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NUMERICAL SIMULATION OF UNDERGROUND MINING EXPLOITATION INFLUENCE UPON TERRAIN SURFACE

MODELOWANIE NUMERYCZNE WPŁYWU PODZIEMNEJ EKSPLOATACJI GÓRNICZEJ NA POWIERZCHNIĘ TERENU

Underground mining exploitation may result in mining damages to building objects located on a terrain surface. Considering high harmfulness of this phenomenon, the scientists from all over the world have tried to describe impact of underground exploitation on deformations of terrain surface and objects located thereon. The first theories, based on the Gaussian distribution, have emerged in the 1950s and are in use until now. Later on, in connection with development of computational techniques, their availability and numerical methods, a possibility of numerical computations use for forecasting of deformations has emerged. These methods, when suitable numerical models are adopted, enable to include higher number of factors influencing the results being obtained. When constructing numerical model, particular attention should be paid on selection of: appropriate geometry of model, proper constitutive model describing behavior of rock and soil layers, adequate values of rock mass parameters prior to execution of mining exploitation, and after it. The author presented in this article part of these problems, based on own experience.

Keywords: numerical modelling, finite element modelling, underground excavation, rockmass classification, ‘‘Back analysis’’ method

Podziemna eksploatacja górnicza może wywołać szkody górnicze w obiektach budowlanych znajdujących się na powierzchni terenu. Z uwagi na wysoką szkodliwość tego zjawiska naukowcy z całego świata próbowali opisać wpływ eksploatacji podziemnej na deformacje powierzchni terenu i obiektów na niej się znajdujących. W latach pięćdziesiątych pojawiły się pierwsze teorie oparte na rozkładzie Gaussa które stosowane są po dzień dzisiejszy. Później w związku z rozwojem technik obliczeniowych, ich dostępności oraz metod numerycznych pojawiła się możliwość wykorzystania obliczeń numerycznych do prognozowania deformacji. Metody te przy przyjęciu odpowiednich modeli numerycznych pozwalają na ujęcie większej liczby czynników wpływających na uzyskiwane rezultaty. Przy budowie modeli numerycznych należy zwrócić szczególną uwagę na dobór: odpowiedniej geometrii modelu, właściwego

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modelu konstytutywnego opisującego zachowanie się warstw skalnych i gruntowych, odpowiednich wartości parametrów górotworu przed przeprowadzeniem eksploatacji i po przejściu eksploatacji. Autor w niniejszym artykule przedstawił część tych problemów bazując na własnym doświadczeniu.

Słowa kluczowe: modelowanie numeryczne, eksploatacja podziemna, klasyfikacje geotechniczne, metoda ‘‘Back analysis’’

