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Numerical simulation of the surface subsidence evolution caused by the flooding of the longwall goaf during excavation of thin coal seams

I Sakhno[1], S Sakhno[1], A Petrenko[1], O Barkova[1] and B Kobylianskyi[2]
[1] Donetsk National Technical University, 56 Potebni Str., Lutsk, 43003, Ukraine
[2] Educational Scientific Professional Pedagogical Institute of Ukrainian Engineering Pedagogics Academy, 16 Universytetska Str., Kharkiv, 61003, Ukraine

E-mail: `ivan.sakhno@donntu.edu.ua`

Abstract. Underground mining has a significant influence on ground movement, which induces serious environmental disturbances on land. Movements of the rock strata can be the cause of changes in the hydrogeological regimes of groundwater. As a result, the risk of flooding of the longwalls goaf increases. The specific phenomenon of the Ukrainian Donbas is the flooding of the underground roadway system at the result of the closure of the mines. Water saturation of rocks leads to a decrease in its strength. The result is repeated subsidence. The activation of the ground movement processes over the longwall goaf due to their flooding has not been studied enough. In this paper, for the geological conditions of thin coal seams typical for the Ukrainian Donbas, ground movement evolution caused by flooding of longwalls goaf was studied. Ansys code was used to analyze the evolution of surface displacement in different hydrogeological conditions. As a result of numerical simulation, it was found that full flooding of the longwall goaf leads to an increase in surface subsidence by 22.4%, while the length of the trough increase by 1.3%. Maximal inclination increases by 34.4%, and maximal curvature – by 74%. This contributes to a significant increase in hazards for surface infrastructure located on the edges of the subsidence trough. The control of the negative impact on surface infrastructure objects, water and agro-industrial objects can be ensured by a timely prediction of ground movement and the implementation of surface controlling methods to prevent critical surface deformations.

1. Introduction

The underground mining causes a failure of the equilibrium state in the rock strata, provokes irreversible deformations and movements of rocks in the undermining zone. Underground mining has a significant influence on ground movement (also known as subsidence), which induces serious environmental disturbances on land [1]. These phenomena have a negative impact on surface infrastructure objects, water and agro-industrial objects, specific objects mining companies such as waste rock dump [2].

In fact, back to the early days of the 1960s, the processes of ground movement and deformations in the zones of longwall undermining had been studied. The study of the subsidence phenomena and its negative impact on surface is carried out by the following methods:

- by field monitoring [3–6];

- by physical similar simulation [7–9];
- by numerical modeling [10–20].

Zhang et al. [3] presented a study of field measurement and numerical simulation on mining-induced subsidence in an area of Northwestern China. The panels with dimensions 241 m wide and over 3000 m long were extracted. It was showed that surface subsidence lags far behind panel extraction; the subsidence influence through the whole length of a longwall panel varies.

Guney and Gul [4] described and discussed the evaluating of the influence of subsidence on irrigation pipeline structure based on the field data using surface deformation prediction system software.

Zhao et al. [5] reported an analysis result of the field investigation of the ground fissures and the establishment of GPS monitoring network. The ground deformation and damage has been monitored and researched for the 10 years. The maximal vertical displacement reached 1,720 mm and accompanied by the rapid development of ground fissures.

Nazarenko and Stelmaschuk [6] developed a spatio-temporal model of the formation of a displacement trough for the conditions of coal mines in Western Donbas based on the results of field instrumental monitoring. A new type of isolines is proposed - chronoisosediments, which characterizing the time and place of occurrence of subsidences.

Zhou and Yu [7] presented results of the physical simulation experiment. Based on the microseismic energy distribution cloud chart, the area of water-conducting fracture zone was divided. After fully mining, the overburden caving height was stable, and the height development range of the water-conducting fracture zone was 100120 m, which is consistent with the height of the overburden caving envelope.

Yanli et al. [8] studied the movements of rocks of the upper layers, which were provoked by mining operations, analyzed the regularities of the evolution of cracks using the methods of measurement and physical modeling.

Stupnik et al. [9] proposed a method to determine quantitative composition of the equivalent material for the study the rock mass stability in the laboratory conditions.

In world practice, the software package Surface Deformation Prediction System (SDPS) has gained wide popularity [10–12]. Based on empirical or site-specific regional parameters, the model quantifies a variety of ground deformation indices for both longwall and high extraction room-and-pillar mines [13].

However, since SDPS is based on statistical analysis, it does not provide an opportunity to investigate the mechanism of activation of subsidence in non typical geological conditions, for example during the flooding of mine roadway system.

Methods of numerical modeling have not these shortcomings. Various software systems are based on the finite difference method (FDM), (FLAC3D) [14, 15], finite element method (ANSYS) [16–20], method of discrete elements [21].

Jeromel et al. [14] presented results of the numerical simulations of sub-level coal mining by FLAC3D. The simulation results are comparable with the values obtained by the in-situ measurements during coal excavation in the Velenje Coal Mine.

Zhao et al [15] presented a case study on predicting the distribution of the ground fissures and water-conducted fissures induced by the coal mining. The analysis of the calculated by FLAC3D movement and deformation of ground surface and strata allowed to predict the distribution of ground fissures and water-conducted fissures.

A finite element analysis was performed by Marian et al [16] to study the state of stresses on the structures of buildings subjected to the impact of underground mining of hard coal seams in the Jiu Valley Basin.

The prediction of subsidence by the finite element method was in the center of attention of scientists of UkrNDMI. For example, Sakhno et al [17] presented the simulation results of ground movement and deformations, which is based on a numerical nonlinear solution by ANSYS. An example of the calculation of displacements for the conditions of the mine "Krasnolymanska" was given. Grishenkov and Golubev [18] presented the results of the numerical simulation of water inflow in mine roadway to the activation of subsidence over a single longwall. ANSYS code is widely used to analyze the stability of rock outcrops [19, 20].

Zhang et al. [21] proposed a locally adaptive remeshing method for FDM modeling of largely deformed surface subsidence induced by underground mining. The effectiveness of the proposed method has been veried by comparing the surface deformation for the Yanqianshan iron mine.

This analysis shows that modeling by numerical methods allows to visualize the process of deformation of rock and the surface and obtain sufficient accuracy of the modeling results.

The basic regularities of the subsidence are sufficiently well-studied and they are the basis of relevant normative documents that take into account regional character. For the conditions of the Ukrainian Donbas, the parameters of the subsidence trough are calculated in accordance with the DSTU 101.00159226.001-2003 "Rules of undermining Earth surface objects" [22]. This makes it possible to predict subsidence in conditions of homogeneous rock with sufficient accuracy.

