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MAREK WESOŁOWSKI*

NUMERICAL MODELING OF EXPLOITATION RELICS AND FAULTS INFLUENCE ON ROCK MASS DEFORMATIONS

NUMERYCZNE MODELOWANIE WPŁYWU ZASZŁOŚCI EKSPLOATACYJNYCH I USKOKÓW NA DEFORMACJE GÓROTWORU

This article presents numerical modeling results of fault planes and exploitation relics influenced by the size and distribution of rock mass and surface area deformations. Numerical calculations were performed using the finite difference program *FLAC*. To assess the changes taking place in a rock mass, an anisotropic elasto-plastic ubiquitous joint model was used, into which the Coulomb-Mohr strength (plasticity) condition was implemented. The article takes as an example the actual exploitation of the longwall 225 area in the seam 502wg of the "Pokój" coal mine. Computer simulations have shown that it is possible to determine the influence of fault planes and exploitation relics on the size and distribution of rock mass and its surface deformation. The main factor causing additional deformations of the area surface are the abandoned workings in the seam 502wd. These abandoned workings are the activation factor that caused additional subsidences and also, due to the significant dip, they are a layer on which the rock mass slides down in the direction of the extracted space. These factors are not taken into account by the geometrical and integral theories.

Keywords: Model of rock mass, rock mass deformations, faults, abandoned workings

Obecnie większość prognoz deformacji powierzchni terenu wywołanych eksploatacją górniczą wykonuje się na podstawie metod geometryczno-całkowych. Metody te charakteryzują się nie tylko znaczną prostotą, ale także pozwalają na uzyskanie stosunkowo dobrych opisów rzeczywistych deformacji nawet w przypadku bardzo skomplikowanych kształtów pól eksploatacyjnych. Jednak w przypadku, gdy górotwór jest znacznie zaburzony tektonicznie lub naruszony wcześniejszą eksploatacją górniczą, zastosowanie metod geometryczno-całkowych nie daje już tak zadowalających rezultatów. Dlatego też w ostatnim czasie rozwinął się nowy kierunek badań, który do opisu zjawisk deformacyjnych zachodzących w górotworze z powodzeniem wykorzystuje techniki obliczeniowe, opierające się głównie na rozwiązaniach z dziedziny mechaniki ośrodków ciągłych. Wśród znanych metod obliczeniowych wymienić należy metody: elementów skończonych, różnic skończonych, elementów brzegowych oraz elementów odrębnych. Metody te

* INSTITUTE OF MINING, FACULTY OF MINING AND GEOLOGY, SILESIAN UNIVERSITY OF TECHNOLOGY, 44-100 GLIWICE, AKADEMICKA STR. 2, POLAND. E-MAIL: Marek.Wesolowski@polsl.pl

znajdują powszechne zastosowanie w zagadnieniach związanych z mechaniką skał, a także problematyką ochrony terenów górniczych.

Przebieg procesu deformacji jest ściśle związany z warunkami geologicznymi rozpatrywanego górotworu. Jako najważniejsze z tych warunków wymienić należy między innymi istniejące deformacje tektoniczne znajdujące się w zasięgu oddziaływania eksploatacji górniczej oraz zaszłości eksploatacyjne w postaci słabo udokumentowanych zrobów (Kowalski et al., 2010). Obecność w górotworze uskoków oraz dużych płaszczyzn pęknięć może powodować znaczne zaburzenia procesów deformacyjnych (Majcherczyk et al., 2011, Ścigała, 2013). Występowanie tego typu zaburzeń może być powodem tworzenia się na powierzchni deformacji nieciągłych w postaci progów eksploatacyjnych lub szczelin w warstwie nadkładowej. W przypadku występowania zaszłości eksploatacyjnym może dojść do zjawisk ich reaktywacji, które w znacznym stopniu mogą zwiększać zasięg powstałych deformacji powierzchni terenu. Należy w tym miejscu podkreślić, że prawidłowy opis tego typu czynników przy wykorzystaniu metod geometryczno-całkowych najczęściej stosowanych do prognozowania deformacji powierzchni terenu jest praktycznie niemożliwy

