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ANALYSIS OF METHODS USED FOR ASSESSING DAMAGE RISK OF BUILDINGS UNDER THE INFLUENCE OF UNDERGROUND EXPLOITATION IN THE LIGHT OF WORLD'S EXPERIENCE – PART 1

ANALIZA METOD OCENY ZAGROŻENIA OBIEKTÓW BUDOWLANYCH EKSPLOATACJĄ PODZIEMNĄ W ŚWIETLE DOŚWIADCZEŃ ŚWIATOWYCH – CZĘŚĆ 1

Methods used for evaluating damage risk of buildings threatened with continuous strains generated by underground exploitation have been addressed in this paper. The main emphasis was put on methods thanks to which the degree of damage of a large group of structural objects could be approximated. The investigations were focused on the origin of those methods, especially the assumed criteria. The final stage of theoretical study was a comparative analysis of presented methods, thanks to which the basic differences between assumptions to those methods as well as the main advantages and disadvantages could be enumerated. Then the damage risk of buildings was evaluated with selected methods. The obtained results were compared with actual data registered in those objects. This enabled the authors to practically evaluate the adaptability of those methods to the underground exploitation conditions in Poland. The first part of the paper is devoted to the presentation of methods and theoretical anaysis of their shortcomings and advantages, followed by the results of analyses performed on actual data.

Keywords: mining damage, mining, continuous deformation, risk, building vulnerability assessment

W artykule zaprezentowano metody wykorzystywane w świecie do oceny zagrożenia obiektów budowlanych deformacjami ciągłymi generowanymi przez eksploatację podziemną. Główny nacisk został położony na przybliżenie metod, które umożliwiają przeprowadzenie estymacji stopnia uszkodzenia dużej grupy budynków kubaturowych w sposób przybliżony. W badaniach skoncentrowano się na genezie powstania tych metod kładąc szczególny nacisk na wyjaśnienie kryteriów przyjętych do ich budowy. Końcowym etapem badań teoretycznych zaprezentowanych w niniejszym artykule jest analiza porównawcza zaprezentowanych metod. Analiza ta pozwoliła na wyłonienie podstawowych różnic istniejących w założeniach tych metod oraz na uwypuklenie głównych wad i zalet przy stosowaniu tych metod. Następnie podjęto próbę oceny zagrożenia obiektów budowlanych wybranymi metodami. Ostatecznie wykorzystane wyniki porównano z realnymi uszkodzeniami, które zostały zarejestrowane w budynkach.

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Badania praktyczne pozwoliły na ocenę możliwości adaptacji tych metod w warunkach eksploatacji podziemnej w Polsce. Pierwsza części artykułu poświecona jest prezentacji metod oraz rozważaniom teoretycznym dotyczącym ich mankamentów i zalet. Natomiast w drugiej części artykułu rozważania teoretyczne poparte zostały wynikami analiz przeprowadzonych na rzeczywistych danych.

Słowa kluczowe: szkoda górnicza, eksploatacja, deformacje ciągłe, ryzyko, ocena odporności budynków

1. Introduction

Underground exploitation brings about a risk of building damage on the surface. The enhancement of exploitation works increases the damage of objects on the surface, and consequently necessitates assessing the risk of such damage. Since the 20th century a number of methods of determining the potential degree of building damage and the respective prevention measures have been worked out in various countries all over the World. Six methods most commonly applied in England, Australia, United States and R.S.A. have been presented in the paper. Theoretical study was focused on assessing those methods for their accuracy and readiness to use. Special attention was paid to the disadvantages of those methods.

2. Presentation of methods

2.1. Methods for assessing object damage risk on the basis of building geometry

Methods used for evaluating the risk of building damage caused by continuous strains were principally based on the relation between the length of the building and horizontal strains of the ground. The development of those methods could be observed in the 1950's, when the cities were intensely developed, and the underground tunnels had to be reconstructed for the future subways and tubes. One of the first attempts at defining relations between continuous strain of terrain were made by Skempton and McDonald (1956, 1957). Those studies concentrated on the possibility of electing objects in an area liable to strains caused by seasonal precipitations. This was a starting point for analyses concentrating on similar a dependence between terrain strains under the influence of underground exploitation. Thos methods were created by the National Coal Board (1975) (hard coal exploitation, Great Britain) by Wagner and Schumann (1991) (hard coal exploitation, South America) and by the Mine Subsidence Engineering Consultant (2007) (hard coal exploitation, Australia).