However, geomechanical processes can differ significantly from idealized ones due to the presence of systems of geological fissures, rock heterogeneity, hydrogeological processes, etc. These special situations are the subject of research of scientists.

Movements of the rock strata can be the cause of changes in the hydrogeological regimes of underground and groundwater. As a result, the risk of flooding of the longwalls goaf increases.

Another phenomenon that is specific for the coal mines of the Ukrainian Donbas is the flooding of the underground roadway at the result of the closure of the mines and the increase in the mine water level. The risk of increased water inflows into roadways system due to mining stoppages caused by military operations is increasing. Flooding causes changes in the physical and mechanical properties of rock mass, provokes the development of deformation processes in the rock strata, and deepens the negative consequences of undermining.

The intensity of flooding and the geometry of flooded zones are determined by technological factors that depend primarily on the technology of longwall mining. Cavities and open cracks are the main ways of underground water transit.

Nowadays, scientists are paying more attention to the impact of undermining on groundwater system and on surface water objects. For example, Booth et al. [23] discussed the impact of mining on groundwater including decline and recovery of water levels. Dawkins [24] discussed potential management and rehabilitation requirements of environmental effects from longwall subsidence on streams, lakes, and groundwater systems.

However, the activation of the ground movement processes over the longwall due to their flooding has not been studied enough. Water saturation of rocks leads to a disturbance of the equilibrium in the rock stratum and to the destruction of previously formed equilibrium vaults, as a result of a decrease in the strength of the rocks. The deformation characteristics of the rocks are also changing. The result is repeated subsidence.

These phenomena show the importance of timely prediction of subsidence and the development of methods for the protection of surface infrastructure objects due to the flooding of the roadways system of coal mines.

In this paper, for the geological conditions of thin coal seams typical for the Ukrainian Donbas, through numerical simulation ground movement evolution at the result of flooding of longwalls goaf was studied. This study provides a characteristic on the influence of mine water rising level of longwalls goaf on the activation of subsidence.

2. Characteristics of the study area

The case study mine is located in the west-southern part of Pokrovsk region, Donbas, Ukraine.

The Selidove city is located near the western border of the mine field. The villages of Novomykolaivka, Mykhailivka and Kotlyarevka are located within the boundaries of the mine field and near it. Mykhailivka and Marynivka villages are located in the undermining zone.

The average annual water inflow is 500 m^3/year. The rock strata above the southern part of the mine field, namely 1 and 2 the southern longwall the l1 seam, are the objects of the study.

The average thickness of the coal seam in the studied area was 1.05 m, the dip angle varied from 11 to 13 degrees. The research area included two longwall goafs. The depth of the ventilation roadway of the 1th southern longwall of the l1 seam is 376 m; the depth of the conveyor roadway of the 1th southern longwall of the l1 seam is 476 m.

The Donetsk-Novogrodivka highway, Donetsk-Selydove highway and Mykhailivka village located on the undermining surface. The part of the mine plan with surface objects is shown in figure 1.

The highway Donetsk-Selidove is in the undermining zone of southern longwalls. At the same time, the highway located almost perpendicular to the seam strike line. This line is marked as a section line (figure 1) for a numerical simulation.

3. Methods

We used method of numerical simulation and method of engineering and graphic analysis to investigate surface subsidence in undermining zone.

During the analytical analysis of ground movement elements on land, calculations and graphic constructions were carried out, in accordance with the recommendation of normative document DSTU 101.00159226.001-2003 [22].

Traditional ideas about overburden deformation zones caused by longwall subsidence were accepted. The height of the caved zone was taken equal to 8 times the thickness of the seam. The height of the fractured zone was 60% of the length of the longwall, which corresponds to generally accepted ideas [25–27].

Mine water level rise and goaf flooding were modeled in two stages. At the first stage, the height of the flood level was 40% of the height of the fractured zone, at the second stage – 100% of the height of the fractured zone. Schemes of deformation zones caused by longwall subsidence and subsequent flooding are shown in figure 2.

Finite element analysis software system Ansys was used. The modeling was carried out in a volume setting on a natural scale. Due to the obvious symmetry of the model with respect to the length of the panel, the thickness of the model was assumed to be much smaller than its other dimensions and was 10 m. The sidewalls of the model were fixed from the corresponding normal displacement, the bottom boundaries – from vertical displacement. The model was loaded by gravitational forces. The Drucker-Prager model was used to simulate the behavior of rock mass.

The initial data for numerical simulation (modulus of elasticity, Poisson's ratio, cohesion value, angle of internal friction and angle of dilatancy) were taken from the cadastre of physical rock properties [28], according to the stratigraphic column. At the same time, the rocks were modeled as heterogeneous. The variation of the physical and mechanical properties of rocks along and across the layering was determined according to the methodology proposed Sakhno et al [29], which is generally consistent with the research of Rzhevsky.

The excessive detail during modeling was avoided trough grouping of rock properties according to their strength, using average index. The rock strata were combined into groups, where their strength difference was less than 25%. This approach is permissible, since the aim of simulation was not to study the deformation of the rock strata in the undermine zone, but to analyze the surface subsidence.

The general view of the finite element model with its dimensions is shown in figure 3.

The study consisted of three cases:

(i) basic model (no flooding);

