MULTIATTRIBUTE PREDICTION OF TERRAIN STABILITY ABOVE UNDERGROUND MINING OPERATIONS

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Abstract: This paper is dedicated to the problem of stability prediction of the terrain above underground mining operations. After the initial introduction to the problem, then the short analysis of the model approaches used to solve it, and giving the algorithm for rock massif stability prediction, we describe the concept of the multiattirbute terrain stability prediction method. The application of the multiattribute prediction method for stability of the terrain above underground mining operations is presented on the example of the Brown Coal Mine Aleksinac. The used method is original, essentially different from the other methods of mathematical modeling, because its prognosis of the rock massif stability under the influence of underground mining operations is based on the balance of the stability indicators. Our comparative analysis of the results obtained by multiattribute prediction and the data obtained by measurements of real deformations and terrain settling in multiple mines shows high mutual correlation, with an average deviation of less than ±10%. These results are confirmed entirely on the example of the Brown Coal Mine Aleksinac.

Keywords: mining, underground mining operations, terrain stability, mathematical modeling, multiattribute prediction.

1. INTRODUCTION

Surface deformations, displacements, settlings, fissures, quakes and similar phenomena are common consequences of underground mining operations. Giving prognosis on rock massif behaviour above the underground mining operations is a complex and demanding problem of mining engineering, and demands seeking answers to the questions such as:

- What will happen on the terrain surface due to underground mining operations (deformations, displacements, settling, fissures, quakes, or…)?
- When will the instability of the terrain occur, and how long the process will last?
- Which area of the terrain will be included in the destructive process?
- Which consequences are to be expected?
- Which reliability level is achieved in predicting the events?

In general, a prognosis of the rock massif behaviour above the underground mining operations is based on identification and metrics of morphology, geology, lithology, tectonics, engineering geology, hydrogeology, geophysics, physics and mechanics, mining, and technological as well as other features [6,7,8]. Functionally, these features fall into one of the following categories [9,10]: indicator category or criteria category.

The INDICATOR CATEGORY comprises features of the mining operations environment and the surrounding area. These features are correlated with possible occurrences of displacements or instabilities on the terrain above the mining operations.

The CRITERIA CATEGORY comprises features related with the possible forms of instability, geological structure, tectonics, physical and mechanical properties of the terrain, rock massif, geometry, distribution and dimensions of the underground mine objects, technology of mining operations, underground water dynamics, stress and deformation within the rock massif, etc.
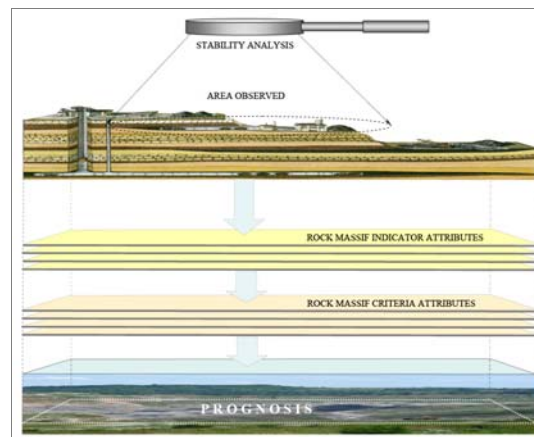

