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CAUSE-AND-EFFECT ANALYSIS OF THE IMPACT OF MINING ACTIVITIES ON BUILDINGS

Katarzyna KRYZIA[1], Aleksandra RADZIEJOWSKA[1*]
[1]AGH University of Science and Technology in Cracow, Faculty of Civil Engineering and Resource Management, Department of Geomechanics, Civil Engineering and Geotechnics, Kraków, Poland

Abstract

The transformations and deformations accompanying mining exploitation adversely affect the surface and its development facilities, leading to damage to building structures and technical infrastructure. These inconveniences often become a source of social conflicts and tensions, especially in highly urbanized areas. Mining companies face the difficult task of carrying out their activities while simultaneously preventing and eliminating mining damages that occur during and after the exploitation of deposits. In this article, the authors have collected a number of factors characterizing mining activities to determine their nature and impact on buildings located in mining areas. These factors were subjected to DEMATEL analysis, which made it possible to examine the strength of their impact as well as their cause-and-effect relationships.

The cause-and-effect analysis enabled the identification of the relationships between the mining factors affecting buildings and the determination of their nature. This analysis will facilitate the easier determination and subsequent planning for the reduction of adverse effects of mining activities in areas affected by mining exploitation.

Keywords: mining, cause-and-effect analysis, buildings, impact

1. INTRODUCTION

Objects affected by mining exploitation often experience forces originating from the deforming ground. These forces are difficult to estimate, both quantitatively and in terms of their location and timing. In mining areas, the exploitation of deposits usually results in continuous ground deformations and tremors that adversely affect buildings. These phenomena in the near-surface rock mass layer may pose a threat to the safety of a building's structure and reduce its comfort by causing damage to structural and non-structural elements, deflection from the vertical, or vibration of buildings. Consequently, significant damage can occur to building structures during mining impacts, requiring ongoing intervention to ensure their safe use. Additionally, after mining exploitation impacts, some facilities may require extensive repairs and refurbishment [1][2][3].

[1*] Corresponding author: Aleksandra Radziejowska, AGH University of Science and Technology in Cracow, Faculty of Civil Engineering and Resource Management, Department of Geomechanics, Civil Engineering and Geotechnics, Al. Mickiewicza 30, Kraków, Poland, address aradziej@agh.edu.pl, +48-12-6173038

According to building laws, ordinances, and technical guidelines, building structures in areas affected by mining exploitation should be secured in accordance with the risk resulting from anticipated mining impacts, understood as forced displacements, deformations, and ground vibrations. The manner in which buildings are secured from a technical point of view is usually decided by building designers using regulations and principles of technical and engineering knowledge [4][5]. It is recommended that before the commencement of construction works, the investor should notify the mining entrepreneur and enable them to participate in the acceptance of works related to the execution of protective measures against mining impacts [6][7].

Existing facilities that were not secured during the construction phase should be secured and suitably adapted to carry additional loads before the mining company commences operations in the area, to ensure their safe use. To protect existing buildings in mining areas, performance criteria have been defined that describe the permissible deformation and damage intensity that can occur in a building used according to its original purpose. Despite applied safeguards, inspections, and mining and construction prophylactics, damage may still occur in buildings located in mining areas if the resistance of a given object is exceeded. This can cause damage such as cracks, breaches of load-bearing walls, landslides of buildings, problems with roof tightness, and damage to installations.

In mining areas, frequent diagnostic tests of building structures are necessary due to the commonly occurring damage under the influence of mining impacts. Irrespective of this, if mining exploitation is permitted under an object or a group of objects, it is necessary to determine the resistance of these objects to the expected mining impacts [10].

In the article, the authors focused on identifying factors of mining activities affecting buildings. These factors were collected and grouped into three categories: direct, indirect, and secondary. Using the DEMATEL method, these factors were subjected to cause-effect analysis to determine their nature and strength of influence. Through these analyses, the authors identified key factors affecting buildings, including those that most frequently cause damage and those resulting from mining activities. The analysis will facilitate the determination and planning of measures to reduce the adverse effects of mining activity in areas affected by mining exploitation.

2. ANALYSIS OF MINING ACTIVITY CONDITIONS AND FACTORS

2.1. Impact of underground mining on surfaces and buildings

The influence of mining exploitation on the deformation of the rock mass and objects on the ground surface is a complex issue that depends on many factors. The removal of a certain volume of ore from the rock mass initiates the process of rock displacement in the vicinity of the created post-mining void. As a result of this phenomenon, the void is filled, and the adjacent rock mass lowers. This process is illustrated in the diagram below (Fig. 1) [11].

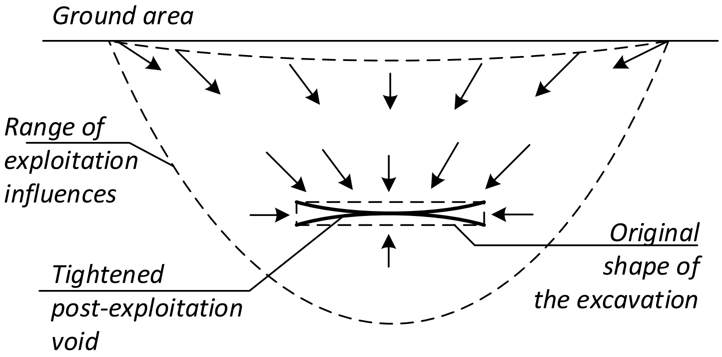

Fig. 1. Distribution of displacement vectors of rock mass points in the mining environment (compiled on the basis of [11])

Geological and mining factors decisively influence the deformation process of the rock mass and ground surface. These include elements related to the geological structure of the medium in which the process occurs, as well as quantities characterizing the location, size, and intensity of mining works. Geological and natural factors are beyond human intervention, whereas mining and technical factors can be modified and selected to minimize the impact of mining operations.