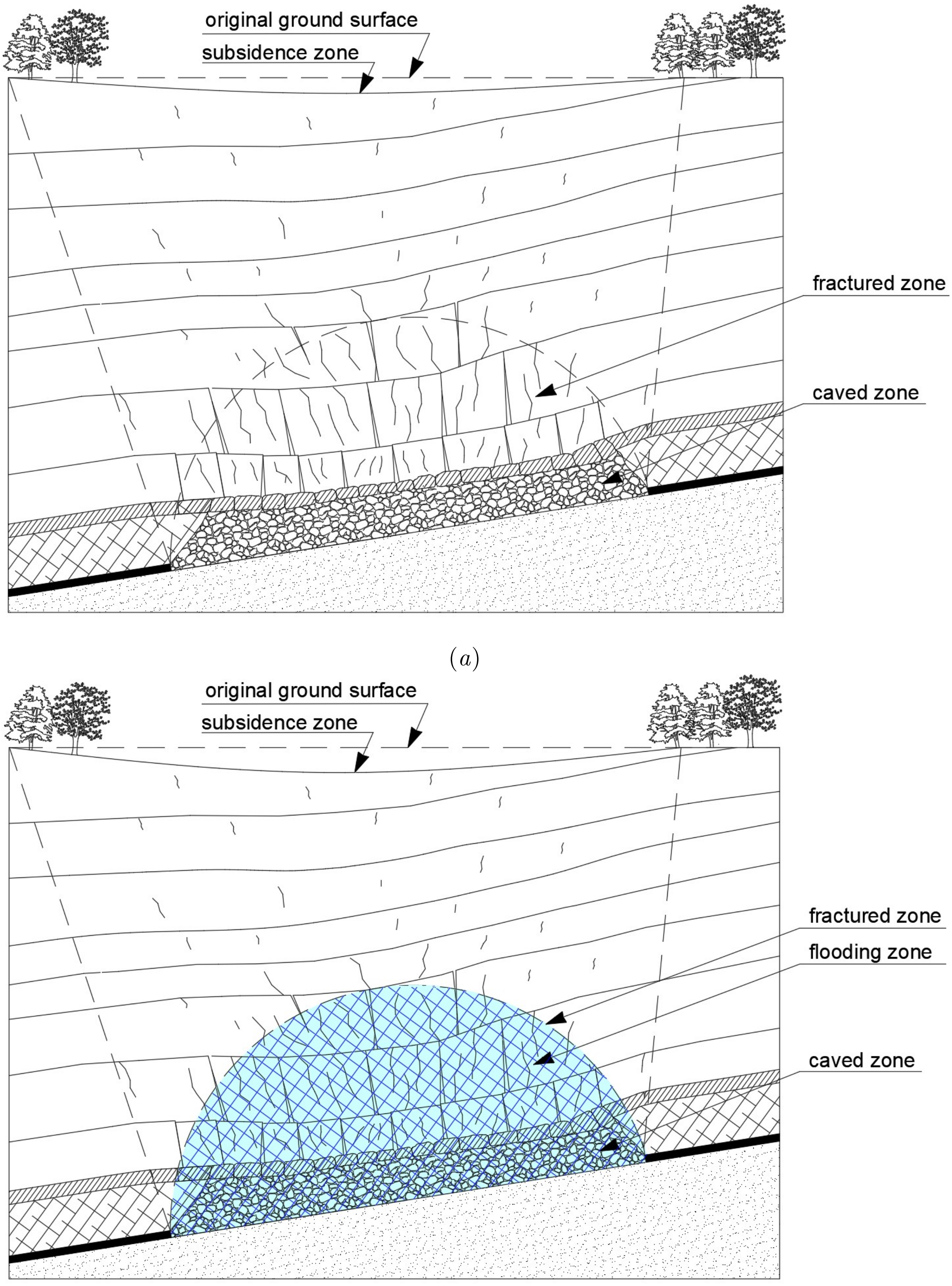
(A-A – section line)

Figure 1. Mine plan and the surface objects.

(ii) model with flooding of 40% of the fractured zone;

(iii) model with flooding of 100% of the fractured zone.

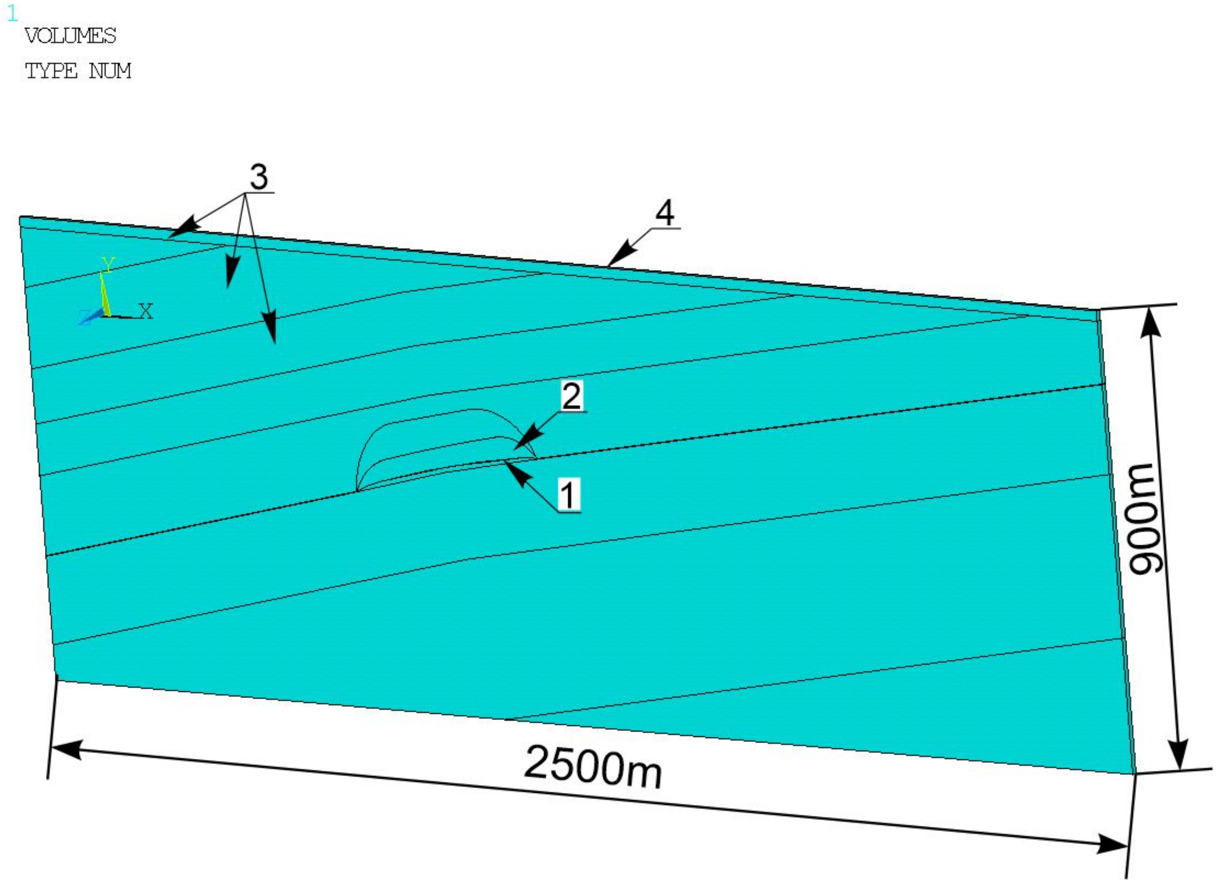
The geometry and grid of finite elements in the models were the same, which made it impossible to accumulate calculation errors.



(*a*)

(*b*)

Figure 2. Overburden deformation zones caused by longwall subsidence: (*a*) before flooding; (*b*) after flooding.



(*1 – caved zone; 2 – fractured zone; 3 – rock strata; 4 – ground surface*)

Figure 3. General view of numerical model geometry.

The simulation was carried out step by step as follows.

Step 1: Loading the model with gravity, followed by writing the values of stresses and displacements in all nodes of the model to a file using the Inistate command in ADPL.