W artykule przedstawiono wyniki modelowania numerycznego wpływu płaszczyzn uskokowych oraz zaszłości eksploatacyjnych na wielkość i rozkład deformacji górotworu oraz powierzchni terenu. Obliczenia numeryczne przeprowadzono z wykorzystaniem programu różnic skończonych *FLAC*. Do oceny zmian zachodzących w górotworze wykorzystano anizotropowy sprężysto-plastyczny model ubiquitous joint, w którym zaimplementowano warunek wytrzymałościowy (uplastycznienia) Coulomba-Mohra. Model ten jest anizotropowym ośrodkiem plastycznym zawierającym płaszczyzny osłabienia określonej orientacji.

W artykule posłużono się przykładem rzeczywistej eksploatacji rejonu ściany 225 w pokładzie 502wg w KWK „Pokój". Na podstawie wykonanych symulacji komputerowych można stwierdzić, że głównym czynnikiem powodującym dodatkowe deformacje powierzchni terenu są stare zroby w pokładzie 502wd. Zroby te pełnią funkcję aktywacyjną powodując dodatkowe obniżenia, a ponadto wskutek znacznego upadu stanowią warstwę, po której ześlizguje się górotwór w kierunku wybranej przestrzeni, powodując znaczne zwiększenie obniżeń terenu po stronie wzniosu warstw górotworu.

Proponowany w artykule schemat modelowania może być wykorzystany do uzupełnienia procesu prognostycznego o elementy dotychczas nieuwzględniane we wcześniejszych pracach.

Słowa kluczowe: Model górotworu, deformacje górotworu, uskok, zaszłości eksploatacyjne

1. Introduction

So far, both in Poland and in other parts of the world, geometrical and integral methods are widely used for predicting deformations of a mining area (Budryk & Knothe, 1950). Not only are these methods considerably simple, but they also provide a relatively good description of the actual deformations, even for very complex shapes of post-exploitation areas (Strzałkowski, 2001, 2010; Białek & Wesołowski, 2014). However, in the case of modeling deformation processes inside a rock mass, and also when one has to deal with a tectonically disturbed rock mass, the use of these methods does not bring satisfactory results. Therefore a new line of research has recently been developed, which describes deformation phenomena occurring in rock masses with the use of numerical models that treat a rock mass as a continuous or solid medium, based on such methods as: The Finite Difference Method, The Finite Element Method, The Boundary Element Method and a relatively new Distinct Element Method. These methods allow for taking into account both the complex geological structures, complicated shapes of workings and diverse mechanical properties of rock masses (Białek et al., 2002; Białek & Wesołowski, 2011). The course of the deformation processes and their final states are closely related to the geological conditions of the analysed rock masses. One of the most important of these conditions that should be mentioned, among others, are the existing tectonic deformations within the range of mining exploitation and exploitation relics in the form of poorly documented abandoned workings (Kowalski et al., 2010; Konopko, 2013). The presence of faults and large planes of cracks in rock masses can cause considerable disturbances of the deformation processes (Majcherczyk et al., 2011; Ścigała, 2013). The occurrence of this kind of disturbances can cause discontinuous deformations on the surface, in the form of exploitation thresholds or cracks in the overburden. The size and nature of the changes taking place in the vicinity of tectonic discontinuities will depend, as in this case, on the type of slip (crack) plane, the range of the discontinuity, the angle of dislocation and the size of a potential throw. In the case of the presence of exploitation relics, the phenomena of their reactivation may appear, which can greatly increase the range of the area surface deformations. It should be emphasized here that the correct description of these types of factors with the use of geometrical and integral methods, which are most commonly used to predict the area surface deformations, is impossible.

Therefore, this article is an attempt to determine the influence of fault planes and exploitation relics on the size and distribution of surface deformations in their uses as an example the exploitation area of the longwall 225 in the seam 502wg of the "Pokój" coal mine. The analysis was conducted with the use of the finite difference program *FLAC* (Itasca Consulting Group, Inc., 1992), which is commonly used in rock mass mechanics.

