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Modeling of the cave-ins occurrence using AHD and GIS

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Abstract

The analysis of mining-induced sinkholes occurrence is a very important problem as far as the spatial development optimization is concerned. Research conducted within this paper was oriented to revealing the applicability of GIS and the associated AHD method for estimating the risk of discontinuous deformation occurrence on the surface. The qualitative factors were accounted for in the sinkhole risk assessment, thus creating bases for the research. These elements play an important role in the process of sinkholes formation; however they were not used in prediction models. Another assumption lied in minimizing the number of variables in the model. Accordingly, the most important qualitative and quantitative risk factors were finally selected, on the basis of which the risk of cave-ins occurrence on the surface could be calculated. The results of estimations of zones with sinkholes potential were verified. The places of actual and high-risk potential discontinuous deformations were compared. The congruence between predicted values and actual observations of sinkholes was very high. The results of presented research prove the necessity to evaluate the sinkhole hazard in view of qualitative factors.

1 Introduction

In areas subjected to underground mining activity the discontinuous deformations most frequently develop quickly and violently. The problem of discontinuous deformations refers to areas with shallow exploitation and also to places where the excavations were conducted at a dozen of panels and at great depths. Depending on the mining and geological conditions discontinuous deformations may vary in shape and size. In Poland discontinuous deformations mostly assume the form of surface deformations. Investigations by Chudek reveal that about 70 % of discontinuous deformations registered at Upper Silesia Region have a conic shape (Chudek et al., 1988). Moreover, an observation was made that discontinuous deformations could take place at various time intervals since the end of exploitation. Sometimes they occurred as long as tens of years later. The feasibility of discontinuous deformation predictions has been intensely investigated since the beginning of the 20th century. The random character of discontinuous deformations was a recurring conclusion. Among the precursors of the research on discontinuous deformations were Ryncarz (1992) – salt domes, Chudek et al. (1988), Lui (1981), Fenk (1981), Reddish and Whitaker (1989) – hard coal beds, Janusz and Jarosz (1976) – zinc and lead ore deposits.

The elaborated prediction models, basing on quantitative mining and geological factors, were a starting point for the estimation of the cave-in height and cracking zone over the working. The probability of occurrence of surface discontinuous deformations can be determined depending on the depth of the workings. The evident shortcoming of the functions is that they do not account for qualitative factors. Among the quantitative factors are, e.g. fault zones, hydration, cumulation of edges of exploitation panels. World's experience proves the necessity to incorporate such factors in the analysis of surface discontinuous deformation hazard.

The use of AHP-based open geographic information systems for evaluating discontinuous deformation hazard is presented in the paper. Selected cave-in risk factors were weighed with the AHP method. On this basis the probability of discontinuous deformation occurrence over a shallow hard coal excavation could be estimated. The proposed methodics and correctness of weighing were verified by comparing sinkhole areas with the endangered regions.

2 Sinkhole occurrence above shallow coal mining

Underground mining evokes changes of rock mass stresses. As a consequence, deformations may be formed on the surface. The geometry, intensity and rate at which discontinuous deformations occur depend on a number of mining-geological factors. As a result of many years' observations, groups of factors having most distinctive influence on the formation of discontinuous deformations on the surface were found out i.e. depth of bed deposition, thickness of selected beds, exploitation system, rock mass tectonics, hydrogeological conditions, way in which the on-lying beds are disposed and their physico-mechanical properties (Chudek et al., 1988; Delle Rose et al., 2004; Fenk, 1981; Janusz and Jarosz, 1976; Kowalski, 2005; Liu, 1981; Ryncarz, 1992; Whittaker and Reddish, 1989). Detailed analyses revealed that the main causes of anthropogenic discontinuous deformations on surface are the following (Chudek et al., 1988):

- shallow exploitation with goaf (68 %),
- reactivation of old workings (13 %),
- activation of a fault, especially by one-wing exploitation or hydration (3 %),
- culmination of exploitation edges (4 %),
- reactivation of vertical workings (4 %),
- fires in shallow excavations (8 %),
- exploitation under hydrated overburden.