Step 2: Reading the recorded file with values and recalculating the model for zeroing displacement. In this case, a situation of the initial stress-strain state of the strata was obtained.

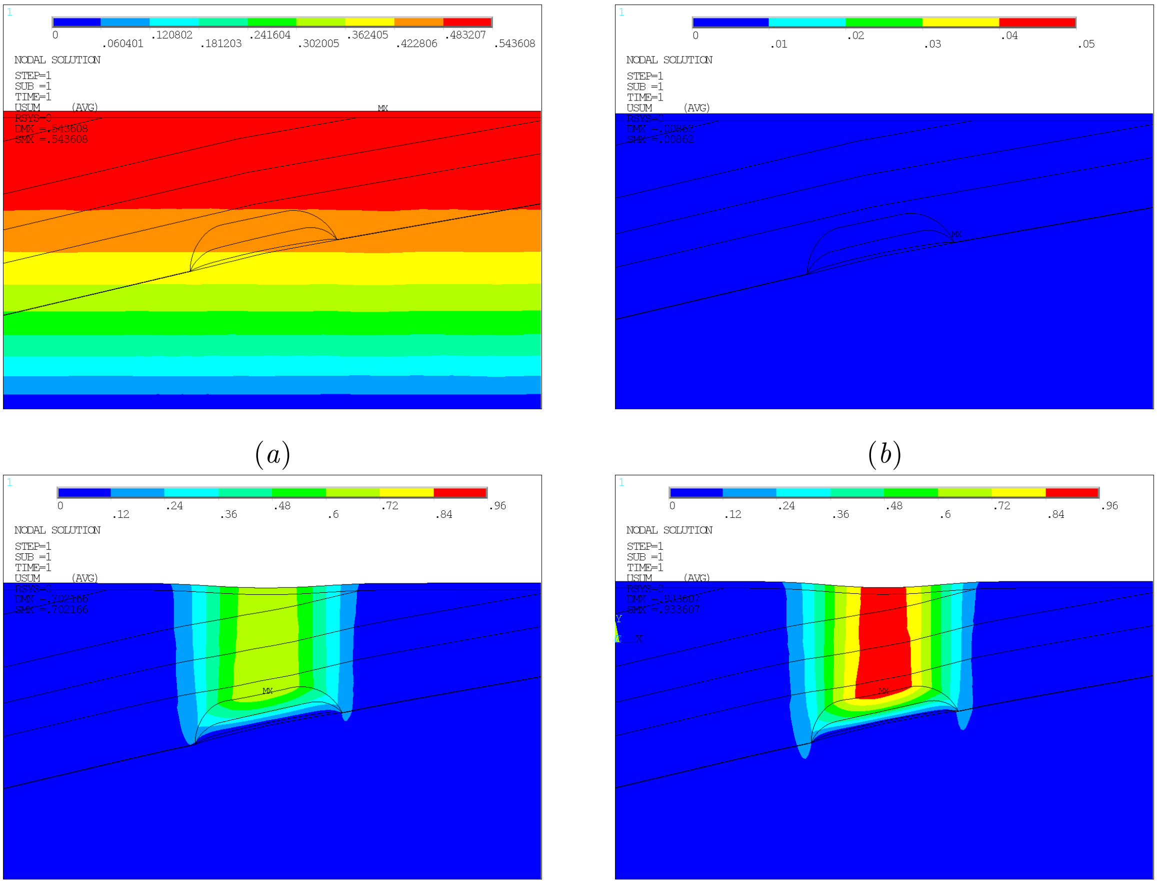
Step 3: Modeling of coal excavation and formation of caved zones and fractured zone (basic model).

Step 4: Simulation of flooding 40% of the fractured zone.

Step 5: Simulation of flooding 100% of the fractured zone. The patterns of vertical displacements in the model, which correspond to the described steps, are shown in figure 4.

To simulate the behavior of rocks in the caved zone and fractured zone, the correction of their properties was used, taking into account the fracturing. For this, the Hoek-Brown criterion was used [30].

To take into account the influence of moisture on the rock properties, the deformation modulus in the flooding zone was reduced and Poissons ratio was increase. The basis of this decision is



(*a*) (*b*)

(*c*) (*d*)

Figure 4. Displacement patterns with a step-by-step modeling (displacement scale 20:1): (*a*) step 1; (*b*) step 2; (*c*) step 3; (*d*) step 5.

numerous experimental study [31–34]. Obviously, this influence depends on many factors, first of all, on the type of rocks and the degree of water saturation.

Sakhno et al. [35] showed that the deformation modulus for wet rock (E_w) can be expressed as:

$$E_w = E 1.0076 e^{-0.239\Delta w}, \text{GPa} \tag{1}$$

where: E – deformation modulus of dry rock (MPa); Δw – water increase (%).

The rise of water level was simulated, therefore the maximum water saturation of the rocks was taken. The properties of the rocks that were used during the simulation are shown in table 1.

4. Results and discussion

The adequacy of any mathematical model is characterized by the divergence of the results obtained during its use with real values in-situ. Since monitoring of surface subsidence was not carried out in this study, the verification and calibration of the basic model were performed with predicted subsidence determined by normative document DSTU 101.00159226.001-2003 [22].

A safe depth 440m was calculated. It has been established that mining was conducted above the level of safe depth. That may cause subsidence of the surface exceeding the permissible ones.

Table 1. Input data for numerical modelling.

	Density, kg/m^3	Elastic modulus, MPa	Poissons ratio	Cohesion, MPa	Angle of internal friction, deg	Dilatancy angle, deg
			Quaternary rock mass			
1	2100	15-9	0.25	5.5-4.7	25	5
			Bed rock mass (continuous zone)			
2	2500	20-9	0.17-0.25	6.4-5.35	32	32
			Caved zone (dry)			
3	2500	0.6	0.25	–	–	–
			Fractured zone (dry)			
4	2500	0.9	0.25	–	–	–
			Caved zone (wet)			
5	2500	0.4	0.30	–	–	–
			Fractured zone (wet)			
6	2500	0.6	0.30	–	–	–

