Effect of Active Mining Impact On Properties with Engineering Structures – Forecast and Final Result Discrepancies

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Abstract. Discusses is one of the stages of an ongoing research study analysing the form and area of active mining impact on properties which include engineering structures. A general back analysis has been applied to the cause and effect method for defining the causes of empirically determined structural damage. The calculation model and numerical model of engineering structure and the environment with different influence are created on all basis data what are known from the project and documents. One of the aspects of the research study analyzed here explores the current assumptions for mining damage forecasts for areas affected by a mine over a planned operation period. Considering that mining forecasts specify the quantity, impact duration, as well as the form of static and dynamic forces responsible for stresses and deformations resulting from active mining, the information is most critical for the construction and industrial sectors. The mining plans for the analyzed areas are based on the final information supplied by the forecasts, and show active mining areas clearly outlined; thus making it possible to delineate the active mining impact areas when preparing guidelines for building and structure construction permits. The mining damage area parameters determine the design and construction requirements for individual projects which must comply with engineering structure foundation specification for areas exposed to other than standard and highly damaging active mining impact. Mining forecast data allow for designing adequate structural, material, and geothermal safeguards which will stabilize the soil and reduce forces negatively impacting soil serviceability limit states. Owing to the high number of problems attributable to discrepancies between the mapped mining damage areas, the calculations and assumptions used in mining forecasts, and the actual conditions, this study aims to analyze the problem. Based on the information supplied and the author’s own observations supported by empirical investigations, the following conclusions have been developed.

1. Introduction

Discussed is one of the stages of an ongoing research study to analyze the type and extent of active mining impact on properties featuring engineering structures. A general back analysis has been applied to the cause and effect method for defining the cause of empirically determined structural damage.

Initially, field trips were made to visit properties reporting damage. More than ten variables affecting the serviceability limit state SLS, and ultimate limit state ULS, of structures were collected for the analyzed functions, which under certain cases strongly affect the behaviour of the structure. The problems have been discussed in a number of publications in professional reviews [1-4], [7], [8], [14],
[15], [17] and general standard as [18]. Empirical tests carried out for various court cases and our own scientific investigations at the university using comparative analysis, mathematical, numerical, and statistical methods served to define a group of variables which – under certain initial conditions – strongly impact the process of generating damage to buildings and structures. The selected representative group comprises the following variables:

- the number, duration, and magnitude of the mining impact (in terms of tremors, settling, and foundation soil displacement),
- the distance between the active mining area and the examined property,
- soil physical and mechanical parameters (required for developing $X_{n1}$, $X_{n2}$, … calculation models),
- data obtained from area monitoring – maps of mine workings, hydrogeological maps of the roof and overlay formations, hydro isohypse maps, topographic maps, and results of special measurements of boreholes – $X_m$, 
- type, size, and nature of damage – $X_{ij}$,
- type of construction material used for the damaged structure,
- extent of the structure wear and tear plus any completed renovation or upgrade.

All the above variables significantly impact the process of identifying the causes of actual damage suffered by properties located on formerly active coal mining areas.

One of the aspects of the research study analyzed here explores the current assumptions for mining damage forecasts for areas affected by a mine over a planned operation period [1], [2], [5], [6]. Considering that mining forecasts specify the quantity, impact duration, as well as the form of static and dynamic forces responsible for stresses and deformations resulting from active mining, the information is most critical for the construction and industrial sectors. Local urban development plans for the analyzed areas are based on the final information supplied by the mines, and show active mining areas clearly outlined; thus making it possible to delineate the active mining impact areas when preparing guidelines for future building and structure construction permits [2], [3], [10]. Important aspect focuses on defining subsoil modifications required to:

- adequately support loads exerted by engineering structures,
- eliminate dynamic and static forces accompanying mining operations which is analyzes in this papers
- protect the newly erected structures and buildings against adverse effects of mining operations.

One of the aspects of my research project considering mining forecasts specify the quantity, impact duration, as well as the form of static and dynamic forces responsible for stresses and deformations resulting from active mining, the information is most critical for the construction and industrial sectors. Very important are analyzes the mathematical model for the required modifications and designing and stabilizing the subsoil. There is one of the stages of an ongoing research study to analyze the type and extent of active mining impact on properties featuring engineering structures as forecast and final result discrepancies. A general back analysis has been applied to the cause and effect method for defining the cause of empirically determined structural damage. A morphological method was applied to the results of analyses and methods for eliminating mining damage: the main issue at hand was divided into sub-problems with partial solutions. This approach allowed for analysing various options and combinations of potential solutions. The final conclusions of the project produced a matrix of solutions applicable to solving the mining damage problem with new differentiation method.