Parenthesized values stand for percentage of a given element of the analyzed population. The depth of mining is definitely the most important factor of cave-ins hazard.

On the basis of the cause-and-effect observations numerous functions were created to be used for estimating the risk of sinkholes. The height of the fracture zone and cave-in over the working are calculated from such measurable parameters as depth of deposition of a void, its height, thickness of overburden and goaf over the working. It should be emphasized that many other qualitative factors exist which may definitely influence the shaping of the sinkhole on the surface. Whether or not they can be used in functions depends on their qualitative characteristic. Among qualitative factors are, e.g.: tectonic disturbances, fracturing of the rock mass, hydrogeological conditions, deposition of onlying starta, etc. The analysis of significance of such factors and their influence on the process of sinkhole formation requires an expert approach. These

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data are characterized by many attributive and spatial variables. For instance, hydrogeological conditions are described by a number of parameters determining infiltration properties of particular layers. However their spatial distribution considerably varies making exact estimation of their percent participation in the subsidence process extremely hard. Accordingly, many significant variables were not accounted for in the functions thanks to which the height of fracture zones can be calculated. Many years' observations of sinkhole formation sites reveal that a number of qualitative factors had a great impact on the caving-in processes (Chudek et al., 1988; Delle Rose et al., 2004; Fenk, 1981; Janusz and Jarosz, 1976; Kowalski, 2005; Liu, 1981; Ryncarz, 1992; Whittaker and Reddish, 1989). Therefore, by incorporating such factors in the evaluation of cave-in occurrence the accuracy of the present prediction methods could be definitely increased. In Poland this type of estimation has a special meaning, particularly in old mining areas, where the risk of discontinuous deformations occurrence is high.

3 Research methodology

The Analytic Hierarchy Process, elaborated by Saaty, is one of the multicriteria methods aiding complex decision processes. It has been used in such disciplines as, e.g.: geology, mining, management, economics, environmental protection (Erden and Karaman, 2012; Le Cozannet et al., 2013; Saaty, 1980). This method is based on the assumption that a complex problem can be stripped out to elements which are then weighed and integrated with the objective to solve the problem. AHP provides expert significance-evaluation of factors having influence on a given effect. The hierarchy of elements is based on their pairwise comparison, and weighing each of them. This method has many critics and advocates. However, the results of world's AHP-based investigations realized in many scientific disciplines prove its high efficiency. AHP brings about satisfactorily good results when performing expert evaluation of qualitative factors, which have an influence on a given phenomenon. The successive stages of an algorithm

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making use of AHP method for the evaluation of the risk of discontinuous deformation of surface are presented below.

4 AHP

4.1 Step 1 the subject of the AHP definition

At the first stage the area of activity was defined. The surveys were focused on creating dependences, on the basis of which the hazard of the surface cave-in could be estimated. Attention was paid to the possibility of incorporating cave-in risk factors of qualitative and quantitative character.

4.2 Step 2 estimation of the risk factors

The risk factors were chosen on the basis of a detailed analysis of world's experiences and in situ investigations. One of the most important tasks at this stage was assessing the availability of reliable information about a given factor. This was related with the necessity to conduct qualitative and quantitative analyses separately. The estimation of quantitative factors and their reliability was a relatively low-complexity task. The following quantitative factors were distinguished (Table 1).

The determining of qualitative factors, however, required a broader look on the sinkhole hazard problem. First, the main study areas were specified, i.e.: geology, hydrogeology and mining. The qualitative factors, which potentially might have influence on discontinuous deformations formation on surface were successively distinguished (Table 2).

Most of the factors depended upon one another. Attempts were made at generalizing these factors and extracting the most important ones. Ultimately, faults and cumulation of edges were selected.

