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Challenges in German subsidence research – retrospectives and perspectives

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Abstract

Due to the fact of a multilateral underground use, mining subsidence relocates more and more from mining to other issues, like post-mining topics, storage or geothermal utilization. This and the influence of the energy policy is why the situation in Germany also describes a transition from active to abandoned mining. Many PhD-theses with different subjects were written within the last 20 years. Every single one with a different topic but all with the same issue: Mining subsidence and its effects and challenges.

These challenges start with the research regarding geological and hydrogeological conditions, which is the basis for calculations like the angle of draw or predictions of subsidence due to water table drawdown. Furthermore, the research investigates issues like risk-management and financial planning. One of these issues are post-mining calculations and another for example potential hazards of storage or the use of geothermal energy.

This paper outlines an overview of German Mining and its consequences due to subsidence. It deals with an overview of the circumstances relating to hard coal mining, lignite mining the use of geothermal energy, gas and opportunities regarding underground storage. Basically it describes the essential steps of processing of mining subsidence, starting with monitoring to forecast and up to safety measures.

With a glance back to the applied research of the prior two decades, we compare given forecasts with experiences already gained.

Even though mining decreases, ground control does not.

1. Introduction

After the Second World War, an economic recovery started in Germany, also advantaged due to the mining industry. Areas like the Ruhr District or Saarland were characterized by hard coal mining. Besides that, there has been lignite mining in the *Rhenish mining area*, the *middle German coal district* and in the *Lausitz area*, gravel and sand companies for the construction industry and many other medium-sized mining companies. Especially in the Ruhr District and in Saarland, where large coal fields were built, mining played a major role. The number of mines increased and therefore the negative effects on the terrain got bigger. While minor open pits or quarries have influences on the landscape only, large open pits and underground mining lead to significant ground movements. This resulted in a larger importance of mining subsidence engineering. Calculations of subsidence and forecasts were developed and refined within several years. Due to the fact, that the mining areas were densely populated – and still are – the forecasts were getting more and more precisely.

Until the turn of the millennium, topics like control of ground movements and security of infrastructure due to the adjustment of mining advance or shaft safety zones were acute. As well due to pneumatic stowing ground movements were reduced, whereby the safety increased and costs decreased. Later, with the abandonment of mines, issues like surface fracture were – and still are – present and also the mine water management was getting more significant. Hard coal mining played a major role in German ground control research.

Within the last ten years, things are changing regarding mining subsidence engineering in Germany. With the end of underground hard coal mining, it is now a question of following effects of mining on the terrain. This is primarily a matter of possible uplifts as a consequence of rising mine water and legal issues. Also beyond this time, the focus in Germany is on subsurface spatial planning, because of the coordination of many underground potentials. Research topics change from active mining to storage, spatial planning, geothermal issues and post mining interests.

The following figure is showing the wide range of usage potentials as well as the availability of utilization capacity of the subsurface space in Germany. An overview of several different forms of underground usage is given (2014). Divided into three main topics – extraction of resources (e.g. coal and salt mining, extraction of gas), enclosure of substances (e.g storage in underground mines, caverns) and in situ-utilization and infrastructure (e.g. geothermal energy, tourism in closed mines) – it shows thematic areas of research [1].

