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STOCHASTIC MODEL AND GIS SPATIAL ANALYSIS OF THE COAL MINE SUBSIDENCE****

Abstract

The occurrence of subsidence caused by the underground coal mining may be a complex process that causes damage to the environment. In the last century, there was a significant development in prediction methods for calculating the surface subsidence. In this paper, a new prediction method has been developed to calculate subsidence by combining a stochastic model of the ground movements and Geographical Information System (GIS). All the subsidence calculations are implemented by an original program package MITSOUKO, where the components of the GIS are used to fulfil the spatial analysis. This subsidence prediction technique has been applied to calculate the ground movements resulting from excavating 21 mining panels that are mined successively in the coal mine "Rembas"-Resavica, Serbia. Details of movement were sequentially predicted and simulated in terms of years exploitation. Predictive calculation of the undermined terrain displacement parameters by the stochastic method and integration into the GIS is a powerful risk management tool.

Keywords: underground coal mining; stochastic prediction method; GIS; spatial analysis

1 INTRODUCTION

The underground coal mining is accompanied by a ground subsidence which presents a pressing issue and needs attention in order to avoid its harmful effect on the surface and subsurface structures. Therefore, prediction of subsidence using the reliable methods is of a great importance. With the aim to predict subsidence induced by the underground coal mining, the scientists from all parts of the world applied various methods, such as [1]:

Empirical methods are the most numerous group based on the results of systematic measurements in the local conditions of a

coal basin. The values of subsidence in the main cross sections by the seam strike and dip were obtained on the basis of type curves. They are the result of approximation and averaging of curves obtained by the measurements or theoretical assumptions. The analytical form of type curves, depending on the author, can vary (Averšin 1950; Kolbenkov 1961; Müller et al. 1965; N.C.B. 1963; Anon 1975; Peng et al. 1981, 1993; Kratzsch 1983; Hood et al. 1983; Kapp 1985; Whittaker and Reddish 1989; Kay 1991; Holla 1997; Holla and Barclay 2000; Seedsman 2001, 2004, 2006; Gale 2008).

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Profile function methods are based on application the influence function of the elementary excavated volume on the ground surface subsidence. They originate and were mostly applied in Germany, and their authors are: Schmitz 1923; Keinhorst 1925; Bals 1931; Flaschentrager 1938; Perz 1945; Sann 1949; Hoffman 1964; Daemen and Hood 1981; Peng and Chyan 1981; Kumar et al. 1983; Karmis et al. 1984; Alejano et al. 1999; Díez and Álvarez 2000; Torano et al. 2003; Asadi et al. 2004; Zhao et al. 2004; Asadi and Shakhriar 2014.

Influence Function Methods was first proposed by Bals in 1931. In Poland, since 1950 two influence function methods have been developed based on applying distribution of impacts using the Gaussian normal distribution curve (Budyk-Knothe 1953, 2005) as well as method by Kochmanský's (1959) based on the distribution of impacts on a specified derived curve. Using these methods, a subsidence calculation can be performed for horizontal and slightly inclined coal seams (Zenc 1969; Brauner 1973; Marr 1975; Ren et al. 1987; Karmis et al. 1990; Lin et al. 1992; Sheorey et al. 2000; Álvarez-Fernández et al. 2005; Luo and Cheng 2009; Luo 2015; Polanin 2015; Nie et al. 2017; Malinowska et al. 2020). *Stochastic Influence Function Methods* start from the assumption that the massif is layered, divided by a series of cracks into a large number of rock blocks whose movements have a random character. The displacement of a rock massif, as the sum of the movements of a large number of clastic elements, obeys the laws of mathematical statistics (Pokrovsky 1929; Litwiniszyn 1957, 1974, 2014; Liu Bao-chen 1965; Pataric and Stojanovic 1994; Vulkov 2001; Meng et al. 2014; Borela 2016; Cai et al. 2016; Malinowska et al. 2020).

Numerical models. Theories of rock mechanics and mathematics are the base of numerical models for subsidence prediction. In mathematical modeling, the mechanisms of rock deformations are approximated to the components that can be

defined and quantified since this view means understanding the physical behavior of attacked rocks. A reliable model is formed on the basis of defined mutual interactions of components. Many theoretical studies and mathematical modeling of the underground mining-induced surface deformations are performed applying the methods that rely on numerical models. The most important methods are: the *elastic methods* and *visco-elastic method*. Numerical models include usage of the *finite-element methods-FEM* (e.g. Reddish 1984; Najjar and Zaman 1993; Yin et al. 2008; Migliazza et al. 2009; Zhu et al. 2016; Liu et al. 2017), *boundary element method* and *distinct element method* in predicting the ground subsidence and deformations. In addition, the numerical methods were used for the subsidence modeling and calculating the movement of rock strata (Yao et al. 1989; Alejano et al. 1999; Zhao et al. 2004; Keilich et al. 2006; Shabanimashcool and Li 2012; Zhang and Xia 2013; Unlua et al. 2013; Zhu et al. 2016; Zhang et al. 2017).