The analysis of the models presently used for predicting discontinuous deformations of surface reveals that most of the risk factors are not statistically related to the prob-

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ability of cave-in occurrence. This mainly stems from a high complexity and qualitative character of many of these factors. The AHP method is frequently used when integration and inferring from numerous factors is involved. For this reason, the authors decided to present the applicability of this method for determining the cave-in hazard.

4.3 Step 3 weighting of the risk factors

The selected risk factors were of both qualitative and quantitative character. To determine the significance of risk elements with the Saaty method, their number had to be reduced to maximum five. The experience with the AHP method proves that this method is most efficient for maximum 4 weighed elements. Sometimes hierarchical analyses based on a higher number of variables are used. Most frequently these are quantitative data. The hazard related to mining-induced partial deformations of surface depends both on qualitative and quantitative variables. In the case of exploitation with goaf the self-backfilling of voids could be observed in a longer time perspective. Accordingly, the contracted space should not generate any significant increase of height of the fracture zone over depleted workings. Prediction methods based on quantitative factors to be used for estimating cave-in hazard had low efficiency when the post-exploitation space was contracted. In this case the cave-in hazard should be estimated considering qualitative factors. The analysis of geological, tectonic and hydrogeological conditions in the study area allowed authors to finally select the most important elements. On this basis the elements were finally chosen and their hierarchy estimated. Eventually two qualitative variables were selected: fault and cumulation of edges, and two quantitative variables: thickness of exploited layer and depth of void's deposition. The hierarchy was determined by pairwise comparison of elements and weighing of them. The preferred element was ascribed a table value (Table 3). The rating proposed by the author assumed four grades of preference. If needed, intermediate values can be also introduced.

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Each element was weighed forming a triangular preference matrix. An assumption was made that each element of the matrix was equivalent to itself. The determined weights of elements were expressed as eigenvectors.

4.4 Step 4 consistency of the pairwise comparison

The correctness of induction of pairwise comparison was measured by inconsistency in the form of: CI (Consistency Index) and CR (Consistency Ratio). Consistency index was defined from the maximum eigenvalue of preference matrix (λmax) and the number of variables (n):

$$\lambda \mathrm{CI} = (\lambda_{\max} - n)/(n-1) \quad (1)$$

For above defined weights the consistency ratio was CI = 0.06.

On the other hand, the Consistency Ratio (CR) could be used for evaluating the coherence of weighing against randomness of weighing.

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RI} \quad (2)$$

The randomness was evaluated from the Random Consistency Index (RI), the value of which was approximated on the basis of estimations of weights in 500 randomly generated matrices. The RI value strictly depended on the number of variables. In four cases, RI equaled to 0.9. The ultimate value of Consistency ratio was 6.5 %. The admissible boundary value for this parameter was 10 %, therefore the weighing was deemed to be correct.

5 GIS

GIS is widely applied in many branches of economy and science (Forte et al., 2005; Hejmanowski and Malinowska, 2010; Ju et al., 2012; Mergili et al., 2012; Taramelli, 2008; Theilen-Willige, 2010). The work presented were done with Quantum an Open Source GIS software package. The GIS surveys were performed on raster surfaces. The first stage of spatial data work lied in defining boundary conditions, on the basis of which the most extreme values could be rejected (Step 5). Then the variables were re-classified in the interval 0–1 (Step 6). A re-classified raster surface (RN1, RN2, RN3, RN4) was generated for each of the factors. Such data were used for the final evaluation of cave-in hazard CHN.

5.1 Step 5 detection of outliers and additional assumptions

In the analyzed area the thickness of mining oscillated about the average of 2.00 m (1.5 to 3.0 m). Most of shallow panels were closed long time ago. In this case the boundary conditions did not have to be specified (Fig. 1).

The exploitation was conducted at 20 to 900 m of depth, and the panels deposited shallower than at 100 m were considered as potential sources of sinkhole hazard (Fig. 2).

Two remaining factors were of qualitative character.

In the case of a fault, the thickness of overburden and depth of fault outpits were analyzed. On this basis assumption was made that the range of the risk area around the fault was maximum 50 m of radius. Accordingly, a 50 m wide buffer area was determined around the fault (Fig. 3).