2.1.1. National Coal Board Method

The intense hard coal exploitation carried out under the developed areas of England since the beginning the 20th century has generated considerable damage to buildings, therefore it was necessary to create a method for predicting potential damage and use respective prevention measures. Attempts were made to determine a dependence between the intensity of the deforming ground on the building and the observed damage degree on the basis of damage registered on households and observed surface strains recorded on 165 observation lines. The resistivity of the building was equated with its length. The risk of occurrence of continuous ground strains was defined on the basis of one strain index, i.e. maximum predicted horizontal strain. The dependence between the length of the building, horizontal strain of the ground and risk of damage to the object was determined with hyperbolic functions (Fig. 1). The length of buildings for which the damage risk can be estimated with this methods, ranges from 0 to 250 m. This facilitates the analysis of damage risk for majority of buildings, even in-series objects (no dilatation). The horizontal strains range from 0 to 6 mm/m. Five degrees of building damage have been defined: very small, small, considerable, severe, very severe. For each of them a plot was made. Those plots cut off values, for which a given damage degree may occur from the domain of horizontal strain and the building's length.

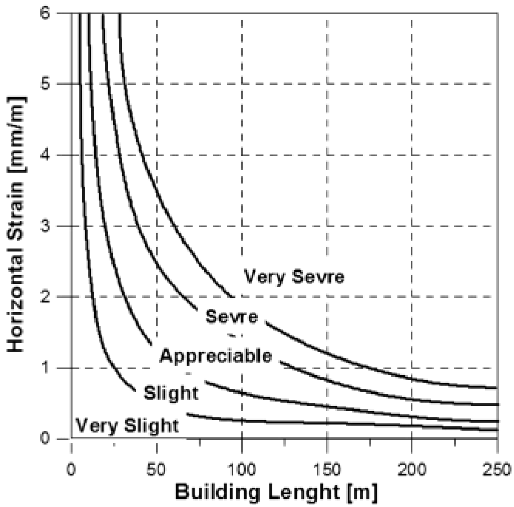


Fig. 1. Scheme of National Coal Board method (NCB, 1975)

Authors of this method tried to characterize possible results of continuous strain on definite objects. In the lowest class strains there appear small breaks in the plaster (invisible on the outside) as a result of change of the length of the building by 0.03 meter. The next degree of potential damage is associated with breakings visible outside and hindered use of the object (warped carpentry). The successive degree of building's elongation increases the damage by visible, severe to very severe damage of the building, leading to the partial or complete rebuilding of the object and the associated infrastructure.