Values of in situ rock mass parameters are necessary for all numerical models. All subsidence phenomena such as the decay of rock, detachment, sliding, and rotation of seam cannot be quantified in laboratory tests or incorporated into numerical models. The reliability of the prognosis depends on the number and degree of approximations of the real conditions that are always involved in the subsidence modeling. Manipulating certain parameters is usually necessary for obtaining a model which approaches the measured subsidence profile results very closely.

The shape and position of subsidence trough in relation to the excavated area depend on the geological and technological conditions of the underground exploitation. For the horizontal coal seams, a subsidence trough is symmetrical in relation to the excavated area, while it becomes asymmetrical for the sloped coal seams.

Surface subsidence due to the underground mining and evaluation the subsidence-induced damages of objects are nowadays growing problems in the Serbian coal mines with the underground exploitation. The sloped seams, with a thickness of 10-20 m at small and medium depths and an extremely steep relief as well as not large population of the mine area, are specific for Serbia. Material costs and psychological responses have forced the underground coal mining companies in Serbia to start resolving these problems by the subsidence prediction methods that minimize damages instead of previous repairing the buildings or compensating their owners.

The stochastic method proposed by the authors Pataric and Stojanovic [2] has been applied for almost four decades in predictive calculations the subsidence at most brown coal mines with the underground exploitation in Serbia. The results of long-term measurements at these mines with different naturally-geological and mining-technological conditions of exploitation indicated a correlation between the elements related to the cause- excavation of the coal seam and elements related to the consequence - subsidence on the ground surface. By comparison the calculated and measured values, it was revealed that using this stochastic method the extent of change on the ground surface can be successfully predicted, thus indicating the expected damage level of objects due to the subsidence above the mining works [3]. This confirmed the possibility of applying the stochastic Pataric-Stojanovic method for a reliable subsidence prediction.

Modern geoinformation technologies provided the use of progressive systems for the management of spatial data with their integration in the Geographic Information System-GIS. By general definition, the GIS represents a "...computerized database management system for capture, storage, retrieval, manipulation, analysis and display of spatial (i.e. locationally defined) data" [4]. Computer-based analytical methods

that realistically simulate spatially distributed, time-dependent subsidence processes are desirable for the reliable design of mining layout to minimize the impact of underground excavation on the ground surface. GIS is designed to support the integrative modeling, perform an interactive spatial analysis and comprehend different processes. Furthermore, based on the simulation of complex subsidence processes that are spatially distributed and progressive in time, it is possible to create the innovative thematic maps containing the land-surface properties [5-8]. The stochastic calculation model for the mine subsidence without GIS would be time-consuming and very complicated in cases of a large number of excavation areas [9-12].

The aim of this paper is to present a new approach for subsidence prediction, based on the stochastic Pataric-Stojanovic method with integration into GIS, applied to the exploitation of the "Strmosten" pit in the underground coal mine "Rembas"-Resavica (Serbia) for the period from 2018-2038. The subsidence calculations are implemented by the original program package MITSOUKO, created by professor Vusovic, based on the Pataric- Stojanovic stochastic method. Spatial analysis in GIS is based on the integration of the subsidence prediction results using MITSOUKO software and data processing in the ArcGIS computer program [13].

2 STOCHASTIC METHOD FOR THE MINE SUBSIDENCE PREDICTION

Ground movements, caused by the underground coal mining, are very complex and therefore difficult for modeling due to the complicated behavior of the overlying rock mass and land profiles. In the mid-twentieth century, for the mining-subsidence prediction, several idealized media were used. Since the behavior of overlying strata is complicated due to numerous known and unknown factors that affect and conduct moving of the rock mass, the sto

chastic theory of ground moving was used in these models for the mine subsidence prediction [14,15]. Generally, it is easier to predict the definite subsidence than the movements caused by the sequential and complicated mining processes. Therefore, the stochastic theory can be a universal method for the mine-subsidence prediction [16-20].

2.1 The stochastic theory model

The idea of the stochastic theory model was introduced by Pokrovsky (1929) and further was applied and developed by the other authors of stochastic methods [2, 14, 21, 22]. During studying the pressure variation with a depth due to the concentrated force on the surface, Pokrovsky concluded that the pressure change at the horizontal plane can be represented by the standard Gaussian distribution curve. The massif movement, which is a sum of movements a large number of elastic elements, obeys the laws of mathematical statistics. Litwiniszyn (1957) proposed the stochastic subsidence model presuming the ground mass as a discontinuous medium where element movement towards a collapsing cavity is considered as the Markovian process [19]. According to the stochastic theory, moving of the rock mass above the excavated element might happen randomly with a certain likeliness [22]. Numerous solutions of rock movement computing in various geological and mining conditions have been realized based on this stochastic method. This method proved to be effective allowing to find the theoretical solutions to many problems [17]. Liu and Liao (1960) established a stochastic method named the Stochastic Medium Theory Model (SMTM), a profile function based on the statistic medium algorithm method, for prognosis the underground mining-induced surface movement, which is the most commonly

used method in China [23]. Nowadays, SMTM is also used for calculating the ground movement caused by a tunnel construction. The Stochastic Medium Theory Model arose into Probability Integral Method-PIM, based on the statistical theory which is more reliable and easier to use for subsidence and deformations prediction in the entire excavation field [24].