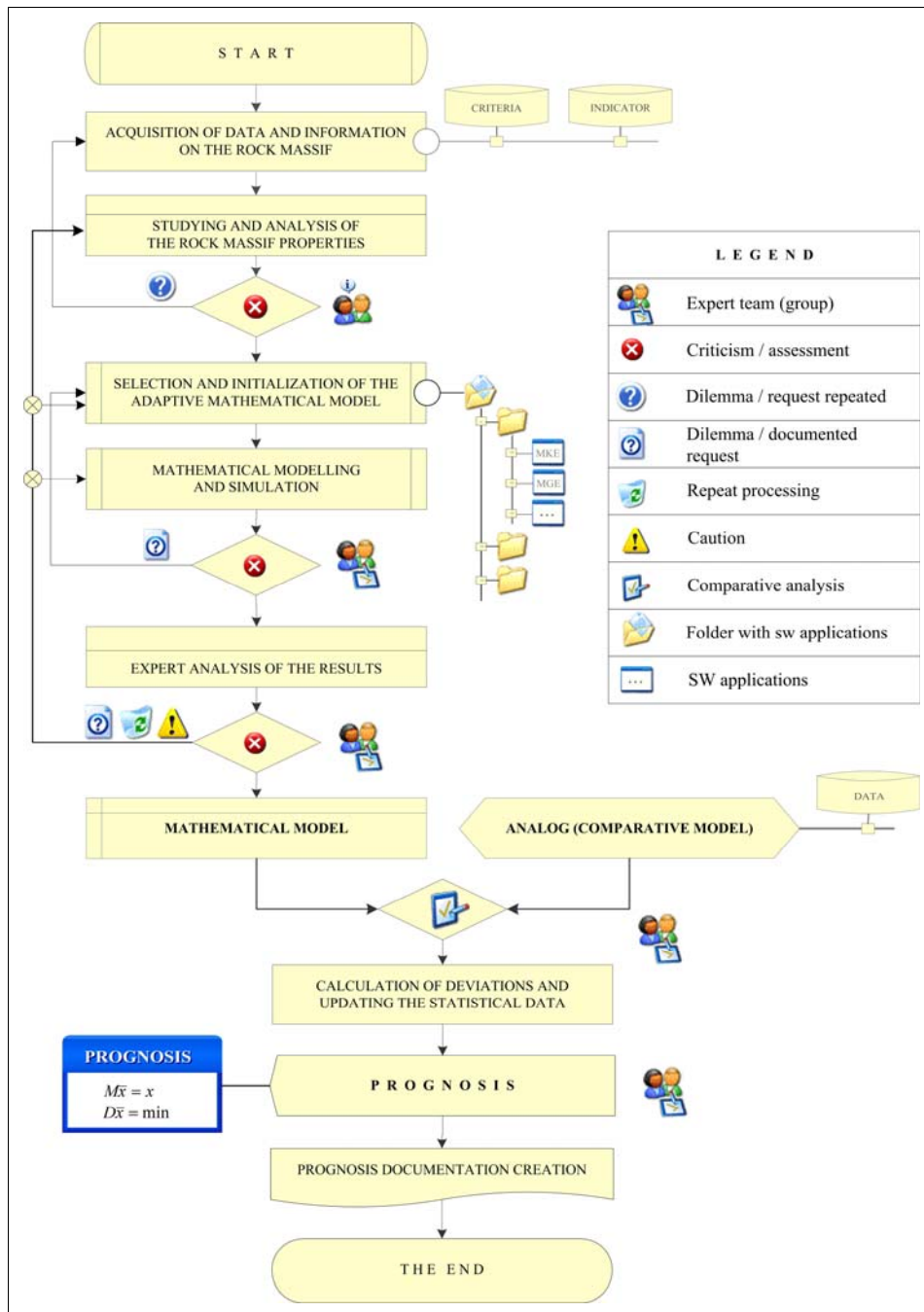**Figure 1.** Schematic presentation of the rock massif stability analysis procedure

Figure 2. The algorithm of the rock massif stability prognosis

Both groups of features have the following common properties: spatial dispersion, anisotropy, occurrence of discontinuity and the chance. These facts suggest that data on environment features (where mining processes are undertaken) should be: as numerous as possible, represented evenly (both spatially and structurally), reliable and adjustable (at the same time) for the analysis of potentially destructive processes on the terrain surface. Reliability of a prognosis depends on reliability, quantity and spatial distribution of the data at hand, but also on mathematical modelling approaches and applied conclusion logic. Mathematical modelling approaches are not some constant category – quite the opposite - they constantly develop and expand. Right selection of the mathematical modelling approaches means to establish harmonized relations between mathematical principles, properties of the modelled process, and the data used for analysis [3,11]. In this sense, mathematical models are generally classified into the following categories:

- Deterministic;
- Stochastic;
- Fuzzy logic;
- Hybrid.

Each of the four modelling type can be used in predicting the displacements and deformations of the terrain as a consequence of mining operations   The deterministic modelling is the most desirable one, but the problem of its application lies in a demand for data with high or even total determination, which is difficult to achieve in practice. In this sense, the stochastic, fuzzy and hybrid models are much more appropriate and more adaptable for solving actual problems [9,11].

Due to the fuzzy nature of the data, their quantity, and complexity of their correlations, the prognosis of displacements and deformations is generally so demanding and complex engineering task, that it cannot be entirely automated by means of mathematical modelling and computer utilization. The solution lies in combining the expert knowledge and mathematical modelling methods with computer technology.

If we agree that the stability prognosis of displacements and deformations of the terrain essentially relies on assessing the indicators and their correlated connections with occurrences of displacements and deformations of the terrain, the logical conclusion follows: the prognosis can be based on the instability indicator balance concept. The balance approach can be accomplished by structuring the prediction problem. We consider this approach to be more suitable than the stochastic, fuzzy or hybrid approach because of its functionality, flexibility, adaptability, openness and integrability [11].

This approach conceptually relies on the multiattribute method for the prognosis of ore-bearing, developed by S. Vujic, in cooperation with S. Jankovic and R. Jelenkovic [9,11].

2. CONCEPT OF THE MULTIATTRIBUTE PREDICTION OF DISPLACEMENTS AND DEFORMATIONS OF THE TERRAIN

Let X be an evaluative two-dimensional matrix, presenting a discretized model of the terrain surface potentially endangered due to underground mining operations. The evaluation matrix is initially defined as a set of elements $x_{i,j}$:

$$X = \{x_{i,j}\} \tag{1}$$

Where $x_{i,j} = 0$ for $i = 1, 2, 3, ... m; \quad j = 1, 2, 3, ..., n$.

