Monitoring of Water-Bearing Adits – Current Results and Perspectives

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Abstract

Water-bearing adits represent underground drainage and outflow systems whose functionality is of considerable importance in many mining areas all over the world with regard to safety issues at the surface. In the sense of a perpetual task, stable hydraulic, geotechnical and rock mechanical conditions must be guaranteed in the water-bearing adits. A variety of monitoring methods have to be used to analyse and document the functioning of water-bearing adits and the interconnected mine workings. Water-bearing adits are technical structures that have often been in place for several centuries. In most cases, accessibility is no longer granted directly behind the adit entrance.

situation of a large number of galleries in the southern Ruhr area/Germany. Hydrochemical parameters have been investigated, the rate of discharge and precipitation compared and infiltration tests undertaken. An essential step forward is the evaluation of available mine survey maps of the water-bearing adits and the hydraulically connected mine workings. These prerequisites are needed in order to determine, if possible, the catchment area of a water-bearing adit.

The aim of the work is to gradually better understand the functioning of the water-bearing adits. This is one part of the perpetual obligations of the former mining industry. The essential goal is to predict the mode of operation of the water-bearing or drainage adits and to implement this knowledge in a risk management system. This approach, that uses the over 100 galleries in the southern Ruhr area as an example, has a holistic character. Our innovative research approach combines the fusion of extensive sensor data with in-situ expertise.

The investigations and analyses show that, in order to achieve a reliable process understanding of the water-bearing adits, it is necessary to conduct and evaluate comprehensive geomonitoring.

Keywords: Water Bearing Adits, Monitoring, Perpetual Tasks, Risk Management, Hydro Chemical Parameter

Introduction

In many mining districts around the world, adits were and are still being built today for the purposes of providing access to the deposit, serving as transport pathways and mine ventilation and, in particular, ensuring mine water drainage. In this case the galleries slope upwards. In conjunction with the connected mine workings, these galleries form an underground drainage and outflow system whose functionality extends far beyond the actual operating period (Goerke-Mallet *et al.* 2016). When mine operation is being abandoned the consequence is usually the closure of the access to the gallery system from the surface. The drainage effect of the mine workings remains however completely unaffected and will continue, invisibly, for an unknown time period. It is therefore justified to speak of a mode of action that is designed for eternity.

When a (water-discharging) adit enters into the post-mining phase, it is usually associated with a loss of observation, since ventilation and stability of the mine workings is lost over time (Fig. 1). In the case of water-

Figure 1 Water-bearing adit in the southern Ruhr area (image: THGA).

bearing adits, information on the discharge rate per time unit as well as data on the hydrochemistry of the mine water can only be accessed at the portal. It is impossible to obtain results from 'visual inspection' about the processes taking place underground. These processes include local loosening of the rock and cave-in areas within the mine workings. As a result, obstacles can form that affect the orderly flow of water down the adit. This can lead to temporary or permanent complete blockage of the outflow and to the formation of a water accumulation or stagnant water in the mine workings and the rock mass. As the stowage height so the water pressure increases, the risk of spontaneous failure of the blockage rises. As a consequence, a sudden outburst of water may occur at the portal. The impact of a water outburst and flooding has a considerable impact on the safety of the public and on the ground surface, as events in various mining districts have repeatedly shown.

An adapted risk management system is therefore required, in which particular attention is paid to the occurrence of abrupt water discharges. In addition, the uncontrolled formation of water accumulation in the mine workings can be associated with the risk of sink holes occurring at old shafts and above mining areas close to the surface. Furthermore, the changing level of the water table provokes spatially unexpected leaks of the mine water at the surface. This can happen at natural hydraulic connections (e.g., tectonic faults) or at to date dry and possibly unknown adits.

These explanations are intended to illustrate the complexity of risk management of water bearing-adits. The reliability of the assessments and statements depends to a large extent on the available information and the monitoring methods used. Furthermore, a proper handling of the risks requires a careful consideration of the relevance and resilience of the statements.

The investigations carried out by the Research Center for Post-Mining pursue the objective of improving the process understanding of the principle of operation of water-bearing adits and of developing adapted monitoring measures. As a result, reliable information will be generated to enable the long-term safe and economically feasible management of individual water-bearing adits. The results from risk management also serve as a credible and binding communication with essential stakeholders and with the public. For the organization responsible for the water-bearing adits, it is also a matter of reputation, so to speak the 'social license'.