When analyzing the exploitation edges, a surface with the total number of all coinciding edges was generated. The maximum number of coinciding edges was 5 (Fig. 4).

The values of above factors considerably varied, therefore they had to be normalized.

5.2 Step 6 data normalization

Owing to their character, the variables were normalized. As a result, vectors, whose values belong to the interval $\langle 0,1 \rangle$ were obtained. The data were transformed by accounting for the minimum value $r_{i\_\min}$ and maximum value $r_{i\_\max}$ of a given variable:

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$$R_{\mathrm{Ni}} = \frac{r_i - r_{i\_\min}}{r_{i\_\max}} - r_{i\_\min} \tag{3}$$

Normalization does not account for the variable distribution, which is a significant shortcoming. Therefore, in the case of values that considerably differed from the average one, they were contracted in a very narrow interval. Accordingly, the previous stage of rejecting extreme values turned out to be very important. The remaining factors were subject to normalizing reclassification. The first qualitative variable (R_3), i.e. fault, was ascribed the highest normalized hazard ($r_{\mathrm{N}_3\_\max=1}$) directly at the fault output. The buffer zone edges were ascribed the lowest normalized risk ($\mathrm{r}_{\mathrm{N}_3\_\min=0}$) The second qualitative factor was the cumulated panel edges (R_4). The highest normalized hazard ($r_{\mathrm{N}_4\_\max=1}$) was attributed to the highest number of coinciding edges. A similar reclassification was made for quantitative variables. The depth (R_2), at which the analyzed panels were deposited ranged between 45 and 100 m. The highest sinkhole risk was observed for 45 m and the normalized one equalled to $r_{\mathrm{N}_2\_\max=1}$. The thickness of mining (R_1) oscillated around 1.5 and 3.5 m. The highest normalized hazard ($r_{\mathrm{N}_1\_\max=1}$) was connected with the thickness of 3.5 m. Thanks to normalized reclassification all variables were represented by values belonging to the same interval.

5.3 Step 7 WLC- sinkhole hazard map estimation

The last stage was weighing of factors and generating a spatial model of sinkhole hazard. Each of the normalized raster surfaces was multiplied by the significance weight of a given factor. The ultimate surface of sinkhole hazard was a sum of all weighed factors:

$$\mathrm{CH_N} = 0.06 \cdot R_{\mathrm{N}_1} + 0.12 \cdot R_{\mathrm{N}_2} + 0.26 \cdot R_{\mathrm{N}_3} + 0.56 \cdot R_{\mathrm{N}_4} \tag{4}$$

The surface was continuous. The higher was the value (tending to unity), the higher was the sinkhole risk (Fig. 5).

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The presented model was verified and information about places where discontinuous.

The comparison of predicted sinkhole sites with the actual ones proved the high efficiency of the proposed solution.

6 Results discussion

The evaluation of sinkhole hazard is a very important problem encountered in a number of active and closed mines. Discontinuous deformations occurring on the surface create a special risk in intensely developed areas. The cave-ins appear on the surface suddenly and unexpectedly. The correct estimation of zones where the risk of discontinuous deformation occurrence is high plays a very important role. This mainly refers to the common safety and spatial development issues. The process of sinkhole formation is connected with a number of factors. Many of them have qualitative character. On the other hand, taking into account qualitative and quantitative variables requires using of a flexible modelling tool, thanks to which the variables can be integrated and ranked. To meet this goal, the AHD method was selected for modelling. This is an expert and subjective tool aiding the decision processes, where the weights of risk factors should be estimated by experienced professionals. At the stage of preliminary selection, all factors having influence on discontinuous deformation formation were identified. Basing on the data availability analysis and then on their reliability analysis, 4 most significant risk factors were chosen. The analyses performed in the study area revealed that quantitative factors were most important. The main factors generating sinkhole hazard were cumulation of panel edges, and faults. Such quantitative factors as depth of the exploited panel or its thickness were less important. The correctness of weighing was proved by low CR value (6.5 %). Thanks to the integration of data in the raster form spatial analysis based on a defined function could be performed. The resulting raster surface allowed for an easy identification of zones, where the risk of discontinuous deformation occurrence was high. The resulting model of sinkhole occurrence hazard took values ranging between 0 and 1. Low cave-in risk zones occupied about 70 % of analyzed area, whereas zones of considerable sinkhole risk covered up to about 30 %.

