Sensitivity analysis of factors influencing mine water rebound in underground coal mines by the Design of Experiment approach

Sebastian Westermann[1], Dmytro V. Rudakov[2], Christian Melchers[1]

[1]Technische Hochschule Georg Agricola University, Research Center of Post-Mining, Herner Str. 45, Bochum, Germany, sebastian.westermann@thga.de, christian.melchers@thga.de

[2]Dnipro University of Technology, D. Yavornytskoho Ave, 19, Dnipro 49005, rudakov.d.v@nmu.one

Abstract

This study presents the joint application of an analytical groundwater flow model and Design of Experiment to examine the relevance of different factors including residual cavity volume, rock conductivity, scale of area hydraulically affected by mine water, and infiltration rate. For the first time, Design of Experiment were applied to post-mining water management. These results allowed evaluation of both the relevance of individual factors (single effect) and their interaction (interdependence) relating to the conditions of the mine flooded. The case studies included the collieries Ibbenbüren, Königsborn and Westfalen that differ in their geological structure.

Keywords: Mine water rebound, analytical modelling, sensitivity analysis, flood-influencing factor

Introduction

Hard-coal mining in Europe is in decline and mines in many European regions have been closed over the past decades (Melchers *et al.* 2019). During the operational stage of coalmining, water abstraction from underground workings is required to ensure safe mining conditions. At mine closure, abstraction is often terminated or may be reduced that leads to mine water rebound in the underground workings.

Prediction of mine water rebound is complicated due to variable rock properties, the different geological structural and hydrogeological settings of a mine, complex underground mine geometry, and lack of data and information. Access into closed and abandoned underground mine workings is difficult or impossible so data cannot be readily collected without extensive and expensive investigations. The complexity of the mining geometry and the hydrogeological rock qualities specific for each location result in the fact that mine water rebounds behave differently at each site. This variability, in conjunction with the frequently occurring lack of knowledge on the parameter distribution, complicates any prediction of a mine water rebound.

Depending on the objective and size of the area investigated, different model approaches can be applied to calculate the flows of both groundwater and mine water (Younger & Adams 1999). For more than two decades, mostly numerical models (Paul *et al.* 1998) have been applied in mine water management, however, their development and testing require detailed knowledge of natural and anthropogenic properties distributed in space at the deposit. Numerical modelling of previous mine flooding cases has often incorrectly estimated the rates of rising water level; mine water rebound has taken another time than predicted (e.g. Ibbenbüren colliery [Westfeld]; Goerke-Mallet 2000). The inaccurate forecast disregarding model parameter relevance was often the reason why no respective measures were taken timely when closing the mine. The deviation in the flooding duration is often due to insufficient information about the input data required by the model.

Analytical modelling

RThis study applies a model of transient radial groundwater flow to the shaft in order to calculate the mine water level and the inflow rate; this model has been developed based on analytical methods of groundwater dynamics and water balance relationships. One shaft is assumed for similarity with the pattern of radial free surface groundwater flow governed by Dupuit-Thiem formula. Compared to numerical models of a more complex structure such as MODFLOW, FEFLOW, Spring, Boxmodel, the developed analytical model requires less extensive knowledge of how the hydrogeological and mining parameters are spatially distributed. Moreover, the analytical approach allows for a purposeful variation of selected factors (either single or combined) whose impact on the mine water rebound can be evaluated in a clear manner.

The analytical model simplifies natural conditions by dividing the deposit into horizontal layers and calculates minimum, maximum, and expected estimates of factors, such as the residual volume of underground workings created by mining (fig. 1), for each of the layers. The model parameters are assumed to be constant within each geological layer. This simplified model structure is applicable to underground workings which are hydraulically isolated from adjacent mines, although additional flows from other mines or aquifers can be included in the water balance equation within a more complicated model.

Design of Experiments

One standardised method for the systematic design and statistical evaluation of test series is the Design of Experiments method, originally introduced by Sir Ronald Aylmer Fisher in 1935 as the Design of Experiments (Fisher 1935). Contrary to the trial-and-error approach or the OFAT method in which only one factor is varied, the Design of Experiments method allows for investigating the interdependent influences on a system by varying several factors at the same time within a fixed range of values (Goh 2013). Since the 1980s, this method has increasingly been used in research, development, and industry; however, it has not been widely applied in post mining hydrogeology.