2.2 Stochastic method by Pataric and Stojanovic

The Pataric-Stojanovic stochastic method presents a model based on the original mathematical formulas [2]. This method applies the mathematical statistics and starts from the assumption of Litwiniszyn that the massif is a multi-layered, divided by a series of cracks into a large number of elements whose movements have a stochastic character [22]. This environment can be presented by symmetrically arranged elements with the approximately similar dimensions. Such an area does not exist in nature, but this assumption is statistically correct because the pressure change curve in a homogeneous medium is symmetrical and therefore elements in the profile must be symmetrical. Owing to this symmetry, the force got by one element is transmitted and equally divided into two parts on which it relies [25].

If the sides of the excavation panel are $2a$ by the seam strike and $2l$ by the seam dip, the coordinate origin is at the intersection point of the rectangle diagonals, and using the function:

$$\Phi(x) = \frac{2}{\sqrt{2\pi}} \int_0^x e^{-\frac{1}{2}t^2} dt \quad (1)$$

a definite formula for calculating the *subsidence during horizontal seam excavation* is obtained [2,25].

$$U(x, y) = U_0 \cdot X_0(x) \cdot Y_0(y) \quad (2)$$

where:

$$X_0(x) = \frac{1}{2} \cdot \left[\Phi\left(\frac{a+x}{n}\right) + \Phi\left(\frac{a-x}{n}\right) \right]$$

$$Y_0(y) = \frac{1}{2} \cdot \left[\Phi\left(\frac{l+y}{n}\right) + \Phi\left(\frac{l-y}{n}\right) \right]$$

The function Φ from expression represents the standard Gaussian distribution curve.

Equation (2) presents a general case for the subsidence calculation during excavating the horizontal seam of a rectangular area which is illustrated in Figure 1.

Figure 1 Subsidence during excavating the horizontal seam of a rectangular area with parameters: H - seam depth; $2a, 2l$ - dimension of excavation area; $U_{\max}$ - maximum subsidence; δ - draw angle; θ - angle of maximum subsidence.

Basic formula for calculating the subsidence during inclined seams excavation is obtained [2,25]:

$$U(x, y) = U_0 X(x, y) Y(y), \quad (3)$$

where:

$$X(x, y) = \frac{1}{2} \left[\Phi\left(p \frac{a+x}{\sqrt{H \cdot \text{ctg} \alpha - y}}\right) + \Phi\left(p \frac{a-x}{\sqrt{H \cdot \text{ctg} \alpha - y}}\right) \right]$$

$$Y(y) = \frac{1}{2} \left[\Phi\left(q \frac{b+m+y}{\sqrt{H \cdot \text{ctg} \alpha - y}}\right) + \Phi\left(q \frac{b-m-y}{\sqrt{H \cdot \text{ctg} \alpha - y}}\right) \right]$$

where:

$$p = \frac{P_0}{\sqrt{\sin \alpha}}, q = (1 - \lambda \sin \alpha)Q, b = \frac{l \cos \alpha}{1 - \lambda \sin \alpha}, m = \frac{H \lambda \cos \alpha}{1 - \lambda \sin \alpha}$$

The subsidence curve will be the same in any profile by the dip, so it is a plane subsidence:

$$U(y) = U_0 Y(y) \quad (4)$$

where $Y(y)$ is calculated from the formula (3).

Figure 2 presents subsidence during excavation of the inclined coal seam

Figure 2 Subsidence during excavation of the inclined coal seam with parameters δ, β, γ - angles of the draw.

In the case that $\alpha = 0$, formula (3) is reduced to the basic formula (2) for calculating the subsidence of a horizontal seam [2,25].

3 RESULTS AND DISCUSSION

The problem of subsidence and protecting objects above the mining works has been present for decades in the coal mine "Rembas"-Resavica with an underground exploitation of the "Strmosten" pit.

This study presents a predictive calculation of the subsidence based on the stochastic method by Pataric and Stojanovic and GIS model using the input data from this underground coal mine in Serbia [13].