The displacement of rock mass layers into the empty spaces left by excavation causes dislocations in the adjacent rock mass. This leads to the gradual formation of a characteristic depression on the ground surface. The shape and size of the deformation depend on several factors, including the thickness of the extracted layer, the size of the excavated area, the type of rock forming the rock mass, and the method of filling the post-mining void. Mining activities may also cause rock mass tremors and changes in water relations.

On the surface, hydrological and natural transformations occur, leading to changes in topography, surface displacement, and deformation, as well as other indirect effects of mining exploitation, which significantly influence development. Underground mining exploitation negatively impacts areas particularly affected by its direct influence, especially in urbanized regions where infrastructure and land-use facilities may suffer damage. This damage can cause a permanent or temporary reduction in the comfort of use, affecting both unprotected structures and those protected against mining exploitation throughout their life cycle [2][3][12]. The elements shaping the influence of underground mining exploitation on the surface, and consequently on the damage to structures, are presented in Fig. 2 [2].

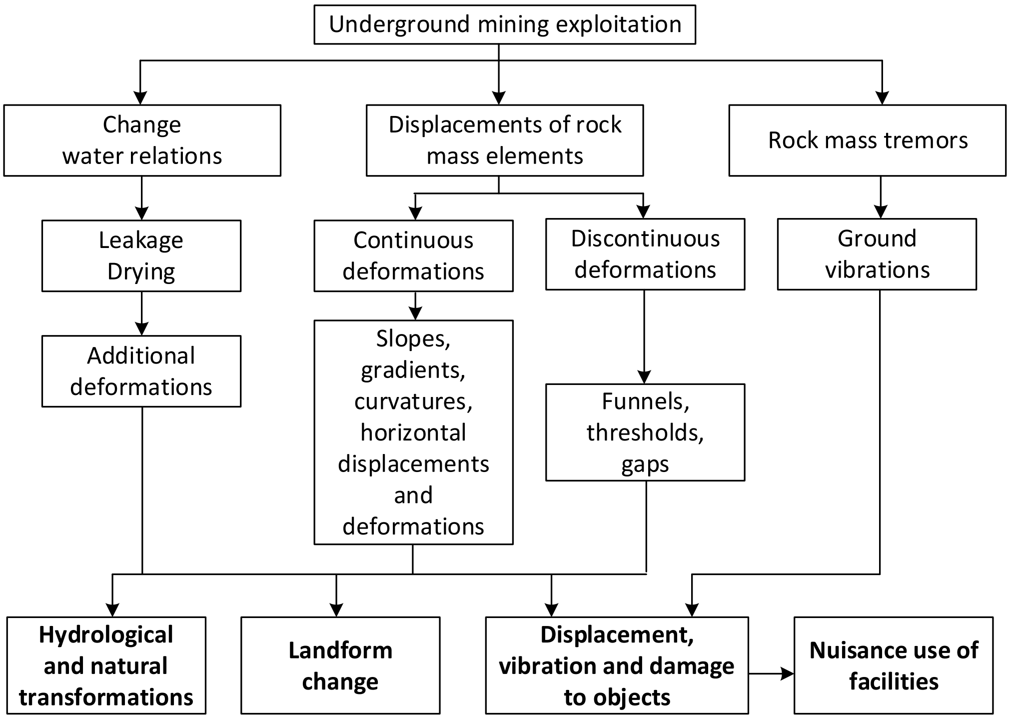

Fig. 2. Elements shaping the impact of underground mining on surfaces and buildings (on the basis of [2])

Continuous deformations are the most frequent changes in the shape of the ground surface that do not interrupt its continuity and are the consequence of rock movements within the rock mass caused by underground mining activities. Continuous deformations always accompany mining exploitation, regardless of geological-mining conditions. They are manifested on the ground surface in the form of vertical displacements, i.e., subsidence. The basic forms of continuous deformation on the terrain surface are the so-called subsidence troughs [13][14]. Hence, the term basin is used to describe the differences between the original ground surface and the surface affected by underground mining works within their range of influence. The characteristics of a subsidence basin involve determining the values of displacements and deformations at specific points of the terrain or in their groups, which are called deformation indicators.

2.2. Characteristics and division into groups of analysed factors

The impact of mining activities on buildings can be characterized by factors that affect the deformation of the rock mass, which in turn deforms the ground surface and consequently affects the structures located on it. These factors can be classified as direct, indirect, and secondary.

Direct factors are related to the structure of the rock mass and the initial phenomena that occur in the rock mass and that are determined at the start of excavation. This group of factors may be classified as follows:

a) *the geological structure of the overlying rock mass* (D.1) characterized by deformation and strength properties of the rocks and the nature of its layering, disturbances and discontinuities,

b) the nature and thickness of the Triassic or Tertiary and/or Quaternary strata defined as *overlying strata* (D.2),

c) *the depth of the excavation* (D.3) from which the deposit is extracted,

d) *the shape and dimensions of the excavation* (D.4),
e) *the method of mining exploitation* (D.5), including the method of removal of the mining void,
f) *the speed of advance of the mining front* (D.6) and of stoppages in operation, pages should include.

Indirect factors are phenomena that accompany and are a consequence of the aforementioned direct factors, resulting from changes in rock mass conditions. The second group of factors includes the following:

a) *hydro-geological conditions* (I.1) and their effect on changes in the rock mass and overburden and on the ground surface,
b) *continuous deformation* (I.2) occurring in the rock mass layers and on the surface,
c) *time/duration/quickness of transformation* (I.3).

The last group consists of factors referred to as secondary, which are the consequences of transformations of the rock mass as a result of disturbing its previous structure. The group of secondary factors includes the following:

a) *changes in the rock mass* (S.1) caused by excavations previously carried out or by the presence of natural caverns or cavities in the rock mass,
b) *paraseismic phenomena* (S.2) of mining origin in the form of rock tremors and rock bumps,
c) *formation of discontinuous deformation* (S.3) in surface or linear form.

Assigning the above-mentioned factors to specific groups may be debatable due to the complexity of underground mining processes and the impossibility of fully understanding the structure of the rock mass and the degree of interaction between the selected factors.