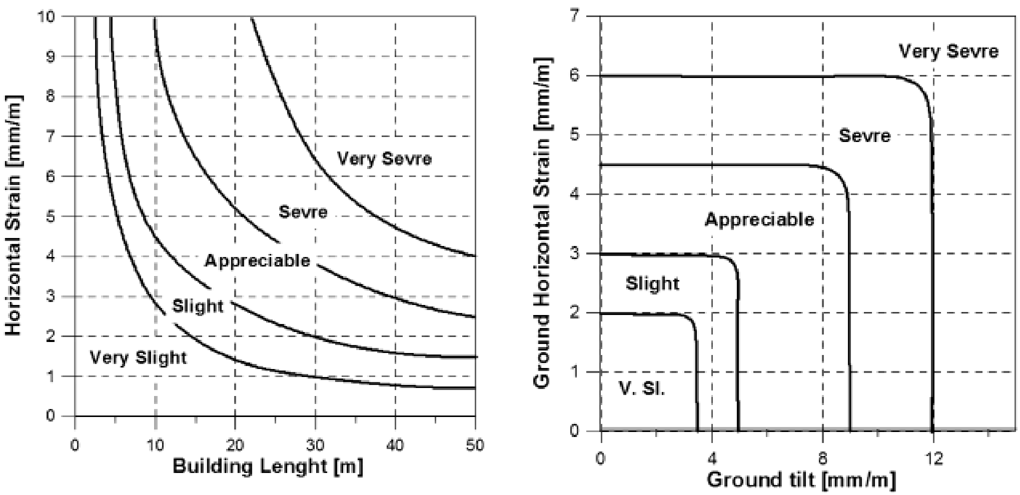
Remarks on National Coal Board Method

The risk of damage is associated with one factor, which is the maximum horizontal strain. There is no distinction between compressive and tensile strains. Neither is analyzed the direction of this index, nor time of its operation. Horizontal strains of 0 to 6 mm/m are analyzed, i.e. a moderate degree of horizontal strains under the objects is assumed. The analysis of the plot reveals that in the case of objects up to 100 meters long the influence of horizontal strains reaches up to 2 mm/m. Accordingly, this method may create certain problems for small-size buildings.

2.1.2. Wagner and Schumann method

Another empirical method of assessing the risk of damage to objects from coal exploitation was created by Wagner and Schumann in the 1990's (Wagner & Schumann, 1991). They made observations of damage to households in the area under the influence of the Coal Mine Brandspruit in Secunda (South Africa). The observations led to the conclusion that damage to the buildings mainly resulted from the tilts and horizontal strains. No unexpected, catastrophic damage was observed there. In majority of cases the damage to the buildings was fixable. This method was based on a relation between horizontal strains of terrain surface, length of the object and degree of its damaging (Fig. 2a). It was assumed that horizontal strains might be equal to 0 to 10 mm/m and the length of the object should not exceed 50 meters. Five classes of building damage were defined: I-negligible, II-slight, III-considerable, IV-severe, V-very severe. Each of them was defined by a hyperbolic curve. In this way the degree of damage which might potentially affect the building could be determined on the basis of the length of the building and expected horizontal strains underneath.

Basing on their observations, the authors of this method defined additional relations between tilt and strain of terrain surface (Fig. 2b). The terrain tilt was assumed to be even 20 mm/m.



a) b)

Fig. 2. Scheme of Wagner and Schumann method (1991)

Remarks on Wagner and Schumann method

Presented cases referred to single households and the damage categories were defined analogous as in the NBC method. The shape of the damage plot resembles a hyperbole. A strong emphasis was put on smaller objects and higher values of horizontal strains. The risk of damage to buildings can be relatively strictly determined from the basic plot in this method. It should be also emphasized that the assumed ground tilt may help analyze the risk of damage to high objects.

2.1.3. Mine Subsidence Engineering Consultant classification

Another method based on a relation between continuous strains and the length of the building was created in Australia. The concept of direct implementation of NCB method to evaluation of risk of damage to buildings in that area was not successful. The NCB method was adapted in Australia by changing basic assumptions of the risk factors. The plot representing damage degree was based on the following variables: length of the building and horizontal strains observed in the building (MSEC, 2007). The authors of this method suggest that the deformation of the object should be defined on the basis of curvature of the terrain surface.

Similar to the two already discussed methods, the damage categories were defined and characterized by potential damage which may typically occur in a given class. Among additional criteria of risk evaluation are aperture opening and deflection ratio of the object as a constant inter-class boundary value enables one to calculate the deflection ratio on the basis of the height of the object (Fig. 3).

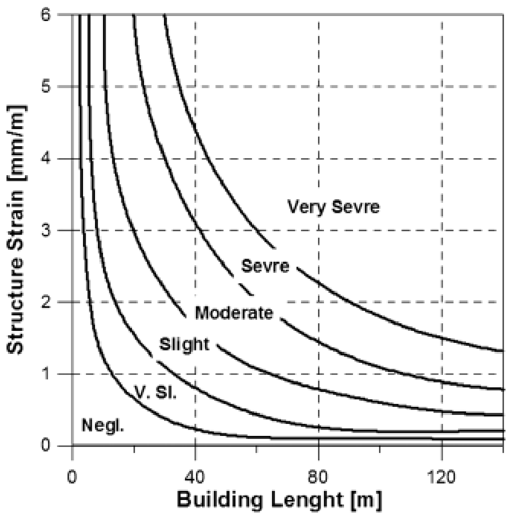


Fig. 3. Scheme of Mine Subsidence Engineering Consultant method (2007)