The application and evaluation of the Design of Experiments method can be facilitated by using specific statistics software (for example, Design Expert [STATCON GmbH], Stavex [AICOS Technologies AG]). For this investigation, we used the software MODDE Pro (version 12.1) of Sartorius Stedim Data Analytics AB (Sweden) (Eriksson *et al.* 2008).

Case studies

The DoE approach in combination with the analytical model was applied to the

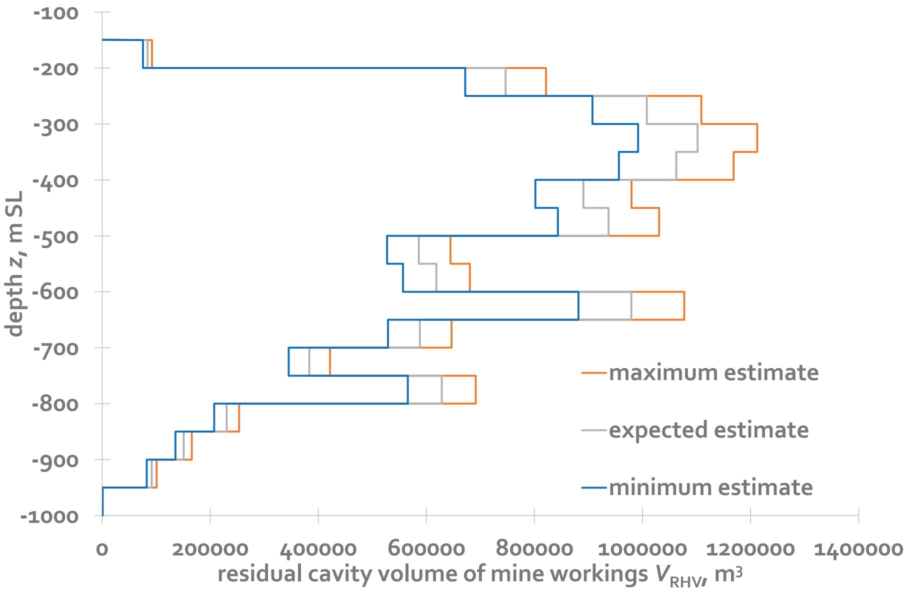

Figure 1 Estimated residual volumes of underground workings for each layer (Königsborn colliery).

Ibbenbüren (closed in 1979), Königsborn (Unna; closed in 1981; water abstraction was stopped in 1996) and Westfalen (Ahlen; closed in 2000) collieries of the North-Rhine Westphalia coalfield in Germany. These mines have been closed a considerable time ago and mine water drainage had been terminated. Thus, the mine water rebound has already advanced a lot and has been monitored by measurements and documented. Underground workings have no hydraulic connection to adjacent mines. The main differences between the collieries selected are the thickness of their overburdens which consist of clay marl rocks of low hydraulic conductivity (Emscher formation, Upper Cretaceous) and lime marl rocks of a higher hydraulic conductivity (Cenomanium and Turonium, Upper Cretaceous). Ibbenbüren colliery shows no overburden, whereas the overburden thickness of the other two collieries range between 300 m (Königsborn colliery) and 800 m (Westfalen colliery).

Modelling results

The model yields a data series that show how the mine water level and the flow rate of both groundwater and mine water are evolving in time. At all three collieries investigated, only little differences between the data series of the measurements and calculations were found (tab. 1) for the basic variant interpreted as the variant that generates the minimal deviation from the actual measured curve. As the example, the mine water rebound with minor deviations during the period of measurements is shown for the basic variant evaluated for the Königsborn colliery (fig. 2).

This investigation analyses the impact of a four-factor variation on the development