2.2.1. Geological structure of the overlying rock mass (D.1)

The geological structure of the surrounding rock mass significantly influences the form, regularity, and extent of deformations in the rock mass and how they manifest on the ground surface. Rock mass movements caused by the excavation of an underground mine strongly depend on the mechanical properties of the rocks. Different types of rock vary markedly in their mechanical properties. Rocks such as clays, shales, and salts have low strength and high deformability, whereas others, like granites, basalts, and quartzites, are very strong with low deformability. There are also rocks with intermediate properties, such as sandstones, dolomites, and limestones. The movements of the rock mass caused by the excavation of an underground mine strongly depend on the mechanical properties of the rock. The more compact the rock mass, the greater the range of influences, while softer rock masses result in smaller deformations. In the case of rock masses composed of ductile rocks, the range of influences is shorter, but the basins are steeper [2][9][15][16][17].

One of the most important features of the rock mass structure is its stratification. In a stratified rock mass, the angle of inclination of the layers has a significant impact on the character of displacements caused by excavation. The subsidence basin created as a result of excavation in a horizontally stratified rock mass is symmetrical and shows the greatest depth along a vertical line passing through the center of the excavation. In a rock mass with inclined strata, the influence shifts towards the direction of subsidence, with larger deformations occurring above the lower-lying part of the seam [15][16].

2.2.2. Overlying strata (D.2)

The form of deformation and the range of its impact are strongly influenced by the occurrence of Triassic, Tertiary, and/or Quaternary strata in the rock mass above the exploited deposit, which consist of clays, loams, gravels, and sands. The thickness of these formations varies widely, from several to several hundred meters. The manifestation of rock mass movements on the surface of the ground depends to a large extent on the thickness of these formations lying directly under the surface on which the buildings are located [15][18][19]. Discontinuities in the rock mass, such as a rock sill resulting from the displacement of part of the rock mass along a fault plane under thick overburden, are "softened" by the Tertiary and Quaternary strata and will appear on the ground surface in the form of a gentle slope (Fig. 3) [15].

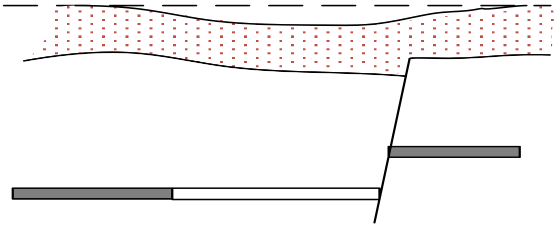

Fig. 3. Influence of alluvial overburden on rock mass movements near fault outcrops [15]

2.2.3. The depth of the excavation (D.3)

The depth at which underground workings are located has a significant impact on the movements of the rock mass and its surface. A cave-in of the excavation at a shallow depth may cause discontinuous deformation, such as a sinkhole on the surface of the ground. Although the horizontal range of this deformation will be small, the value of the maximum surface subsidence in the center of the sinkhole will be large. A cave-in of the same excavation at a much deeper location will be visible on the ground surface in the form of a relatively large but shallow subsidence basin [15][16].

2.2.4. The shape and dimensions of the excavation (D.4)

The shape, size, and height of the selected underground workings depend on the size of the ore deposit. With larger deposits, surface deformation covers a larger area [16]. Regulating the shape and size of excavations is one element of mining prevention. The shape and size of an excavation pit, the length of the front, the spacing, the sequence of operation of individual pits, and the direction and manner of driving the pit over time significantly affect the amount of surface deformation and are used to minimize it [17][20][21].

2.2.5. The method of mining exploitation (D.5)

In the excavation process, it is possible to prevent significant movements of the rock by leaving unselected parts of the deposit in the form of rock pillars that support the seam roof and prevent large-scale collapses. Among the methods of exploitation, one can distinguish between full exploitation, by selecting 100% of the deposit, and partial exploitation, in which the degree of the selected deposit in relation to the one left behind may vary. In some cases, artificial pillars, usually concrete, are built in the formed excavations to support the roof and reduce rock displacement.

Thus, mining can be carried out with roof collapse - without filling in post-mining voids - or with hydraulic or pneumatic backfilling [2][15]. The methods of exploitation and decommissioning of post-mining space fundamentally influence the form and size of surface deformation indicators. They also affect the indirect or secondary effects of previous post-mining goafs [2][17][22].

2.2.6. The speed of advance of the mining front (D.6)

The extent of damage to facilities is influenced by both the speed of operation and the variation in that speed over time. To limit the effects of mining on the ground surface and the buildings on it, it is recommended to limit the speed of mining. Fast excavation of underground workings causes correspondingly fast changes in the state of stress of the rock mass. Therefore, as the speed of excavation increases, the speed of subsidence and deformation of the rock mass and the ground surface also increases. On the other hand, a theoretical twofold or even threefold reduction in deformation is obtained with fast-advancing mining fronts, compared to values at low extraction speeds.

In the case of a fast-moving front, the extreme deformations of the ground surface are smaller, but the speed of their accumulation is higher. Technological breaks, weekends, and public holidays should be as short as possible as they cause an uneven distribution of deformations.

It is assumed that, irrespective of the operating speed, the final value of the surface deformation and the type of deflection at a selected point in the structure of the object caused by the surface deformation is the same [23][24][25].

2.2.7. Hydro-geological conditions (I.1)

The changes in water relations within the rock mass due to mining activities and the consequent alterations in the properties of the bedrock beneath buildings are complex and dependent on multiple factors, necessitating individual analysis for each case. The geological structure of the rock mass and the mining impact on its hydrogeological properties determine whether subsidence will cause a relative lowering or raising of the groundwater table [20][24][26][27].

Water exposure is a common cause of void reactivation, particularly in limestone and halite regions. Water can erode the backfill material used in post-mining voids and corridor excavations, altering their shape and dimensions [28].

