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Modelling of cave-in occurrence using AHP and GIS

A. A. Malinowska and K. Dziarek

AGH University of Science and Technology, Al. Mickiewicza 30, 30059 Kraków, Poland

Correspondence to: A. A. Malinowska (amalin@agh.edu.pl)

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Abstract. The analysis of mining-induced sinkholes occurrence is a very important issue as far as the spatial development optimization is concerned. Research conducted for this paper was focussed on examining the applicability of GIS and the associated AHP method (analytic hierarchy process) for estimating the risk of discontinuous deformation occurrence on the surface. 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 lay 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 whether the risk of cave-ins occurrence on the surface could be calculated. The results of the estimation of potential sinkhole zones were verified. The locations of actual and high-risk potential discontinuous deformation were compared. The congruence between predicted values and the actual observations of sinkholes was very high. The results of research presented prove the necessity to evaluate sinkhole hazards in view of qualitative factors.

1 Introduction

In areas subject to underground mining activity, discontinuous deformations most frequently develop quickly and violently. The problem of discontinuous deformation refers to areas with shallow exploitation and also to locations 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 et al. revealed that about 70 % of discontinuous deformations registered in Upper Silesian Coal Basin have a conic shape (1988). Moreover, an observation was made that discontinuous deformations could take place at various time intervals after the end of exploitation. Sometimes they occurred even tens of years after. 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, and Janusz and Jarosz (1976) – zinc and lead ore deposits.

The elaborated prediction models, based on quantitative mining and geological factors, were a starting point for the estimation of the cave-in height and cracking zone over the workings. The probability of surface discontinuous deformations occurrence can be determined depending on the depth of the workings. The evident shortcoming of the models is that they do not account for qualitative factors. Among the quantitative factors are, for example, fault zones, hydration, and cumulation of the panel edges. Events around the world proves the necessity of incorporating such factors in the analysis of surface discontinuous deformation hazards.

The use of analytic hierarchy process (AHP)-based open geographic information systems for evaluating risk of discontinuous deformation occurrence 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 methods and correctness of weighting were verified by comparing sinkhole areas with the at-risk regions.

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2 Sinkhole occurrence above shallow coal mining

Underground mining induces changes in rock mass stress. 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' observation, groups of factors with the most distinctive influence on the formation of discontinuous deformations at the surface were found: depth of bed deposition, thickness of selected beds, exploitation system, rock mass tectonics, hydrogeological conditions, way in which the overlying 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 the 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 %),
- cumulation of the panel 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 in the analysed population. The depth of mining is definitely the most important factor of cave-in hazards.

On the basis of the cause-and-effect observations, numerous functions were created for estimating the risk of sinkholes. The height of the fracture zone and cave-in over the workings are calculated from such measurable parameters as depth of deposition of a void, its height, thickness of overburden, and the leftover goaf from the workings. 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 characteristics. Among the qualitative factors are, for example: tectonic disturbances, fracturing of the rock mass, hydrogeological conditions, deposition of on-lying strata. The analysis of significance of such factors and their influence on the process of sinkhole formation requires an expert approach. These 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 due to whether or not the height of fracture zones could be calculated. Many years' observation of sinkhole formation sites reveals that a number of qualitative factors have 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 can be definitely increased. In Poland this type of estimation has a special importance, particularly in old mining areas, where the risk of discontinuous deformation occurrence is high.

3 Research methodology

The analytic hierarchy process, elaborated by Saaty, is one of the multi-criteria methods aiding complex decision processes. It has been used in such disciplines as, for example: geology, mining, management, economics, and environmental protection (Erden and Karaman, 2012; Le Cozannet at al., 2013; Saaty, 1980). This method is based on the assumption that a complex problem can be stripped down to elements which are then weighed and integrated with problem solving as the objective. The analytic hierarchy process provides expert significance evaluation of factors having influence on a given effect. The hierarchy of elements is based on their pairwise comparison and on weighting each of them. This method has many critics and advocates. However, the results of global AHP-based investigations in many scientific disciplines prove its high efficiency. The analytic hierarchy process 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 making use of AHP for the evaluation of surface discontinuous deformations are presented below.

4 AHP

4.1 Step 1 – The subject of the AHP definition

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

4.2 Step 2 – Estimation of the risk factors

The risk factors were chosen on the basis of a detailed analysis of global events and in situ investigations. One of the most important tasks at this step was assessing the availability of reliable information about a given factor. This was related to the necessity of conducting 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).

Determining of qualitative factors, however, required a broader look at the sinkhole hazard problem. First, the main study areas were specified: geology, hydrogeology, and mining. The qualitative factors, which potentially might have influence on discontinuous deformation formation on the 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. In the research area, there were no hydrological problems. Geological characteristics of the onlying layers and geomechanical state of workings were comparable. That is why only faults and cumulation of the panel edges were selected as the most significant risk factors..