The correctness of modelling was verified by comparing high risk zones with places where a discontinuous deformation has been already observed. The verification results confirmed very high congruence of modelled zones with the registered sinkhole areas. Only one discontinuous deformation occurred in a zone where the modelled hazard was average.

The results of presented analyses confirm the necessity of assessing sinkhole hazard partly on the basis of qualitative risk factors (faults, edge cumulations). The use of AHP proved the high efficiency of this method and necessity to account for qualitative and quantitative factors.

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Table 1. Quantitative risk factors.

Geomechanics	Mining	Geology
Compressive strength of rocks	Thickness of void Width of void Depth of void Continuous deformations of surface	Thickness of overburden

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Table 2. Qualitative risk factors.

Geology and tectonics	Mining	Hydrogeology
Faults	Cumulation of edges	Quicksands
Overburden	Exploitation in one fault wing	Hydration
Type of on-lying layers	Fires in workings	Intense precipitations
	Geomechanical state of workings	

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Table 3. Continuous rating scale for pairwise comparison of Saaty's method.

Value	Important
9	Extremely
7	Very strongly
5	Strongly
3	Moderately
1	Equally

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Table 4. Eigenvector estimation.

Factor i	R1	R2	R3	R4	Eigenvector (weight) V_{Ri}
Thickness (R1)	1.00				0.06
Depth (R2)	3.00	1.00			0.12
Fault (R3)	5.00	3.00	1.00		0.26
Edge (R4)	7.00	5.00	3.00	1.00	0.56

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Table 5. Evaluation of reliability of presented model.

AHP interval	Number of observed deformations	% of all deformations
0.00–0.25	2	4.5
0.25–0.50	6	13.3
0.50–0.75	27	60.0
0.75–1.00	10	22.2

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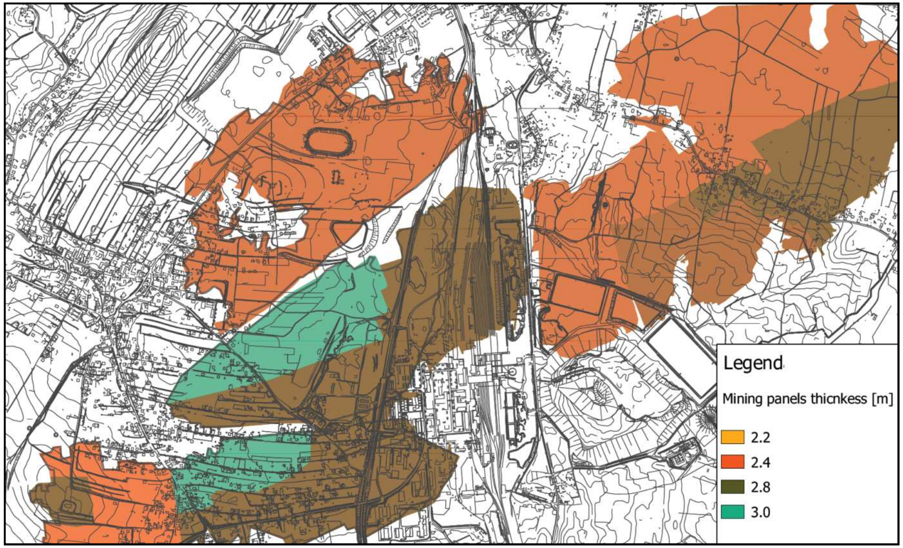

Fig. 1. Thickness of the mining panels.