1. Introduction

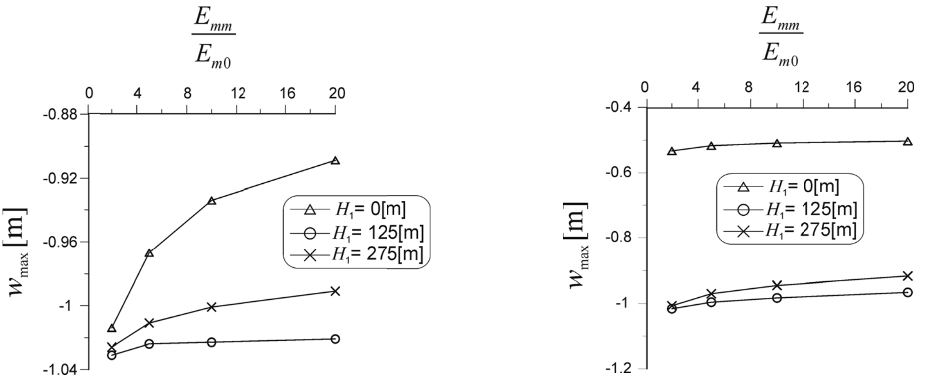
Leading of underground mining exploitation results in mining damage arising on the terrain surface, in the form of: collapse sinks, craters and subsidence troughs. They constitute serious problem on many areas, resulting in damages in building objects, which consequences, including the economical ones, are considerable (Rusek, 2009). Prevention of the damages is based to a large degree on forecasting them. Until now, forecasting methods developed in 50s of the last century are in use over the world, from among of which one can distinguish: the methods based on normal Gaussian distribution of influences, such as the Ruhrkohle method, the Knothe method; empirical methods such as: the NCB method or the „Senkungsschwerpunktes” center of gravity methods, for example: the Bals method, Keinhorst Beyer method, etc. The methods based on normal Gaussian distribution of influences have found the widest application, and are commonly in use to date in the Europe, USA, Canada, China, etc. The above listed methods have many advantages, and among them: simplicity of assumptions and solutions, availability (there are many computer applications using this method), the lessons learned during their use since over 60 years, selection of the method parameters for various mining-geological and mining conditions, etc. Simplifications used in them, however, which do not take into account to the proper degree many significant features of rock mass structure, its composition, quality of rock layers, water inflow, etc, may in many times lead to obtaining of computation results significantly deviating from results of measurements. This applies in particular to regions of high exploitation intensity. Construction of adequate numerical models and executing of computations by means of numerical methods (Finite Element Method, Finite Difference Method, etc.) appears the solution enabling taking into account a number of those factors. The problem has been addressed by many scientist both domestic and world ones, using various methods and trying with various results to adapt them to local mining and geological conditions.

Construction of numerical models is crucial issue here. When constructing them, particular attention should be paid on selection of : *appropriate geometry of model*, *proper constitutive model, describing behavior of rock and soil layers, adequate values of rock mass parameters prior to execution of mining exploitation and after it.* For the numerical model selected, computations are executed and their results analyzed. The analysis of the results, and also in some instances, comparison of obtained results with measured ones, enables to realize whether the model has been adequately selected.

2. Selection of model geometry and problems connected with it: i.e. adequate size of the model, consideration given to rock layers, consideration given to natural discontinuities, etc.

Proper selection of the model geometry is one of the essential problems for modeling the phenomenon of underground exploitation influence on the terrain surface. The model should have such dimensions, so that to take into account the most important elements of the underground exploitation being modeled and range of its influence on surrounding rock masses, structure of the rock masses, past exploitation (goafs), etc. It should be taken into account that goafs (present in many mines) in effect of reactivation may cause significant changes of state of stresses range and deformations in rock masses, or result in local increase of fractured zones. Furthermore the mining exploitation causes substantial destruction of rock layers within overburden. The degree of their destruction depend both on exploitation parameters (height of gate, length and run of longwall panel, etc.) and properties of the layers: their strengths, thickness, etc., and the pressure acting on them. It is generally recognized that two zones of main weakening are created, differing from each other with a degree of original rock structure damage. The first one: *the caved zone*, developing within immediate roof and partly in the principal roof, characterized with damage (significant fracturing and disintegration of rocks), creation of separate rock blocks, which are displacing themselves towards selected space, while experiencing rotations and in consequence filling the created void in chaotic manner. Over it a *fractured zone* develops, characterized with fracturing of rocks, sometimes leading to creation of separate rock blocks, which undergo to vertical and, to the lesser degree, horizontal displacements, small rotations (wedging of rock blocks is locally possible). Height and range of the zones: the break down and fractured one, influence values of deformation indices, value of vertical displacements in particular. It results from earlier completed computations (Tajduś, 2009) that increase of caved zone height leads to approximately linear increase of maximum terrain surface subsidence value $w_{\max}$ and increase of exploitation influences reach. Whereas change of caved zone shape has relatively small influence on $w_{\max}$ value, distribution of surface vertical displacements and reach of exploitation influences. The laminar structure of rock masses is subsequent element that should be taken into account in modeling process. Completed FEM numerical analyses (Tajduś, 2009) demonstrated that presence of layers featuring high strength parameters (so called "strong layers") within overburden of a seam under exploitation, has deciding influence on value of dislocations within the exploitation region. Existence of "strong layers" within overburden structure significantly reduces value of displacements on surface, as compared to uniform rock mass having medium and low strength parameters. The dislocations on the terrain surface depend also on the location in which the "strong layers" are present. The maximum decrease of terrain surface vertical dislocation takes place, when "strong layers" are located near the terrain surface (which is very rare case) or directly over the seam under exploitation (which is directly connected with reduction of caved zone (fig. 1). Whereas presence of "strong layers" within overburden does not significantly influence the reach of main influences over the terrain surface (Tajduś, 2009).