The evaluation matrix X can be presented in a tabular form as follows:

Table 1. Evaluation matrix

		j				
		1	**2**	**3**	**...**	**n**
	1	$x_{1,1}$	$x_{1,2}$	$x_{1,3}$	…	$x_{1,n}$
	2	$x_{2,1}$	$x_{2,2}$	$x_{2,3}$	…	$x_{2,n}$
i	**3**	$x_{3,1}$	$x_{3,2}$	$x_{3,3}$	…	$x_{3,n}$
	...	…	…	…	…	…
	m	$x_{m,1}$	$x_{m,2}$	$x_{m,3}$	…	$x_{m,n}$

The dimensions m and n of the evaluation matrix depend on the degree of discretization of the observed surface of the terrain. The density of discretization network (i.e. the values of m and n) is determined by the expert (or an expert team) dealing with the problem, but taking into account that the density of discretization network is adjusted to the spatial distribution of available data and the extent of task complexity.

THE ALGORITHMIC FLOW FOR THE MULTIATTRIBUTE APPROACH

STEP 1: Defining attribute sets significant for the prognosis

This phase requires team work in decision-making. The involvement of several experts diminishes the probability of possible errors in identifying the potentially significant sets of prognosis attributes. Based on our (previous) knowledge, five sets of indicator attributes (Figure 3) depict the operational and surrounding environment sufficiently well, thus enabling the highly reliable multiattribute prognostication. We use the following definition of the structure of indicator attribute sets.

Set A: Geological properties in the zone of mining operations and their influence.
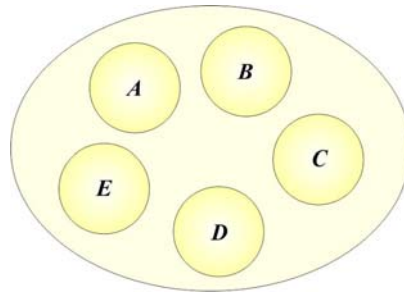
$$A = \{A1, A2, A3, A4\}$$
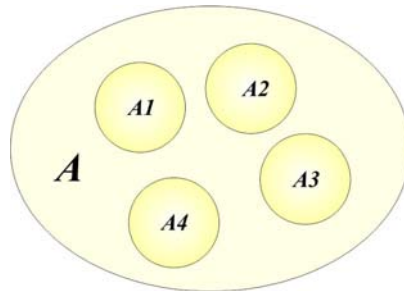
Figure 3. Indicator attributes sets

Figure 4. Set **A**, Geological properties

Set A subsets:

$A1 = (a1_i, i \in N1)$ - Lithological structure of the rock massif;

$A2 = (a2_i, i \in N2)$ - Tectonics and disruptions of the rock massif;

$A3 = (a3_i, i \in N3)$ - Type of rock in the massif (sedimentary, eruptive, metamorphic);

$A4 = (a4_i, i \in N4)$ - Presence of water in the rock massif;

Set B **:** Stress conditions in the zone of mining operations and their influence

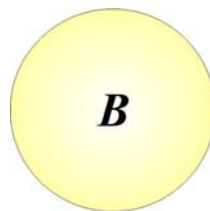$$\boldsymbol{B} = (b_i, i \in N_\delta)$$

Figure 5. Set **B**, stress conditions

Set C: Technological effects, i.e. the influence of mining operations on the rock massif stability
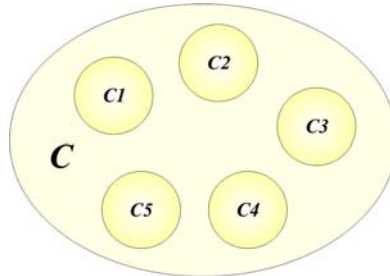
$$C = \{C1, C2, C3, C4\}$$

Figure 6. Set C, technological influence effects

Set C subsets:

$C1 = (c1_i,\ i \in N1)$ - Depth of the underground mining operations (in relation to the terrain surface);

$C2 = (c2_i,\ i \in N2)$ - Vertical grasp of the mining operations;

$C3 = (c3_i,\ i \in N3)$ - Surface of mining operations on a horizontal plane;

$C4 = (c4_i,\ i \in N4)$ - Way of covering the excavation area;

$C5 = (c5_i,\ i \in N5)$ - The dynamics of mining operations (for an active Mine)

Set D: Physical and mechanical properties of the rock massif

$D = (d_i,\ i \in D)$

Set E: Registered displacements and instabilities within the rock massif
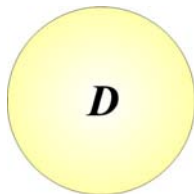
$E = (e_i,\ i \in E)$

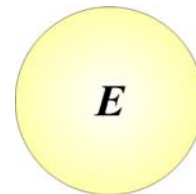**Figure 7.** Set D, Physical and mechanical properties

Figure 8. Set E, Registered displacements and instabilities

STEP 2: Defining structure of the preferences

In order to achieve balance between the attributes sets significance, generalized preferences are necessary. In Table 2, a scale of preferences is presented. This scale

conforms to the prognosis procedure. In the process of scale creation we used experiences of operations research, i.e. methods such as the multicriteria and multiattribute decision-making, and the method of analytical hierarchy processes.

