Subsidence through formation simulation with the use of cellular automata theory on the example of real, multi-longwall example

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Abstract. The paper presents an example of real subsequent underground hard coal mining (3 longwalls), which caused the formation of a subsidence trough on the surface of the mining area. Surface deformations were covered by systematic leveling measurements along the measurement line “1”. For the illustrated example of underground mining, numerical calculations were made using the theory of cellular automata. Calculated data were compared with the results of leveling. The aim of the article was to verify the theoretical assumptions of the model and to demonstrate the practical possibilities of applying the method to assess the subsidence of the mining area.

1. Introduction
There are many methods of prediction of underground mining impact on the land surface. The most important and popular in Poland are:

- methods based on empirical formulas, where deformation indices were determined on the basis of various graphs, patterns and nomograms [1],
- methods which uses geometric-integral theory to describe the distribution of deformation [2, 3] (despite the passage of time, the method is the subject of research by the next generation of scientists [4]),
- methods basing on models of continuous centre where the state of stresses and displacements defines a system of differential equations and the equation of state dependent on the adopted model [5],
- methods based on models of stochastic centers used for the first time by J. Litwiniszyn [6],
- methods that uses the artificial neural networks [7].

The results of model studies of J. Białek [8], R. Mielimąka [9, 10] and especially P. Sikora [11, 12, 13, 14] showed that methods using the theory of cellular automata should be added to the group of mentioned methods. So far, the characteristics of the basic rock mass model as a cellular automaton has been developed. In the case of a flat model, which maps a two-dimensional cross-section through a rock mass, it has been shown that it is possible to simulate vertical displacements qualitatively and quantitatively consistent with those observed in reality. In addition, it has been shown that using cellular automata it is possible in a natural, direct way to simulate the impact of inhomogeneous properties of rock mass on deformation distribution and the effect of nonlinear summing of mining
influences on deformation distribution. Similar characteristics, although not yet so complete, were
developed for the spatial model.

The aim of the article is to attempt to verify the theoretical model assumptions. The work uses an
example of multiple underground mining of hard coal deposits. The article presents the basic
characteristics of the rock mass model as well as the mining and geological conditions and the results
of geodetic observations. Subsequently, the parameters of the model were determined and a series
of simulations were made as a result of which a subsidence trough was created in relation to the progress
of mining operations.

2. Cellular automaton as a spatial rock mass model

The principles of the method were already widely discussed in literature. It should be noted that
despite the long history and a potential of the theory of cellular automata [15] and its versatile use
beyond the mentioned authors, it has never been used practically in rock mass mechanics and to
simulate rock mass deformation. Cellular automata theory begun in the 1940s of the last century [16]
and today is commonly used e.g. in computer science, to test the algorithms, in physics to simulate the
spread of fire, gas, heat, etc., or to simulate the traffic [17]. The possibility of using the cellular
automaton method to simulate the deformation of the rock mass and its surface was signaled for the
first time by T. Niemiec [18]. In turn, the basic characterization of the model allowing for the practical
use was first made by P. Sikora [11].

One of the basic advantages of the model is that it does not require special mathematical
knowledge to use it. However, it must be remembered that the cellular automaton is an algorithm and
at the moment requires the knowledge and application of programming tools in order to practical
usage. Due to the lack of commonly available computer programs dedicated to simulating
deformations with the use of cellular automata, the method has not found a wider application so far.
For this reason, some of the most important model assumptions will be described below.

The build concept of the simplest rock mass model as cellular automaton assumes defining the
basic elements of the automaton. These include defining the shape and size of the cell grid,
determining cell dimensions, defining the cell state space, boundary conditions of the simulation,
defining the cell neighborhood and the transition function.

The space in which the simulation will take place is created by a network of cells of the same shape
and size. In addition, cells must adhere closely to each other. By assigning to the cell metric
dimensions (width $S_k$, length $D_k$ and height $W_k$) a fragment of a rock mass can be discretized in the
form of a specified number of cells forming a spatial grid. The figure 1 shows a fragment of a regular
grid of a cellular automaton with a specified number of cells.

Also it is a way to map mining operations in such a rock mass model. It is done by assigning to the
appropriate cells the size of a certain volume corresponding to the resulting void as the product of the
height of the extracted longwall $g$ and the so called exploitation coefficient $a$ (describes the ratio
between the height of the extracted panel $g$ and a resulting maximal subsidence $w_{\text{max}}$ in a subsidence
trough on the surface).

The mapping of one or more exploited panels in the grid completes the determination of the so-
called initial conditions for deformation simulation.