There are discusses on one stage of my research project covering the analysis of an interdisciplinary approach to mining damage, including legal, engineering, construction, geotechnical, mining, economic, and financial aspects. Despite being so different, all of them show certain common variables and significant interactions. The results of our analyses, data from actual forecasts and evaluations of interactions induced by coal mining operations support our conclusions and validate
comparisons to empirical analyses and model investigations of certain selected types of mining interactions [1], [3], [5], [6], [9]. Depending on the number of variables available for the analysis in selected cases, for some carefully tested and classified output data, the comprehensive function we have developed for a component model of engineering structure in subsoil and mining interactions, has yielded results comparable to the empirically established structural damage [3], [5], [6], [10], [13] and [17]. The presented interactions have been defined for several variables, which depend on interactions induced by mines operating mining equipment, and mining interactions which affect the strength and physical parameters of the soil supporting buildings and structures exposed to additional harmful static and dynamic interactions [7], [8], [12], [11], [13].

2. General Characteristics of the Research Project
I often prepare valuations and legal expert opinions for lawsuits contesting initial data, analytical methods and calculations. For their analyses, mining industry experts use information submitted by mines to forecast potential active mining impact with respect to time, area, and type. The main requirement for launching a claim for damage to buildings and structures consists in proving the property is indeed located within the mining impact area marked out in the documents supplied by the mines. However, there are cases where new buildings, after merely a few years of proper use and maintenance, show numerous and growing problems caused by tilting and shifting of the building and floors tilting at various levels, very big problems are in cracking and fractures of floors, lintels, walls and shifting and tilting damage to expansion joints, chimneys, porches, balconies, water and sewer systems and central heating systems [4], [8]. Owners of damaged buildings demand their homes be repaired while the mine insists the damage has not been caused by mining impact since the buildings are located outside any active mining areas. Quite frequently, mines suggest various hypothetical reasons for the impact which might have led to structural damage. Such lawsuits give rise to questions from the bench which an expert witness attempts to answer using a cause and effect method based on data available in the court files and the results of potentially feasible calculations and simulations [9].

This paper discusses the results of analysing theoretical and empirical assumptions for mining forecasts. Specific constitutive models have been selected for numerical analyses, starting with the most popular elastic-perfectly-plastic model with the Coulomb-Mohr strength criterion whose principal soil parameters include Young’s modulus (kN/m²), Poisson’s ratio ν (-), critical angle of repose φ (0), cohesion c (kN/m²), and the angle of dilation ψ (0), plus other analyzed models with isotropic amplification which depends on the volumetric and deviatoric mechanisms (Hardening Soil Standard and Hardening Soil-small models) in which the amplification mechanism is represented by separate hypersurface layers and separate isotropic amplification laws. The Hardening Soil-small model which has been expanded and clarified with respect to degradation of the secant modulus of elasticity Gs limited to the so-called minor deformations only. The model also realistically presents the effect of compaction (decrease in air volume owing to plastic deformations), the effect of historical loads (pre-consolidation effect), plastic deformation, the relationship between stiffness and effective tension (higher stiffness modulus at greater depths or stress level) and dilation (volumetric change during plastic deformation). The best calculation model is matched to an individual output data group to facilitate the back or cause – effect analysis; the analyses are carried out based on available input data.

General rules apply to testing the soil bearing capacity in order to precisely evaluate the reliability level of the analyzed solution, which helps simplify calculations when estimating the ultimate soil bearing capacity as a function of forces affecting the soil and vice versa, without considering their interaction characteristics. For example, one can analyze a quasi-continuous measurement of the strain of a building external wall and its immediate surroundings so as to make it possible to calculate the stress tensor components for a specific structure. The results of calculations and analyses comparing
the building strain values to soil deformations represent one of the aspects of checking the cause and effects of interactions found in the analyzed cases.

3. Fundamentals of forecasting the type and extent of active mining impact

The S. Knothe – W. Budryk theory is widely used to predict the impact of underground mining operations. It is based on observations of the ground behaviour in the analyzed area and that is why certain initial assumptions ideally corresponded to the number, type and extent of the mining impact. The major findings of those investigations were limited to information that the active mining area impact is far-reaching and may stretch out over a certain distance from the active mining area. Furthermore, they provided information about the type of active mining impact, later used to formulate guidelines for the shape of subsidence troughs and soil settling calculations. The active mining impact estimate theory must meet the requirements of a mathematical model of the medium. This theory must satisfy specific requirements, such as the transitivity requirement which determines the properties of the variability function of the major active mining impact radius for the analyzed area. The requirement typically represents the result of calculating displacements at a certain level which is independent of the location used in calculations [8], [13].