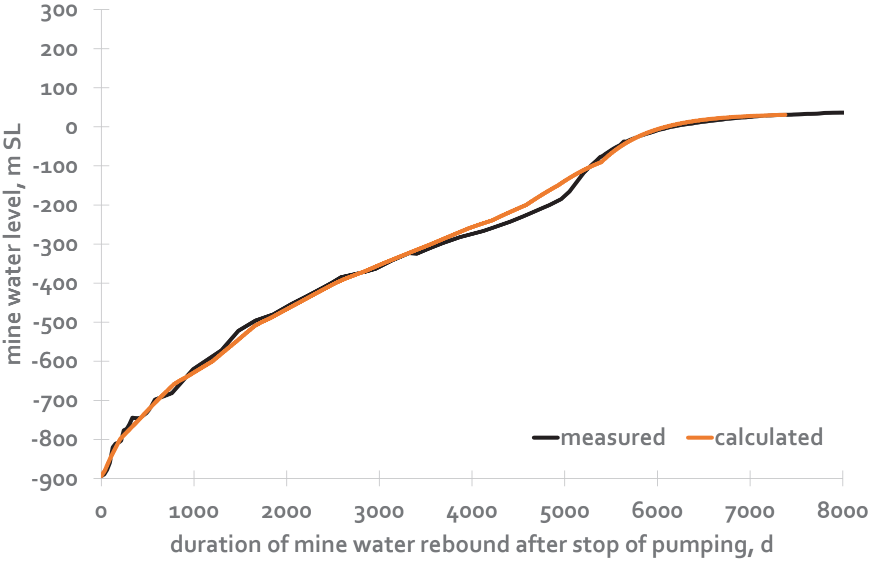

Figure 2 Comparison of measured curve (black) and optimal variant (orange) with minimum deviation for the Königsborn colliery.

Table 1 Mean square deviations between the data series of the measured and calculated (base variant) temporal development of the mine water (pressure) area and inflow rate.

	Ibbenbüren colliery %	Königsborn colliery %	Westfalen colliery %
mine water level	2.1	1.2	1.0
initial inflow rate	0.8	0.1	0.1

of the mine water rebound in each of the collieries. These four factors comprise:

- residual cavity volume created by mining
- distance to the outer limit of the depression cone
- hydraulic conductivity of the rock
- infiltration (recharge) rate

The factors were varied within the predefined value ranges by the relative expected value *XE* (0.9 *XE* < *XE* < 1.1 *XE*). These result in the set of curves (fig. 3). From a mathematical viewpoint, the sensitivity is quantified by the mean deviation between the data series calculated for the basic variant and that of the respective model curve.

The data series of the mine water level are based on individual measurements (weekly to monthly sounding measurements in shafts over a multiyear period); however, the data series of the inflow rate include only a measurement made before the mine water rebound began, whereas the inflow rate at the end of the mine water rebound is only estimated. Thus, there are no further considerations regarding the inflow rate. Nevertheless, the available data series enable making important conclusions on the flooding process in the underground workings.

Results of Design of Experiments and Interpretation

The functional interdependence of one or more factors (independent variables) and a target value (dependent variable) is described using a non-linear, multiple description model. The regression coefficients – calculated by the statistics software – enable the quantification of not only any individual factor but also of the square and interdependent terms on a process. The results were interpreted according to the following rule: the greater the regression coefficient, the higher the impact. These coefficients are also referred to as sensitivity coefficients.

The sensitivity coefficients determined are always site-specific; however, their results can be generalised and transferred to natural conditions, thus, making them site-independent. To do that, the sensitivity coefficients will be compared to the specific hydrogeological features of the deposit. The proportion of overburden thickness to total