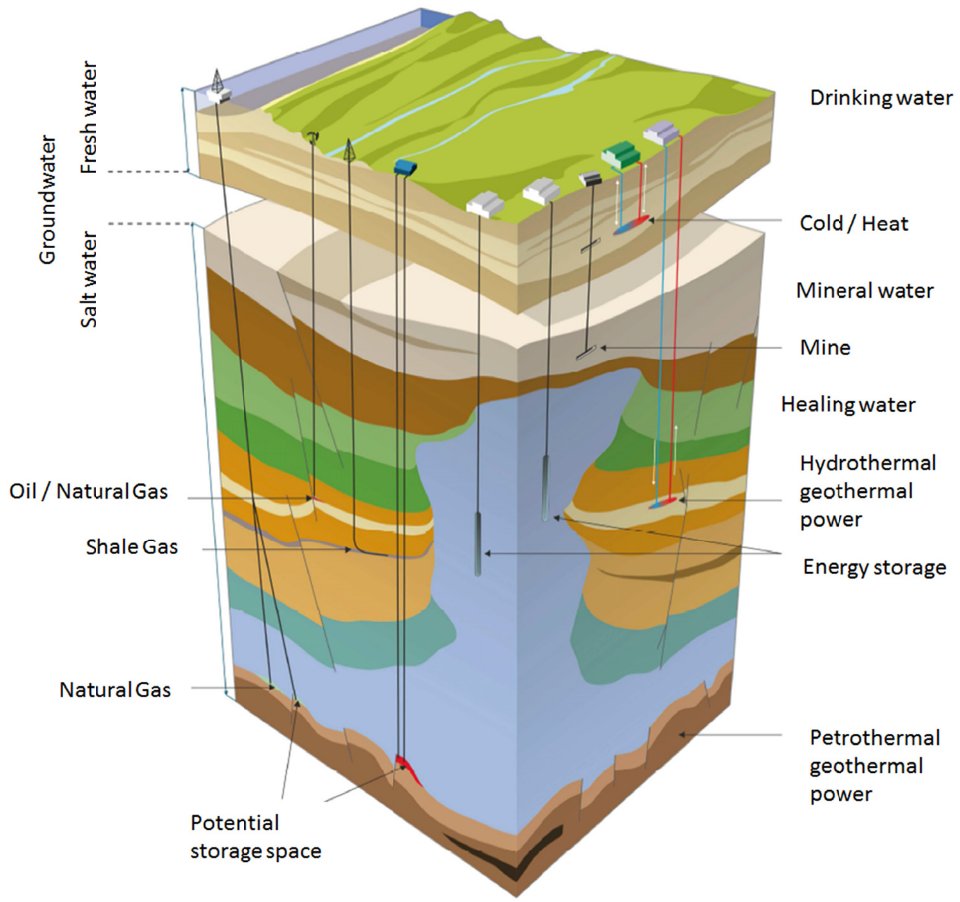

Fig. 1. Schematic illustration of different usage forms [1]

As it was during active mining it will be in the future. German experiences in mining subsidence engineering will be transferred to the world. Other mining nations might benefit from German expertise, which was gained under difficult boundary conditions, both in active and abandoned mining and always with a view on the dense population structure.

This paper deals with the retrospective of subsidence topics within the last decades and the perspectives of what is going to do in the future. In the following chapters, several issues of mining subsidence engineering are described.

2. Review of ground control Research since 2000 – focus on hard coal mining

a. Active mining

Dynamic aspects of underground coal mining

The doctoral thesis edited by Kateloe (2002) discussed the temporal subsidence process by means of dynamic models. In consideration of the theory of stochastic media, the focus was lying on the influence of face advance rates and stoppages on the temporal subsidence process. For an instantaneous movement process and a constant face advance rate during the working week, the simulation, referring to a surface point, showed the influence of regular two-day weekend stoppages by the stepped curves of the considered ground movement components over time. Their acceleration curves in this case oscillate among positive and negative values (Fig. 2). The thesis pointed out that the dynamic effects due to the weekend stoppages are less distinct for a slower movement process. The influence of irregular face advance rates as well as stoppages is for an instantaneous movement process highly visible in the curve of subsidence over time [2].