The model size is highly influenced also by tectonic conditions present within the region of executed exploitation. It has been found on the grounds of experiences and observations of many numerical computation results, that significant tectonic dislocations within radius of influence reach from the edge of exploitation being modeled should be taken into account. It comes from the computations that faults significantly change distribution of dislocations, vertical ones in



a) thickness of the "strong layer" 25 m

b) thickness of the "strong layer" 50 m

Fig. 1. Reduction of maximum vertical dislocation value of surface with increase of ratio of the values: "strong layer" elasticity modulus (E_{mm}) to elasticity modulus of overburden layers (E_{m0}) for various distance of the "strong" layer of overburden from the seam (H_1) (Tajduś, 2009)

particular, leading to creation of discontinuous dislocations on surface. Value of displacements is essentially influenced by value of friction factor, present on the fault contact (the fault fissure). In order to take into account an existing fault, it is necessary to know: the geometrical parameters of the fault, type of contact and its geomechanical properties, quality of fault fissure fill, degree of humidity, and the like (Cieślik & Tajduś, 2011).

Taking the all of these factors into consideration leads to significant increase of model dimensions, and in consequence, increase of numerical model elements and elongation of computation time. Size of numerical model can be in many instances reduced by use of symmetry rule.

3. Selection of constitutive model describing behavior of rock mass within mining exploitation region

The first numerical models used isotropic elastic model for description of rock mass behaviour within region of mining exploitation. It has been assumed in them that whole rock mass behaves in elastic manner, linearly-elastic as a rule. As time passed, the models have been subjected to modification in order to obtain adequate values of subsidences and reach of main influences. The following have been created, among others: elastic models with inter-layer contact modeled (Shippman, 1975; Salamon et al., 1993), elastic models that „do not transmit tensile forces" (Chrzanowska-Szostak, 1988), elastic models with contact on boundaries of influences reach, and the like. In majority, however, these models did not bring about expected results, and discrepancies between measured and calculated values of dislocations and shapes of troughs were significant, particularly in scope of influences reach.

The subsequent group of models that should have adequately simulated deformation or rock mass developed in result of underground exploitation, were elastic-plastic models (Siriwardane, 1985; Dahl, 1972; Najjar & Zaman, 1993; Whittacker & Reddish, 1989). Utilisation of the models, however, have not resulted in obtaining of satisfying results to date, although efforts to use them for description of rock mass deformation in result of underground exploitation are still being undertaken. The author have also approached to use an elastic-plastic model for simulation of mining exploitation impact on terrain surface for the region of the „Siersza" hard coal mine (Tajduś et al., 2009). The computations with use of Coulomb-Mohr elastic-plastic model, completed for eight computational variants differing from each other with strain and strength parameter values, have not yielded expected results, i.e. the results obtained from numerical computations were significantly different from the results of in-situ measurements. Subsidence troughs obtained for these models had significantly larger reach of deformations, while tilt values obtained were significantly lower than those measured in-situ.

The subsequent measurements and observations of rock mass nature within mining exploitation region have demonstrated that after the exploitation, high anisotropy is noted between elastic-strength parameters in vertical and horizontal directions as compared to their values for layered rock mass intact with exploitation. The fractures developed in effect of mining operations result in change of the anisotropy character, i.e. considering a number and type of fractures, the layered anisotropic model changes the plane of isotropy from the plane parallel to lamination to a plane parallel to an axis of fractures (Tajduś, 2009). Because of high number of fractures, the above-mentioned caved and fracturing zones are developing within immediate vicinity of a seam under exploitation.

