen Tomographie Messfelder C und D, Neckarschleuse Hessigheim, unpublished report

GGU, Gesellschaft für Geophysikalische Untersuchungen mbH (2011): Geophysikalische Vorerkundung bei der Karstproblematik, GGU Fallbeispiel

Kauther, R., Schulze, R. (2015): Detection of subsidence affecting civil engineering structures by using satellite InSAR, *Proceedings of the 9th International Symposium on Field Measurements in Geomechanics*, Sydney, Australia

Knödel, K., Krummel, H., Lange, G. (1997): Geophysik, Handbuch zur Erkundung des Untergrundes von Deponien und Altlasten Band 3, *Springer Verlag,* Berlin Heidelberg

Kolymbas, D. (2011): Geotechnik – Bodenmechanik, Grundbau und Tunnelbau, 3. Auflage, ISBN 978-3-642-20481-4, *Springer Verlag*, Heidelberg Dordrecht London New York

McCann, D. M., Jackson, P. D., Culshaw, M. G. (1987): The use of geophysical surveying methods in the detection of natural cavities and mineshafts, *Quarterly Journal of Engineering Geology*, London, Vol. 20, p. 59-73.

Standard Test Methods for Crosshole Seismic Testing, ASTM D 4428/D 4428M -00