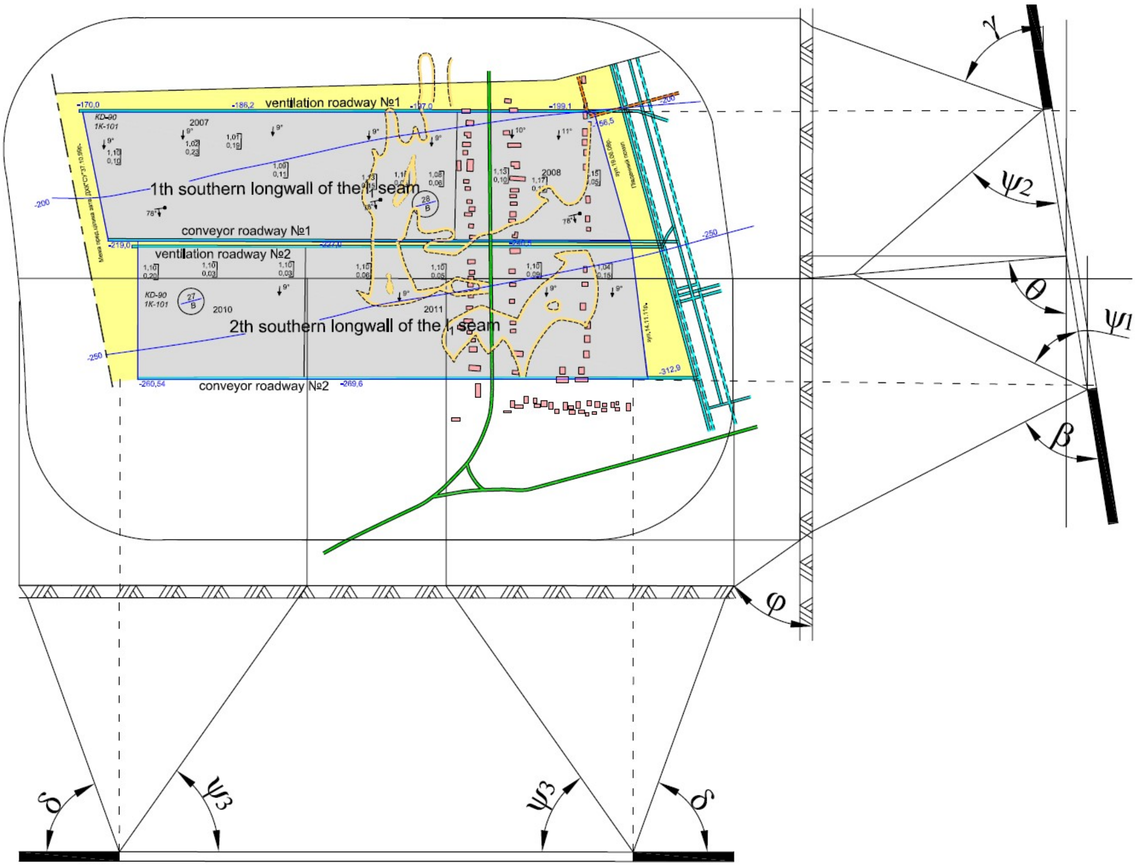


Figure 5. Subsidence trough (in accordance with DSTU 101.00159226.001-2003 [22]).

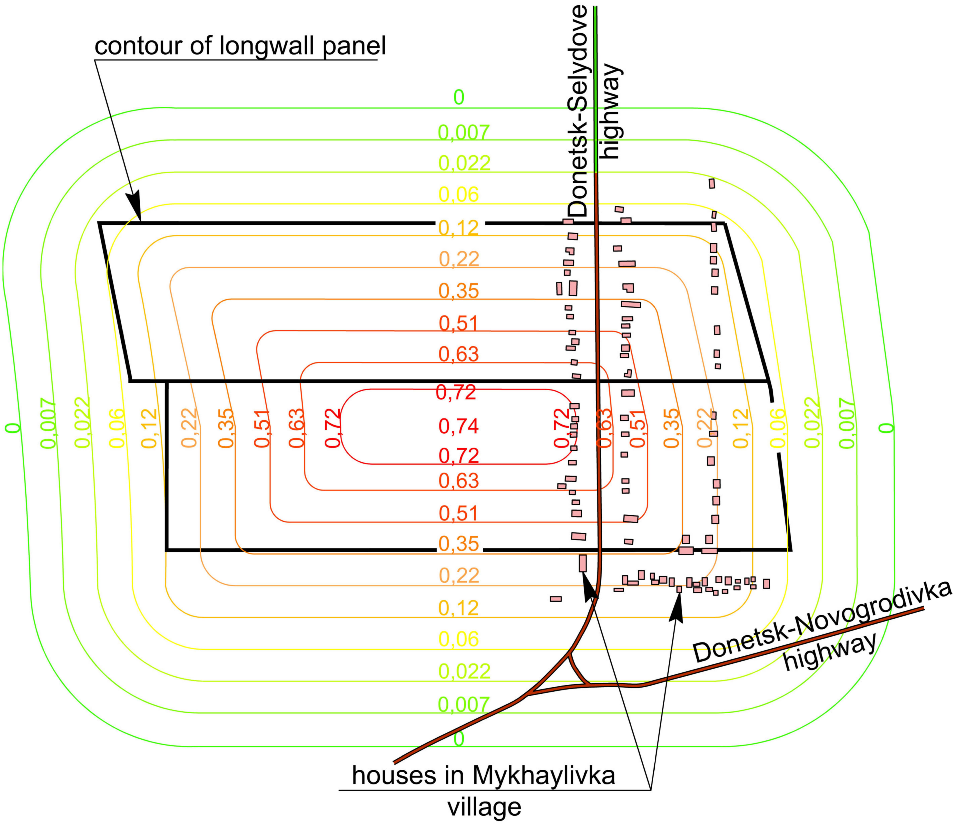


Figure 6. Isolines of subsidence caused by undermining.

The results of the graphic calculation of the subsidence trough with the corresponding cross sections are shown in figure 5.

Initial parameters of the subsidence process [22]: limit angle $\delta = 70^o, \gamma = 70^o, \beta = 63^o, \psi_1 = 55^o, \psi_2 = 58^o, \psi_3 = 55^o$, maximum subsidence angle $\theta = 83^o$, maximum possible surface subsidence $\eta_{max} = 0.74$ m.

Plan of subsidence isolines caused by undermining of 1th and 2th southern longwalls of the seam l_1 is shown in figure 6.