Before the actual simulation is performed, it is necessary to define further necessary parameters of
the model, i.e. the so-called cellular neighborhood and the transition function. The cellular
neighborhood is the space around a single cell in the cellular network grid with which this cell can
exchange its assigned data. An elementary assumption of the operation of the cellular automaton is the
simultaneous evaluation of the entire model. In other words, each cell of the automaton must undergo
a function - called the transition function. The transfer of data from the cell to other cells from the grid
takes place only within the range defined by the cellular neighborhood and in the proportions defined
by the transition function. However the transition function may be deterministic - used in this study or
stochastic [12].
Figure 1. A spatial grid of a cellular automaton with a defined number of levels (W), columns and rows (D x S). Cells are assigned real-size dimensions: length (D_k), width (S_k) and height (W_k) [14].

In the model the rocks collapse is simulated to the resulting post-mining void. The simplest model assumes a linear and lossless process of propagation this phenomenon. In addition, it is assumed that clenching the void is caused only by the force of gravity. In the deterministic model, the system and the ratio of the void “transition” to specific cells from the cellular neighborhood is strictly defined. Adopted, as the most appropriate [14], the cellular neighborhood limited to 5 cells relative to the base cell and the basic characteristics of the simplest deterministic transition function are shown in the figure 2.

Figure 2. The cellular neighborhood and the characteristics of the transition function based on the value of the partial main transition P from the base cell to the overlying cell [12].
The algorithm presented above is described in more detail in previous publications [9, 14]. It is worth noting the P parameter - so-called main transition parameter. It determines the ratio of the partial volume transition assigned to the base cell (given to the cell considered at a discrete time in the context of the evaluation of the entire model) to the overlying cell and the remaining four cells from the cellular neighborhood. The parameter P assumes values from the range (0÷1).

The operation of the simulation ends when the sum of volumes assigned to cells at the beginning (at the stage of determining the initial conditions) will be equal to the sum of the volume at the level that maps the surface of the rock mass.

The basis for the practical application of the presented model as a deterministic finite automaton is the dependence binding basic parameters: determined cell dimensions $S_k$ [m], $D_k$ [m] and $W_k$ [m], depth of mining operations $H$ [m], the value of the maximum subsidence $w_{\text{max}}=ag$ [mm] in a full subsidence trough and a maximum slope $T_{\text{max}}$ [mm/m] [14]:

$$
T_{\text{max}}(x) = A \frac{ag}{H} \left( \frac{W_k}{D_k} \right) \left( \frac{W_k}{H} \right)^{-0.5} \left[ \frac{\text{mm}}{m} \right]
$$

(1)

where: A - adjustment parameter due to the value of the main transition parameter P.

The model defines the maximum slope ratio $a_T$ describing the ratio of the maximum slope to the maximum subsidence:

$$
a_T = \frac{T_{\text{max}}H}{ag}
$$

(2)

From formulas (1) and (2) it follows that the $a_T$ parameter, in contrast to the similarly defined $tg\beta$ parameter in S. Knothe's theory, is variable depending on the depth of exploitation $H$ [3].

The above-presented algorithm leads to the characterization of the distribution of subsidence consistent with the distribution for the theory of the stochastic center of J. Litwiniszyn [6, 12].

3. Description of the mining operations carried out in the seam 338/2

The selected example of the real underground exploitation of hard coal was chosen due to the fact that it was the first in this area of the rock mass and due to properly stabilized, in order to the observations of the effects of mining operations, the measurement line on the surface of the mining area.

Mining enterprise "A", in the period between March 1994 and February 1996, extracted 3 longwall workings in the deck 338/2. Exploitation of the first panel was completed in November 1994. In the same period, the second wall was started. The extraction of longwall no. 2 was ended in May 1995 and at the same time there were started mining operations in the panel no. 3. The arrangement of longwalls on the background of the measuring line is presented in figure 3.

