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Prediction of Linear Objects Deformation Caused by Underground Mining Exploitation

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Abstract

Underground mining operations could adversely affect the land surface and buildings on which it is located. Objects in the range of impact are affected by displacement and deformation. Mining Basin area is often highly industrialized and many important objects of the technical infrastructure is there. A considerable portion of these objects is characterized by elongated shapes. For this type of objects (pipelines, roads, railways, power lines) predictive analyzes of deformation are performed to assess the safety of their operation. For different linear objects, determined rates of deformation have different significance. The article presents various aspects of forecasting deformation for different types of linear objects. It presents the methodology of predicting deformation. It shortly characterizes a calculation model for deformation indexes used in Polish mining. The presented examples come from different extended engineering facilities, for which predicted indicators of deformation were set.

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1. Introduction

The rapid development of technology in the twentieth century brought a strong demand for mineral resources. This fact was related to increase mining activity, often in heavily populated and urbanized areas. Intensive mining operations had both direct and indirect negative impact on the environment. Therefore, adverse effects of mining

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include the important issue of predicting deformations and displacements that may arise and threaten all sorts of facilities [8].

One of the basic criteria for determining the possibility of mining a resource is the impact of this operation on the surface of the site and the buildings occurring upon it [2]. Adverse impact of mining on the environment is observed both in the form of direct and indirect, or secondary, impact [9]. Direct effects include displacement and deformation of the rock mass and land surface caused by the movement of rocks in the direction of the working space.

Objects subjected to the influence of mining can be generally divided into three groups: point, linear and surface ones. In the case of linear objects, one of their dimensions is much larger than the others. The calculation of such an object is simulated through a sequence of points. Point objects are generally compact, and for the purpose of computing can be reduced to a single point. Surface structures are characterized by two significant dimensions. For the purpose of computing, such objects are converted into sets of points usually placed in a regular computational grid. Depending on the specifics of the object, its construction and purpose of various indicators describing the state of deformation will have a dominant influence on the possibility of it losing its functionality, or damage [3]. Currently, the design criteria for engineering structures include three aspects:

- safety (the possibility of a disaster – e.g. rupture of a pipeline, a train derailment)
- social issues (interruptions in the supply of media – e.g. water pipe burst)
- economic (cost of security objects or defect removal – e.g. installing expansion joints on a pipeline, repairing damage to road surface).

In this paper, methodology of forecasting displacements and deformations caused by planned mining activities will be presented the along with two examples of completed calculations for linear engineering structures.

2. Computing objects

The functioning of the society in urban and industrialized areas is based on the use of the technical infrastructure. In Europe today, in the mining regions of highly industrialized countries it is not possible to have a functioning economy and society without all kinds of media provided by (reliable) technical infrastructure. One could say that land surface is entwined by an overhead, ground and underground utilities network. The proper functioning of this network is essential for the welfare of society.

Underground mining operations may cause displacements and deformations of structures within its influence range. Over the decades, we developed the series of mathematical models used to describe linear deformation. The actual process of deformation takes place in highly complex geological conditions, therefore, it is difficult to predict. In addition to linear deformation, mining operations may imply the formation of discontinuous deformations and dynamic (shock) effects. The methods of prediction still leave much to be desired.

Forecasts of the influence of the mining operations are determined by various indicators of deformation, which can be verified on the basis of the conducted geodetic measurements [7]. Depending on the development of the land surface and engineering structures occurring therein, different rates of deformation are estimated. Due to the diversity and specificity of linear objects of infrastructure, the rules for calculating the deformation indexes are as follows:

- pressure pipelines (gas pipelines, oil pipelines, water supply lines): basic risks are associated with rupture and leakage of fluids transported under pressure. Deformation indicators determined for this type of objects are: diminution, displacement and deformation of the horizontal and transverse axes.
- overhead telecommunication lines (power lines, phone lines): the risks are related to the deflection of poles and loss of stability. Another important element are changes in the shape of line spans, which might cause breaking or overhanging of the lines. The basic indicators of deformation are diminution, maximum slopes and maximum horizontal displacements.
- sewerage systems, water courses: for objects of this type it is essential to form counter-slopes limiting the fundamental functionality. In the case of sewage systems, it is necessary to build appropriate pump stations, and for the reconstruction of watercourses, redirecting them or changing the flood shafts. The basic indicators of the deformation are inclination,

- roads – main risks are related to the formation of defects in the road surface due to the occurrence of the compressive deformation (humps) and tensile strain (formation of cracks). The basic indicators of deformation are diminution and deformation transversely to the axis of the road.
- railroads – mining operations can jeopardize the safety of railway traffic by changing the slope of a railway track and changing the shape of the track. The basic indicators of deformation that should be noted are diminution, lateral inclination, displacement and horizontal deformation.
- structures – some structures can be considered linear, particularly in the case of long buildings (without appropriate joints). The prediction includes the calculation of diminutions, inclinations, curvatures and deformations in the horizontal longitudinal direction,