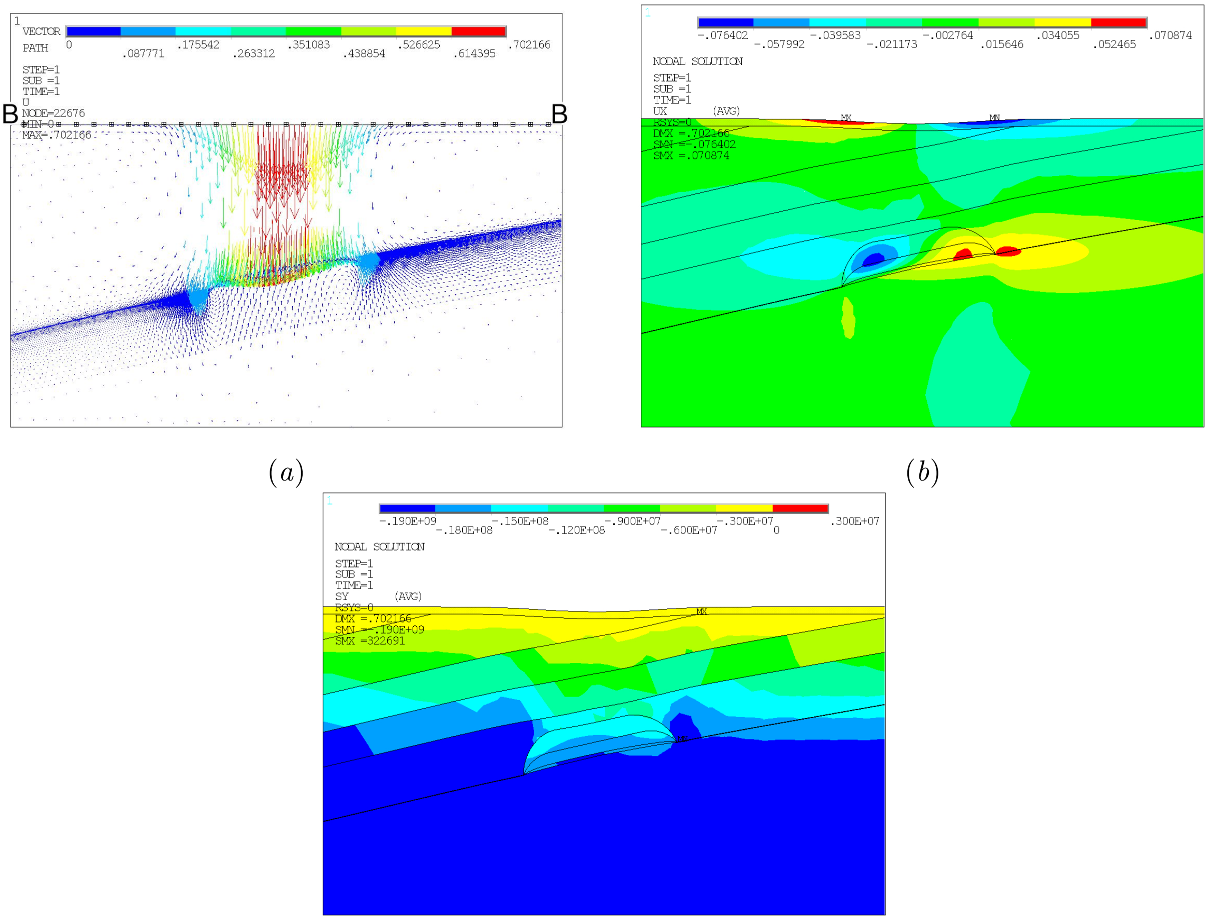
As can be seen from figure 6, Donetsk-Novogrodivka highway, Donetsk-Selydove highway and Mykhailivka village are located in the mining influence zone. Some houses are located above the zone of maximal subsidence. The results of numerical simulation for the base model are shown in figure 7.

The scale for converting colors in digital format is shown in the upper parts of the figures. Numerical designations on the scale line of figure 7a, b are given in meters, in figure 7c – in Pascals. In order to more clear display of the subsidence trough boundaries, the scale of displacement in figure 7 is increased by 20 times.

At the first stage of simulation process, the numerical model was calibrated. For this purpose, graphs of displacements and curvature along the B-B line were made (figure 8) and their convergence with the results of settlement calculations according to the DSTU 101.00159226.001-2003 was checked [22].

As can be seen from figure 8, the numerical model allows to adequately describe the process of surface deformation.

The maximal vertical displacement in the numerical model is 735 mm. The maximal vertical



(*a*)

(*b*)

(*c*)

(*B-B – monitoring line*)

Figure 7. Base model simulation results (displacement scale 20:1): (*a*) pattern of displacement vectors; (*b*) pattern of horizontal displacements; (*c*) pattern of vertical stress.

displacement that was calculated according to DSTU 101.00159226.001-2003 [22] is 738 mm. In the model, the displacement at the border of the trough subsidence is equal to 7 mm at a distance of 40 m from the longwall axis, according to normative document [22] – 380 m. Thus, the respective divergences are –0.2% and +4%.

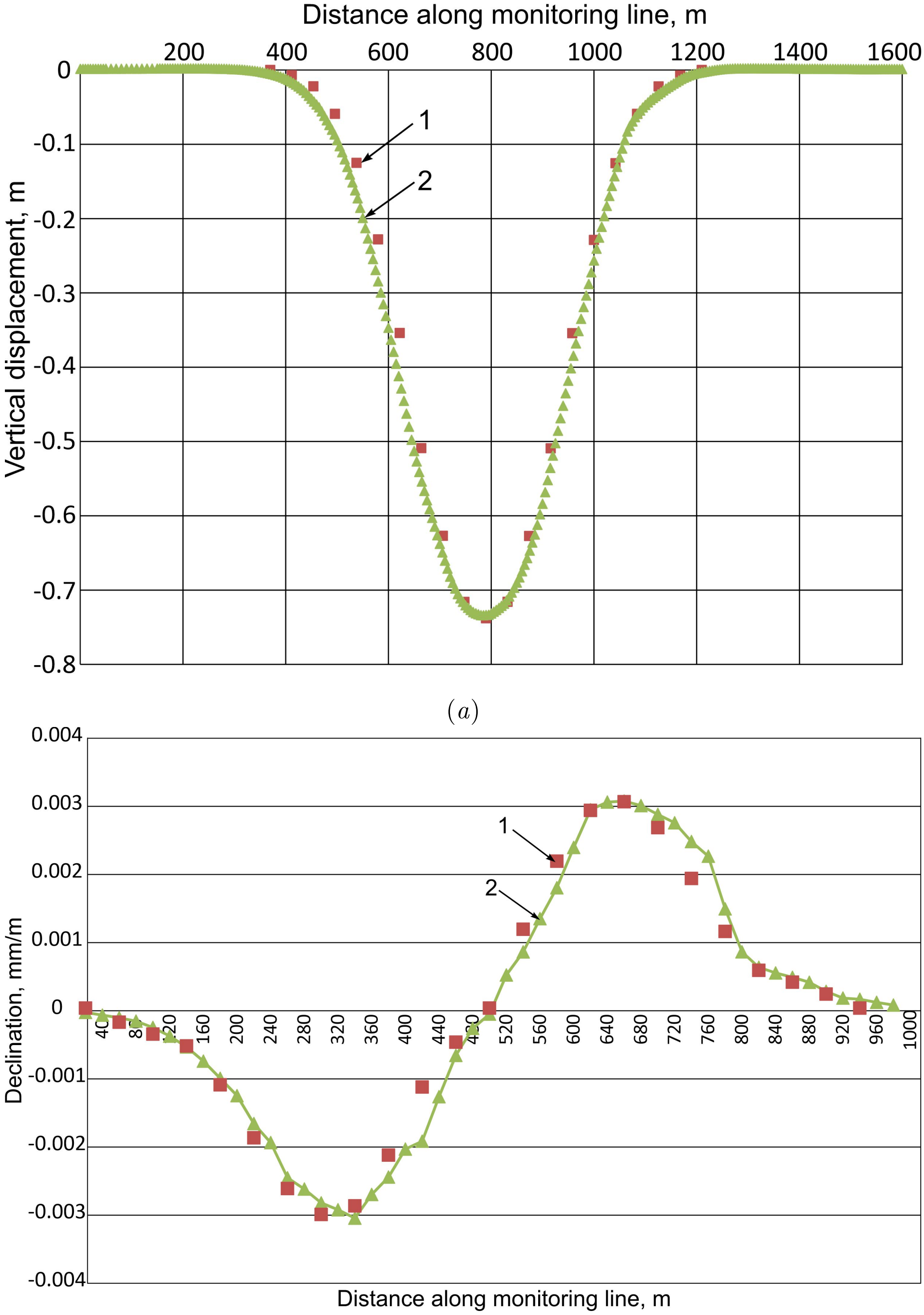
The maximal inclination in the model is 0.003082, calculated according to [22] – 0.003029; the divergence is 1.7%. The mean squared error of the simulation results for the inclination factor is 5.23%, for the vertical displacement factor is 5.1%. Such results are quite acceptable.