Table 2. Generalized preferences scale

Preference	Value	Explanation
w_{max}^{+}	1.50	Absolutely the most significant
w_{max}	1.30	Close to the most significant
w^{+}	1.00	Significant
w	0.65	Less than significant
w_{min}^{+}	0.30	Not very significant
w_{min}	0.10	Less than not very significant

Based on the experimental tests and analysis performed, it is concluded that the following preferences belong to the named attribute sets, significant for the prognosis:

Table 3. Attribute set preferences

Set	Preference
E	w_{max}^{+}
B, D	w_{max}
A2, A4	w^{+}
A1, A3, C2	w
C1, C3, C5	w_{min}^{+}
C4	w_{min}

STEP 3: Defining the expert scale of attribute weights

For this phase of analysis, an expert (or an expert team) forms his scale of preferences for the attribute sets significant for the prognosis in the way presented graphically in Figure 9.
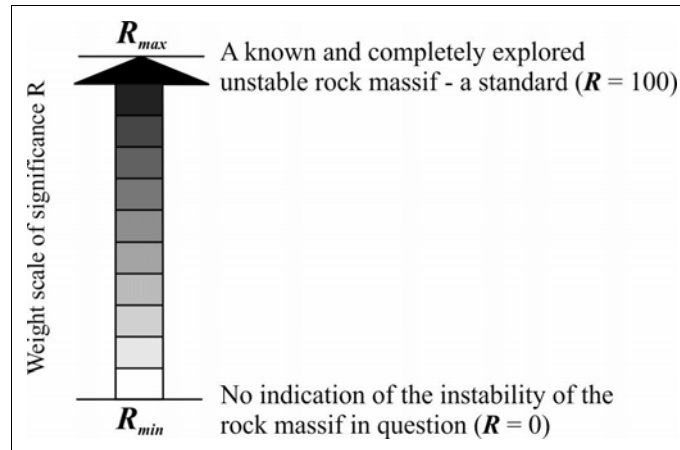
Figure 9. Attribute weight scales

For the standard with the highest weight R$_{max}$, an analogous (known) working environment is recommended, with the clarified instability processes within the rock massif, and occurrences of deformations on the terrain surface as a consequence of underground mining operations. In relation to the accepted standard, an expert sets the scale of his/her "own" attribute weights, which cannot be changed during the analytical procedure.
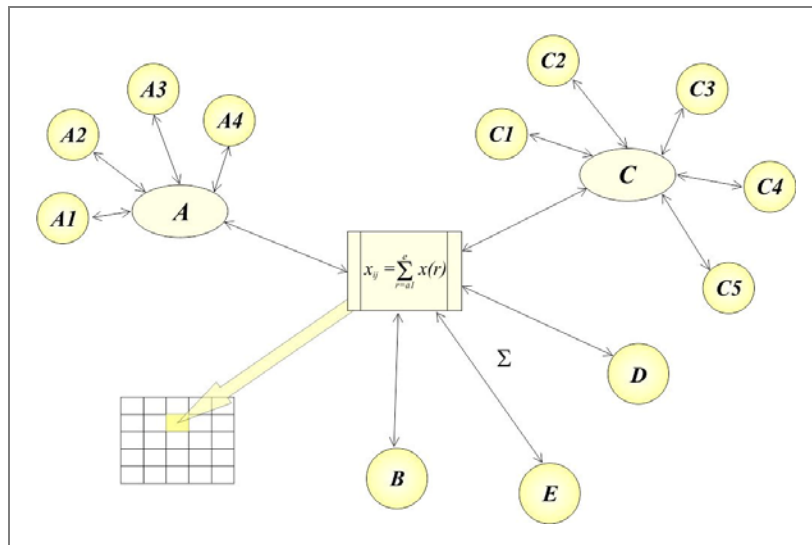

Figure 10. Graph of input-output flows.

In the procedure of evaluation matrix formation (i.e. formation of the prognostics matrix model of displacements and deformations of the terrain due to the underground mining operations (Figure 10)), the values of sets or subsets of attributes significant for the prognosis are analyzed for each position in the matrix, in a way defined through (2).

$$S(a1) = \sum_{a_i \in A1} a_i; S(a2) = \sum_{a_i \in A2} a_i; S(a3) = \sum_{a_i \in A3} a_i;$$
$$S(a4) = \sum_{a_i \in A4} a_i; S(b) = \sum_{b_i \in B} b_i; S(c1) = \sum_{c_i \in C1} c_i;$$
$$S(c2) = \sum_{c_i \in C2} c_i; S(c3) = \sum_{c_i \in C3} c_i; S(c4) = \sum_{c_i \in C4} c_i;$$
$$S(c5) = \sum_{c_i \in C5} c_i; S(d) = \sum_{d_i \in D} d_i; S(e) = \sum_{e_i \in E1} e_i;$$

(2)

When the previous partial calculations are done, the calculations of the summarized values of attributes significant for the prognosis for each member of the evaluation matrix follow:

$$\boldsymbol{S} = \sum_{i=1}^{4} \boldsymbol{S}(a_i) + \boldsymbol{S}(b) + \sum_{i=1}^{5} \boldsymbol{S}(c_i) + \boldsymbol{S}(d) + \boldsymbol{S}(e)$$