3.1 Characteristic of the research site

The "Rembas" coal mine is engaged in the underground exploration of a high-quality brown coal. It is part of the Public company for the underground coal mining

"Resavica" (JP PEU "Resavica"), the most important center of underground coal mining of the Balkan. Brown coal mine "Rembas" has a tradition of coal mining for more than 150 years ([wwwhttp://www.jppeu.rs](http://www.jppeu.rs)). Today, the "Rembas" coal mine consists of three production pits: "Jelovac", "Strmosten" and "Senj mine". The "Strmosten" pit as well as its wider environment is formed of rocks with the different lithological composition. The carboniferous Miocene series is inserted between the cretaceous limestones and andesites, which form the paleorelief, and the Permian red sandstones. The Pliocene and Quaternary sediments lie transgressively across the Permian sandstones that represent the coal seam roof. The floor seam consists of clayey sandstones, clays, conglomerates and rarely of marl.

The coal seam thickness (d) is taken from the geological interpretation of the deposit and isolines of the main coal seam; it ranges from 2 to 8 m. The dip of coal seam (α) is determined as the mean value of certain parts of an excavation field, with values in the range of 5-15°. For the predictive calculation of the subsidence parameters, the mean values of the seam dip for each excavation panel (EP) are taken. Seam depths (H) were determined based on the geological interpretation of the deposit with the values ranged from 380-525 m. So far, during the exploitation of the "Strmosten" deposit several excavation methods have been used in order to reach the optimal solutions for very complex and difficult layer conditions. Traditionally, the pillar excavation methods "G" and "V" were used, as well as the longwall mining method with mechanized hydraulic support. Coal deposit recovery (i) is determined with losses of $g = 35\%$, which corresponds to the projected excavation method and its value is con-

firmed to $i = 65\%$. Under the given conditions, it can be considered as the highest deposit recovery. The rate of caving (q) is adopted based on the analysis of the previous studying of the displacement process of the undermined rock massif in the "Strmosten" deposit. The value $q = 0.70$ is accepted [13].

3.2 Software solution for the mine subsidence prediction based on the stochastic method

The prediction of subsidence using the equations of the stochastic Pataric-Stojanovic method is a very complex mathematical calculation considering the accuracy of determining the input parameters, choice of density of the grid of points and interpolation of the subsidence contour lines, which would be a time-consuming in case of manual data processing. Therefore, for internal purposes, the original computer program package with the title MITSOUKO has been created based on the stochastic method proposed by Pataric and Stojanovic.

The MITSOUKO program package enables calculating the process of mine subsidence at any point of the land surface and representating the results owing to possibility of their integration and further processing in the GIS [25]. It offers the sequential subsidence calculations by simulating the excavation process according to the adopted dynamics of mining the excavation panels in the excavation field. The MITSOUKO software is designed in the Python v. 3.8 programming language.

The excavation field, with a total area of 29 ha, is composed of 21 excavation panels, which are exploited one by one successively from 2018 to 2038 (Figure 3).

Figure 3 Excavation panels (EP) mined successively in the excavation field of the "Strmosten" pit [13]

The MITSOUKO software consists of two modules: PARAMETERS and SUBSIDENCE which represent the individual independent functions and are mutually connected by a hierarchical structure [25]. Names of the modules suggest their functions and purpose in the MITSOUKO program. Each module starts with form according to a textual description explaining its name and function, tags of the input data that are loaded (Read parameters) or computed (Calculate parameters) into a particular module, and data values

returned by a module through the control loop.

Firstly, by entering the MITSOUKO program, in the PARAMETERS module, the function (Eq. 1) is initialized, according to the tabular data [26]. Then, through the menu, the data obtained based on geometric characteristics for each excavation panel are entered: ID , dimensions (a, l), seam depth (H), seam thickness (d) and seam dip angle (α). In the next step, in a specified subroutine of the PARAME-

TERS module, the following is calculated for each panel: maximum subsidence (U_0), parameters (m, b, p), rate of caving (q), angles of draw (δ, β, γ), and angle of full subsidence (θ). The local coordinate system is situated symmetrically with respect to the first excavation panel (EP1), with x -axis in a direction of seam strike, y -axis in a direction of seam dip and coordinate origin in the diagonal intersection of this panel. The positions of all excavation panels (x_i, y_i, F_i) are determined with respect to the defined

local coordinate system. During the calculation for each excavation panel (EP), it is necessary to rotate its coordinate axes for the value of angle F_i (expressed in degrees) to a direction of axes of the local coordinate system. The calculated parameters, together with the geometric characteristics of each EP and information concerning their positions in the local coordinate system (x_i, y_i, F_i), represent the input data for subsidence calculation in the SUBSIDENCE computational module (Table 1).