Longwalls were extracted by the method of roof collapse along the direction of the deposit's strike. The slope (dip angle) of the deck was insignificant and amounted to about 6°. The exploitation depth ranged from 590 m to 665 m - the average working depth was approx. 625 m. The thickness of the extracted panels was more or less equal to the thickness of the deck, i.e. 1.8 m for longwalls 1 and 3 and 2.0 m in case of longwall 2. The length of the first wall was about 215 m while the second wall was about 260 m long. The length of the face (longwall’s width) of first longwall was about 215 m and in the case of the second and a third it was approx. 260 m. Overall length of the advance of the longwall no. 1 (longwall’s length) was respectively about 746 m, 850 m in case of the longwall no. 2 and approx. 990 m in case of the longwall no. 3.
On the surface of the mining area, the "1" measuring line has been stabilized with permanent benchmarks, running from the south (point 101) to the north (point 140) according to the arrangement shown in figure 3. The distances between points were on average around 39 m. Cyclic measurements on the observation line were made using the precise geometric leveling method with the use of a code leveler and invar leveling rods. This is a huge advantage in contrast to the increasingly common GNSS RTN measurements or using UAV technology, which solve many problems [19] but due to the limitations of accuracy in similar analyzes often cause difficulties in the interpretation of the obtained results. The so-called "zero" measurement being a reference for subsequent measurement cycles and aimed at determining the stability of the soil was made before the first mining operations have started. This work uses the results of leveling measurements made only after the exploitation of individual longwalls and before starting the next one. Increment of subsidence and calculated slope values in relation to the zero measurement are summarized in the table 1.
The results of leveling measurements show that an incomplete subsidence trough was created on the surface of the mining area. After extraction of the first longwall, the maximum measured subsidence was 575 mm, after the second it was maximally 1315 mm and finally after extraction the last one approx. 1518 mm. Noteworthy are the values of the calculated slope increments. After extraction of the first coal panel, the maximum inclinations were approx. 3.5 mm/m. The values were similar over both operational edges. It can be assumed that the subsidence trough was symmetrical. After extraction of the second longwall inclinations above the edges of the operating field were already different. Over the edge on the side of the first longwall it amounted to approx. 7.5 mm/m, above the edge of the second longwall approx. 5.5 mm/m. Even more the phenomenon was visible after extraction of the third one. Over the edge of the extraction field on the side of the first longwall it amounted to approx. 7.75 mm/m, above the edge of the second longwall approx. 4.5 mm/m. The asymmetry of the subsidence trough was caused by the non-linear summation of deformation resulting from the extraction of subsequent longwalls. The phenomenon has been well described in the literature, including by R. Mielimąka [20].

**Table 1.** The results of leveling measurements as the subsidence w [mm] at the points of the "I" measuring line and the calculated slopes T [mm/m].

| Point no. | w [mm] (L.1) | w [mm] (L.1+2) | w [mm] (L.1+2+3) | T [mm/m] (L.1) | T [mm/m] (L.1+2) | T [mm/m] (L.1+2+3) |
|-----------|--------------|----------------|-------------------|---------------|-----------------|-------------------|
| 101       | -1 -2        | N/A            | -0.05 -0.05 N/A   | 121           | -512            | -909              |
| 102       | -3 -4        | -19            | -0.03 -0.03 0.03  | 122           | -563            | -1077             |
| 103       | -4 -5        | -18            | -0.04 -0.04 N/A  | 123           | -575            | -1198             |
| 104       | -5 -6        | N/A            | 0.00 -0.20 N/A   | 124           | -536            | -1277             |
| 105       | -5 -15       | -30            | -0.09 0.11 0.21  | 125           | -473            | -1306             |
| 106       | -9 -10       | -20            | -0.05 -0.07 -0.23| 126           | -313            | -1315             |
| 107       | -11 -13      | -30            | -0.04 -0.04 0.04 | 127           | -177            | -1281             |
| 108       | -12 -14      | -30            | -0.06 -0.06 -0.12| 128           | -118            | -1237             |
| 109       | -14 -16      | -34            | -0.04 -0.04 0.15 | 129           | -83             | -1122             |
| 110       | -16 -18      | -27            | 0.00 -0.04 0.04  | 130           | -53             | -939              |
| 111       | -16 -19      | -26            | 0.00 -0.06 -0.82 | 131           | -41             | -416              |
| 112       | -16 -20      | -39            | -0.13 -0.15 -0.23| 132           | -36             | -319              |
| 113       | -21 -26      | -48            | -0.37 -0.54 0.23 | 133           | -29             | -239              |
| 114       | -34 -45      | -40            | -0.13 -0.30 -0.55| 134           | -21             | -119              |
| 115       | -37 -52      | -53            | -0.45 -0.81 -0.70| 135           | -11             | -70               |
| 116       | -53 -81      | -78            | -0.83 -1.53 -2.50| 136           | -5              | -32               |
| 117       | -83 -136     | -168           | -1.85 -2.98 -2.48| 137           | -2              | -27               |
| 118       | -127 -207    | -227           | -2.09 -3.29 -3.56| 138           | -1              | -22               |
| 119       | -229 -368    | -401           | -3.68 -6.47 -6.97| 139           | 0               | -17               |
| 120       | -421 -706    | -765           | -3.36 -7.48 -7.85| 140           | 0               | -16               |

The chart in figure 4 shows the profiles of subsidence trough designated after the end of operation of subsequent longwalls.
4. Simulation of the rock mass subsidence caused by extraction of the longwalls no. 1, 2 and 3 in the seam 338/2 with the use of cellular automata theory

Simulation of rock mass subsidence caused by the extraction of longwalls 1, 2 and 3 in the seam 338/2 was made with the original CA3D software. The basic mining and geology parameters were adjusted by the method of least squares, which assumed the following values:

- rock mass parameter \( a_T = 2.3 \),
- exploitation coefficient \( a = 0.8 \),
- exploitation rim \( A_{obr} = 0.07 \)H,
- proportionality ratio of horizontal to vertical displacements \( B = 0.32r \).