It comes from experience of the author (Tajduś, 2009) to date, that the model which best describes the behavior of overburden within exploitation region, should possess the following structure:

- a caved zone should be modeled immediately over exploited seam, and a fractured zone above it, with heights and shapes described in the work (Tajduś, 2009). Considering heavy damage of rocks in these zones, assumption of continuous elastic model having equivalent strain and strength parameters seems to be most adequate for them (the properties are determined as combination of strength and strain properties of individual discontinuities and rock blocks). Because the zones differ with degree of destruction, number of fractures, the strain and strength parameters within caved zone will be significantly lower than the parameters within fractured zone.
- for so-called deflection zone, located between fractured zone and terrain surface, it is possible to adopt anisotropic model (transversal-isotropic one, Tajduś, 2009), having adequate strain and strength parameters. Selection of adequate strength and strain parameters of rock mass strata within disturbed regions and also those not disturbed with exploitation, is extremely difficult task. One of possibilities to solve this problem, is use of geomechanical grading.

4. Selection of strain and strength properties for rock mass strata non-disturbed and disturbed with exploitation

Prior to making use of geomechanical classification, possibly the highest number of testing results completed in situ, as well as laboratory results from the region covered with mining exploitation should be collected. This gives preliminary view on the geomechanical condition of the region under consideration. Because the area of interest covers high volume of rock mass, therefore it would be beneficial to use proper geomechanical classification for evaluation of strength and strain parameters. Such classification makes possible to consider many properties of rock mass, such as: conditions of rock strata deposition, degree of disturbance, divisibility and blockability, laboratory physical and chemical properties, hydrogeological conditions, original state of stress, etc. The work (Tajduś A. et al., 2012), presents several classification systems used in geomechanics, constituting relatively simple and useful tool, assisting engineering designing system.

Use of classification for the region, where underground exploitation has been completed, is much more difficult task because the rocks have been subjected to fracturing and dislocation in result of rock mass movements. The author of the work has completed a research on adaptation of geomechanical classification for rock strata subjected to mining exploitation influence for 11 regions of Polish hard coal mines (Tajduś, 2010). The quality of rock mass was assessed by him in the research by means of modified Hoek geomechanical classification (*GSI*). Identical proceeding has been used for each of 11 regions of mining exploitation being considered. The first stage covered construction of transversal-isotropic model of rock mass, describing the mining-geological condition together with exploitation in specific mine, to include also caved and fracturing zones. Initial values of strain parameters for rock strata have been selected by means of GSI classification, with use of laboratory values of rock strata parameters. After completion of numerical computations, he has been comparing the obtained results of terrain surface subsidence with the results obtained from land surveys. In case significant differences have been found, then he has been changing in proportional manner the values of strain parameters for rock strata under modeling (E_1, E_3). The scheme has been repeated until good matching of shape and dislocation values for computed subsidence trough and measured one have been obtained. In effect of completed computations he obtained values of elastic moduli for rock strata present in considered Polish mines. It comes from these computations that for transversal-isotropic model value of elastic module for vertical direction, E_3, has significant influence on maximum subsidence value $w_{\max}$. Whereas the value of elastic module for horizontal direction, E_1, significantly influences a shape of subsidence trough. Value of E_3/E_1 ratio is responsible for tilt of subsidence trough. This model has adequately evaluated state of stress, strain and dislocation, both inside the laminar rock mass, and also on terrain surface.