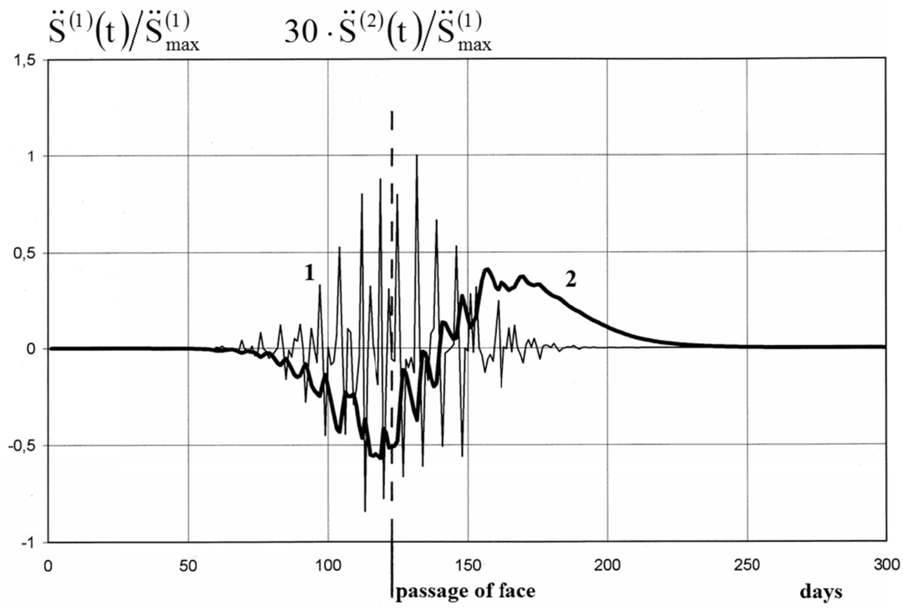

Fig. 2. Temporal subsidence acceleration of surface point P;
curve 1: instantaneous ground movement process, curve 2: lagged ground movement process

Regulation of the face advance rate

At the end of the 20th century hard coal mining was decreasing in Germany. Due to less production the efficiency was more important. This economic compulsion led to a layout planning which was optimized. There are two options to optimize amounts of production. On the one hand by enlarging the length of the longwall and on the other hand by increasing the rates of face advance. The second applicant increases inevitably the mining dynamics of the rock structure and at the surface terrain. For protecting the surface it is possible to affect the mining dynamics by technical measures. An effective method to reducing the mining-induced disturbance potential to surface structures was regulating the face advance rate in longwall mining operations. Due to its mining condition, it was forced to select a slower rate, especially while undermining sensitive infrastructure objects, as mentioned in the previous chapter. One case study dealt with the subsidence in range of a product transmission overhead line. Such transmission overhead lines are affected by influences of mining in a very sensitive way and are determined by technical or operational parameters [3, 4].

Under these circumstances it was possible to predict, that an undermining would lead to local stress maxima within the pipeline string, which could have been reduced by many separate relaxation cuts only. The face advance rate of the panel was adjusted to limit the local stress maxima and within the range of the pipeline, the ground movement process was surveyed. Furthermore, based on the theory of stochastic media it was analyzed via a dynamic precalculating, developed at RWTH Aachen University [5].

The use of pneumatic stowing

Pneumatic stowing and other similar methods were used in many mines in the German mining industry. Within the last decades of the 20th century these methods were developed and used for subsidence reasons. Beside the advantages in ground control pneumatic stowing had the advantage of the reduction of spoil materials on the surface and also less mine damages and a better climate in the mine [5, 6].

Pneumatic stowing had also disadvantages. Besides increased costs, because of an additional infrastructure, the rates of face advance decreased due to the stowing process. This affected the mentioned adjustment of the face advance rate. In that time different case studies of stowing and caving longwalls were made to verify the prediction parameters γ and α. For German mining regions the assumption of $a = 0.5$ (stowing) and $a = 0.9$ (caving) was substantiated. It was verified that the final subsidence above caving longwalls is reached faster than above longwalls conducted with pneumatic stowing. Approvals in the German mining industry showed that the question about the stowing method was gaining importance again. Reduced acceptance of mining activities in general and the participation of the public in these approvals had led to questions about the possible effects of stowing methods onto surface objects. While huge efforts had been taken between the 1950s and the 1990s to optimize especially the pneumatic stowing method in the German mining industry, it had been monitored over all these years that surface influences could only be reduced by the use of pneumatic stowing, but they could not be totally eliminated. This still seemed to be an unknown fact in the public discussion, leading to unacceptable demands towards the mining industry. The different longwalls conducted with pneumatic stowing in all these years did all show that the reduced costs for surface and inner mine damages did not compensate the increased direct costs for additional infrastructure and the indirect costs due to slower advance rates and more stoppages. The actual mine plan approvals, especially the general question about the stowing method and its solution were of vital significance for the future of the German mining industry [5].