Linear objects cannot function without point objects (e.g. armature), so often in the course of the predicting deformation for linear objects also ones for point elements of the engineering infrastructure are prepared. Due to the diversity and specificity of point objects, rules for calculating deformation indexes differ in some elements. Basically, point objects can be divided into the following groups:

- tall objects (chimneys, pylons, towers, etc.): basic risks are associated with inclination of the objects which may lead to the loss of stability of the structure and its overturning. Deformation indicators determined for this type of objects are: diminution and inclination. The inclination is determined by the maximum value and direction in which the maximum tilt can occur with respect to the axes of the assumed coordinate system.
- compact objects (buildings) - compact objects include ones where that none of the horizontal dimensions exceeds 25 m. The main threats from the deformation are associated with the occurrence of a slope (nuisance to use) and horizontal deformations (cracks, plaster peeling). Basically, all indicators of deformation are determined for such objects, but the most important factor are horizontal deformations.

3. Forecasting deformation of objects

On the basis of data concerning the performed and planned mining operation, using appropriate mathematical models describing the formation of displacements and deformations, one can determine the distribution of deformation indexes. Since the nineteenth century in various scientific centres worldwide, engineers have worked on developing a model for predicting continuous deformation [10,12]. Currently, the most popular models are geometric and integral calculation ones, based on a proper function of influences [11]. In Poland, the Knothe [5] theory is commonly used for prediction, amended by Budryk and subjected to various modifications.

The geometric theories of predicting deformation assume that operation of the elementary volume of the resource *dV* with a horizontal surface *dP* is accompanied by elementary diminution *dS* at point *A*, remaining within the range of impact of the operation. This reduction can be described as follows:

$$dS_A = f\left(x, y\right) dP \tag{1}$$

where $f(x,y)$ is a function of influences.

Integrating elementary displacement on individual mining sites, and summing up the influences of all these sites (*n*), we obtain vertical displacements:

$$S_A = \sum_{i=1}^{n} S_{\max_i} \iint_{P_i} f\left(x, y\right) dP \tag{2}$$

where S_{max} is maximum subsidence for the *i*-th site

Knothe, based on the approximation of the curve of influence to the Gaussian curve proposed the following form of the function of influence:

$$f(x,y)=\frac{1}{r}\exp(-\pi\frac{x^2+y^2}{r^2}) \quad (3)$$

where *r* is the radius of major influence dependent on characteristics of the rock mass and depth of operation, according to:

$$r=\frac{H}{\operatorname{tg}\beta} \quad (4)$$

where *H* is the depth of operation [m], and the angle β is the angle of the main range of influence.

The classical Knothe theory allowed only to predict the deformation that occur in the vertical plane. Performing theoretical calculations in the horizontal plane can be carried out based on the observation by Awierszyn [1] that allows the interrelation of indicators in the horizontal and vertical directions:

$$\frac{du(x)}{dx}=-B\cdot K(x) \quad (5)$$

where:

$u(x)$ – is horizontal displacement along the profile *x*.
B – coefficient of proportionality,
$K(x)$ – curvature profile of the depression (second derivative of vertical displacements).

Budryk's considerations have been important for the prediction of horizontal displacements and deformations in Poland. Budryk [6], based on theoretical analysis and the many practical examples, obtained the following formula for the coefficient B:

$$B=\frac{r}{\sqrt{2\pi}}\approx 0.4r \quad (6)$$

Other indicators of deformation in the vertical plane are determined by calculating the derivative of vertical displacement, and so inclinations (7), curvature (8):

$$T_x=\frac{dS}{dx}\ ,\ T_y=\frac{dS}{dy}\ ,\quad T_\alpha=T_x\cos\alpha+T_y\sin\alpha\ ,\ \mathrm{T}_{\max}=\sqrt{T_x^{\ 2}+T_y^{\ 2}} \quad (7)$$

$$K_x=\frac{d^2S}{dx^2}\ ,\ K_y=\frac{d^2S}{dy^2}\ ,\ \Lambda_{xy}=\frac{d^2S}{dxdy}\ ,\ K_\alpha=K_x\cos^2\alpha+2\Lambda_{xy}\sin\alpha\cos\alpha+K_y\sin^2\alpha$$
$$K_{\max(\min)}=0.5(K_x+K_y)\pm\sqrt{\frac{(K_x-K_y)^2}{4}+\Lambda_{xy}^2} \quad (8)$$

Indicators of deformation in the horizontal plane or horizontal displacements and deformations are determined using the formula:

$$U_i=-BT_i\ ,\quad \varepsilon_i=-BK_i \quad (9)$$

where *i* is the index of the direction of deformation.