(3)

Generalized preferences are assigned to the attribute values defined in such manner:

$$x(e) = S(e)w_{max}^+$$
$$x(b) = S(b)w_{max}$$
$$x(d) = S(d)w_{max}$$
$$x(a_2, a_4) = CINT(((S(a_2) + S(a_3)) / S)100)w^+$$
$$x(a_2, a_4, c_2) = CINT(((S(a_2) + S(a_3) + S(c_2)) / S)100)w$$
$$x(c_1, c_3, c_5) = CINT(((S(c_1) + S(c_3) + S(c_5)) / S)100)w_{min}^+$$
$$x(c_4) = S(c_4)w_{min}$$

(4)

The ultimate values of the prognosis assessment per position within the terrain surface discrete model, i.e. by $x_{i,j}$ members of the evaluation matrix X, are calculated as sums:

$$x_{ij} = \sum_{r=a1}^{e} x(r)$$

(5)

where: r - takes values calculated according to the expressions (4), from e to c_4.

The procedure is repeated for each member of the evaluation matrix, until its final form, presenting the prognosticated model of displacements and deformations of the terrain is reached.

$$X = \left\{ x_{ij} \right\}, x_{ij} \geq 0 \tag{6}$$

STEP 4: Ranking

From the evaluation matrix with base values of prognostic ranks, the matrix of prognostic ranks R is formed, an equivalent format of the matrix X, and with elements which values belong to one of the declared ranks.

$$R = \left\{ r_{ij} \right\}, r_{ij} = I, II, III, ..., V;$$
$$i = 1, 2, 3, ..., m; \tag{7}$$
$$j = 1, 2, 3, ..., n$$

The criteria rank scale shown in Table 4 is recommended; the assumption that the known and explored geological environment, where mining operations took place, is taken as standard, with the highest rank of $R_{max} = 100$.

Table 4. Ranking criteria

Rank	Criteria	Prognosis
I	≥ 150	Major certainty in rock massif instability (occurrence of quakes, fissures and major settling of the land)
II	120 - 149	Significant certainty of rock massif instability (occurrence of quakes and major settling of the land)
III	90 - 119	Certainty of rock massif instability (occurrence of displacements and land settling)
IV	50 - 89	Certainty with unclear perspective regarding the rock massif instability
V	< 50	Minor certainty in instability

3. AN EXAMPLE OF THE MULTIATTRIBUTE PROGNOSTICS APPLICATION

The application of the multiattribute prognostics of displacement and settling of the terrain above the underground mining operations is shown on the example of "Aleksinac" brown coal mine, located in the south of the Republic of Serbia. The Mine was opened in 1878, and closed in 1989, after a major accident. This mine is taken as a demonstrative example because of the quantity of data collected during the last 55 years, and the preciseness of the periodical geodetic measures of terrain displacements and settling as consequences of the coal underground exploitation. These facts give us excellent possibilities to perform comparative analysis of the prognosticated and actual deformities on the terrain surface, thus to achieve the objective valuation of the practical applicability of the multiattribute method.

Geological structure of the Aleksinac coal basin is made up of heterogeneous tertiary layers, with red conglomerates and sandstones in its base, clay sandstone in the floor layer, and with bituminous shales and bituminous marls in the roof layers [5]. The coal-bearing layer, with the slope of 10-55°, and the thickness of 2 to 6 *m*, is made of

brown coal, gas coal and the coal clays intercalations. Coal mining was accomplished by the longwall face method.
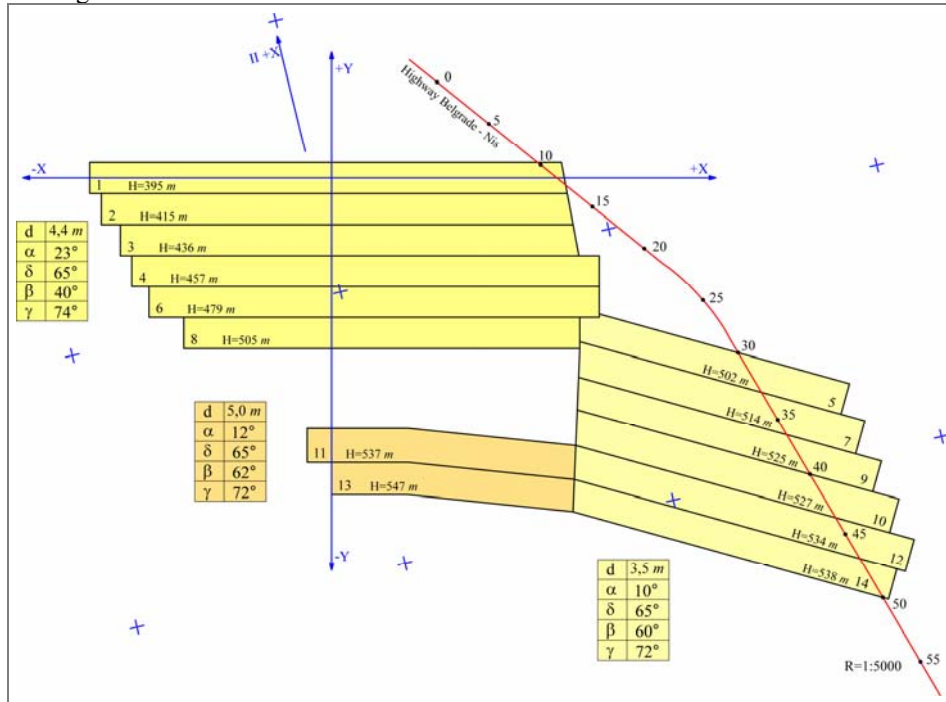