5. Example of numerical modeling of exploitation influence on terrain surface

Numerical modeling of exploitation influence on terrain surface has been presented on example of Polish „Siersza“ mine. First of all mining conditions present in the seam and its region have been familiarized with. It can be concluded on the grounds of data obtained from the enterprise, that within analyzed time period, the mine conducted exploitation of two 501, 502 longwalls in the 209/210 seam with caving method. It was an exploitation counted among group of primary exploitations, that is no mining exploitation have been earlier conducted within its region. Depth of the exploitation fell within 325÷330 m range. The overburden in the region under exploitation is built, among others, of thin Quaternary layer (4 m-8 m) in form of fine grained sand, and also yellow sandy clay of loess nature, present in places. Underlying there are layers of Triassic rocks, deposited up to approx. 80 m depth, in form of dolomites, dolomitic marles and dolomitic limestones. Carboniferous, deposited below the Triassic rocks, comprising the 209/210 coal seam, is built mainly from thick packets of fine-grain sandstones, which thickness reaches several dozens of meters, with small, several meters interbeddings of clay shales and coal.

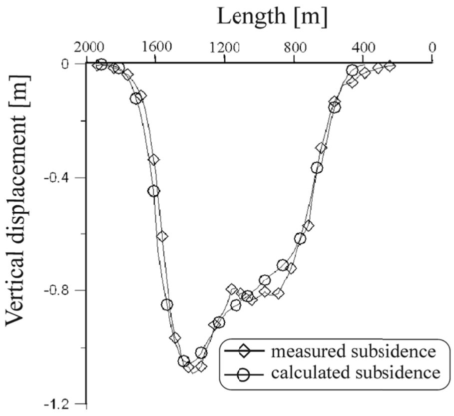


Fig. 2. A comparison between measured profile of subsidence trough and profile computed according to the Knothe theory for complete exploitation of 501 wall and partial exploitation of 502 wall in 209/210 seam of the „Siersza" mine (Tajduś, 2009)

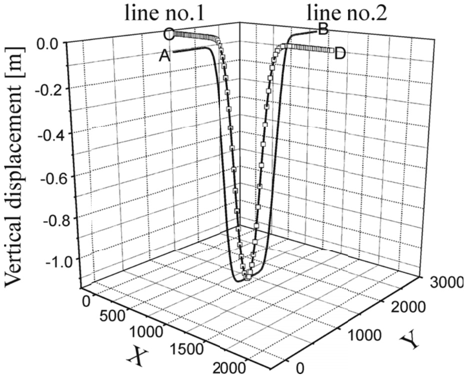


Fig. 3. Final troughs of vertical dislocations over selected 501 and 502 plots of the 209/210 „Siersza" coal mine seam, computed by means of Knothe method

Land survey has been led on surface over 501 longwall under exploitation. Within period of land survey, the mine has completely exploited the 501 longwall of 2.5 m up to 3.1 m thickness (*g*), and partially the 502 longwall, with the thickness equal to 3.1 m (Tajduś et al. 2010). Because the land survey was stopped during exploitation of the 502 longwall, an interpolation was performed based on geometrical-integration Knothe method for a situation, when both longwalls would have been completely exploited. To this end a Knothe theory parameter values have been used, obtained from matching of subsidence trough to values of measured subsidence (angle of main influences $\beta = 54.5°$ as well as exploitation coefficient $a = 0.42$ were obtained) (fig. 2). With use of the Knothe theory, a trough of terrain surface subsidence has been computed for completely exploited 501 and 502 longwalls, having total length of 350 m and 1000÷1080 m panel run within 209/210 seam. The cross-section through the trough was shown for two lines located over exploitation center and running perpendicularly and parallel to the longwalls under exploitation (fig. 3).

Further on, numerical computations have been performed for presented conditions. A numerical model has been constructed for purpose of computations, i.e.: its geometry and laminar structure have been determined, as well as initial values of strain parameters for modeled rock strata. Three-dimensional model has been constructed of 1.950 m × 2.770 m × 430 m dimensions, comprised of 332,687 eight-node elements.