4. Examples of predicting deformation for linear objects

Before starting any stage of the mining for a resource in an area a forecast of surface deformations is compiled. If in a given area includes "important" objects, a detailed prediction of influences is drawn up for them. On the basis of this forecast, engineers decide whether the operation can be executed or should be modified. Below, two examples of a prediction of deformation for linear objects are provided.

Example 1 includes a forecast for the portion of a two-lane national road, which was subjected to renovation. Figure 1a shows the mutual arrangement of objects and operation carried out and planned.

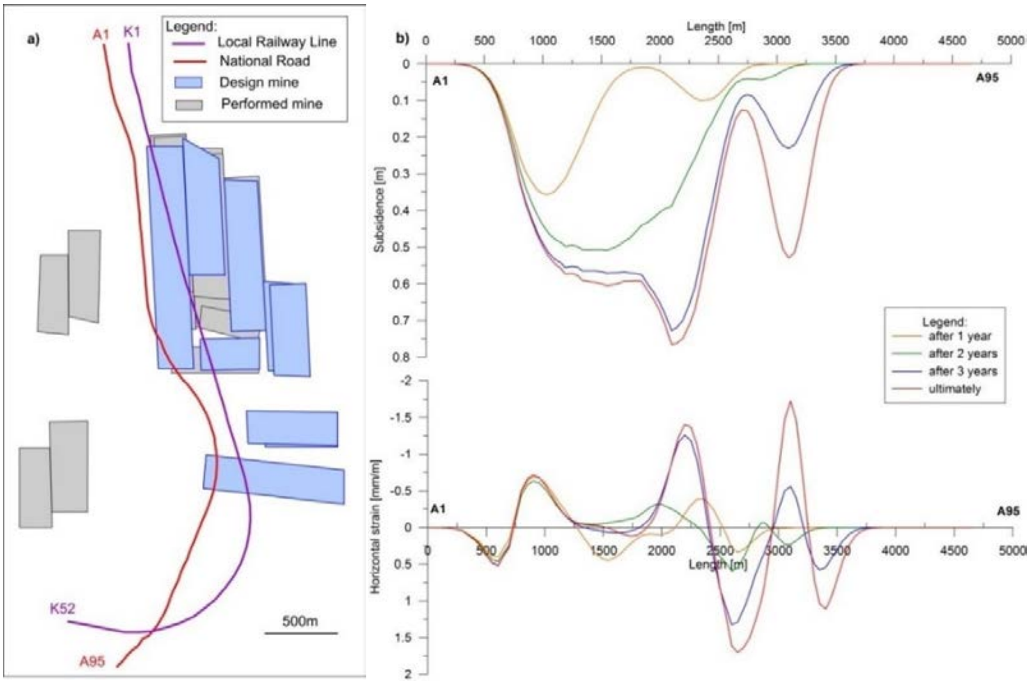

Fig. 1. Example 1 of the predicted deformation (a) a scheme of mining sites arrangement of the objects, (b) the projected distribution of vertical displacements and horizontal deformations.

On the occasion of indicators, deformations were calculated for the local railway line running near the national road. For the analyzed portion of the road, 95 computational points were assumed, and along the railway line – 52 points. Mining operations included in the calculation consisted of 11 sites of operation and 10 planned operation sites. The prediction involved calculations of increases in deformation indexes in depressions, inclinations and deformations along and across the line objects after 1, 2, 3 years from the repairs and after a target period. The resulting deformation rates were too high and it was decided to abandon the operation on one of the planned mining sites. By contrast, Figure 1b shows examples of indicators of the final prognosis.

Example 2 describes mining operations implemented under a power line with a voltage of 110kV. The range of influence of the operation includes 14 power line poles with a height of about 20m. As a result of earlier years of mining activity, significant inclination changes of the poles have taken place. Two of them have been rebuilt. As a result of the surveying measurements [4], present inclinations of the poles have been specified. The designer defined a maximum deflection of the tops of poles at 15 ‰ for the analyzed network. Calculations were performed assuming indicators of deformation for calculation points at the locations of poles, and directions of calculating the indicators were adopted according to the direction of the power line. In the analyzed area, a mine exploited over 110 sites, however, the calculation includes 3 parcels where operation was carried out, the impact of which was still evident, and 5 parcels where operation was planned. Figure 2a shows a schematic arrangement of mining sites relative to the power line.