Figure 11. Positions and the sequence of block excavations

According to the multiattribute procedure presented in section 2, the attribute sets, significant for deformation and settling of the terrain above the exploitation field of the "Aleksinac" mine southern parts, were defined. The discrete mathematical model of the multiattribute prognostics, with the network of 25×25 *m*, was fed with data available for the attribute sets *A*, *C*, *D* and *E*, while data for the set *B* were not available. In order to avoid unnecessary details, we give only the most important inputs of the model:

- The depth of mining operations in the Mine ranges from 395 *m* in the Northern to 547 *m* in the Southern region of the exploitation field;
- The depth of the coal layer is 4.4 *m* in the Northern area of the deposit, 5.0 *m* in the Southwest area and 3.5 *m* in the Southeast part of the deposit;
- Exploitation field is divided into 14 exploitation blocks, excavated in order 1 to 14, as shown in Figure 11;
- Slope of coal layer (α) ranges from 10° in the South to 23° in the North;
- Borderline angles in the general extension and slope direction of the layer (δ, β, γ) are given in tables in Figure 11;
- Recovery of the coal layer is 0.75;
- Coefficient of the roof settling ranges from 0.30 to 0.40.

According to the algorithm defined in section 2, the 2D and 3D prognostication models of terrain displacement and settling in the zone of mining operations of the Southern part of "Aleksinac" brown coal mine were developed by the process of mathematical modeling, shown in figures 12 and 13. According to the prognostication model, the largest settling of 1910 *mm* (and 1927 *mm* is the field measured value) occurred in the zone of exploitation blocks 6 and 8, the highest settling slope is 11.20 *mm/m*, the largest horizontal deformation is 7.90 *mm/m*, while the highest settling curve is at $\pm 65.10^{-6}$.
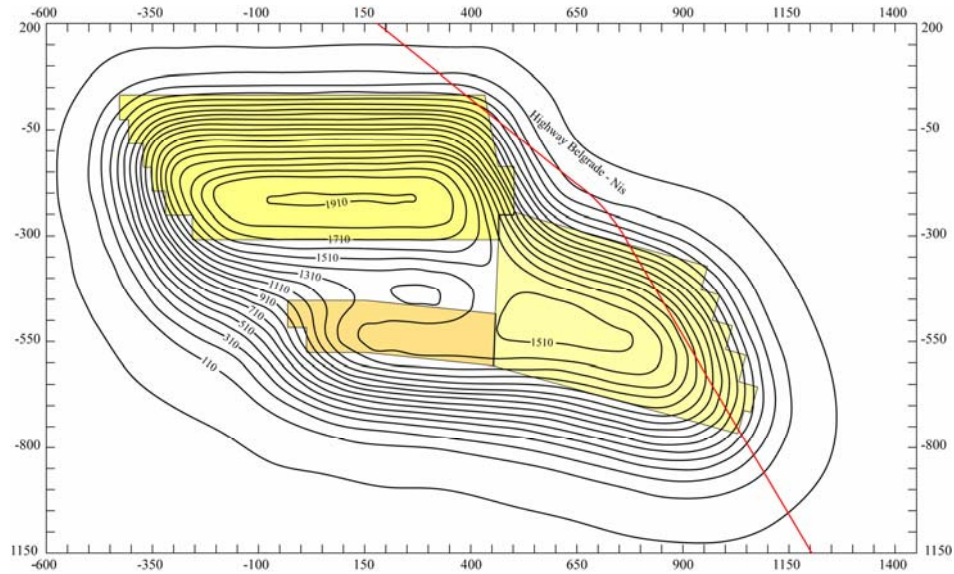