2.2.8. Continuous deformation (I.2)

Continuous deformation results from the deflection of near-surface layers over a selected mining space. The average extent of the direct impacts of mining operations on the surface is approximately twice the mining depth. If the mining field is large enough, continuous deformations manifest on the ground surface as a subsidence basin. In this basin, the central part of the surface remains parallel to its pre-deformation state, while the marginal fragment gently transitions between the subsided area and the unaffected area. This condition is schematically illustrated in Fig. 4.

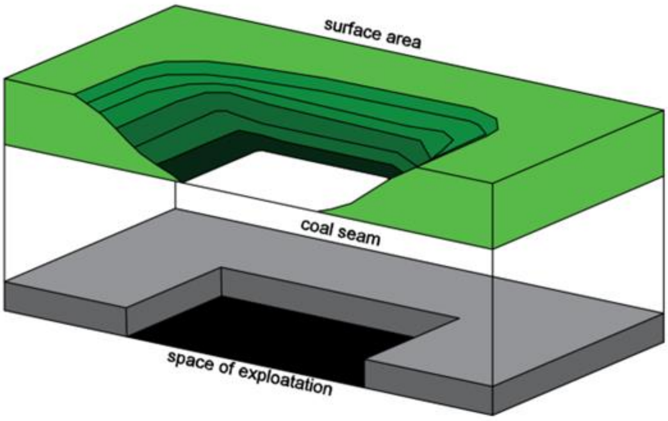

Fig. 4. Continuous surface deformation above the exploited seam

The magnitude of continuous surface deformation is described by so-called deformation indicators. The most commonly used are subsidence, the slope of the subsidence basin profile, and curvature. The most significant part of the subsidence basin is the marginal part, due to its greatest influence on the structure of objects [29].

The behavior of a building affected by mining activities in any position in the basin is shown in Fig. 5. As a result of ground deformation, the building moves from the initial position 1-2-3-4 to the position 1'-2'-3'-4'. In this process, treating the object as a rigid solid, there is a vertical lowering of w_b and a horizontal shift u_b of the geometrical center of the building S, as well as rotation of the building determined by its deflection from the level T_b . There may also be additional settlement Δs_b resulting from the horizontal loosening of the soil, causing the building to finally assume the position 1"-2"-3"-4". Two situations can be distinguished in this position: a convex (ε^+,R^+) or concave (ε^-,R^-) edge of the mining basin [10].

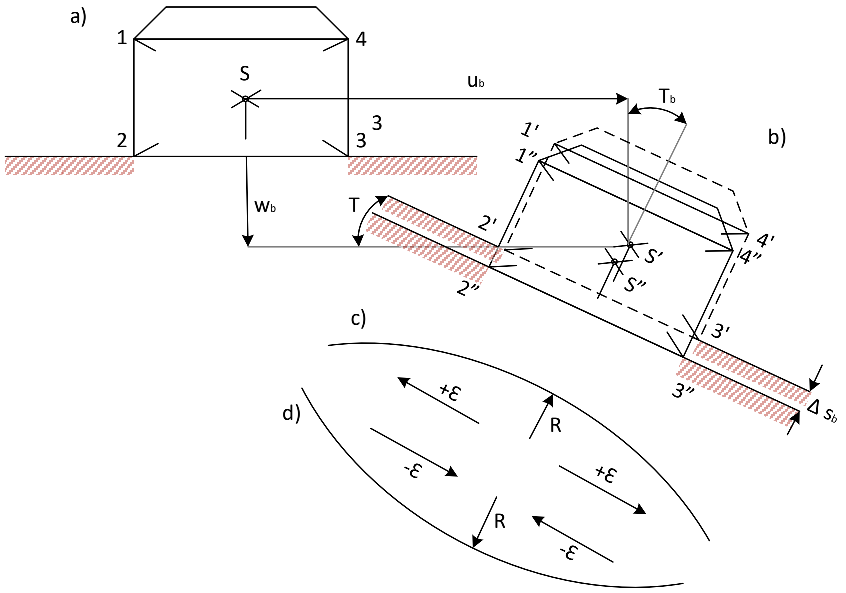

Fig. 4. Building in any position in the basin; a) initial position; b) position after displacement; c) convex edge of the basin; d) concave edge of the basin; developed from [10]

2.2.9. Time/duration/quickness of transformation (I.3)

The process of subsidence is characterized by its duration and course. In the case of strong and compact rocks, subsidence is slower than in rock masses formed by weak rocks or those disturbed by exploitation. In the case of slow exploitation, subsidence of the rock mass and the ground surface builds up slowly. Increasing the exploitation speed results in faster accumulation of deformations [9] [17] [19] [23] [25].

The first deformations on the surface begin to appear when the excavation pit reaches a width of up to 20-25% of the excavation depth.

The development of subsidence as a function of time is characterized by a retardation phase and an initial phase, during which subsidence develops; these phases occur sometime after exploitation below a given point and last up to several weeks. Then comes the intensive phase, which is a period of increased intensity of subsidence—point movements are the most intense and last from about one month to several months. The last phase is the final phase, during which a period of fading subsidence occurs, manifesting as slow decreases toward the final value. The duration of this phase is the longest, and in the case of deep exploitation, it may even last several years [30].

2.2.10. Changes in the rock mass (S.1)

Changes in the rock mass structure usually occur as a result of previous excavations. In some cases, voids and open spaces of natural origin may exist in the rock mass, for example, as a result of some rocks being washed away by flowing groundwater. If a new excavation is created in this rock mass at a deeper level, the movements of the rock mass caused by the new excavation disturb the unstable equilibrium that prevails in the vicinity of the old excavations, thus creating new collapses and movements of the rocks. This phenomenon is called the reactivation of old goafs. In such a situation, total displacements from newly excavated workings and from old "reactivated" workings or naturally occurring caverns may appear on the surface.

Activation of shallow post-mining voids, and less frequently voids of natural origin, is now an increasingly frequent cause of discontinuous deformation [17] [19] [30] [31].