Methods

TThe methodology to evaluate old and abandoned mine objects like water-bearing adits integrates the available historic information, data and knowledge and combines them with current information and data as well as with the gathered data from the evaluation. Only the full integration of all available information will enable a sustainable analysis and interpretation in the sense of a risk assessment.

Analysis of the mine maps

An essential step in the analysis of the functionality of a water-bearing adit consists in the systematic, three-dimensional evaluation of available mine maps and plans of the requested object and of other mine workings that are hydraulically connected with the gallery (Fig. 2). The documents, based on mine survey work, were created during the drivage of the adit and in the phase of its operational use. Their reliable evaluation requires technical expertise, which is already required for the georeferencing of maps that are often based on historical coordinate systems. The symbols used and the representation of tectonic elements must be interpreted correctly. Elevation information is often missing. In order to obtain a sufficiently accurate picture of the original subsurface conditions, the interpretation of the old mine maps must be based on expertise in mine surveying, mining and geology. Understanding the functionality of water-bearing adits is the prerequisite for the risk management of the respective object.

In this context, for example, the spatial location of coal seams, tectonic elements, natural and anthropogenic created flow paths and hydraulic connections must be considered. Thus, the Ruhr Carboniferous structure has to be considered as a fissure aquifer. In the following, the water (seeped rainwater, infiltration of waterbodies, anthropogenic sources) and mine water pathways, feeding the drainage adits, have to be identified. If the hydraulic connections or even the adit itself are restricted in terms of hydraulic capacity in the course of caves, stagnant water accumulations occur in the mine workings. In this case, the amount of mine water discharged at the portal can temporarily drop to zero.

As part of risk management, it is necessary to analyse the effects that the formation of water accumulations can have on water seepage at the surface. For example, spontaneous water outbursts may occur at the portal if the rock mass in the caved area is pushed away by the water pressure. However, unexpected water outburst at the surface is also possible if the level of water accumulation overtopped higher hydraulic connections. The forming of a stagnant water can also pose significant risks to neighboring mines if mine water was to flow into these mines through hydraulic connections.

Risk management also includes investigating the risk of sink holes occurring above old shafts, mine workings and the gallery itself. The type of land use at the surface and its distance from mining features must be included in the analysis.

The explanations illustrate the scope and importance of the systematic analysis of the information available in old mine maps and plans about water-bearing adits for risk management. Practical experience not only in the Ruhr area has shown that a wide range of findings can be obtained on this base. However, the recording of the current development in the system of a water-bearing adit requires more far-reaching concepts for monitoring (Goerke-Mallet *et al*. 2016). This means that exploration methods from the air (e.g., satellite remote sensing, copter flights), from the day surface (e.g., perpetrations) and in the subsurface (e.g., boreholes, seismic, gravimetry) can be considered. The integrated application of such methods is also necessary, in particular, if no or only little information from mine maps is available about the adit.

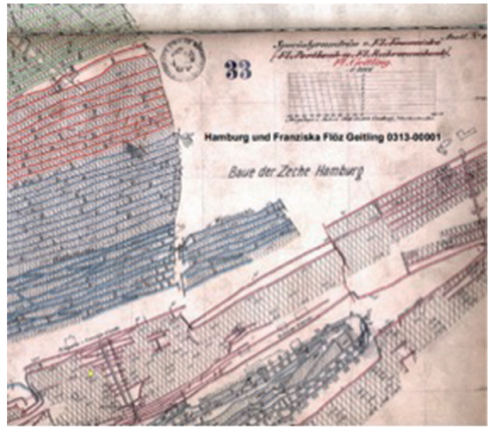

Figure 2 *Exemplary mine map of seam "Geitling" in the area of the mine "Hamburg und Franziska" and the dewatering system of "Franziska" (1888).*

The exploration can also provide a basis for long-term monitoring of the adit. In this way, boreholes can be developed into measuring points for the mine water level and used within the framework of spatial models of the hydraulic pathways. In this context, DMT GmbH has shaped the term 'box model (box = hydraulically active area of an underground mine)'. In these models, the levels of potential water discharge points at the surface or even in the mine workings are also shown in the direction of the catchment area of a neighbouring adit.