Table 1 Input parameters for subsidence calculation [13]

[EP]ID	a[m]	l[m]	H[m]	d[m]	Alf[s]	U0[mm]	m[m]	b[m]	p	q	Teta[deg]	xi[m]	yi[m]	Fi[deg]
EP1	20.00	195.00	385.00	6.00	8.00	3151	26.92	197.00	0.73923	0.52316	86.00	0.00	0.00	0.00
EP2	20.00	206.00	395.00	6.50	8.00	3414	27.62	208.00	0.73923	0.52316	86.00	-40.00	-13.50	0.00
EP3	20.00	218.00	415.00	6.50	9.00	3405	29.02	220.70	0.69634	0.49346	86.00	-79.70	-24.80	0.00
EP4	20.00	229.00	435.00	5.50	9.00	2881	30.42	228.69	0.69634	0.49346	86.00	-119.00	-42.00	0.00
EP5	20.00	241.00	450.00	5.50	10.00	2873	39.37	241.00	0.65997	0.46836	86.00	-159.00	-54.00	0.00
EP6	20.00	252.00	460.00	4.50	11.00	2343	40.24	251.58	0.62857	0.44680	86.00	-199.00	-67.00	0.00
EP7	20.00	263.00	465.00	4.00	11.00	3667	29.37	125.83	0.69634	0.49346	86.00	4.50	-284.00	0.00
EP8	32.00	272.00	470.00	3.00	11.00	2895	32.17	118.13	0.79088	0.55907	86.00	-41.00	-339.00	0.00
EP9	31.50	120.00	460.00	2.00	13.00	2369	33.56	112.12	0.79088	0.55907	86.00	-80.00	-359.00	0.00
EP10	28.00	126.00	420.00	7.00	9.00	2083	40.68	262.56	0.62857	0.31888	86.00	-238.50	-81.50	0.00
EP11	23.50	118.00	460.00	5.50	7.00	1562	41.12	271.54	0.62857	0.44680	86.00	-291.00	-92.00	0.00
EP12	23.00	112.00	480.00	4.50	7.00	1034	48.35	119.76	0.57676	0.41150	86.00	-353.00	38.00	0.00
EP13	24.00	105.00	500.00	4.00	8.00	2101	34.96	105.00	0.73923	0.52316	86.00	-120.00	-383.00	0.00
EP14	23.00	87.00	510.00	3.00	9.00	1572	35.66	86.88	0.69634	0.49346	86.00	-161.00	-384.00	0.00
EP15	20.00	57.00	525.00	2.50	8.00	1313	36.71	57.00	0.73923	0.52316	86.00	-200.00	-382.00	0.00
EP16	20.00	36.00	525.00	2.00	5.00	1057	27.51	36.03	0.93692	0.66110	86.00	-242.00	-384.00	0.00
EP17	115.00	30.00	415.00	3.50	15.00	1793	50.96	29.93	0.53537	0.38363	86.00	110.00	-546.00	-46.00
EP18	140.00	40.00	415.00	2.00	15.00	1025	50.96	39.91	0.53537	0.38363	86.00	35.00	-557.00	-46.00
EP19	123.00	23.00	410.00	4.50	6.00	2374	21.49	23.00	0.85481	0.60367	86.00	254.00	-702.00	-46.00
EP20	123.00	21.00	410.00	2.00	6.00	1055	21.49	21.00	0.85481	0.60367	86.00	227.00	-732.00	-46.00
EP21	38.00	53.00	380.00	2.00	10.00	1045	33.25	53.00	0.65997	0.46836	86.00	370.00	-841.00	-136.00

Subsidence are calculated in the SUBSIDENCE module. A certain subroutine allows entering the coordinates of points in a grid of a given density, through the assigned distances between points ($\Delta x, \Delta y$), in the x and y axes directions of the local coordinate system. In this way, it is possible to define the calculation limits for all panels up to a limit subsidence value of 10 mm. Further, the subsidence values after mining each panel are calculated cumulatively, according to the projected mining dynamics of excavation field (Figure 3). The results of predictive subsidence calculation can be exported in tabular form in an Excel file, individually for each excavation panel,

which is also the preparation of data for graphical presentation and spatial analysis of these results in GIS.

3.3 Spatial analysis in GIS

Spatial analysis in GIS is based on integration the subsidence prognosis results obtained using the MITSOUKO computer program package and data processing in ArcGIS [13]. The main steps in this integration are: transfer of mining subsidence prediction tabular data from MITSOUKO to GIS, building a geodatabase, spatial data analysis, and combination of maps layers to predict the subsidence [27].

GIS is used for creating a complex geodatabase, converting numerical data, imported from the SUBSIDENCE module, in feature classes and graphical data as well as for performing the spatial analyses of subsidence and deformations [6,7]. Since the "Strmosten" pit consists of multiple EPs with complex geometry, using the stochastic method for spatial analysis of subsidence requires a long time without GIS because for each EP subsidence must be presented cumulatively, assuming all previous and current EP.