Two weakening zones has been distinguished in the model, which developed over the seam under exploitation, i.e. caved zone $h_z = 6$ m[1] and fractured zone, $h_s = 34$ m (it has been assumed, that fractured zone will reach to the 40 m thick sandstone layer, which, considering its high strength parameters and significant thickness, will not fracture). Taking into account prevailing presence of thick sandstone layers with small interbeddings of shale within overburden, the model did not distinguish individual rock strata within the overburden. Initial values of rock strata elastic moduli

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[1] The break zone was limited by additional sealing of goafs with dusts.

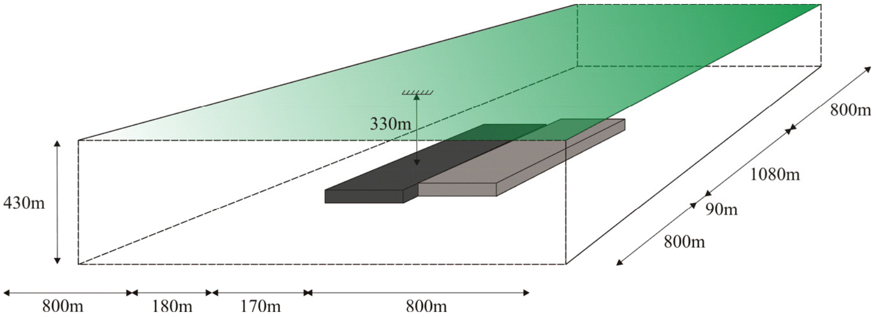

Fig. 4. The geometry of the "Siersza" coal mine computational model

have been selected with use of *GSI* classification (Hoek, 1994; Hoek & Diederichs, 2006). Using a compressive strength laboratory data for individual rock strata comprised in overburden, and having determined initial value of *GSI* number based on observations of profiles, E_{GSI} parameter value has been obtained (table 1). Such determined value of elastic module was used in further numerical computations.

TABLE 1

Initial parameters of overburden, coal and floor used in FEM numerical computations

Rock strata	R_c[1] [MPa]	***GSI***	E_{GSI} [GPa]	**Poisson ratio**
Overburden	14	40	0.82 (assuming lack of rock damage, D = 0)[2]	0.2
Floor	18	43	0.78 (assuming lack of rock damage, D = 0)	
Coal	10	44	0.62 (assuming lack of rock damage, D = 0)	
Fractured zone	15	40	0.59 (assuming some degree of rock loosening, D = 0.2)	
Caved zone	13	21	0.059 (assuming complete rock damage, D = 1.0)	

[1] The value of compressive strength for rock strata being modeled has been determined on the grounds of average laboratory testing results of rock samples for individual strata.

[2] The D parameter is the Hoek parameter determining degree of rock mass destruction within underground mining works. Value of this coefficient falls within 0 to 1 range (Hoek, 1994).

The rock mass after exploitation of Siersza coal mine has been modeled as transversal-isotropic elastic material. It has been assumed for further computations that E_{GSI} value is equal to E_3 value, that is value of elastic modulus in vertical direction, while E_1 has been changed in iterative manner so that to achieve a shape and displacement values obtained from measurements (matching them with "back analysis" method). After several dozen of iterations have been completed for adopted numerical model, with changing E_1 value in individual layers, the E_1 end values have been obtained, for which the subsidence trough computed in numerical manner, practically coincided with subsidence trough obtained from measurements, with correction according to the Knothe theory (fig. 5). Determined value of elastic modulus, E_1 was equal to: $E_1 = 0.15E_3$ for each layer (table no. 2). Precision of matching the results obtained from numerical model, with the results according to the Knothe theory was assessed comparing the tilt of FEM troughs and those of Knothe (fig. 6). The difference in values of maximum tilt for considered models amounted to, for the measurement line no. 1, $\Delta T = 2\%$ both in tensioning zone, and in compressing zone, while for measurement line no. 2 the difference in maximum tilt values amounted to $\Delta T = 12\%$ in tensioning zone and $\Delta T = 6\%$ in compressing zone. This testifies good matching of the model.