The aim of the analyses and evaluations described above is to develop a reliable monitoring concept that adequately reflects the risk parameters determined. The Research Center of Post-Mining is therefore working intensively on converting the mine maps available for individual tunnels into 3D systems. This will allow to make the expertise of the analysts transparent and use it for the development of integrated risk management, monitoring and communication/science transfer with stakeholders (Goerke-Mallet *et al*. 2018 & 2020). Currently, the extent to which geometric engineering planning and evaluation systems can be used in analysing the functionality of water-bearing adits to create a spatial understanding is being examined (Rudolph *et al*. 2020). For example, the PETREL reservoir tool has already been successfully used to visualize the surface and underground situation. The DUDE (Digital underground and deposit) platform, which RAG AG has already used in the production phase of its mines to edit the mine maps, offers considerable potential that will be investigated in greater detail in the near future.

Analysis of existing historic mine structures

Wherever it is possible, existing mine structures, like shafts, should be incorporated into geomonitoring analysis (Rudolph *et al*. 2020). These shafts are one entry point to the subsurface and provide important information on the hydrology, hydrogeology, and hydrochemistry.

As a showcase, a former mine shaft in a city in the southern Ruhr area was logged with a combined temperature, conductivity and pH sensor (Fig. 3).

The depth profile shows a stratification of water with a slightly elevated temperature T of T = 16 °C above cooler water with a temperature T of T = 15 °C down to a depth $h$of h = -70 m NHN (Fig. 3). These temperatures do not show a full geothermal depth gradient, as this is a mining influenced rock with e.g. induced fractures.

The conductivity and the pH value do not increase with depth and thus do not indicate an increase in the mineralization of the water. The pH value of pH = 7 is considered normal. The conductivity L of L = 1.2 mS/cm indicates normally mineralized waters. The very slight changes in conductivity at depth h of h = 0 m NHN and h = -70 m NHN could indicate slight mine water stratification.

In principle, however, the results are to be interpreted in such a way that within the open shaft column a full convection of the water takes place. Whereby in the top of the shaft surface water probably flows in, as it was also documented in other technical reports. The low mineralized water at the greater depth of the shaft column indicates that there is likely to be inflow and outflow, although this cannot be shown over the entire mining levels.

In summary, the results show that no highly mineralized waters of the Carboniferous were detected, as it is normal

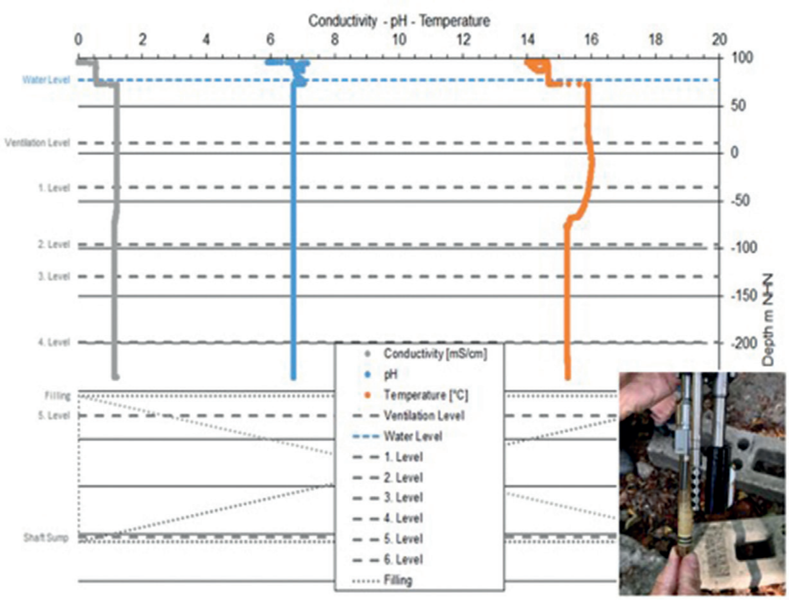

Figure 3 *Results of the trip-out-run with the multi-parameter sensor (inlay: Multiparameter sensor).*

for the Ruhr-area, in the open part of the shaft. There was also no typical stratification of the mine water. This indicates that there must probably be a hydraulic connection with other hydraulic systems.

Assessment of the hydrology and hydrogeology

During the mapping of the vicinity of water bearing adits it is important to understand the local hydrological and hydrogeological situation to build up a complete process understanding. In one particular case the mapping showed that a small river was crossing one part of the water bearing adits and there was the indication that the river could infiltrate via the Carboniferous sandstone beds directly into the adit (Fig. 4 A).