Remarks on Mine Subsidence Engineering Consultant classification

Per analogy to above methods, the damage risk also depends on the length of the building. Another variable is the horizontal strain of the building. This is a serious shortcoming making predictions of strains in buildings on the basis of excavation-induced strains almost impossible. The strain of the ground under the building cannot be directly transposed onto the change of the length of the building. The proposed evaluation of the degree of building damage on the basis of ground curvature would be a good assumption if not the difficulties with obtaining reliable results from the measurements of curvatures. For this reasons the predicted curvatures cannot be verified. The strains of the building block could be measured making this method useful if not the assumed mass applicability.

2.2. Analytical methods

In the 20th century the research carried out by the Building Research Establishment revealed that insurance companies introduced a clause of continuous strain of the ground (protecting estate houses against landslides). Hence, the damage classification had to be made. Three main damage categories were listed:

- aesthetic: affecting the outlook of the estate;
- usefulness: breaks and deformations making the use of the object difficult;
- stability: conditions at which the construction may be destroyed unless suitable prevention measures are taken.

2.2.1. Burland method

Burland continued studies of this subject and finally six damage categories were distinguished. Categories 0, 1 and 2 stand for aesthetic damage, categories 3 and 4 are usefulness damage, category 5 is damage affecting the stability of building construction. The investigation were continued by the year 1997 when Burland presented his object damage assessment methodology. This method was based on the plot of damage category vs. two variables: horizontal strain of building (up to 0.3%) and deflection ratio of building (up to 0.3%) (Fig. 4). Deflection ratio is determined as a ratio of horizontal strain-induced area to its length.

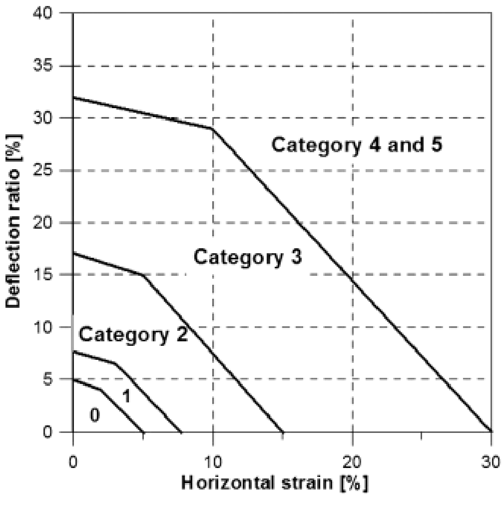


Fig. 4. Scheme of Burland method (Burland, 1997)

There was also worked out an algorithm for assessing damage risk in buildings, accelerating the evaluation of hazarded objects (Aye et al., 2006):

I. Preselection

Buildings staying in the zone of predicted subsidence over 10 mm are fit for further analyses.

II. Elimination of building of low damage-risk
Only objects having potential damage degree above 2 and particularly sensitive objects are qualified for further analyses.
III. Detailed assessment of hazarded objects
The last stage focuses only on buildings of damage category 3 or higher. Every such building is subjected to detailed strength analyses by construction experts.

2.2.2. Boscardin and Cording method

Analogous to the previous method, Boscardin and Cording (1989) continued their investigations, focusing on strains in the building. The damage classification was based on two variables: angular strains β and horizontal strains of the building εh (Fig. 5). The horizontal strain in the building ranges between 0 to 3.5 mm/m, angular strain is up to 7 mm/m. Five classes of building damage were introduced in this method.

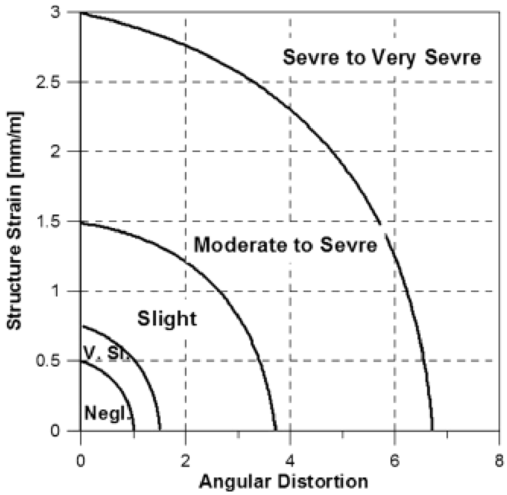


Fig. 5. Scheme of Boscardin and Cording method (Boscardin & Cording, 1989)

Angular strain was evaluated on the basis of a difference between expected subsidence of two opposite edges of the object or two neighboring foundation supports:

$$\beta = (SV1 - SV2) / L \quad (1)$$

where:
$SV1$ — vertical deformation of building's end;
$SV2$ — vertical deformation of another end of the building;
L — building's length.

