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Methods for assessing resistance and threats to building structures in mining areas

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Abstract

The first part of this research paper presents methods for assessing threats and resistance of the existing building structures to the influence of continuous surface deformation and mining tremors. The discussed assessment methods were used for the analysis of a large number of buildings located in the mining area, and they allowed to assess both the resistance of those buildings as well as the extent and intensity of potential mining damage.

The second part demonstrates the results of the research involving a methodology that allows for a detailed assessment of dynamic resistance of a single building structure to the impact of mining tremors. This assessment is based on a comparison of the behavior of a structure when exposed to the loads from the design stage, with its response to the influence of the seismic combination, which takes into account mining impacts in the form of mining tremors. The paper also presents exemplary results of the conducted analyzes which evaluated dynamic resistance of an existing portal frame industrial building with a steel structure to mining tremors.

Based on the adopted methodology, the direction of further research was defined. It will determine the criteria for detailed assessment of dynamic resistance of the existing building structures to the influence of mining tremors, considering the fact that these structures were designed with only the impacts of continuous surface deformation taken into account.

Keywords: Mining tremors, dynamic resistance, ground deformations, bridge structures, portal hall building structures

1. Introduction

Underground mining of deposits has adverse consequences on the surface, including continuous and discontinuous surface deformations as well as mining tremors [15, 31]. Both surface deformation and mining tremors result in additional strength of structural elements, but are of a different character, though. Kinematic excitation of supports caused by surface deformation is static, and mining tremors induce an additional load in the form of inertia forces [1].

All types of impact caused by mining operations must be taken into account, either at the design stage of newly erected objects or, in the case of existing structures, during their service life. In both cases, it is necessary to adjust the structure to carry additional load caused by mining operations. The distinction between new and existing building structures divides both technological solutions regarding the applied safety measures and the methods of identifying potential loads generated by underground mining, and manifested on the surface of the mining area [13, 15].

In practice, it is often necessary to assess the resistance of those building structures which were not protected against the occurrence of either surface deformation or mining tremors during the construction stage. As a result, mining companies can take appropriate preventive actions, and it is also possible to assess the extent and intensity of potential damage that a given mine is obliged to repair.

The first part of this research paper presents methods for assessing threats and resistance of the existing building structures to the influence of continuous surface deformation and mining tremors. The discussed assessment methods were used for the analysis of a large number of buildings located in the mining area, and they allowed to assess both the resistance of those buildings as well as the extent and intensity of potential mining damage. Reference was made to the results of the research which included damage as part of the analysis of the degree of technical wear $\boldsymbol{s_z}$ [33] and the damage intensity index [4].

The second part demonstrates the results of the research involving a methodology that allows for a detailed assessment of dynamic resistance of a single building structure to the impact of mining tremors. This assessment is based on a comparison of the behavior of a structure when exposed to the loads from the design stage, with its response to the influence of the seismic combination dictated by *Eurocode 8* [23], which included mining tremors in the form of a model acceleration response spectrum for the area of *Legnica-Głogów Copper District*, according to [37, 38]. The paper also presents exemplary results of the conducted analyzes which evaluated dynamic resistance of an existing portal frame industrial building with a steel structure to mining tremors. The research assumed that this structure had not been designed to carry either surface deformation or mining tremors.

Based on the adopted methodology, the Author pointed out that it was possible to extend it to the structures which were designed with the impacts of continuous surface deformation taken into account.

2. Methods for assessing resistance and risk of the occurrence of mining damage for numerous groups of existing buildings constituting the development of a mining area

In the case of existing structures that have not been protected at the design stage, it is necessary to assess the threat from the occurring or predicted mining impacts that these structures may be exposed to. Such assessment is possible when the resistance of a given building structure (or group of structures) is known, both to the effects of continuous surface deformation and mining tremors.

For the resistance to continuous deformation, the *point-by-point method* has been applied for many years [16, 17, 34]. The result of the evaluation of the structure resistance (KO) is the mining area threat category (KT), which a given structure can carry without the risk of damage that may be significant due to safety reasons. Such formulation of the method allows to relate the building's resistance to the existing or predicted area category [14]. Its additional advantage is the ability to analyze a large group of building structures. This method, however, has certain limitations and may only be applied to buildings with traditional structure, with load-bearing walls constructed of small-size elements, up to 5 stories, which failed to be protected at the design or implementation stages [16].