In the next stage of modeling, flooding of the longwall goaf was simulated in two stages (40% and 100% of the total height of the fractured zone). The simulation results are shown in figure 9.

The graphs of subsidence, inclinations and curvatures are shown in figure 10.

After the first step of flooding, the maximal subsidence increases to 821 mm, i.e. by 86 mm (11.7%), after the second step of flooding – to 900 mm, i.e. by 165 mm (22.4%). At the same time, the length of the subsidence trough during flooding increases by only 5 m (1.3%).

The simulation result shows that the length of the subsidence trough increases less significant than the maximal subsidence, thus, flooding provokes the increase of inclination, curvatures and horizontal displacements.

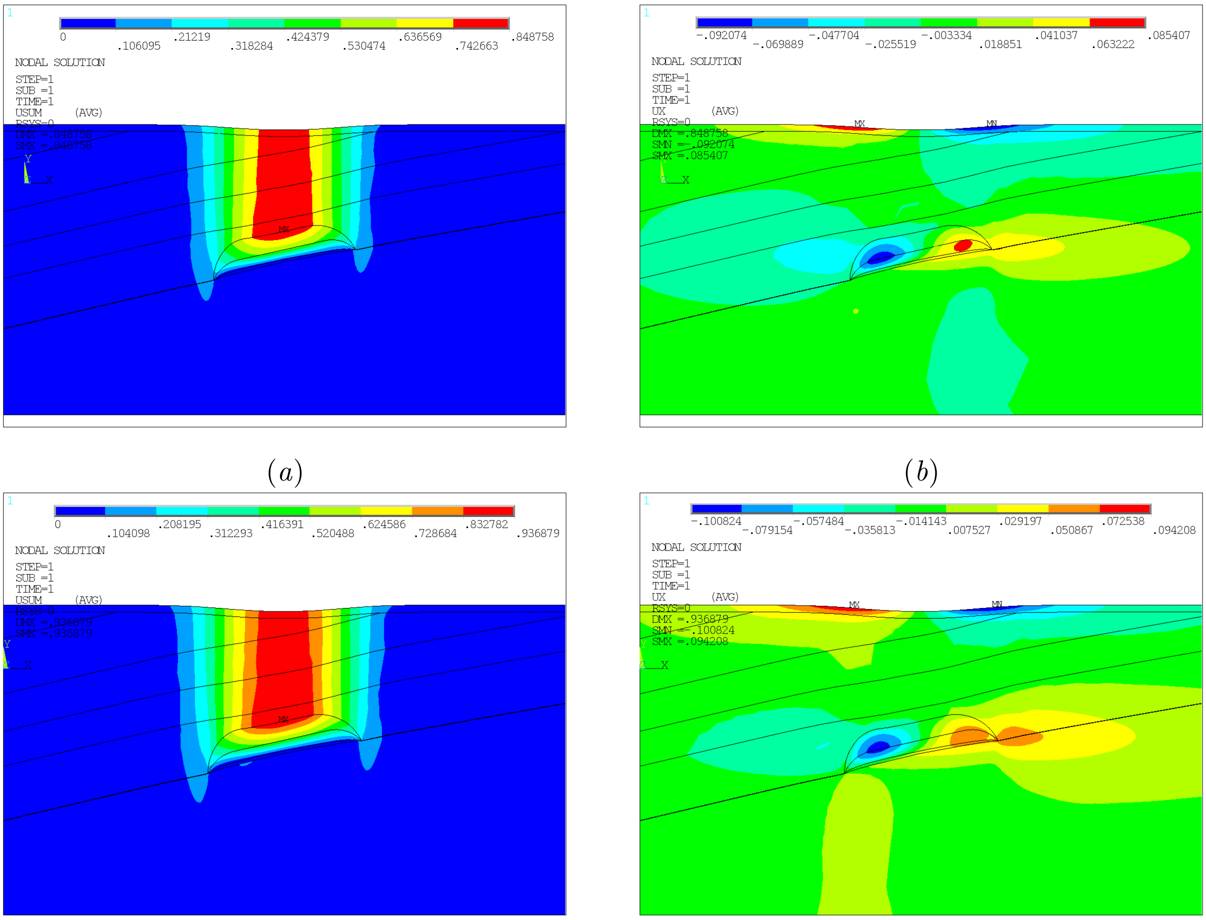


(*a*)

(*b*)

(*1 – according to the DSTU 101.00159226.001-2003 [22], 2 – numerical simulation results*)

Figure 8. Graphs of vertical displacements (a) and inclination (b) along the B-B line.



(*a*) (*b*)

(*c*) (*d*)

Figure 9. Distribution of vertical and horizontal displacement during the first (a, b) and second (c, d) steps of flooding (displacement scale 20:1).