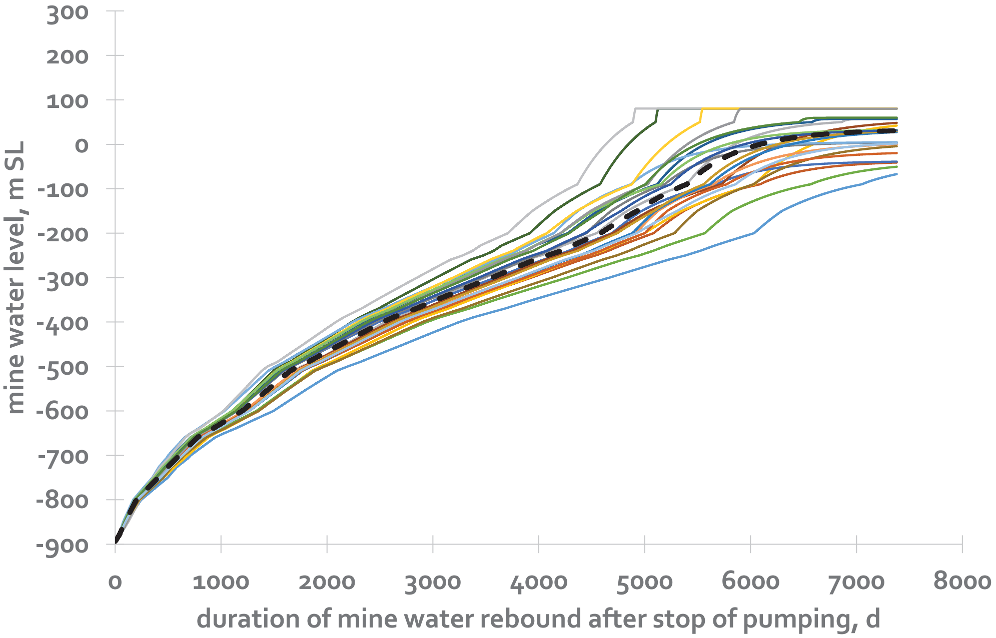

Figure 3 *Set of mine water rebound curves resulting from the variation of factors (optimal variant: black dotted) shown by the example of Königsborn colliery.*

depth considers, for example, the impact of the overburden on the mine water rebound (fig. 4). Deposits without overburden, such as Ibbenbüren Colliery, are characterised by low proportions (close to 0), in contrast, deposits with thick overburden layers demonstrate higher proportions tending to 1.

This chart helps to recognise the trends for the factors in relation to the overburden thickness. The influence of the factor "infiltration rate" on the mine water level steadily decreases with an increasing overburden thickness. At the same time, the factor "hydraulic conductivity" becomes more significant with increasing overburden thickness. This trend emphasizes the increasing importance of the hydraulic rock conductivity for deposits where the overburden is flowed through as part of the mine water rebound once the open mine workings have been flooded.

Conclusion

The combination of an analytical modelling approach with the Design of Experiment method enables a systematic investigation of the key factors of flooding the mines. In conjunction with the Design of Experiment method, the influence of these factors including their linear, square and interdependent terms on the mine water rebound process is quantified within sensitivity analysis. This classification and the subsequent prioritisation of factors contribute to optimising the monitoring measures at all stages of the mining life cycle by focusing the investigation on the system-relevant factors. Factors which are less system-relevant can be assessed cost-efficiently and without a larger time investment using experiential values and analogous comparisons.

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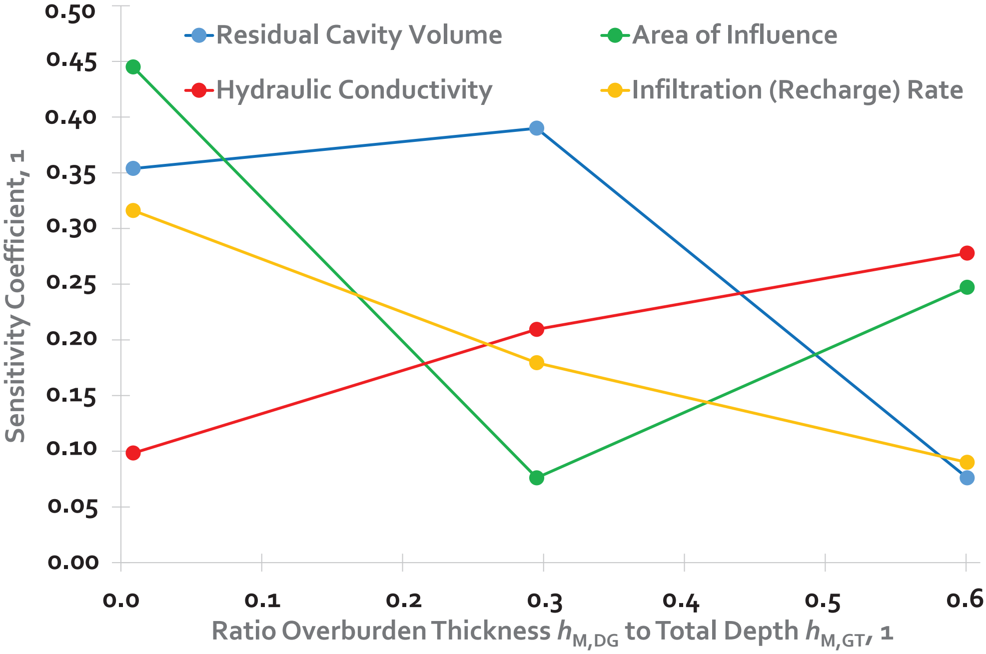

Figure 4 Effectiveness depending on the proportion between overburden thickness and total depth of underground mine workings.

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