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 probability of cave-in occurrence (Malinowska and Dziarek, 2013). This mainly stems from the high complexity and qualitative character of many of these factors. The AHP method is frequently used when integration and inference from numerous factors is involved. For this reason, the authors decided to present the applicability of this method for determining risk of cave-ins occurrence.

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 a maximum of five. The experience with the AHP method proves that this method is most efficient for a maximum of four weighed elements. Sometimes hierarchical analyses based on a higher number of variables are used. Most frequently these are quantitative data. The hazards related to mining-induced partial deformations of a surface depend both on qualitative and quantitative variables. In the case of exploitation of goaf, the self-backfilling of voids could be observed with 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 used for estimating cave-in hazards had low efficiency when the post-exploitation space was contracted. In this case, the cave-in hazards 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 the panel edges; and two quantitative variables were selected, thickness of the exploited layer and depth of void's

Table 1. Quantitative risk factors.

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

deposition. The hierarchy was determined by pairwise comparison of the elements and their weighting. 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 also be introduced.

Each element was weighted, forming a triangular preference matrix. An assumption was made that of the matrix was weighted as one, relative to itself (Table 4). 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). The consistency index was defined from the maximum eigenvalue of preference matrix (λmax) and the number of variables (n):

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

For above defined weights the consistency ratio was $\mathrm{CI} = 0.06$.

On the other hand, the consistency ratio (CR) could be used for evaluating the coherence of weighting against the randomness of weighting.

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

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 weighting was deemed to be correct.

5 GIS

GIS is widely applied in many branches of economics and science (Forte et al., 2005; Hejmanowski and Malinowska, 2010; Ju et al., 2012; Mergili et al., 2012; Taramelli et al., 2008; Theilen-Willige, 2010). The work presented was done with Quantum, an open source GIS software package[1]. The

[1] http://www.qgis.org/en/site/forusers/download.html, last access: 1 June 2013.

Table 2. Qualitative risk factors.

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

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

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

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

GIS surveys were performed on raster surfaces. The first stage of spatial data work lay 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-ins occurrence (CH_N, Eq. 4).

5.1 Step 5 – Detection of outliers and additional assumptions

In the analysed area, the thickness of mining oscillated, on average, by 2.00 m (1.5 to 3.0 m). Most of shallow panels were closed a 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 depth, and the panels deposited shallower than at 100 m were considered as potential sources of sinkhole hazards (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 analysed. On this basis, the assumption was made that the range of the risk area around the fault was a maximum of 50 m radius. Accordingly, a 50 m wide buffer area was determined around the fault (Fig. 3).

When analysing the panel 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 0–1 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:

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

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, 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), that is, fault, was ascribed the highest normalized hazard ($r_{\mathrm{N3\_max=1}}$) directly at the fault outpit. The buffer zone edges were ascribed the lowest normalized risk ($r_{\mathrm{N3\_min=0}}$) The second qualitative factor was the cumulation of the panel edges (R_4). The highest normalized hazard ($r_{\mathrm{N4\_max=1}}$) was attributed to the highest number of coinciding edges. A similar reclassification was made for quantitative variables. The depth (R_2), at which the analysed panels were deposited, ranged between 45 and 100 m. The highest sinkhole risk was observed for 45 m and the normalized one equalled to $r_{\mathrm{N2\_max=1}}$. The thickness of mining (R_1) oscillated between approximately 1.5 and 3.5 m. The highest normalized hazard ($r_{\mathrm{N1\_max=1}}$) 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 step was weighting the factors and generating a spatial model of sinkhole occurrence. The weighted linear combination method (WLC) was used to create a final map of risk of cave-ins occurrence. Each of the normalized raster surfaces was multiplied by the significance weight of a given

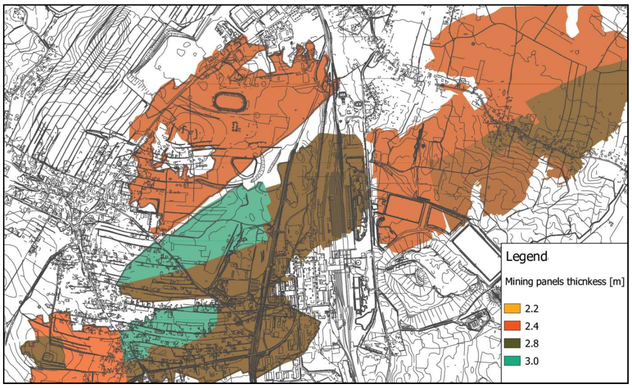

Figure 1. Thickness of the mining panels.