The soil in which mining is carried on represents a multi-phase medium we learn more and more about and for which we can now develop very detailed calculation models. The theory has given rise to an entire function of various mining interaction ranges in the rock mass. Currently, investigations are underway to test various models of the Knothe theory modification which attempt to define factors that take the existing output data into account. The soil model has evolved as well to include a great number of new physical and mechanical parameters affecting the action – reaction of the mining impact – soil systems – engineering structure systems. At present, active mining often takes place in areas that had been actively mined in the past century, resulting in the rock mass structure being now altered by materials and anthropogenic components that had been absent at the time the theory was first being developed.

More work is underway to further detail and update the mining impact description and the research results either support or reject new solutions. A number of theoretical analyses have looked at basic mining operations only; whereas the results of contemporary empirical investigations are presented as a function of numerous variables. A number of calculations strictly follow the K-B theory guidelines which do not correspond to the measured impact values. When looking for the cause of structural damage, the answer to the question posed by the back analysis employed find out whether the actual damage type and extent could have been caused by actual (but not forecast) active mining impact must be in the affirmative, even though the analyzed structure is located outside the estimated mining impact area.

The anticipated, theoretically most viable cumulative effect of mining activities on the analyzed area is calculated using typical, time-variable parameters, such as subsidence, average deflections $T_{\text{max}}$, average curvature radius $R_{\text{max}}$, and average specific deflection $E$.

4. Model Factors

Nowadays, thanks to high computational capabilities, we can model soil interactions as a multi-phase medium with any type of loads affecting it. Models of engineering structures interacting with the surrounding soil to analyze deformations and stresses are but an attempt to find out what happens to the structure exposed to external or internal static and dynamic loads. The back analysis used for this purpose looks at the cause of any damage found by examining all the potential responses of the structure with a specific reliability factor to the impact. An analysis of the load-bearing capacity and the type of use of the location where the soil loads are transferred to the structures which are affected by the static and dynamic mining impacts is suitable for an optimal model of the supporting soil geotechnical parameters with its corresponding partial factors, for impacts or impact effects when
testing threshold values according to EC7 [19]. Moreover, Eurocode PN-EN 1990 spells out mandatory requirements for the structural appraisal of existing buildings based on the reliability theory using advanced, state of the art mathematical computation methods. For the analyzed additions we are looking for mutually equivalent reliability measure $P_f$ - probability of destruction which is related to the reliability factor $\beta$, relationship $P_f = \Phi(-\beta)$, where $\Phi(-\beta)$, is a cumulative distribution function for a standard normal variable.

The engineering reliability concept provides for a three-step consequence class with the economic consequence of a structure losing its serviceability being most vital for the applied back analysis. The structural reliability factors, just like the structure destruction probability, are a function of $X_1$, $X_2$, … $X_n$ variables. The variables are quite often a function of the structure operating time, mining impact, technical wear and tear, … etc., which – in turn – leads to the above reliability measures being dependent on time. In this way, probability calculations are tied to the concept of designing for a defined useful life. In our cases, we calculated the likelihood of mining damage occurring either by adding variable $T=1$ year or assuming a specific $T_d$, or the varied useful life together with an appropriate interpolation formula for the reliability factor $\beta$. Calculating the extent to which such individual factors affect the standard deviation obtained by means of the comparative analysis is mostly a question of individual preference. As more factors exerting influence on the basic and secondary indicators are evaluated, there emerges a hierarchy of prioritized cause-effect interactions among them.

Measurable interdependence of the factors affecting the analyzed indicators may be expressed as a quotient, product, sum, or difference. One must also keep in mind that the sum of partial variations must add up to the total variation. Depending on how the effect of such factors on the overall variation is calculated, there are a number of detailed cause-effect analysis methods to be used, i.e. the iterative method, the method of chains substitution, or the differentiation method.