2.2.11. Paraseismic phenomena (S.2)

In the case of underground mining, parasitic effects result from sudden relaxation of the rock mass around the excavation, which is amplified by high strength of the surrounding rocks. In general it may be assumed that a mining shock is caused by a local disturbance of the rock mass balance as a result of previous mining activities. A change in the original stress state of the rock mass (apart from exploitation of the deposit) is strongly dependent on the existence of geological faults. This increases the possibility of geodynamic phenomena (e.g. rock bumps). The current mining situation in Poland results in exploitation of seams with the highest risk of rock bursts. This translates, directly, into an increased possibility of mining tremors. Shocks are short-term or non-periodic vibrations of rapidly diminishing amplitude. At the same time, the average energy of recorded tremors increases. The risk level is increasing due to the ever-increasing mining depth, geomechanical properties of the seams and rocks and the thick rock mass. Not without significance is the fact of maintaining high concentration of extraction and conducting it in the areas of influence of exploitation background or in residual parts of seams [9] [32] [33] [34].

2.2.12. Discontinuous deformation (S.3)

Discontinuous deformations, as opposed to continuous ones, have a local range, do not accompany every instance of exploitation, and may occur both during exploitation and several dozen years after it. They are very dangerous not only due to their form but also because their occurrence is not preceded by any signs, and their course is very fast (most often sudden), while the range of deformation itself is local. Discontinuous deformations are divided into two main types:- superficial, usually in the form of funnels or irregular sinkholes; - linear, occurring as cracks and fissures in the terrain and sills, humps, ditches, and landslides.

Discontinuous deformations are clearly visible deformations of the near-surface layer of the rock mass in the form of fissures, steps, funnels, and sinkholes [9] [24] [31] [35].

Linear discontinuous deformations usually form in the vicinity of tectonic fault outcrops or outcrops of inclined seams disturbed by mining works. They may also occur in areas of large horizontal deformations of the near-surface rock mass layer, especially in areas of horizontal loosening [24].

Discontinuous terrain deformations create much less favorable conditions for buildings than those occurring within the range of a mining basin. With significant intensities of terrain discontinuities, damage to buildings may lead to the loss of stability of part or even the whole structure, or have a decisive impact on the use value of the building.

Today, activation of shallow mining voids, less frequently voids of natural origin, is an increasingly frequent cause of discontinuous deformation [30].

3. RESEARCH METHODOLOGY

3.1. Selection of the research method

In the scientific literature, various methods of causal analysis can be found. The most commonly used ones include the Ishikawa diagram and the cause-and-effect tree, which primarily focus on identifying one-way relationships [36, 37, 38]. Statistical methods, such as regression or correlation analysis, are subsequently applied, but these methods rely on data analysis and mathematical modeling. On the other hand, the DEMATEL method allows for the inclusion of expert assessments and subjective opinions in the analysis process, which can be important in cases where numerical data is lacking. Additionally, it enables the consideration of mutual dependencies, graphical representation of results, evaluation of influence and dependencies, and facilitates multi-criteria assessment [39, 40]. Therefore, to identify causal relationships in the presented issue, the authors decided to utilize the DEMATEL method.

Studies to analyze the impact of mining activities on buildings were performed in the following order:

1. Critical analysis of the literature on the subject of the study.
2. Analysis of sources and factors of mining activities affecting buildings.
3. Defining factors resulting from mining activities affecting buildings based on literature and construction practice (existing knowledge).
4. Developing a matrix containing all the factors, determining the relationship between the various factors, and determining a measure of their significance.
5. Conducting a cause-effect analysis of the relationship between factors using the DEMATEL method.
6. Discussion and conclusions.

The basis of the DEMATEL method is pair-wise comparison, similar to decomposition in analytical hierarchy methods, but in this case the direct mutual influence of the examined factors on each other is analyzed. A discrete scale is adopted for comparison, this time with an arbitrary number N, where the lower the value of N the lesser the influence of one factor on the other. Importantly, it is possible to analyze feedbacks here, which reflects well the actual relationships between factors. In the original version of DEMATEL, a 4-point scale was used, with scores indicating: 0 - no influence; 1 - little influence; 2 - clear influence; 3 - very clear influence.

Determining the strength of the relationship between pairs of factors allows the construction of a direct influence incidence matrix A. Based on this, in subsequent steps, the processed data allow the construction of the indirect influence matrix (ΔT) and, consequently, the total influence (T). From the total matrix, the values of position (prominence) and relationship indicators are determined, which identify the nature of the factors under consideration and allow the determination of their role in the process of determining the structure of influence of objects and influence on other objects. This makes it possible to determine the degree of total influence of objects, and consequently to rank them and identify their sometimes twofold causal and effectual character. The position and relationship indicators are presented in a two-dimensional graphical chart, which provides a readable form for the decision-maker [39].

An additional reflection of the results is the total influence map, which shows the influence relations occurring between the individual factors. In this case, the strength of the relations allows the creation of a graph with the properties of layered Hertzian graphs.

For the identification of cause-and-effect relations in the issue of a possible demolition of a building, the author proposes using the DEMATEL method [40].

3.2. The procedure of DEMATEL method

The procedure for the calculation is as follows:

1. Identify a set of impact factors, in the proposed study (Tab.1);
2. The development of a direct influence diagram, according to the DEMATEL method, allows to express the targeted influence of the considered factors on each other, in a cause-and-effect context. A scale with parameter value N = 4 (where: 0 - no influence, 1- weak influence, 2 - influence, 3 - strong influence) was used to assess the "strength" of influence of each factor. The values of the direct influence relations within each pair of factors were determined on the basis of the assessments of the expert group;
3. On the basis of the relationships determined by the graph, a matrix of direct mutual influence of the factors on each other was created A_D (Fig. 6 &7);
4. Determination of the normalized direct influence matrix A'_D, which contains all parameters taking values in the interval [0,1] (Table 2). The normalization number (n) is taken as the largest of the sum of rows or columns of the matrix A_D:

$$A'_D = \frac{A_D}{n}, \tag{3.1}$$

$$n = \max\{\sum_{i=1}^{n} a_{ij}; \sum_{j=1}^{n} a_{ij};\}, \tag{3.2}$$

5. It is also possible to develop an indirect impact matrix ΔT:

$$\Delta T = A'^2_D \cdot (I - A'_D), \tag{3.3}$$

6. Determination of the total influence matrix T (Table 3):

$$T = A'_D \cdot (I - A'_D), \tag{3.4}$$

7. On the basis of the above matrices, the determination of the position and relationship indices, respectively, which are expressed as follows:

s^+ - refers to the role of a given factor in the process of determining the structure of links between objects, while:

s^- - expresses the total effect of a given factor on the others.