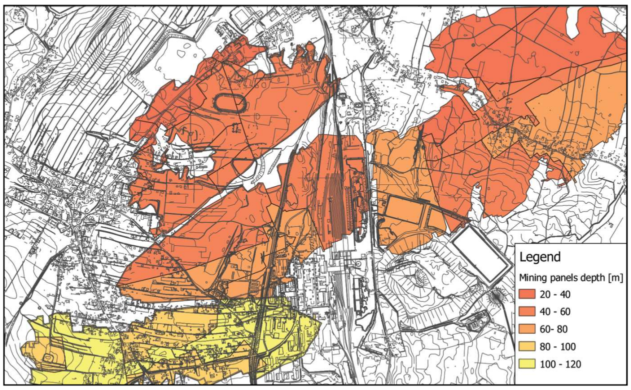

Figure 2. Depth of the mining panels.

factor. The ultimate surface of risk of cave-ins occurrence was the sum of all weighed factors:

$$\mathrm{CH_N} = 0.06 \cdot R_{\mathrm{N1}} + 0.12 \cdot R_{\mathrm{N2}} + 0.26 \cdot R_{\mathrm{N3}} + 0.56 \cdot R_{\mathrm{N4}} \quad (4)$$

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

The presented model was verified by information about registered discontinuous deformation.

The comparison of predicted sinkhole sites with the actual ones proved the high efficiency of the proposed model (Table 5).

6 Results discussion

The evaluation of sinkhole hazards 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. Cave-ins appear on the surface suddenly and unexpectedly. The correct estimation of zones where the risk of discontinuous deformation occurrence is high is a very important task. This mainly refers to common safety and spatial development issues. The process of sinkhole formation is connected with a number

Figure 3. Faults and buffer zones around faults.

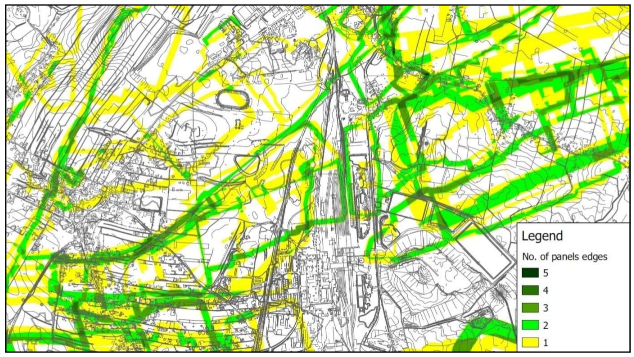

Figure 4. Number of panel edges.

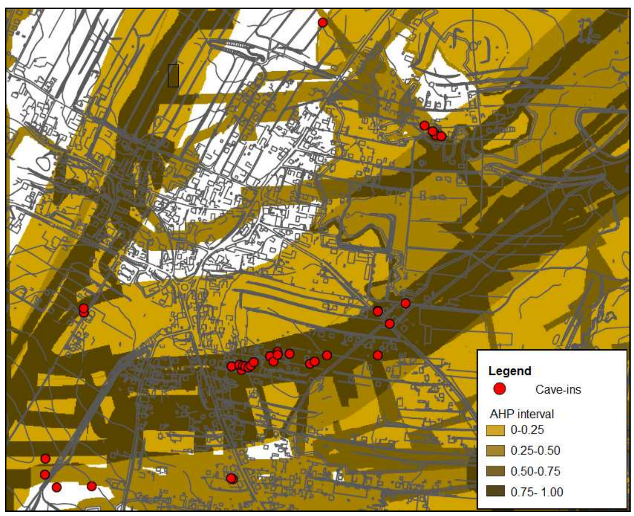

Figure 5. Modelled zones of risk of cave-ins occurrence.

of factors. Many of them have a qualitative character. On the other hand, taking into account qualitative and quantitative variables requires use of a flexible modelling tool, thanks to which the variables can be integrated and ranked. To meet this goal, the AHP method was selected for modelling. This is an expert and subjective tool for aiding the

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

decision-making processes, where the weights of risk factors should be estimated by experienced professionals. At the stage of preliminary selection, all factors influencing discontinuous deformation formation were identified. Based 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 qualitative factors were most important. The main factors causing sinkhole occurrence were cumulation of the panel edges and faults. Such quantitative factors as the depth of the exploited panel and its thickness were less important. The correctness of the weighting 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 was able to 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 risk of cave-ins occurrence took values ranging between 0 and 1. Low cave-in risk zones occupied about 70 % of the analysed area, whereas zones of considerable sinkhole risk covered up to about 30 %.

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

The results of the presented analyses confirm the necessity of assessing risk of cave-ins occurrence partly on the basis of qualitative risk factors (faults, cumulation of the panel edges). The use of AHP proved the high efficiency of this method and necessity to account for qualitative and quantitative factors.

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