2. Geological and mining conditions. Geodetic observations

Over the period 2008-2009 the "Pokój" coal mine conducted mining exploitation with caving of roof rocks by the longwall 225 in the seam 502wg. The length of the longwall front was 270 m, and its panel length was 330 m. The depth of the exploitation at the beginning of the longwall 225 was 495 m, and at its end – 545 m (average depth 520 m). The height of the longwall 225 was 2.1 m. The exploitation of the longwall 225 was carried out approximately 500 m south of the "Saara Północna" fault outcrop. The scope of the planned exploitation of the longwall 225 was limited by numerous faults with a slight throw, that were present. In the exploitation area, the slope of the layers was 5°-12°, and in the vicinity of the "Saara Południowa" fault it could rise to 20°. Because of the complex tectonics, the characteristics of exploitation in the area of the southern part of the Nowy Bytom district present a very large diversity of shapes in different seams. In the inter-fault part of seam 504, backfilling exploitation was conducted from 1990 to 1991 and caving exploitation in 1992.

Before the beginning of the longwall 225 in the 502wg seam exploitation, the mine performed a points stabilization of two measurement lines located along the Czarnoleśna street (lines 1-43), and along the PKP (railway) trail (line 51-89), and made a zero measurement of points belonging to these lines. The subsidence of a large network of dispersed points located on the ground and on selected buildings were also measured. The position of measuring lines in relation to analysed mining exploitations are shown in Figure 1.

The analysed area has complex tectonics. The largest geological disturbance is the "Saara" fault, which is in the area of the "Pokój" coal mine, which splits into two parallel faults: the „Saara Północna“ and the „Saara Południowa“, that run roughly latitudinally and drop layers in a southerly direction. The throw of the "Saara Północna" fault is approx. 80 m and the slope of the fault plane reaches 81°. The „Saara Południowa“ fault throw increases from 30 m to 110 m east to west. The slope of the fault plane is variable and it ranges from 40° to 80°. Near the surface, the slope of the fault plane reaches approx. 70°.