Another method of assessing mining impacts, both static and dynamic ones, is the analysis of the increase in technical wear s_z [%]. This approach proposed in [33], allows for the assessment of the extent of the so-called *mining damage*. Quantitative measure of mining damage expressed as an increase in technical wear has a universal use, allowing to analyze various types of buildings (traditional buildings [35], buildings in industrialized technology [7, 36]). Additionally, with the right amount of data, it is possible to analyze the cases where mining impacts (surface deformation and mining tremors) and, at the same time, construction factors (quality of structural elements, type of protection, quality of maintenance, etc.) are taken into account. The created model of the course of technical wear, presented in the research paper [26], may be an example of the extent of possible uses of such an approach. In that study, the *SVM* (*Support Vector Machine*) method was used, which allowed for the analysis of changes in technical wear in relation to the variables adopted for the construction of the model, including the factors describing the intensity of mining impacts. This research was carried out based on the sensitivity analysis, studying partial derivatives of the created model.

Firek [8] detailed the method proposed by *Wodyński* [33]. It consisted in defining the *damage intensity index* w_u [4], which described both the morphology as well as the levels of intensity of damage to structural and finishing elements. This index was determined so that its value was co-linear with the general value of the technical wear of buildings $\boldsymbol{s_z}$. As research studies for different types of structures demonstrated (the results of which have been described in [5,6]), the index w_u may form the basis for the construction of advanced assessment models for the risk of occurrence of damage to buildings located in mining areas [27]. In addition, it may help estimate predicted costs of repairing mining damage, which was also emphasized in [9].

On the other hand, if it is necessary to assess the threat of dynamic impacts of mining exploitation to a large group of buildings, the *Dynamic Impact Scale* [21] and *Mining Intensity Scale* [32] are used. They allow to assess the scale of potential damage that may occur as a result of a tremor of a given intensity.

The presented methods allow to identify those buildings for which a detailed analysis of the load-bearing capacity should be carried out (*point-by-point method*) and, on the other hand, to assess the general (*Wodyński's* approach) or a more detailed (*Firek's* approach) extent of mining damage.

3. Detailed assessment of dynamic resistance of existing building structures subjected to mining tremors

3.1. General findings

With the *Eurocodes* entering into use, the requirements for determining a combination of loads for building structures located in mining areas were unified. In the research paper [2], the loads generated by continuous and discontinuous mining deformations and tremors were adapted for the combination of loads dictated by [22].

According to [2], the loads induced by continuous surface deformation were classified as variable loads in the basic combination (1).

$$\sum_{j\geq 1}\gamma_{G,j}G_{k,j}+\gamma_g Q_{g,k}+\sum_{i>1}\gamma_{Q,i}\Psi_{0,i}Q_{k,i} \tag{1}$$

Where:

$\gamma_{G,j}$ – partial factor for permanent action j,
$G_{k,j}$ – characteristic value of permanent action j,
γ_g – partial safety factor for mining impacts,
$Q_{g,k}$ – characteristic value of mining impact caused by continuous deformation,
$\gamma_{Q,i}$ – partial safety factor for variable action i,
$\Psi_{0,i}$ – factor for combination value of variable action i,
$Q_{k,i}$ – characteristic value of variable action i.

Unless they are dominant variable loads as part of the analyzed combination, they are subject to a reduction resulting from the value of the combination coefficient $\Psi_{o,i}$, according to [22]. Extreme values of the indices describing surface deformation should be considered at this point: ε_{ekstr} – extreme value of horizontal surface deformation [mm/m], K_{ekstr} – extreme value of surface curvature [1/km] and $T_{\max}$ – maximum value of inclination [mm/m]. The influence of discontinuous surface deformation and mining tremors is included in the accidental combination. This combination considers the simultaneity of the occurrence of continuous surface deformation and the accidental effect of a mining tremor, according to (2), as well as the accidental effect of the occurrence of discontinuous surface deformation or mining tremors without simultaneously taking continuous deformation into account (3).