The average horizontal strain of a building can be calculated from the following relation:

$$\varepsilon h = (Sh1 - Sh2) / L \tag{2}$$

where:

$Sh1$ — horizontal deformation of building's end surface;
$Sh2$ — horizontal deformation of another surface of building's end;
L — building's length.

The plot representing building damage degree illustrates intervals of building strains and angular deformation values in the function of depth of exploitation.

Remarks on Burland and Boscardin&Cording methods

In both presented methods special focus was on determining the damage risk from evaluated real strains in buildings. Such an assumption enables one to make a more detailed analysis of strains in the object and so to determine the degree of possible damage. The potential strains in the building cannot be predicted when evaluating the exploitation-induced building damage risk. Predicting subsidence and horizontal strains which may occur under the building cannot be associated with the actual ones. This is the main shortcoming of this method. Accordingly, the evaluation of damage risk with this method may be burdened with error resulting from the lack of accuracy in risk factors evaluation. It should be also stressed that the strength of the building is not accounted for in this method. The only criterion which may be associated with its strength is the length of the building.

2.3. Point methods

In the next method, the building's strength evaluation had to be approached individually, therefore as a consequence point methods were created. With these methods the building strength to continuous strains could be evaluated fast, with an approximated value as a result.

In Poland the point method was created in the 20th century (Przybyła & Świądrowski, 1968). Depending on the design features of the building, its geometry, technical condition, existing protections, foundation and subsoil, the building is ascribed a cumulative number of points for its specific properties. On the basis of statistical analyses of mining areas, the strength points are ascribed strength categories. The category has to be associated with the boundary value of horizontal strain which a given object can transmit without the risk of damage. The mining-induced building damage risk can be evaluated after confronting the building strength categories with terrain category. Similar point methods were also created in, e.g. Germany (Sroka, 2001), America (Yu, 1988) and India (Bhattacharya & Singh, 1984).

Attention should be paid to a method developed at the Virginia Department of Mines, Minerals and Energy (Yu, 1998). The building's strength is assessed on the basis of four properties: foundation, design, building's length to curvature radius ratio, building's length to its height ratio (Fig. 6). The cumulative number of points is ascribed one of four strength categories. Classification of damage introduced to this method is of special interest. Objects can be defined the damage class on the basis of building's strength category and boundary value of horizontal strain ε [mm/m].

Only three damage degrees can be distinguished in this method: architectonic, usefulness and structural. This approach enables one to establish the scope of repairs to be performed in the damaged building.

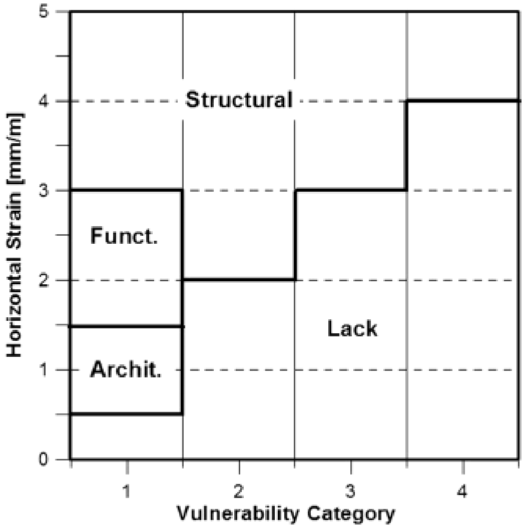


Fig. 6. Scheme of Yu method (Yu, 1988)

Remarks on point methods

In both presented methods it is the building's strength and maximum predicted horizontal strain which are critical as far as the damage risk is concerned. The Polish point method lacks classification of potential damage. The damage degree can be approximated on the basis of a difference between terrain category and building strength category. An interesting classification comes from Yu who introduces only three categories of damage. Structural damage can affect only objects belonging to the first class of strength. In the remaining buildings the strains may cause usefulness damage.