The modern discharge measurements of the river have shown that there is potentially a volume gap between the measurement before and after the crossing of the adit. This was supported by the analysis of the former mine documentation, which reported an increased water inflow during the operation of the mine. Therefore, during summer and at a low discharge an infiltration test with fully saturated brine was conducted to determine the infiltration rate into the underlying mine structure (Fig. 4, B).

The brine infiltrated had a conductivity *L* of *L* = 203,000 µS/cm. The conductivity normally measured at the mouth of the drainage adit is between about *L* = 1,300 µS/cm and *L* = 1,400 µS/cm, so that changes could still be detected, even with a strong dilution.

Figure 4 *A: Photo of the fractured carboniferous sandstone layers in the river bed above the water bearing adit (December discharge); B: Infiltration test (image: THGA).*

The Infiltration rate I of about I = 1 L/m^2min-1 at the two test points was very slow and did not indicate increased permeabilities ("swallow horizons") at the Carboniferous sandstone beds. The externally provided hydrochemical data of the real-time measurements at the adit mouth showed unfortunately no increased conductivity and the data was later interpreted as not properly working measurement devices. The further analysis of the data showed in addition that the bandwidth of data fluctuations of the measured conductivity was about *L* = 400 µS/cm.

In summary, although infiltration of river water was initially considered very plausible, the infiltration test with the very low infiltration rates did not provide a direct indication of the actual infiltration of the river water.

Hydrochemistry of the Franziska Erbstollen

The mine water hydrochemistry of the Franziska Erbstollen (drainage adit) was investigated over three sampling series in the period from 2015 to 2016. The main cations and anions of the mine water were analysed. In addition, an ion balance was generated from the water analyses and the groundwater type was determined. The results of the analyses are shown in the following table.

The mine water is a $Na^-Ca^-HCO_{3-}SO_{4-}$ type showing a comparable water chemistry over the whole sampling period. The main constituents are in the same order of magnitude and largely stable.

The iron and sulfate content in the mine water is related to pyrite oxidation. The sodium content is geogenic and corresponds to the local groundwater conditions of the Carboniferous and the deposit. The same applies to the chloride content and the proportions of strontium and barium. The calcium and hydrogen carbonate contents in the mine water cause natural buffering and lead to the largely neutral pH values in the mine water. The direct influence from near-surface inflow and groundwater recharge has to be regarded as low, as evidenced by the nitrate content. The total mineralization expressed as specific electrical conductivity is comparatively low for mine water. In comparison with the local groundwater situation, it is clearly increased.

In summary, the quality of mine water can be regarded as comparatively harmless. The water-rock interactions are largely constant. The hydrochemistry of the mine water will therefore not be subject to any significant change processes in the future under stable mine conditions and flow paths. This conclusion will be tested by a long-term monitoring program.

Summary

Water bearing adits, drainage adits and galleries are till nowadays an important part for the former mine infrastructure because of their drainage function. As these systems are no longer directly accessible risk managements systems have to be developed and integrated analysis various (sensor-) datasets need to be conducted. The spatiotemporal analysis is the enabler for the verification of the operational functionality.

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***Table 1** Mine water analyses of the Franziska Erbstollen.*

Sample ID	MW 16.1	MW 16.2	MW 16.3
Date	16/6/2015	5/4/2016	26/8/2016
Temperature, °C	14.7	15.1	16.2
Conductivity, µS/cm	1,400	1,420	1,400
pH, 1	7.1	7.1	7.3
Watertype	$\underline{Na}^{-}Ca^{-}\underline{HCO_{3-}}SO_4$	$Na^{-}Ca^{-}\underline{HCO_{3-}}SO_4$	$\underline{Na}^{-}Ca^{-}\underline{HCO_{3-}}SO_4$
Cations			
Ca^{2+}	91	77	88
Mg^{2+}	35	29	32
Na^{+}	182	169	181
K^{+}	14	11	13
Fe^{2+}	3.4	3.4	3.7
Mn^{2+}	0.61	0.56	0.61
Sr^{2+}	1.1	0.99	1.1
Ba^{2+}	0.028	0.011	0.028
Anions			
HCO_{3-}	570	560	570
Cl^{-}	52.8	63	64.2
SO_4^{2-}	202	223	219
NO_{3-}	1	1	1