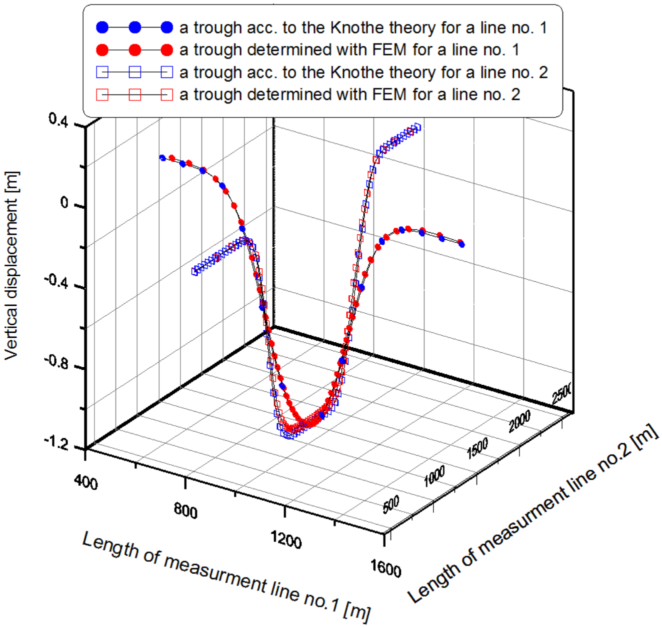

Fig. 5. Comparison of terrain surface subsidence troughs for lines 1 and 2 obtained from numerical computations, with subsidence troughs obtained from the Knothe theory for exploitation of 209/210 "Siersza" coal mine seam

TABLE 2

Final parameters of transversal-isotropic model for 209/210 seam of "Siersza" coal mine

Rock strata building the rock mass	$E_1 = E_2$ GPa	E_3 GPa	$\nu_{12} = \nu_{31}$	G_{12} GPa	G_{13} GPa
Overburden	0.120	0.80	0.2	0.050	0.099
Floor	0.120	0.80		0.050	0.099
Coal	0.105	0.70		0.044	0.087
[1]Fractured zone	0.590			0.246	
[1]Caved zone	0.059			0.025	

[1] Quarternary layers as well as fractured and caved zones are modeled in elastic-isotropic manner.

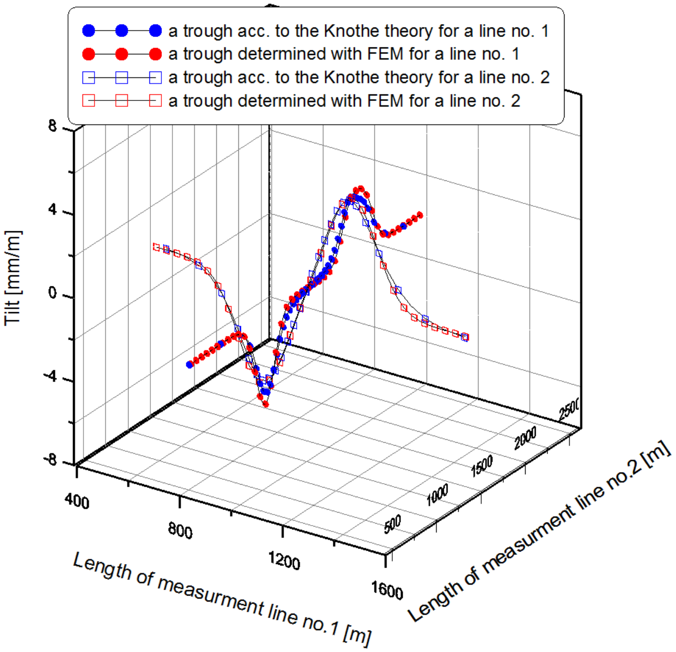

Fig. 6. Comparison of terrain surface tilt for lines 1 and 2 obtained from numerical computations, with subsidence troughs obtained from the Knothe theory for exploitation of 209/210 seam

Below given figures depict the maps of vertical and horizontal displacements of numerical model (fig. 7-9) developed on terrain surface in result of passage of underground exploitation on 501 and 502 longwalls of 209/210 "Siersza" coal mine seam.