3. Critical analysis of presented methods

Six methods used for approximated evaluation of continuous stains in buildings have been presented in the paper. These methods are applied for determining damage risk for a large group of buildings. Those methods differ in the risk factor, accuracy of determining and readiness. Attempts were made to evaluate the accuracy of those methods and their usability in the Polish mining areas on the basis of theoretical considerations.

Risk factors and accuracy of estimation

The first three methods were created on the basis of observations of damage in the mining areas subjected to surface strains. The risk of damage resulting from horizontal strains was defined from maximum horizontal strains (NCB method), maximum horizontal strains and tilts (Wagner and Schumann method) and curvature of terrain radius (Australian method). The objects can be very generally assessed on the basis of selected strain indices. The predicted horizontal strain is defined with an accuracy of 20%, horizontal tilt 13%. The terrain curvature is determined with highest accuracy, i.e. about 50% (Popiołek, 2009). Another variable referring to the building's strength is their length (NCB and Wagner & Schumann methods) or length and height (MSEC method). The length of the building is defined with a very high accuracy of ca. 1%. The height of the building is defined with an accuracy of 10 % per floor.

Analytical methods are also based on predicted indices of terrain strains: subsidence, horizontal shift (Boscardin&Cording) as well as subsidence and horizontal strain (Burland). Subsidence is predicted with high accuracy of ca. 3%, and horizontal strain of about 13%.

The objective of the last group of methods is determining building's strength and predicting horizontal strains underneath. Unfortunately the accuracy of those methods for assessing building strength cannot be evaluated.

Concluding, the first (empirical) group of methods is most accurate in determining the risk factor. The lowest accuracy was observed in the last group. However the reliability of the methods cannot be attributed to the accuracy of determining risk factors. The correctness of assumed attributes deciding about the hazard degree has a definitely most important influence on the accuracy of the method. It should be assumed that in the case of individual evaluation of building's strength the accuracy of the method should be potentially higher. It should be also born in mind that 'Complexity and accuracy are inversely proportional, i.e. if the complexity of a solved problem increases, the accuracy of the analysis decreases' (Zadeh, 1965). Good scaling and categorization of damage have a key influence on the reliability and accuracy of methods.

Fastness of risk evaluation

The presented risk evaluation methods were also analyzed for their fastness in a large population of buildings. Only methods based on the building's length and surface strains were found to be definitely fastest. With simple GIS analyses one can quickly determine the risk for a large group of buildings.

Empirical methods require defining subsidence and horizontal strains under both ends of the building, which does not create any problem if spatial analyses based on screen-vector data are employed. Therefore, those methods are also considerably fast. The evaluation made with those methods is more time-consuming than in the case of methods based only on the building's length and horizontal strain of terrain.

The last group of methods based on the evaluation of building's strength is definitely most time-consuming as it requires individual strength evaluation of each of the buildings. The spatial methods can be used for fast evaluation of the risk when acquiring information about the point strength of building and the predicted strains of terrain.

Empirical and analytical methods are definitely fastest.

4. Conclusions and premises

Theoretical analyses presented in this paper were aimed at approaching World's methods used for evaluating building damage risk with continuous strains. Those methods are based on various risk factors. The length of the building and predicted maximum horizontal strains are most commonly taken into account. Among methods, with which the building's damage risk can be evaluated fastest are empirical and then analytical methods. The evaluation of building's strength with point methods is most time-consuming. However their accuracy should be highest because each object is approached individually. Those methods give information about the degree to which the building can be damaged. The biggest discrepancy between methods is connected with boundary values assumed for specific risk classes. This can be explained by changing intensity of exploitation intensity on terrain deformations and various types of buildings. Some methods functioning correctly in one country had to be modified and re-scaled to the local conditions. In one country the modifications referred to the changing exploitation conditions or other type of buildings. Therefore, it might be postulated that the methods for building damage risk evaluation commonly used in Poland were adapted to regional conditions.

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