$$\sum_{j\geq 1}\gamma_{G,j}\,G_{k,j}+0,8\cdot\gamma_g Q_{g,k}+0,8\cdot\sum_{i>1}\gamma_{Q,i}\,Q_{k,i}+A_w \tag{2}$$

$$\sum_{j\geq 1}\gamma_{G,j}\,G_{k,j}+0,8\cdot\sum_{i>1}\gamma_{Q,i}\,Q_{k,i}+\left(A_w \text{ or } A_g\right) \tag{3}$$

Where:

$\gamma_{G,j}$ – partial factor for permanent action j,
$G_{k,j}$ – characteristic value of permanent action j,
γ_g – partial safety factor for mining impacts.
$Q_{g,k}$ – characteristic value of mining impact caused by continuous deformation.
$\gamma_{Q,i}$ – partial safety factor for variable action i,
$Q_{k,i}$ – characteristic value of variable action i,
A_w – accidental action induced by mining tremors,
A_g – accidental action induced by discontinuous surface deformation.

In the case of seismic actions in the standard [22], in addition to accidental actions, a separate seismic combination (4) is also specified.

$$\sum_{j\geq 1} G_{k,j} + A_w + \sum_{i\geq 1} \Psi_{2,i}\, Q_{k,i} \tag{4}$$

Where:

$G_{k,j}$ – characteristic value of permanent action j,
$Q_{k,i}$ – characteristic value of variable action i,
$\Psi_{2,i}$ – factor for quasi-permanent value of a variable action,
A_w – accidental action induced by mining tremors.

The combinations are used at the stage of examining the ultimate limit states according to [22]:

- EQU: due to loss of static equilibrium of the structure (or any part of it), when considered as a rigid body.
- STR: due to internal failure or excessive deformation of the structure (or its structural members), where the strength of the materials of a structure, or the stability of its members, is decisive,
- GEO: due to failure or excessive deformation of the ground or foundations on which the structure sits, which is essential for its load-bearing capacity, or when deformation of the ground is of great importance to the load capacity of the structure.

Data on the values of mining impact which are taken into account at the design stage, result from predictions.

For predicting impacts in the form of continuous surface deformation, the *Budryk-Knothe* geometric and integral method is most often used [14].

On the other hand, discontinuous deformation analysis on the surface in the form of subsidence craters or irregular sinkholes, is generally based on two theories: pressure arch [29], widely used in geomechanics for calculating the load of roof supports, which was implemented to calculate the probability of the occurrence of subsidence as well as statistical analysis using empirical formulas for the collapse and cracks zones [24].

However, prediction of the parameters describing mining tremors is carried out based on geophysical surveys. Due to the fact that the recommended method of dynamic structure analysis at the design stage is the *response spectrum method* [1], the knowledge of the *model acceleration response spectrum,* characteristic for a given area, is required. In recent years, numerous research papers devoted to this subject have been created. They defined the model acceleration response spectra for the mining area of *Legnica-Głogów Copper District* [30] and the *Upper Silesian Coal Basin* [3]. In addition, the research papers [37, 38] proposed an adaptation of the source response spectrum curves contained in [23] to the seismic activity prevailing in the mining area of *Legnica-Głogów Copper District*.

An important supplementation to the guidelines on the method of classifying loads from mining impacts are indications regarding additional structural protection measures [11,12].

Examples of protective measures used in buildings against continuous deformation include [11-13, 15]: separating layers, diagonal braces (Fig. 1), additional reinforcement of strip foundations and tie beams, monolithization of the raw state, expansion joints. They are designed to increase the spatial rigidity of the structure or to separate individual segments from each other, so that the influence of the deforming ground would be transferred to the higher-located elements of the building as little as possible.

Quite popular and frequently used protective measures against the occurrence of possible mining tremors include properly constructed reinforced concrete pillars in the wall corners [10] (Fig. 2).

The guidelines contained in [2, 10-12] are used by structural engineers at the design stage, when impacts from mining operations are expected for a given area. These directives, however, can also be implemented in assessing the resistance of existing building structures that were not adapted at the design stage to carry such loads.