Figure 12. Prognostication 2D model of terrain displacement
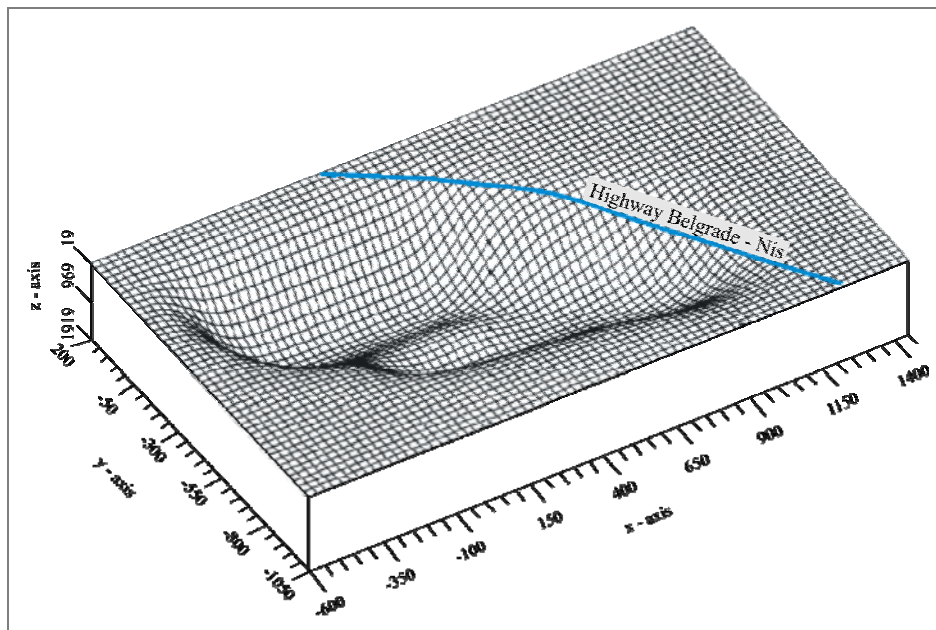in the mining operation influence zone

Figure 13. Prognostication 3D model of terrain displacement
in the mining operation influence zone

The check of validity of the multiattribute prognostication modeling was accomplished by comparing the prognosticated and the measured settling and displacement of terrain in the mining operation zone of influence. Geodetic measurements of vertical and horizontal displacements of the terrain on five profile lines on the coal layer slope, and three lines on the coal layer direction were used for this analysis. For this purpose, a landmark network with 223 points, established in 1964 in the zone of mining operation influence was used. The original purpose of the network was to determine the causality between the terrain displacement and the potential hazard at the mining constructions and the international highway Belgrade-Niš.

The comparative analysis of the prognosticated and the measured terrain displacement and settling shows that there is reciprocal correlation trend with the correlation coefficient of high functional value (0.93), and deviations of ±7%. One of the five profiles, profile G-G is presented in Figure 15, together with the marked prognosticated and measured terrain settling. It can be noticed that the settling lines, prognosticated and measured, follow each other with only minor deviations.

These results confirm reliability and applicability of the multiattribute method in solving actual problems of terrain displacement and settling prognostication above the underground mining operations.
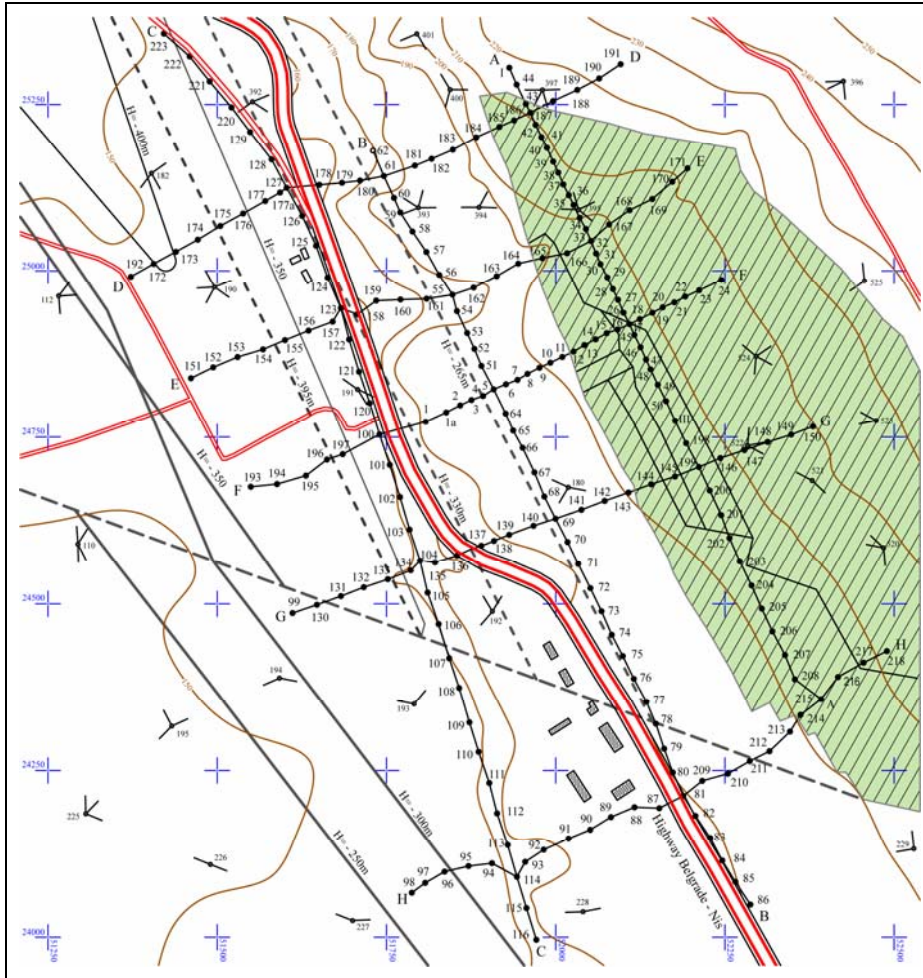
Figure 14. Network of landmarks for perception of terrain displacement in the mining operation of Aleksinac brown coal mine zone of influence
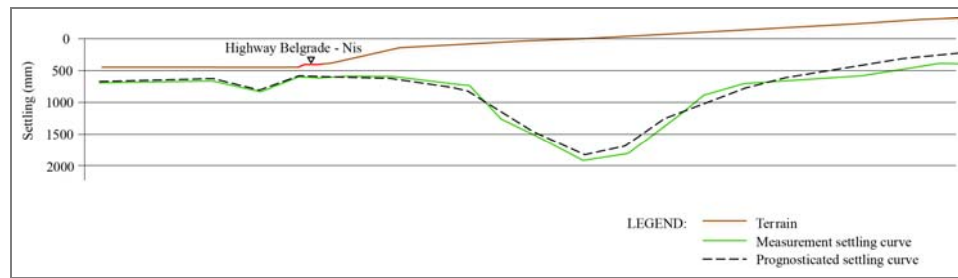
Figure 15. Profile G-G, prognosticated and measured terrain displacement