These values are determined according to the formulae (Table 4):

$$s^{+} = \sum_{j=1}^{n} t_{ij} + \sum_{j=1}^{n} t_{ji} = R_{T_i} + C_{T_i}, \tag{3.5}$$

$$s^{-} = \sum_{j=1}^{n} t_{ij} - \sum_{j=1}^{n} t_{ji} = R_{T_i} - C_{T_i}, \tag{3.6}$$

When these values are plotted on a graph, it is easy to see which factors have the greatest influence on the others and to determine which are causes and which are effects of the actions taken (Fig. 8).

8. Finally, the net impact value is also determined, which tells us which factor has the greatest influence on the others, taking into account both the causal and effectual nature (Table 4):

$$netto = s^{+} + s^{-} \tag{3.7}$$

4. RESEARCH RESULTS AND THEIR ANALYSIS

The most important aspect of undertaking works related to facilities located in mining areas is determining the factors that have had, are having, and will have an impact on the facilities. Based on the presented analysis of determinants, the following groups of factors were identified: direct, indirect, and secondary, which are summarized in Table 1.

Table 1. Summary of factors subject to cause-effect analysis

	Direct factors
D.1	*the geological structure of the overlying rock mass*
D.2	*overlying strata*
D.3	*the depth of the excavation*
D.4	*the shape and dimensions of the excavation*
D.5	*the method of mining exploitation*
D.6	*the speed of advance of the mining front*
	Indirect factors
I.1	*hydro-geological conditions*
I.2	*continuous deformation*
I.3	*duration/quickness of transformation*
	Secondary factors
S.1	*changes in the rock mass*
S.2	*paraseismic phenomena*
S.3	*discontinuous deformation*

The description of the relationship between the respective factors was carried out by the authors of the article based on the state of knowledge in the subject of the study. The determination of the relationship between the respective factors was made after consultation with specialists in the field of protection of mining areas, planning of mining exploitation, the study of the impact of mining operations on the rock mass and land surface, construction in mining areas, the design and implementation of construction, as well as specialists involved in protecting buildings from damage resulting from mining activities.

The mutual influence of the factors was then examined using the DEMATEL method (Fig. 6).

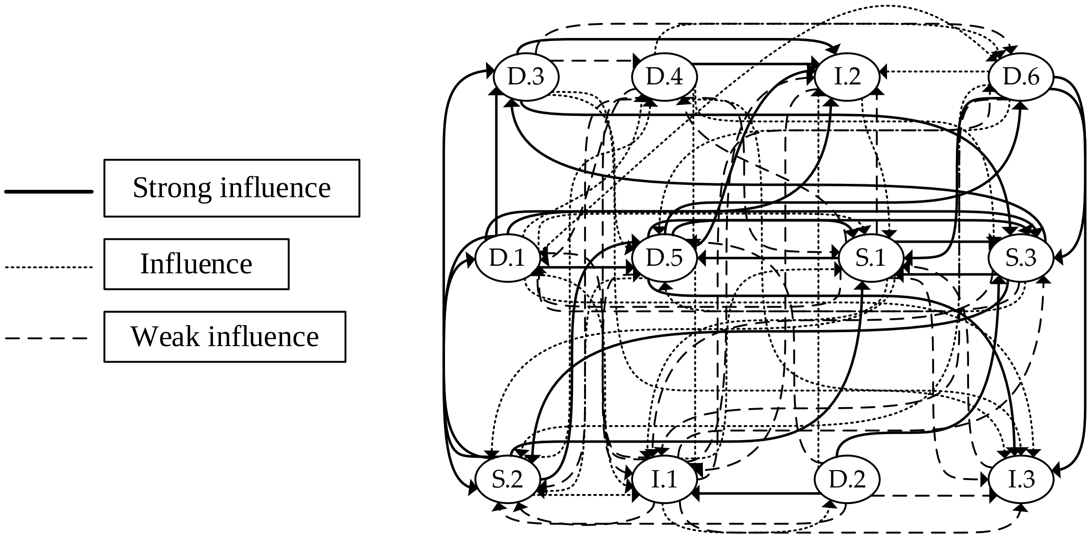

Fig. 6. Direct influence graph - expert assessment results

On the basis of the relationships presented above, a matrix of direct impacts A_D has been created (step 3, Fig. 6 & 7).

$$A_D = \begin{bmatrix} 0 & 0 & 3 & 2 & 3 & 2 & 2 & 3 & 2 & 2 & 3 & 3 \\ 0 & 0 & 0 & 0 & 1 & 0 & 3 & 2 & 1 & 0 & 1 & 3 \\ 0 & 0 & 0 & 1 & 2 & 1 & 0 & 3 & 2 & 0 & 0 & 3 \\ 1 & 0 & 0 & 0 & 2 & 2 & 1 & 3 & 2 & 1 & 1 & 2 \\ 0 & 0 & 0 & 0 & 0 & 3 & 2 & 3 & 3 & 3 & 2 & 3 \\ 0 & 0 & 0 & 0 & 2 & 0 & 1 & 2 & 3 & 3 & 2 & 3 \\ 1 & 2 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 2 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 3 & 0 & 2 & 1 & 1 & 0 & 2 & 3 \\ 3 & 0 & 3 & 2 & 3 & 0 & 2 & 0 & 0 & 3 & 0 & 0 \\ 1 & 0 & 3 & 0 & 2 & 0 & 1 & 0 & 0 & 3 & 3 & 0 \end{bmatrix}$$