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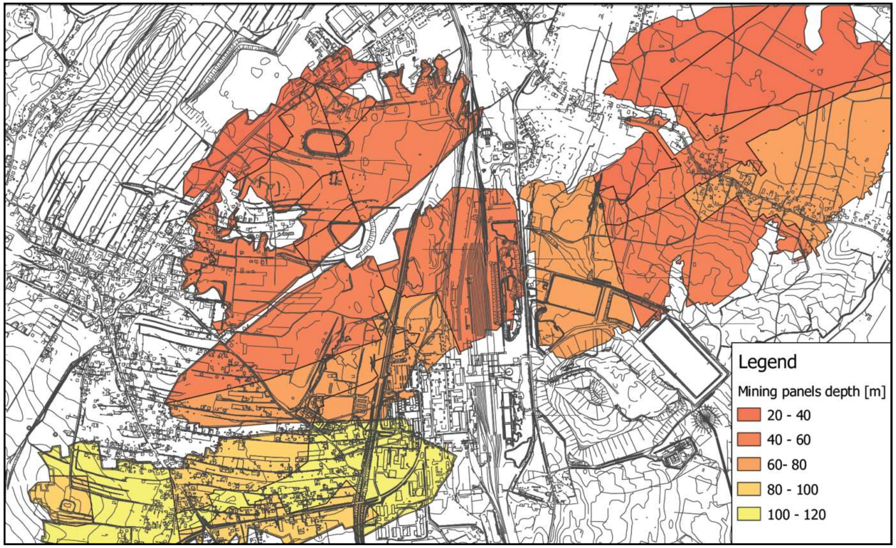

Fig. 2. Depth of the mining panels.

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Fig. 3. Faults and buffer zones around faults.

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Fig. 4. Number of panel edges.

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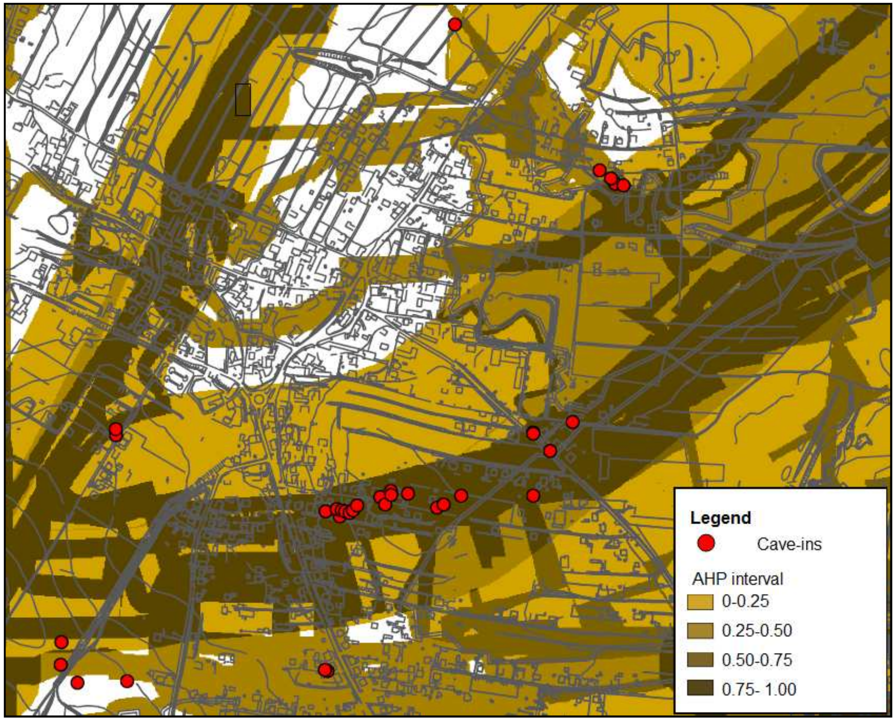

Fig. 5. Modelled zones of sinkhole hazard.

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