This mainly applies to dynamic resistance to mining tremors, due to the fact that additional loads caused by mining tremors are taken into account either in the accidental combination (3) [2] or in the seismic combination (4) [23]. They are separate from the basic combination (1) adopted at the design stage, which does not take into account the impact of mining tremors. Thus, the determination of extra load capacity allowing for the occurrence of additional dynamic load resulting from mining tremor is possible. This procedure involves the comparison of the structure response to the loads adopted at the design stage with the response from the loads included in the accidental [2] or seismic [23] combination.

Fig. 1. Example of the use of diagonal braces at the foundation level

Fig. 2. Example of the use of reinforced concrete pillars in wall corners of a traditional building

3.2. Exemplary assessment of dynamic resistance of portal frame steel structure which was not designed for carrying mining impacts

Paper [25] presents a proposed methodology for assessing the dynamic resistance of bridge structures to the impact of mining tremors. This methodology was also used in [28] to assess the dynamic resistance to mining tremors of two exemplary industrial portal frame buildings with steel and reinforced concrete supporting structures. This research paper refers to the results of assessing the resistance of the industrial portal frame building with a steel structure. As part of the calculation, dynamic resistance was analyzed, taking into account the criteria of ultimate limit state STR [22]. This building was designed in the 1970's, which formed the basis for adopting the basic combination according to [18], the provisions of which were observed at the design stage. In addition to the self-weight of the structure itself and of the fittings, variable loads were taken into account: wind loads [20] and snow loads [19]. Mining impacts in the form of continuous surface deformation were not taken into account. For each group of the elements (pillars, purlins and braces), a maximum level of strength was determined, adequate to the way in which individual members in the load-bearing structure work. Thus, the combinations of loads from the design stage were identified, which generated extreme strength in the sections of individual members (pillars, purlins and braces). The extreme values of normal and shear stresses were a measure of strength. At the design stage, they were used to determine the degree of reinforcement of reinforced concrete elements or to determine the choice of the appropriate section in steel structures. Therefore, it was predetermined that the obtained strength values for individual elements would be the criterion values (effects) in the proposed approach, and will be referred to as E_d^{PN}.

Then, dynamic calculations for mining tremors characteristic for the mining area of *Legnica-Głogów Copper District* were performed for the structure. For this purpose, the response spectrum method was used, taking the shape of a model acceleration spectrum for area B [38]. The analyzed structures were dynamically loaded in three perpendicular planes according to [2], adopting the seismic combination (4).

The obtained results were compared with the response of the structure to the selected load schemes from the design stage. Only those cases that were similar in terms of structure deformation and corresponding internal force graphs were compared. This allowed to compare the extreme value of the strength of a specific element obtained from the loads from the design stage E_d^{PN} with the strength of the analyzed structural member resulting from the loads from the seismic combination E_d^{SE}. During the comparison, the value of the component of the acceleration of ground vibration in the analyzed plane $\{a_x, a_y, a_z\}$ was calibrated so as to equalize the value of the strength in the analyzed member $E_d^{PN} = E_d^{SE}$. In this way, permissible values of individual components $\{a_{x,dop}, a_{y,dop}, a_{z,dop}\}$ were obtained. Taking into account the fact that the seismic combination is separated from the basic combination, the obtained values specify the permissible value of the strength caused by mining tremors in a given plane that the structure can carry using the extra load capacity contained in the basic combination from the design stage.

The described approach led to the permissible values of the components of acceleration of ground vibrations in the horizontal plane $a_{x,dop} = a_{y,dop} = a_{H,dop}$, both for the whole structure as well as for its members. These values are summarized in Table 1. The numerical model of the analyzed building is illustrated in Figure 3. Dynamic excitation in the vertical plane was analyzed during the research studies, but it was demonstrated that it did not have any significant adverse effect on the safety of such structures.