Fig. 7. Matrix of direct interactions of factors with each other

Table 2 shows an extract of the values of the elements of the normalized matrix (step 4):

Table 2. Summary of factors subject to cause-effect analysis

	D.1	**D.2**	**D.3**	**D.4**	**D.5**	**D.6**	**…..**
D.1	0.0000	0.0000	0.1200	0.0800	0.1200	0.0800	…..
D.2	0.0000	0.0000	0.0000	0.0000	0.0400	0.0000	…..
D.3	0.0000	0.0000	0.0000	0.0400	0.0800	0.0400	…..
D.4	0.0400	0.0000	0.0000	0.0000	0.0800	0.0800	…..
D.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.1200	…..
….	…..	…..	…..	…..	…..	…..	…..

Then, on the basis of equation (3.3), the matrix of total relations T:

Table 3. Total influence matrix T (fragment)

	D.1	**D.2**	**D.3**	**D.4**	**D.5**	**D.6**	**…..**
D.1	-0.0288	-0.0064	0.0912	0.0624	0.0608	0.0512	…..
D.2	-0.0144	-0.0096	-0.0192	-0.0032	0.0208	-0.0096	…..
D.3	-0.0064	0.0000	-0.0144	0.0400	0.0640	0.0272	…..
D.4	0.0288	-0.0032	-0.0192	-0.0080	0.0512	0.0656	…..
D.5	-0.0224	-0.0064	-0.0240	-0.0112	-0.0464	0.1168	…..
….	…..	…..	…..	…..	…..	…..	

A summary of the values used to build the causality illustration is shown in Table 4 (Step 7).

Table 4. Summary of the results of the DEMATEL study

criterion i	R_{T_i}	C_{T_i}	s^{+}	s^{-}	**netto**
D.1	0.5152	0.1088	0.6240	0.4064	1.0304
D.2	0.2576	0.0320	0.2896	0.2256	0.5152
D.3	0.2896	0.1536	0.4432	0.1360	0.5792
D.4	0.3232	0.1232	0.4464	0.2000	0.6464
D.5	0.4480	0.3872	0.8352	0.0608	0.8960
D.6	0.3664	0.1888	0.5552	0.1776	0.7328
I.1	0.2112	0.3088	0.5200	-0.0976	0.4224
I.2	0.0576	0.4320	0.4896	-0.3744	0.1152
I.3	0.0176	0.3360	0.3536	-0.3184	0.0352
S.1	0.2496	0.3312	0.5808	-0.0816	0.4992
S.2	0.2208	0.2752	0.4960	-0.0544	0.4416
S.3	0.2000	0.4800	0.6800	-0.2800	0.4000

The analysis was performed using a summed linear aggregation of the values of the position and relationship indicators (s^+ and s^-). The overall calculation is expressed in the graph presented in Figure 4.3, which shows the values of the position and relationship indicators. Based on the aggregated values of the item index, it was found that the greatest role in determining the nature of the factors is played by: D.5, followed by S.2 and D.1. Factor D.1 has a strongly causal character, factors D.2 and D.4 also have a slightly smaller value indicating a causal character. Factors I.2, I.3 and S.3 have an effect character. The remaining factors have both less influence on the others and a more mixed causal and effect character.

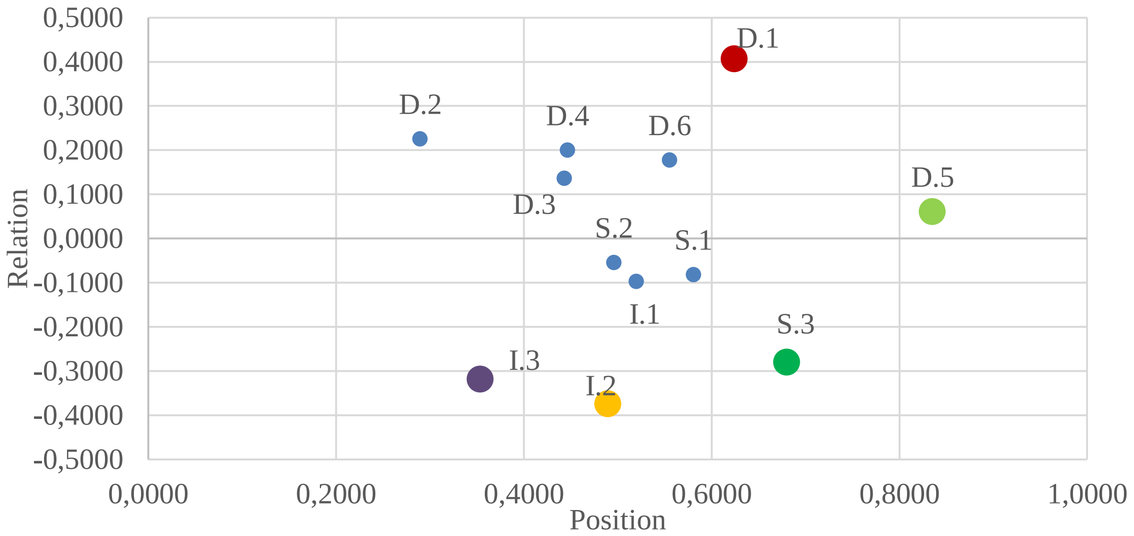

Fig. 8. Graphical interpretation of the DEMATEL results

The conducted analyses have demonstrated that the factor with the greatest impact on the others is D.5, which pertains to the method of mining operations. This factor can be characterized as mixed causal-effect due to its proximity to the zero-axis rating obtained by D.5. The method of mining operations is significant due to the various techniques used in its execution. Mining operations can be conducted with roof collapse - without filling post-exploitation voids, or with hydraulic or pneumatic backfill, which prevents roof collapse phenomena. Additional factors with significant impact on the others include factor S.3, related to discontinuous deformations, and factor D.1, related to the geological structure of the overlying rock mass. Interestingly, these factors have different natures relative to each other. Factor S.3 has a consequential nature, whereas D.1 is distinctly causal.