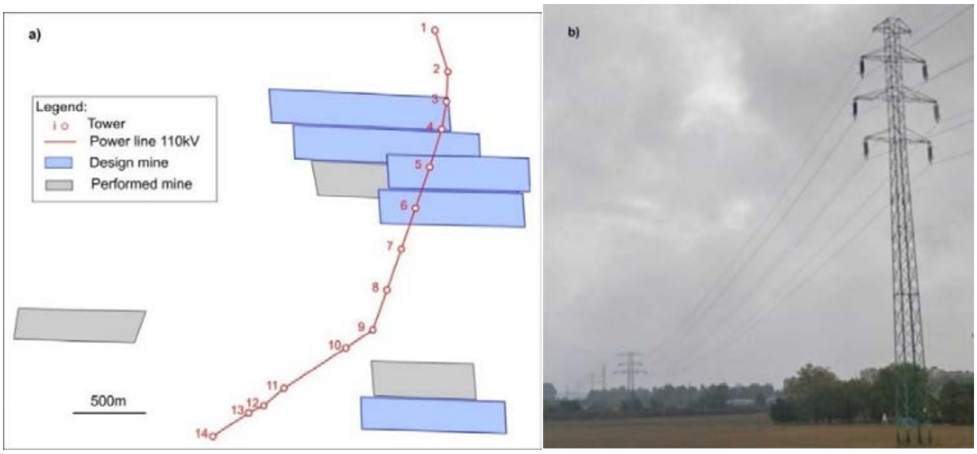

Fig. 2. Example 2 forecasts deformation (a) a scheme of arrangement and shape of the object, (b) view of a fragment of the analyzed power line.

The photo (Figure 2b) shows poles 14-11. To present the results of the calculations, three poles numbered 4-6 were selected. Figure 3 shows the maximum inclination change over time. The calculations assumed the date of the geodetic measurement as the starting point of deformation. The inclinations presented are the sum of the measurement and the corresponding increase in the calculated inclinations.

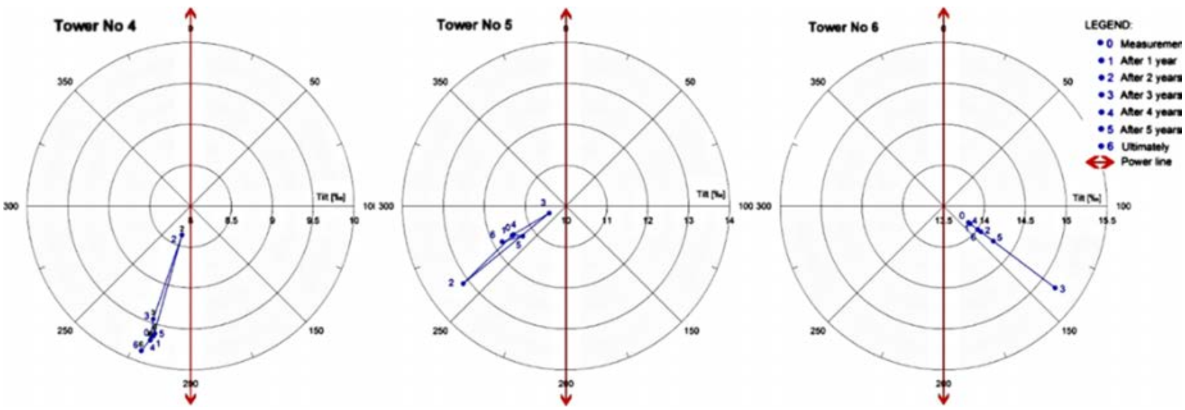

Fig. 3. Example 2 – the projected inclination for towers 4, 5 and 6.

The power poles' inclination presented in Figure 3 post No. 6 exceeds the limit determined by the designer. According to the calculations, it will take place after two years. Based on the results, it was decided to implement the intended operations, provided pole no. 2 is reconstructed within two years and quarterly geodetic monitoring is performed.

5. Summary

Mines are often located in heavily urbanized areas, surrounded by a network of facilities. Safely conducted mining operations mean not just the safety of the mine and the miners working in it, but also the safety of the people and infrastructure located on the surface in the area of influence of the operation. All mining operations negatively affect the environment and engineering facilities, therefore, specialists should properly design the exploitation or secure the objects.

Well-functioning public utilities are a very important factor in the development of a society. The impact of the operation on these networks is evaluated in terms of technical, social and economic effects. The decision to mine a mineral deposit must be preceded by an analysis of its impact on the land surface and engineering structures. Depending on the specific linear object, different types of predictions of deformation are carried out. In the examples shown, the operation was undertaken, and as a result of the executed procedures, the engineers managed to ensure full functionality of the analyzed facility.

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