Implementing the stochastic method for spatial analyses of subsidence in GIS is performed in two steps [25]:

The first step, **Data module**, involves creating a geodatabase of the "REMBAS" coal mine in ArcCatalog, within the ArcGIS application (ESRI <http://www.esri.com/software/arcgis/>) with feature classes, tables, and rasters. The feature class is a set of homogeneous spatial attributes in the form of digitized vector data, in the same National Coordinate System (MGI Balkans7). In order to integrate feature classes thematically and spatially into the mine model, within the given excavation panels (EP), feature datasets have been created, in which all types of feature classes are entered. Feature datasets with feature classes related to the spatial geometry: terrain topographies, buildings, mining facilities, old mining works and new exploitation field in "Strmosten" pit, excavation panels with mining dynamics by years, active and old mining premises, and geological interpretation of the coal seam are created in a geodatabase of "Rembas"- Resavica mine. Outside the feature datasets, tables with subsidence, calculations from the SUBSIDENCE module in the MITSOUKO program, rasters for the subject area in the form of orthophoto, geographic maps, situational plans of mine and photographs are imported in the geodatabase. Feature Datasets have been created, in which all types of feature classes are entered. Also, using the ArcMap, an integrated part of the ArcGIS software package, to create layers for displaying feature classes from the ArcCatalog

(ESRI) is included. All the tables of the subsidence calculations have been transferred from the geodatabase coal mine to the ArcMap.

The second step, **Subsidence module**, involves using ArcMap, which is an integrated part of the ArcGIS software package, to create layers for displaying feature classes taken from ArcCatalog (ESRI), then editing geometry and attributes of geoobjects, querying spatial data and conducting spatial data analysis (geoprocessing) with a map creation. All tables of the subsidence calculations have been transferred from the geodatabase "REMBAS" coal mine to the ArcMap. Using the Display XY Data command, the selected table of excavation panel, e.g. EP21, which contains the x and y coordinates of the points and calculated subsidence values, is added as a new layer in the Table of Contents. Thereby, a new feature class, EP21_events, was formed, which for this excavation panel EP21 contains 21760 points with values of x and y coordinates and associated subsidences, georeferenced to the adopted coordinate system MGI Balkans7. Following the same procedure, the new feature classes were created for all excavation panels [13].

The created feature classes contain x and y coordinates of all points in the grid 10x10 m with associated subsidence values. All the calculation results can be stored into a GIS point-grid. The Spline interpolation method from the Spatial Analyst Tools palette is then used to create the new layers with contour subsidence lines for each excavation panel (EP1-EP21), by cumulative subsidence transformation from the previous to the new state. This provides a successive following of the subsidence process on the map at all stages of the coal seam excavation in the "Strmosten" pit. The subsidence contour lines are calculated from the maximum values to the adopted limit subsidence value of 10 mm after mining the entire excavation field in the "Strmosten" pit.

The third step involves the transformation of feature classes with subsidence contour lines for each excavation panel determined in the local coordinate system to the global MGI Balkans7 coordinate system in which a mine model of the respective observation field is presented [13].

3.4 Subsidence analysis during mining the excavation panels in the "Strmosten" pit

The stochastic method was used to calculate the mine subsidence values in the MITSOUKO program package. The subsidence contour lines are graphically presented in the ArcGIS software package by interpolation and cumulative transition from the previous to the new state, formed on the data of the seam, and according to the adopted excavation dynamics [7,9]. Based on the predicted subsidence values, the

impact of mining works for all EPs was analyzed. With the progress of mining, the subsidence value for each EP is obtained cumulatively, that is, by superimposing the subsidence effects of all previously excavated panels and the actual one.

Figure 4 shows excavations panels (from EP1 to EP20) in the coal mine "Rembas" Resavica - Serbia with the adopted excavation dynamics, subsidence contour lines obtained by simulation the mine subsidence process by the stochastic prediction method and maximum subsidence values.

As it can be seen in Figure 4, the predicted maximum subsidence values on the ground surface continuously increase from -1893 mm reached after excavation of EP3 in 2020 to -2927 mm after excavation of EP16 in 2033. Value of -2927 mm remains unchanged with further excavation, ending with EP20 in 2037.

Figure 4 Simulation of the mine subsidence process in the "Strmosten" pit [13]

Finally, Figure 5 presents the mining operation plan and predicted subsidence contour lines with the maximum subsidence

value ($U_{max} = -2927$ mm) after mining 21 excavation panels in 2038, that is the entire excavation field in the "Strmosten" pit [13].

Figure 5 Subsidence contour lines after mining the entire excavation field in the "Strmosten" pit [13]

Figure 6 presents a digital elevation model (DEM) of the final mine subsi-

dence, with the maximum subsidence value $U_{max} = -2927$ mm, in the "Strmosten" pit.

Figure 6 Digital elevation model (DEM) of the final maximum subsidence in the "Strmosten" pit [13]

According to the predictive calculations, the maximum relative subsidence was determined as the highest subsidence

value (- 2925 mm) after exploitation the excavation panels EP1-EP15. With the progression of mining operations, this

value grows towards the value of maximum absolute subsidence. Maximum absolute subsidence, $U_{\max} = -2927$ mm, is the highest subsidence value, achieved after mining EP16, which does not increase with further mining works (EP16-EP21), but a flat-bottomed subsidence trough, collapsed for that value, appears. The shape of subsidence curve on the profile by the seam dip is in a fundibuliform. On the profile by the seam strike, the shape of subsidence curve is infundibuliform, but with a flat bottom in the narrow central part of the curve, formed because several points have the same value of the maximum absolute subsidence, $U_{\max} = -2927$ mm.