The dimensioning and the extraction of shaft safety zones

During mining activities the dimensioning of shaft safety zones was a substantial task of mining subsidence engineering. On the one hand, coal reserves in shaft proximity were to be mined as complete as possible because they could be mined accessible economically. On the other hand, the maintenance of the shaft operation had to be ensured at all times, since the shafts represented the most important link between underground and surface. The optimization of shaft safety zones was based upon empirical rock statistics. The dimensioning of appropriate shaft safety zones results from the limit value of vertical deformation. The radius R of a shaft safety zone can be calculated as long as the maximum vertical deformation does not exceed the limit value. In mining practice, a number of extraction methods in shaft safety zones were suggested. Some of these methods are generally used, others are not due to too large rock deformations or due to technical problems. The following types of extraction are performed in shaft safety zones:
- Extraction underneath a shaft
- Extraction which cuts the shaft structure
- Extraction in a shaft safety zone, but not in the direct shaft array

The extraction in a shaft safety zone is simplified if it does not cut the shaft structure. If the extraction in a shaft safety zone cuts the shaft structure, it is more complicated. Regarding this method, safeguarding of the shaft support is necessary. Figure 3 shows a two-wing longwall mining with different directions of face advance, with two possible versions:
- Extraction by two longwalls, each conducted towards the shaft (Fig. 3, left side),
- Extraction by two longwalls, each starting from the shaft (Fig. 3, right side).

Extraction methods in shaft safety zones by dividing the seam into harmonically distributed sections are outstanding. Due to the minimization of subsidence issues like the shaft's tilt, nearly all extractions of shaft safety zones were conducted by this method in Germany up to 1940 [5].

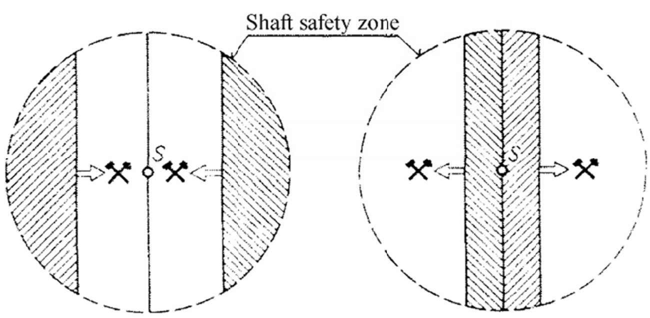

Fig. 3. The scheme of two-wing extraction

Seismic events

Another risk of active mining is the possibility of seismic events, which occur in different intensities. Their extent on the surface depends on several geological and mining operational factors. The German federal state of Saarland experienced an outstandingly strong mining-induced ground vibration, measuring 4.0 on Richter scale with a maximum vibration velocity of 93.5 mm/s on 23th February 2008. Due to this event the mining authority of the provincial government imposed an immediate stop of the longwall that caused the quake. The RAG Company decided to cease the entire production at Saar colliery temporarily. Within the following period, the risk of ground vibrations due to a continuation of the initiating panel was analyzed. The main factors discussed in that investigation were geological (e.g. Sandstone percentage, mining depth, seam thickness) as well as mining operational conditions (e.g. multiple seam, face length, face advance rate) and the assessment was based on a general technical expertise and findings from former seismic events at Saar colliery. Based on the assessment they assumed that no stronger seismic event is expected while mining the mentioned panel [7].

However, due to the significant risk of seismic events, hard coal mining was shut down in the federal state of Saarland a few years later.

b. Abandoned mining

The evaluation of surface fracture endangered ranges over shallow mine workings

Later on, after the abandonment of several mines, both deep and shallow mines, the focus was lying on surface fractures due to that issue. Different reasons like abandoned mine shafts, day-drifts and shallow mine workings can cause surface fractures as a consequence of former mine workings (Fig. 4).

Fig. 4. Surface cave-in over an abandoned shaft

The surface inside different mining regions in Germany was affected by several shallow mine workings from an earlier era. Due to light overburden load, many of these mine rooms did not converge, so that a downfall can suddenly happen, at a later time.