Factor S.3 is a criterion of a strongly effectual character. Discontinuous deformations most frequently occur locally and may occur both during the exploitation of deposits and many years after its completion. Most frequently, their occurrence is connected with a lack of appropriate protection both during and after exploitation. Apart from S.3, factors I.2 Continuous deformation and I.3 Duration/quickness of transformation, which belong to the group of indirect factors, showed the most effectual character. Therefore, it seems justified to assign them to this group of factors. Their effect nature results from the activities carried out during the exploitation of the deposits. I.2 is a factor related to the occurrence of continuous deformations, while I.3 pertains to the rate of transformation within the rock mass. However, these factors have significantly lower values on the position axis, as shown in the graphical representation of the DEMATEL analysis results (Fig. 8). This indicates that their occurrence is not as significant as the impact of S.3.

Among the causal factors, D.1 received the highest rating. D.1, which refers to the geological structure of the overlying rock mass, is the most frequently occurring cause of negative impacts resulting from mining activities. Often, the heterogeneous layering of the rock mass leads to the formation of voids, sinkholes, and collapses of strata above mine corridors as a consequence of mineral extraction. Besides the prominent D.1 factor, other distinctly causal factors include D.2, which relates to the nature and thickness of the overburden, and D.4, which pertains to the shape and size of the excavation. These factors are influenced by the size of the deposit, with larger deposits leading to a greater extent of deformation.

Observing the distribution of other analyzed factors, their relatively even distribution along the axis of relationships is apparent, with approximately half exhibiting either a consequential or causal nature. Some factors have values close to zero on the relationship axis, indicating a mixed nature. This mixed nature depends on slight changes, such as shifts in the influence between factors, which could be introduced by a panel of experts assessing the interdependencies among the studied factors, potentially placing them on the other side of the relationship axis.

5. IMPACT OF MINING ACTIVITIES ON BUILDINGS

Sustainable underground mining exploitation adversely affects building structures. To minimize potential damage to buildings, known as mining damage, mining and building prophylaxis are used.

Construction prophylaxis and mining damage repair are applied on a large scale and have a long tradition in practical implementation as well as in the organization of this activity. Since the early days of mining, both the technical principles and financing principles of mining damage repair have been established.

The scope of safety work involving the preventive reinforcement of buildings is extensive and varied, depending on the type of building, its technical condition, and the previously described influences that mining activities cause in its surroundings.

However, the scope is primarily limited by economic, but also technical considerations. As a result, mining damage is almost always an inherent part of mining exploitation.

Mining operations negatively affect surface development and technical infrastructure. Construction objects within the range of these influences lower and move unevenly with the ground. As a result of ground deformation, objects with little deformation experience the action of additional loads, and deformable objects experience complex deformations. All objects may experience short-term loads caused by ground vibrations and be exposed to adverse changes in the level of the water table. For construction objects in mining areas to be used safely and normally, they must be properly adapted to the anticipated influences.

Damage to structures may cause a risk to stability, safety risks to structural elements, threats to safety of use, reduced utility value, reduced aesthetic value, and accelerated technical wear and tear .

The activities of mining plants focus on maintaining the current use of the land, and regarding to building structures, ensuring public safety. The occurrence of minor damage to buildings, including their structural elements, is allowed, provided it does not cause a deterioration of their utility value and can be repaired as part of regular maintenance. For this purpose, it is necessary to properly diagnose the technical condition of buildings to assess the impact of underground mining activities.

At present, mining exploitation is prepared in such a way as to cause the least possible impact on the surface. However, the occurrence of continuous deformation may cause the activation of old mining voids, which in turn may lead to the appearance of discontinuous deformation. In such cases, the cause-and-effect relationship between the appearance of continuous and discontinuous deformations cannot be separated.

As part of the development of this topic, it is planned to describe specific protections for buildings in future publications. The work will continue in the field of protecting buildings from the negative effects of mining activities.

6. CONCLUSION

The article presents and analyzes factors that may constitute the necessary knowledge for decision-making and subsequent actions related to a facility located in areas exposed to the negative impact of mining exploitation. Through expert assessment, the individual factors of mining activities were evaluated and their mutual cause-effect relations were established. The DEMATEL method made it possible to determine the nature of the factors examined. The causal analysis showed that the factors with the greatest impact on the others are D.5, followed by S.2 and D.1. Interestingly, these factors represent different characters on the relationship axis. Factor D.1 has a strongly causal character, while S.3 is a factor with a clearly effectual character. Factor D.5, despite having the greatest impact on the others – the highest values of the item index, has a mixed character with a slight predominance of causality.

The most causal character was achieved by the afrementioned factor D.1 The geological structure of the overlying rock mass, but also by D.2 Overlying strata and D.4 The shape and dimensions of the excavation, while the highest values indicating the effect character were obtained by factors I.2 Continuous deformation and I.3 Duration/quickness of transformation.

The cause-and-effect analysis made it possible to identify the relationships between the mining factors affecting buildings and to determine their nature. Thanks to the analysis, it will be easier to determine and subsequently plan for the reduction of adverse effects of mining activities in areas affected by mining exploitation.

This article is important for better understanding the nature and magnitude of displacements that can affect surface infrastructure.

As part of the continuation of this topic in subsequent publications, it is planned to describe the damage to buildings that may occur as a result of factors caused by mining operations. There will be a description of the principles of protecting buildings against the effects of mining activities at the building design stage and during building operation. In the next work, the authors plan to present recommendations and ways to protect buildings in areas influenced by mining exploitation, as well as to present examples, including case studies, related to the resulting damage and ways to repair it in buildings.

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