3.5 Mine subsidence monitoring

The values of the predicted parameters for the ground surface subsidence should be

verified throughout the entire period of coal seam excavation. This requires the systematic geodetic surveying. The main goal of these surveying is to realize the surface subsidence process in space and time during the excavation of the coal seam [28,29].

The basic grid for surveying consists of profile lines arranged in directions of seam dip and seam strike. This grid must satisfy the requirement of long-term subsidence observations, which will last more than twenty years so that the stability of benchmark should not be compromised. Working benchmarks are stabilized in the zone to be affected by the subsidence process and by periodic defining the benchmark position, intensity, and state of the subsidence process for a certain period of time. Figure 7 shows the profile lines I-I and II-II for coal seam strike and coal seam dip with predicted subsidence curves at cross sections [13].

Figure 7 Profile lines I-I and II-II for dip and strike of the coal seam with the associated predicted subsidence curves in the coal mine "Rembas" Resavica, Serbia [13]

Geodetic surveying on profile lines gradually follow the general development of subsidence process through the data that define the beginning of displacement, beginning of the intensive displacement phase, intensive displacement phase, completion of this phase and regression phase process.

The extent, type of measurements, field conditions and required accuracy of measurements demand the application of modern geodetic surveying methods and processing of measurement results. Surface movement and deformations in wider areas have been simpler monitored by introducing the airborne, satellite-based remote sensing techniques, GPS and UAV systems (drones). The rapid development of remote sensing techniques such as LiDAR is leading to very high accuracy and cost-effectiveness and therefore more viable option.

The tabular and graphical processing of the measurement results give the values of characteristic displacement parameters: subsidence, horizontal displacement, slope, deformation and radius of curvature. The subsidence trend during time is tracked on charts. There are two types of charts along the profile lines - the first are the subsidence curves while the second are the parameters of displacement process in the form of diagrams of horizontal displacements, diagrams of slope change and diagrams of curvature change which serve to estimate the vulnerability degree of objects [1-3,13,25].

4 CONCLUSION

The stochastic method for the subsidence prediction and analysis of spatial data in GIS enable the calculation and presentation the subsidence on the surface of undermined terrain at any point in the grid with a large number of numerical data which require a long time of processing and interpretation of the obtained results by the standard data processing method. The answer to the set task lies in the MITSOUKO

program package, intended for the predictive subsidence calculation according to the stochastic method, which allows user to process a large amount of data, thus excluding the time factor, and the obtained numerical data can be quickly and easily graphically processed and displayed in GIS.

The calculation of subsidence by the stochastic method Pataric- Stojanovic and integration with GIS is a powerful and reliable tool for predicting the subsidence and monitoring the impact of underground mining works on the land surface. This work presents an important research study, actual and significant for the mining profession and practice.

REFERENCES

- [1] Djordjevic D., Vusovic N., Prognosis of the Displacement and Deformation of the Underground Terrain, University of Belgrade-Faculty of Mining and Geology, Belgrade, 2014.
- [2] Pataric M., Stojanovic A., Moving the Underground Terrain and Protecting Objects from Mining Works. University of Belgrade - Faculty of Mining and Geology, Belgrade, 1994.
- [3] Diyab RT., Comparative Analysis of Predicted and Measured Values of Displacement and Deformation of Undermined Terrain at Coal Mines in Serbia. Dissertation, University of Belgrade - Faculty of Mining and Geology, Belgrade, 2011.
- [4] Burrough PA., McDonnell RA., Principles of Geographical Information Systems. 2nd ed. Oxford, London, 2006.
- [5] McDonald J., Evaluating Mine Subsidence Using a GIS Software Application, Conference: Digital Mapping Techniques'10,-Workshop Proceedings, Sacramento, California, 2010.