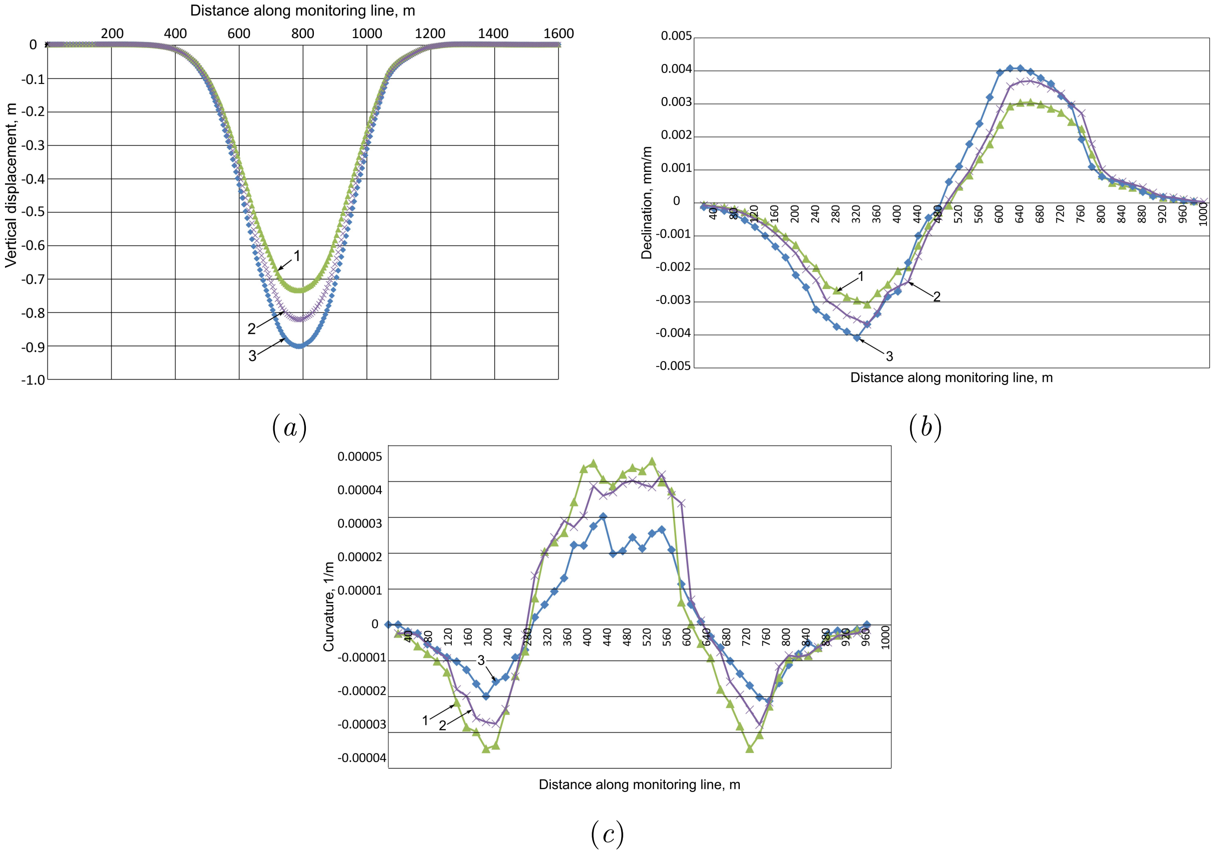
The maximal inclination as a result of full flooding of the fractured zone, according to the simulation results, increases from 0.00302 to 0.00406 (by 34.4%). Flooding by 40% of the height of the fractured zone leads to an increase in maximal inclination from 0.00302 to 0.00368 (by 21.8%).

Curvature at the edges of the trough subsidence increases from 0.0000200 to 0.0000348, and in the central part of the trough – from 0.00003032 to 0.00004525, by 74% and 49% respectively.

The increase of maximal subsidence, inclination and curvatures occurs disproportionately to the goaf flooding height. Thus, flooding by 40% of the height of fractured zone leads to an increase of maximal subsidence on 52.1%, maximal inclination on 63.4% and maximal curvature on 48.9% respectively.

Thus, flooding leads to activation of surface deformation. This cause increased hazards for surface objects, especially at the extension trough zone. For the case study, the risk of destruction of houses in the Mykhailivka village, which located in the subsidense prone land, increases. In addition, the risk of destruction of the Donetsk - Selidove highway, which is located in the area of subsidence impact, increases.

The current study is based on the results of numerical modeling and represents a theoretical solution. In the future, field monitoring is planned to confirm and verify the obtained results.



(1 – before flooding, 2 after flooding of 40% of the fractured zone, 3 – after flooding of 100% of the fractured zone.)

Figure 10. The graphs of subsidence (*a*), inclinations (*b*) and curvatures (*c*) in the undermining zone (along monitoring line B-B) (displacement scale 20:1).

Modern methods of the surface monitoring allow making large areas observation quickly [3, 36]. This significantly save time and human resources for field measurement.

This study opens up opportunities for development of different ways of surface subsidence control. The goaf backfilling is one of the most well-known control methods of strata deformation. Backfilling in Ukraine is carried out mainly for the conditions of ore deposits [37, 38]. The theoretical studies are also carried out for coal deposits [39–41]. The presented study is planned to develop in this direction.

5. Conclusions

This paper presents the numerical simulation results of the longwall goaf flooding impact on the activation of ground movement during excavation of thin coal seams.

Based on the results of this investigation, the following conclusions can be drawn:

1. One of the characteristic phenomena with which the future of the Ukrainian Donbas is connected is the flooding of the longwalls goaf of coal mines. The risks of mine roadways flooding are increasing as a result of military operations in Ukraine. Therefore, save of the surface objects from the negative impact of undermining is becoming one of the urgent problems. Timely planning and development of control methods require an adequate prediction of subsidence evolution caused by mine roadways flooding.

2. The finite element model was created in the Ansys code, which allows to predict the ground movement caused by underground coal mining. The error of the trough subsidence calculation did not exceed 6%.
3. It was showed that the longwall goaf flooding leads to the activation of the subsidence process. As a result of the analysis, it was proved that the flooding on the full height of the fractured zone above the longwall goaf leads to an increase in subsidence by 22.4%, while the length of the trough increase by 1.3%. Maximal inclination increases by 34.4%, and maximal curvature – by 74%. This contributes to a significant increase in hazards for surface infrastructure located on the edges of the subsidence trough. Risk decrease for surface infrastructure can be ensured by timely prediction of subsidence and implementation of surface controlling methods.

ORCID iDs

I Sakhno `https://orcid.org/0000-0002-8592-0572`
S Sakhno `https://orcid.org/0000-0003-3917-9143`
A Petrenko `https://orcid.org/0000-0002-6324-0541`
O Barkova `https://orcid.org/0000-0002-2572-8415`
B Kobylianskyi `https://orcid.org/0000-0002-826-1123`

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