4. CONCLUSION

The multiattribute model for prognostication of displacements and settling of the terrain due to underground mining operations differs from other mathematical modeling methods by establishing the rock massif stability prognostication on the stability indicators equilibrium. If used, this method demands: structuring the problem, number of experts in achieving more objective definition of criteria for attribute weight assignment, generalization of attribute sets preferences, definition of ranks and the composite prognostication vector.

Due to the fuzzy nature of rock massif instability indicators, inclusion of a large number of attributes and the complexity of their correlation, the prediction of terrain displacements and settling above the mining operations is a complex and demanding engineering task, which cannot be fully automated. It is necessary to combine "experts" knowledge, mathematical modeling tools and the computing technologies.

Our comparative analysis of the results is obtained by the multiattribute prognosis and the measurement data of actual deformations and settling of the terrain in multiple mines. The example of the "Aleksinac" brown coal mine confirms our experiences, but it is also important to state that the reliability of prognosis lies, above all, on the reliability, quantity and the uniform spatial distribution of input data into the mathematical modeling process.

REFERENCES

[1]   Agterberg, F., "Application of image analysis and multivariate analysis to mineral resource appraisal", *Econ. Geol.,* 76 (1981) 1016-1031.
[2]   Agterberg, F., "Regional mineral appraisal - An analytical approach", *Future Resources. Their Geostatistical Appraisal,* in: R.T. Newcombe, (ed.), West Virginia University Press, Morgantown, (1982) 37-51.
[3]   Bugaec, A.N., and Dudenko, V.A., *Mathematical Methods of Prognostication of Ore Deposits*, Nedra, Moskva, 1976. (in Russian)
[4]   Bugackiy, V.V., and Suganov, B.I., *Spatial Statistical Analysis of the Geological Structure Somplexity and its Application in Metalogeny. Dokl. AN SSSR*, (1968) 65-168. (in Russian)
[5]   Djordjevic, D., Kujundzic, B.Z., and Ganic, A., "STOHM Program package for computing and presentation of parameters of the shifting process and deformations of the under-mined terrain by applying statistical model", in: *X International Congress of the International*

Society for Mine Surveying "Mining in the 3rd Millennium-The Social and Environmental Impact", Fremantle, Australia, (1997) 469-476.

[6]   Hoek, E.T., *Rock Slope Engineering,* A. A. Balkema, Rotterdam, 2001.

[7]   Ivanov, V., "Analysis of the geomechanical stability of the area of the Mirovski salt Mine", in: *Industrial Mineral Resources of Bulgaria,* Scientific and Technical Centre of Bulgaria, Sofia, 2006,1-12. (in Bulgarian)

[8]   Ivanov, V., "Geomechanical assessment of the competence of the rock mass in the vicinity of Seslavtsi abandoned underground mine in the Buhovo ore field", *Annual of University of Mining and Geology "St. Ivan Rilski",* 50 (2007) 45-51. (in Bulgarian)

[9]   Jankovic, S., Jelenkovic, R., and S. Vujic, *Mineral Resources and Potential Prognosis of Metallic and Non-metallic Mineral raw Materials in Serbia and Montenegro at the end of the 20th Century,* Academy of Engineering sciences of Serbia and Montenegro, and Faculty of Mining and Geology, Belgrade, 2003. (in Serbian)

[10]   Vujic, S., and Ivic, A., "*Mathematical Methods in Mining and Geology – Theory and Application*, University of Belgrade, Faculty of Mining and Geology, Belgrade, 1991. (in Serbian)

[11]   Vujić, S., "MAP: A method of multiattributive prognostication of mineral resources", *Yugoslav Journal of Operations Research*, 11 (2001) 211-220.