5. Statistical and Econometric Analyses

‘Live’ analytical dashboards are used to analyze large databases of time-variable data, which is filtered, merged, scrubbed and drilled in order to study initially assumed and newly emerging derivatives.
Figure 2. Computers analysis with pre-selection using currently available calculation methods
Figure 3. Recommended visualizations of suiting data for “n” sample of analysis of the mining impact on properties with engineering structures – back analysis for forecast.
Figure 4. Residuals analysis of the selected representative group comprises the following variables in six models of active mining impact on properties with engineering structures.

Very often, selection of data for a new derivative produces results closely resembling several cases but they cannot be generalized and applied to an already classified data group – Figure 2, 3 and 4. For that reason, automatically recording the data preparation process and the analyses themselves play a key role when trying to draw specific final conclusions which would allow for more detailed guidelines and tentative assumptions to better substantiate the analytical results. Several studies produced results typical for the analysed cases; however, the calculations did not yield any additional information. On the other hand, data visualization in the form of stream analysis has shown another way to analyse data by identifying new relationships manifested at the time atypical behaviour was detected: certain anomalies of results which were earlier assumed and expected. Detailed predictive analytics of individual derivatives is required before proceeding further since the variable database is quite substantial and already pre-selected.

Attempting an analysis without some pre-selection and grouping while using currently available calculation methods seems too complicated for the time being. Every analytical and calculation model calls for defining the reliability of the results obtained for specific assumptions, and the option to deliver a quick, preliminary evaluation of the relevant level, without having to wait for any additional data needed for the analysis; especially when successive levels of mining interactions, which produce even more damage, are being exceeded. The models have been discussed in a number of publications in professional reviews [2], [5], [6], [8]. Work is under way to launch a pilot project that would analyse data from monitoring the extent of mining interactions and automatically optimize verification procedures. The project would be implemented as a pilot project of a three-component mining interaction model. With defined rules and assumptions, and with a suitable method of “teaching” the right model, it would be possible to respond to mining interaction events in real time; whereas having the right intelligent model and the ability to visualize the investigated causes and deviations, would allow anticipating future impact of engineering structures on the planned mining activities.
6. Results and Conclusions

New time lines must be defined for building/structure damage that may or may not appear in the analyzed mining interaction areas and in the proposed areas of engineering structure response to mining activities.

There is no legal or strictly scientific criterion to define the quality of active mining impact forecasts; instead, the necessary guidelines are designed with a tentatively assumed error. Thus, mine forecast values must not be taken for granted.

The forecast error scale is directly proportional to the type, quantity and quality of the inputs. Mining impact calculations will be reliable if they are accurate; however, there is no clear definition for such forecast quality. It would be a mistake to assume forecasts are 100% reliable and that if the mining forecast excludes any chance of mining damage occurring, the damage will surely not occur.

A forecast utilizing the most accurate value is always the best choice and it should certainly not factor in a “client’s optimistic assumptions”, even when the variances do not exceed the maximum permissible error. The method for forecasting mining interactions which does not account for diffusion is inadvisable and must not be used for analyses and calculations.

Furthermore, forecasting a higher value, with room to spare, is also incorrect.

Accounting for diffusion using the “expert method” to approve mining operations, however, to evaluate strain effects in engineering structures for average forecast values, may lead to erroneous conclusions and should be discounted; a fact confirmed by numerous lawsuits for compensation for damage to properties caused by active mining impact which – according to the forecasts – was entirely avoidable.

We would recommend resorting to mining and construction preventive practices to safeguard mining operations as well as protect the surface soil and attached structures, i.e. engineering structures, against potential damage. Certain forecast variances may always appear but the underlying reasoning must be investigated when comparing the forecast to actual data. Consultations and conclusions resulting from analysing the history and scale of mining interactions with soil provide the starting point for fine-tuning the methodology of estimating the value of mining forecasts. An undiscriminating approach to the forecast parameters in not a prudent practice.

The engineering, construction, and geotechnical aspects of the analysis take into account the impact of mining interactions on the structural damage suffered by the analyzed buildings and structures. An opinion rendered based on such analyses should reflect all the relevant findings. In the event that the rendered opinion differs from the initial analysis, however, the underlying reasons for errors must be investigated. Once the assumptions made for every solution have been examined, i.e. comparing inputs to outputs by using the back analysis, the source of errors must be identified and the data adjusted accordingly. In the course of our investigation the method for calculating the estimated surface deformation values should be changed to reflect the incorporation of the diffusion phenomena. The diffusion phenomena are mainly used by experts in the process of approving mining operations; such approach takes into consideration building strain effects for medium forecast values including diffusion. The method must be adapted since previously applied data may no longer prove adequate and / or conform to such highly modified soils.

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