It can be considered that these are typical (average) values for the region of the Upper Silesian Coal Basin. Occurrence of exploitation rim (figure 3) was assumed due to the fact that the exploitation was the first in this region of the rock mass and due to the significant depth of the deposit in relation to the size of the exploitation field. For the adopted mining and geological parameters, the parameters of the cellular automaton were determined based on the equation 1, which are summarized below:

- an equal width and length of the cell \( S_k = D_k = 20 \) m was assumed,
- height of the cell \( W_k = 4 \) m,
- main transition parameter \( P = 0.53 \).

The figure 5 shows a contour map of the final increase of subsidence caused by the extraction of all longwalls.
Figure 5. Final subsidence trough [mm] determined by cellular automaton evaluation (extraction of all longwalls in the seam 338/2 including the exploitation rim) against the background of the "1" measuring line.

Subsequently, the values of subsidence and slopes at points of the "1" measuring line were interpolated. Additionally, a calculation variant taking into assumption only deformations caused by the extraction of the first longwall was taken into account. The following diagrams (figures 6 and 7) presents the subsidence trough profile and the slopes after extraction of the first longwall.
Figure 6. The calculated and measured profile of the subsidence trough along the measuring line "1" created as a result of the extraction of the first longwall [10].

Figure 7. Calculated and determined from measurements total slopes T [mm/m] along the measurement line "1" resulting from the extraction of the first longwall [10].

The presented data show that the results obtained from numerical simulation correlate well with the results of leveling measurements [10]. This applies to both qualitative and quantitative description. Extreme sizes – both subsidences and slopes – are very similar to each other. In case of slopes, the maximum values differed by less than 0.4 mm/m, which is about 10% of the difference in comparison to the measurement results. Subsequently, the results of measurements and calculations for the variant including deformations caused by the operation of the entire longwall field were compiled in an analogous way. Figures 8 and 9 show, respectively, the subsidence trough profile and the total slopes (for the "1" measurement points).
The results obtained in the case of subsidence allow to conclude a conspicuous convergence with the results of measurements, in particular as regards the size and location of maximum subsidence. However, in the case of calculated slopes there’re huge discrepancies [21, 22]. The difference between the maximum values above the southern edge of the exploitation field (covering all longwalls) reaches approx. 45%. The maximum inclinations above the northern edge are essentially the same. The difference between the received slope values over the southern edge results from the activation of the goaf caused by the initial extraction of the first longwall [22]. The algorithm - transition function adopted for the simulation - assumes a linear addition of influences. Obtained values of slopes are characterized by symmetry.
5. Summary and final conclusions
In the article, another attempt was made to model the rock mass and extracted panel of underground deposit in it using the theory of cellular automata. The presented example of actual exploitation concerned three longwall workings in the 338/2 seam extracted in-sequence as a first panel in this region of the rock mass. Mining operations were carried out between March 1994 and February 1996. Based on the basic characteristics of the rock mass model as a deterministic finite cellular automaton [23], an example of exploitation was mapped and a simulation of the distribution of vertical displacements within the model was done. For the simulation there were adopted typical values of mining and operational parameters. As a result, an incomplete subsidence trough was obtained on the surface of the model. The results of the simulation were compared with the results of geodetic observations carried out cyclically on the measuring line located over the exploitation field. After extraction of the first longwall in accordance with the schedule of exploitation, the results obtained from numerical calculations in terms of surface subsidence as well as values of final slopes were qualitatively and quantitatively consistent. The resulting subsidence trough was characterized by symmetry with respect to the value of the maximum subsidence. Also, the maximum inclination values occurred above the operational edges and were equal. However, after extraction of the second and third longwall, satisfactory results were obtained only in terms of the distribution of subsidences, while slopes over the northern edge – it is the edge of the operational field from the side of the first longwall – were measured about 33% higher than those determined from simulations [10] and after extraction of the third panel similarly almost 45% higher. The inclinations over the opposite exploitation edge were convergent in case of maximum values. The difference obtained over the first edge was the result of non-linear summation of influences, which in the presented distribution function has not been mapped.

Despite some discrepancies, it should be recognized that the results of numerical calculations confirm the validity of the current theoretical assumptions of the method. In the case of a 2D model, it has already been demonstrated, following the similar solutions of J. Litwiniszyn [6], that in the rock mass model built as a cellular automaton it is possible to simulate the influence of non-linear accumulation of deformation on the distribution of vertical displacements. On this basis, it can be concluded that work related to the development of a similar solution for the spatial model should be continued.

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