Also above already converged rooms the developing of downfall and loosening zones in the roof layers might lead to further convergences, either gradually or suddenly, e.g. in connection with a changed load entry into the subsurface or by additional influence of water. Breaks and recompactions within the mined layers are connected with mass movements which can cross up to the surface. The outcome are ground movements, which might appear as surface fractures. Due to that issue, a model of stochastic media was adapted regarding the conditions of abandoned shallow mining. At RWTH Aachen University, this model was enhanced as an Excel-application, called SAB ("**S**tochastic Theory for the **AB**andoned Mining"). It was programmed in order to compute and illustrate possible ground movements due to mine workings next to the surface. Characteristic values for the evaluation of the surface fracture possibility in a comparative view of different cases were determined, based on the computation results by SAB. Mining in Germany has a long history. This is why there are many locations where the surface fracture problem is still current. The evaluation of surface fracture and subsidence endangered ranges requires further research, which meets the interests of claimants and of the companies and authorities who are finally responsible for the impacts from abandoned mines [5].

Risk Assessment of Surface Fracture

Due to surface fracture endangered ranges over shallow mine workings, risk management had – and still has – a special emphasis. RWTH Aachen University developed a method for analysis and comparative assessment of the incidence probability of surface impacts due to abandoned shallow mining. Part of the analysis was to perform theoretical cases of surface-fracture-inducing mining situations. The developed method generally based on the theory of stochastic media and the determination of specific key parameters of shallow mining. In areas with dense population and public facilities a determination of the probability of occurrence of surface impacts is most important. Within a few years, more than 50 surface fractures in the southern Ruhr district were analyzed in order to develop a risk assessment of surface fracture endangered ranges over shallow mine workings. The developed method created defining ranges with increased probability of incidence of surface impacts due to shallow mine workings [8].

c. Post mining

Mine water rise and efficiency issues

Due to abandoned mining in Germany, the focus relocates more and more to eternity burdens. With the decision of the shutdown of subsidized German hard coal mining in 2018, the issue of rising mine water was getting more important. Also without active mining the industry will affect the former mining regions and the aftercare will have to be performed for an indefinite period. As well, this issue leads to the questioning of probable uplifts due to geological processes inside geological strata and possible methods of predictions regarding an optimal mine water rise. Predictions which took the efficiency into account as well, due to the fact that rising mine water can cause different processes which potentially lead to costs. Different theses were edited in the recent past. One of them was edited by Papst (2015) and dealt with the topic “Quantification and optimization of mine water level associated cost in the post mining Ruhr-District”. Potentially triggered processes were identified and finally examined in regard to their dependence on the level of mine water. The costs of the dependent processes were quantified and a consolidated optimization model was edited. For the future, this model may be used to determine the mine water level with the minimal cost [9].

Seasonal storage of geothermal energy in abandoned coal mines

The aspect of the mine water rise leads to another challenge at the institute of mine surveying regarding German subsidence research: The impacts of seasonal storage of geothermal energy in abandoned coal mines.The Ruhr district is the biggest coal mining area in Germany with a high number of abandoned mines. Furthermore the area is densely populated and an important economical location with high demand of electrical and thermal energy. With the new agenda of sustainability research is conducted to store the thermal energy of the industry in the summer and utilize it during winter. One prosperous approach is to use the hollow spaces created by mining activities as heat storage for geothermal energy. Due to the fact, that the abandoned coal mines are underneath industrial areas, living areas and cultural heritage it is important to minimize the impacts on those structures. The conducted research focusses on the uplift of the ground surface induced by the heat up of the abandoned coal mine.

The technical approach is to connect flooded cavaties, via geothermal drilling, with the regional heat network. During the warm seasons heat will be stored in the water underneath and removed during the cold seasons. The change of the temperature leads to an increase in the pressure thus leads to an increase of the volume of the surrounding rock. The surface is the only direction where the volume surplus will take effect. The research focusses on the calculation and prediction of this uplift (e.g. total uplift, shape, tilt, compression, …) and the possibility of subsidence at the surface.

3. Current and future topics in German subsidence research

a. Production and storage of gas

With the relocation of research topics from active to abandoned mining and furthermore to general subsurface issues there are some other research areas regarding subsidence engineering in Germany. One topic mentioned in this paper is the production of gas, its effects on the surface and the related legislation.