Tab. 1. Dynamic resistance of the analyzed portal frame steel structure taking into account the resistance of its structural members [28]

No.	Structural components	Resistance of the component determined relative to the normal stress failure criterion	Resistance of the component determined relative to the shear stress failure criterion	Resistance of the component $a_{H,dop,i}^{Element}$ [m/s²]	Resistance of the object $a_{H,dop}$ [m/s²]
i.		$a_{H,dop,i}^{Element,\sigma}$ [m/s²]	$a_{H,dop,i}^{Element,\tau}$ [m/s²]	$min\left\{a_{H,dop,i}^{Element,\sigma}, a_{H,dop,i}^{Element,\tau}\right\}$	$min\left\{a_{H,dop,i}^{Element}\right\}$
1.	Purlins	6.98	NO LIMIT	6.98	2.11
2.	Transoms	6.58	12.15	6.58	
3.	Posts	3.54	6.50	3.54	
4.	Roof slope braces	2.32	N/A	2.32	
5.	Vertical braces	2.11	N/A	2.11	
6.	Longitudinal braces	8.16	N/A	8.16	

3.3. Proposed assessment of dynamic resistance of existing building structures designed to carry continuous surface deformation

In the analyzed case, the dynamic resistance of an existing building structure was assessed. This structure was not designed for the possibility to carry mining tremors, nor was it adapted to carry continuous surface deformation.

Using the fact that the basic combination (1) for ultimate limit states (STR, EQU, GEO) is a separate scenario of the potential structure loading with respect to the accidental combinations (2) and (3), the proposed method can be extended by the assessment of the dynamic resistance of building structures adapted to carry continuous surface deformation already at the design stage.

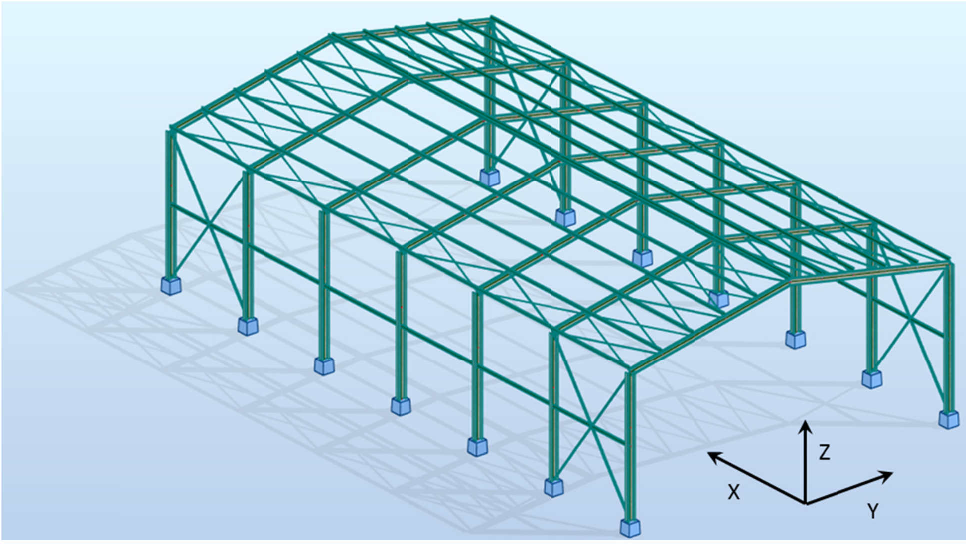

Fig. 3. Numerical model of portal frame steel structure [28]

The possibility of applying the proposed methodology to assess the resistance of existing building structures to the influence of discontinuous surface deformations is also considered. As in the case of assessing the dynamic resistance to mining tremors, it results from the fact that the influence of discontinuous surface deformation is taken into account as part of the accidental combination (3). Thus, the separability of the basic combination (1) and the accidental combination (3) can be used to determine the permissible strength or deformation that the structure can carry in the event of the occurrence of discontinuous deformation.

4. Summary and conclusions

This research paper presents methods allowing to assess threats and resistance of the existing building structures subjected to mining impacts. The issue of performing such assessments for a large number of buildings was discussed, and results of the research on the detailed assessment of dynamic resistance to mining tremors were presented. As an example, the results of the analyzes carried out for a portal frame industrial building with a steel structure were demonstrated.

It is planned that future studies will verify whether the applied methodology for the assessment of dynamic resistance could be extended to the areas specified in Section 3.3.

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