- [6] Cao J., Ma F., Guo J., Lu R., Liu G., Assessment of Mining-Related Seabed Subsidence Using GIS Spatial Regression Methods: a Case Study of the Sanshandao Gold Mine (Laizhou, Shandong Province, China). *Environmental Earth Sciences* 78 (2019) 25-35.
- [7] Cai Y., Jiang Y., Liu B., Djamaluddin I., Computational Implementation of a GIS Developed Tool for Prediction of Dynamic Ground Movement and Deformation due to Underground Extraction Sequence, *International Journal of Coal Science & Technology* 3(4) (2016) 379–398.
- [8] Trofymchuk O., Anpilova Y., Yakovliev Y., Zinkiv I., Ground Deformation Mapping of Solotvyno Mine Area Using Radar Data and GIS, *European Association of Geoscientists & Engineers, Conference Proceedings, Geoinformatics: Theoretical and Applied Aspects* (2020), pg.1-5 - <https://doi.org/10.3997/2214-4609.2020geo138>
- [9] Esaki T., Djamaluddin I., Mitani Y., A GIS-based Prediction Method to Evaluate Subsidence - Induced Damage from Coal Mining Beneath a Reservoir Kyushu, Japan, *Q J Eng Geol Hydroge* 41(3) (2008) 381-392.
- [10] Esaki T., Zhou G., Djamaluddin I., Development of GIS-based Rigorous Subsidence Prediction System for Protecting Surface Environment, *Environmental Rock Engineering*, Saito & Murata (eds) Swets & Zeitlinger, Lisse, 2003.
- [11] Miao F., Mingxing Y., Xiaoying Q., Chengming Y., Baocun W., Rui L., Chen J., Application of DInSAR and GIS for Underground Mine Subsidence Monitoring, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. Vol. XXXVII. Part B1. Beijing, 2008.
- [12] Unlue T., Akcinb H., Yilmaza O., An Integrated Approach for the Prediction of Subsidence for Coal Mining Basins, *Engineering Geology* 166 (2013)186-203.
- [13] Vusovic N., Technical Mining Project for Determining the Parameters of Displacement of Undermined Terrain and Protection of Sladaja Village Objects from the Influence of Underground Mining Works Above the "Strmosten" Pit at RMU "Rembas" Resavica, University of Belgrade-Technical Faculty in Bor, Bor, 2018.
- [14] Liu B., Liao G., Basic Regulars of Coal Mine Subsidence, China Industry Press, Beijing, China, 1965.
- [15] Kratzsch H., Mining Subsidence Engineering, Springer-Verlag, Berlin, Germany, 1983.
- [16] Vulkov M., About the Generalisation Possibilities in a New Stochastic Model of Mining Subsidence, 50 Years University of Mining and Geology "St. Ivan Rilski" Annual, Vol. 46, Part II, Mining and Mineral Processing, Sofia, 2003, pp.153-154
- [17] Djamaluddin I., Mitani Y., Esaki T., Evaluation of Ground Movement and Damage to Structures from Chinese Coal Mining Using a New GIS Coupling Model, *International Journal of Rock Mechanics and Mining Sciences* 48(3) (2011) 380-393.
- [18] Blachowski J., Application of GIS Spatial Regression Methods in Assessment of Land Subsidence in Complicated Mining Conditions: Case Study of the Walbrzych Coal Mine (SW Poland). *Nat Hazards* 84 (2016) 997-1014.
- [19] Borela VR., Stochastic Modeling and DEM Simulation of Granular Media Subsidence due to Underground Activity, Master Thesis, Purdue University, West Lafayette, Indiana, 2016.

- [20] Malinowska A., Hejmanowski R., Dai H., Ground Movements Modeling Applying Adjusted Influence Function, *International Journal of Mining Science and Technology* 30(2) (2020) 243–249.
- [21] Knothe S., Equation of the Subsidence Profile. *Archives of Mining and Metallurgy* 1 (1953) 22–38.
- [22] Litwiniyszyn J., The theories and Model Research of Movement of Ground Masses. In: *Proceedings of the European Congress on Ground Movement*. University of Leeds, 1957, pp. 202–209.
- [23] Liu B., Theory of Stochastic Medium and its Application in Surface Subsidence Due to Excavation, *Transactions of Nonferrous Metals Society of China*, 2(3) (1992)
- [24] Li P., Yan L., Yao D., Study of Tunnel Damage Caused by Underground Mining Deformation: Calculation, Analysis, and Reinforcement, *Advances in Civil Engineering* Vol. 2019, pp.1-18.
- [25] Vusovic N., Vlahovic M., Ljubojev M., Vlahovic M., Krzanovic D., Software Solution for Mine Subsidence Prediction Based on the Stochastic Method Integrated with GIS, *Mining and Metallurgy Institute Bor*. No. 1 (2020)
- [26] Djordjevic D., Vusovic N., Ganic A., Svrkota I., Angular Parameters of Undermined Ground Movement Process in Unknown Areas, *University of Belgrade, Faculty of Mining and Geology, Belgrade Underground Mining Engineering* 19 (2011) 125-136.
- [27] Banerjee TK., Roy S., Dey S., A GIS Solution for an Integrated Underground Coal Mine Management: A Conceptual Framework, *Journal of Management Policies and Practices* 2(2) (2014) 129-143.
- [28] Cui X., Wang JA., Liu Y., Prediction of Progressive Surface Subsidence Above Longwall Coal Mining Using a Time Function, *International Journal of Rock Mechanics and Mining Sciences* 38(7) (2001) 1057-1063.
- [29] Malinowska A., Hejmanowski R., Evaluation of Reliability of Subsidence Prediction Based on Spatial Statistical Analysis. *Int J Rock Mech Min Sci* 46 (2009) 432–438.