Primary the production of gas should have been regulated with changes in law, which came into force in 2016/2017. But beyond, the compensation of mining damages were expanded to the extraction by drilling from the surface and underground storage. For the compensation of mining damages the area of main influence, which includes subsidence up to 10 cm, takes a significant role. Within this area an affected landowner is supported by the “reversal of burden of proof” (in German: Beweislastumkehr) under certain circumstances. Subsidence up to subsidence border are considered for “special plants” (such as bridges and sluices) [10].

For the first time the range of mining impact of a cavern field was analyzed by a dissertation with regard to the legislation amendment. The outcomes base on research using the example of the cavern field Epe, which is located in the northwestern part of the Münsterland region (North Rhine-Westphalia). The area of main influence and the subsidence area of mining subsidence (subsidence up to subsidence boarder) were subject of the research considering the legal issues. One of the outcomes were the development of the range of the area of main influence and the area of mining subsidence for a period of 24 years. The extension of both areas correlate with the cavern field extension. New caverns induce the range of the mining subsidence area only after a few years. For five sample periods an angle of draw (limits the minings subsidence area) has been calculated. For this calculations the angle of draw for caverns has been defined. It could be shown, that the calculated angles of draw nearly stayed constant for a period of 24 years. In the area where further caverns do not enhance the cavern field for a certain period, it seems, as if the expansion of the subsidence boarder is mostly completed. It has been shown, that the defined angle of draw can be used to determine the mining subsidence area. In addidtion to that, the research shows, that it is very complex to calculate the angle of main influence (limits the area of main influence), because a lot of caverns which are located at the edge of the cavern field are located outside the area of main influence. For this reason, it is recommended to determine this area by measurements and resign of the angle of main influence. Regarding deep drillings there is further need for research due to the determination of the range of the mining induced area. For example with regard to the production of hydrocarbons or production of geothermal energy [11].

This aspect leads to another challenge in German subsidence research, the impact of seasonal thermal storage on the surface. Meanwhile this is considered for the Ruhr district in cooperation with the International Geothermal Centre in Bochum.

b. Groundwater-based georisks along geological faults – lignite mining

The diversified field of work within the subsidence research includes open pit mining as well. Beside competitive subsurface issues, open pit mining has effects on the environment and also on the surface structure as well. In interaction with the dewatering for the lignite mining the geological conditions of the Lower Rhenish Basin entail a large scaled subsidence and unequal effects along geological faults. In different reports, edited by the Institute of mine surveying of the RWTH Aachen University, these movements are discussed. While large scaled sinking has no damaging effects on infrastructure, movements within a small range along a geological fault might have. The discussed reports determined the affected area along a fault to a few meters up to tens of meters. A lightly too inaccurate range which requires further research.

To monitor or even to predict effects like those, it is necessary to use any possible measurement method. Within the next decades, the open pit mines in the Rhenish mining area will be shut down and the groundwater, which is pumped currently, will rise. With rising water, the soil mechanical conditions lead to movements again. Effects occurring during dewatering will occur in the opposite way. And so, geological layers, on the one and the other side of a fault, react differently on rising ground water. Both, ground movements due to dewatering and movements due to rising ground water have to be monitored during and especially after active mining. The effects on the environment do not end with the end of mining. In this context it is of high importance that detailed geological maps exist. Research topics like that and these mentioned in the chapters before are discussed at the Institute of mine surveying at the RWTH Aachen University [12].

4. Summary

Mining subsidence engineering in Germany is closely connected with hard coal mining and its consequences on ground control. Within the last decades and especially within the last 20 years, while the active hard coal mining in Germany run out, many issues were dealt with.

Already during and of course after active hard coal mining, proceeding issues of mining subsidence engineering plays a major role in Germany. Topics like post mining issues, mine water and ground water control or gas storage and its consequences on the environment dominate research activities. While improvements were made due to the angle of main influence regarding caverns, the research of other issues has to be forwarded.

Since the turn of the millennium several issues were dealt with and many results were generated. Nevertheless, underground usage potentials in Germany provide many challenges regarding subsidence engineering in future. Primarily the questioning of eternity burdens in connection with geological and hydrogeological conditions and economic requires will be a challenge for several decades.

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