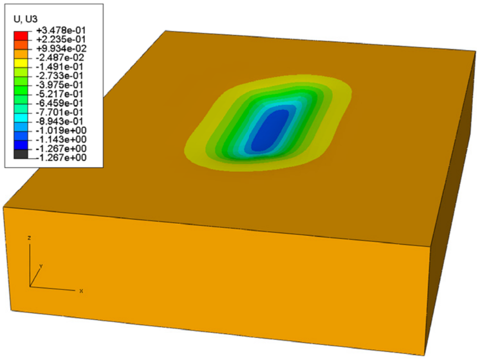

Fig. 7. The map of $w = u_3$ vertical displacements for 209/210 "Siersza" mine seam exploitation model (Tajduś et al., 2010)

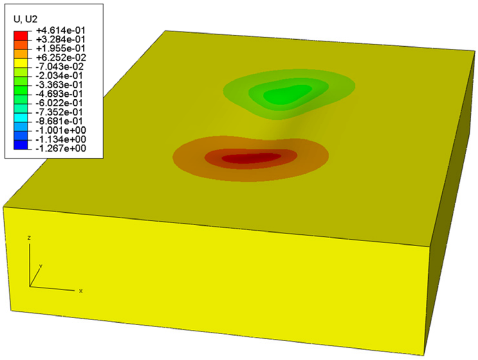

Fig. 8. The map of u_2 horizontal displacements for 209/210 "Siersza" mine seam exploitation model (Tajduś et al., 2010)

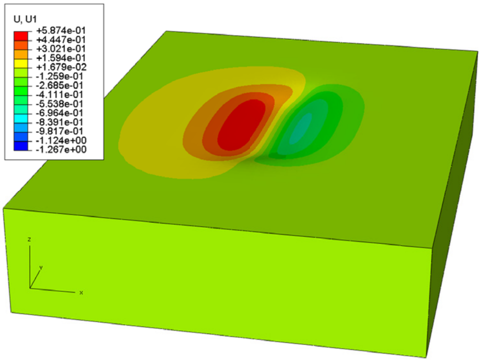

Fig. 9. The map of u_1 horizontal displacements for 209/210 "Siersza" mine seam exploitation model (Tajduś et al., 2010)

Two-dimensional computations for the same mining-geological situation within the Siersza mine region have also been executed (not inserted in this publication). The averaged values of overburden strain parameters obtained for three-dimensional computations differ from the averaged values obtained for flat 2D model for the same mining-geological situation of the Siersza coal mine. The average value in 2D model for overburden strain parameters amounted to E_3 = 1.9 GPa, E_1 = 0.29 GPa, while E_3 = 0.9 GPa, E_1 = 0.14 GPa for fractured zone (Tajduś, 2009). These significant differences in values of strain parameters obtained for the flat and spatial model demonstrate that spatial models should be used in computations of deformations within region of mining exploitation.

6. Conclusions

The consideration presented in the article concerning modeling of underground exploitation influence on terrain surface, demonstrate complexity of the issue that scientists must face. Continuous approach of creating numerical model describing influence of exploitation on terrain surface, that accounts for complex geological structure and mining conditions is just from the assumption. One should be however aware of problems connected with it, particularly taking into account that mining areas in Europe have been subjected for years to multi-seam exploitations, leading to significant and difficult to evaluate degree of original rock mass structure destruction. On the grounds of gained experience, observations and analyses, the author of the work has proposed utilization of transversal-isotropic model for purpose of description of rock mass subjected to mining exploitation. The principles of its construction, selection of strain properties with use of GSI classification system were stated and also the specific example of using the proceeding method proposed by himself was shown. Results of testing for eleven different regions of hard coal mines testify for justness of this proceeding path (Tajdus, 2009).

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