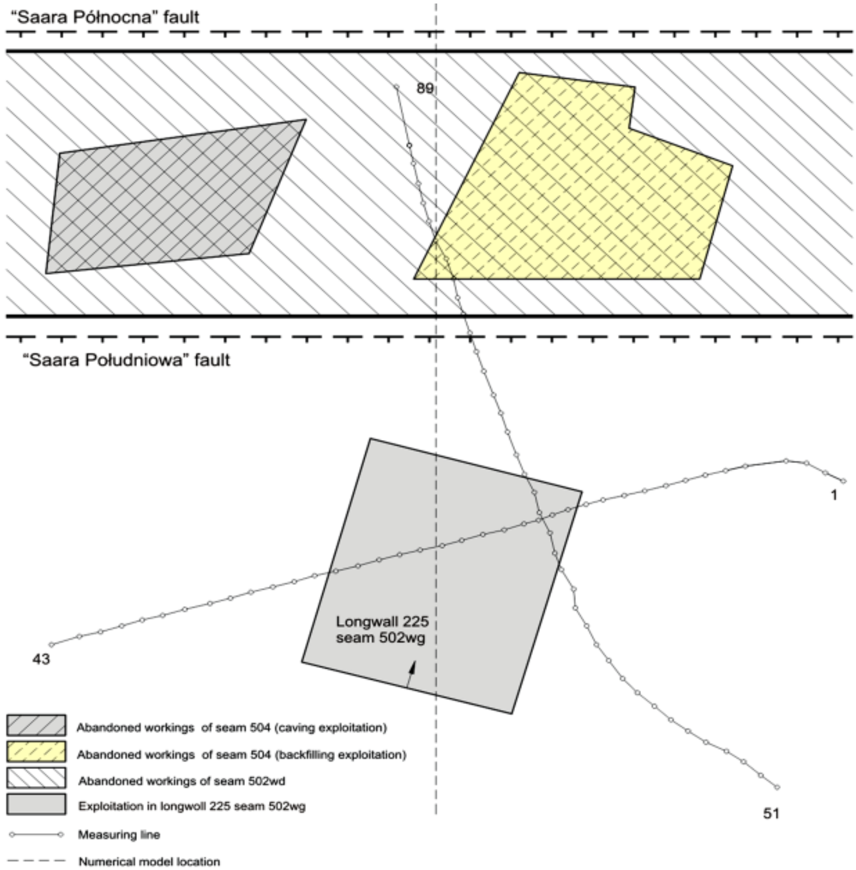

Fig. 1. A scheme of ongoing and projected exploitation in seams 502wg and 504

3. Re-prognosis of the mining area surface deformation

The re-prognosis of the mining area surface deformation in the vicinity of the longwall 225 exploitation in the seam 502wg of the "Pokój" coal mine was made with the use of computer programs by J. Białek, with implemented S. Knothe theory formulas and extensions of these formulas developed by the author of the programs (Białek, 2003). Geodetic measurements were used to determine the parameters of S. Knothe's theory: a = 0,73, tgβ =1,6 periphery d = 30 m. The results of the re-prognosis are shown in Figures 2 and 3. On the line 1-43 (Fig. 2) which does not intersect the "Saara Południowa" fault, a very accurate fit was obtained, with the mean square fit error σ = 36 mm. On the line 51-89 (Fig. 3), running approximately along the slope of the carboniferous strata in the area of direct influence, a good match of calculated subsidences to measured subsidences were obtained.

A problem appeared with relatively small, but still much higher than expected influences in the area situated to the north from the longwall 225. It is believed that despite the very large distance from the fault, a crack associated with the fault (or abandoned workings in its vicinity)

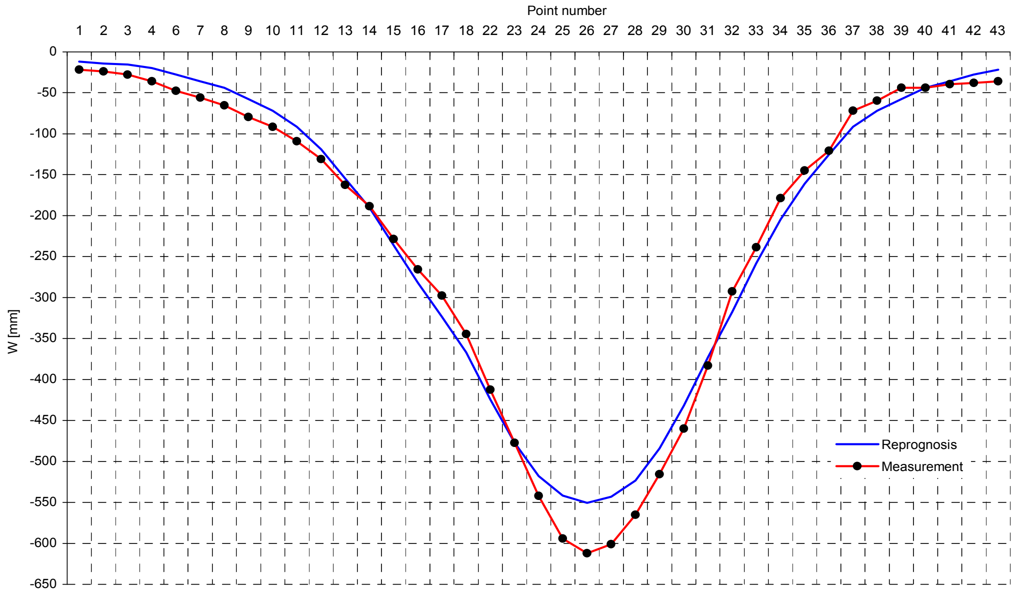

Fig. 2. The comparison of the results of prognostic calculations and geodesic measurements on the 1-42 line

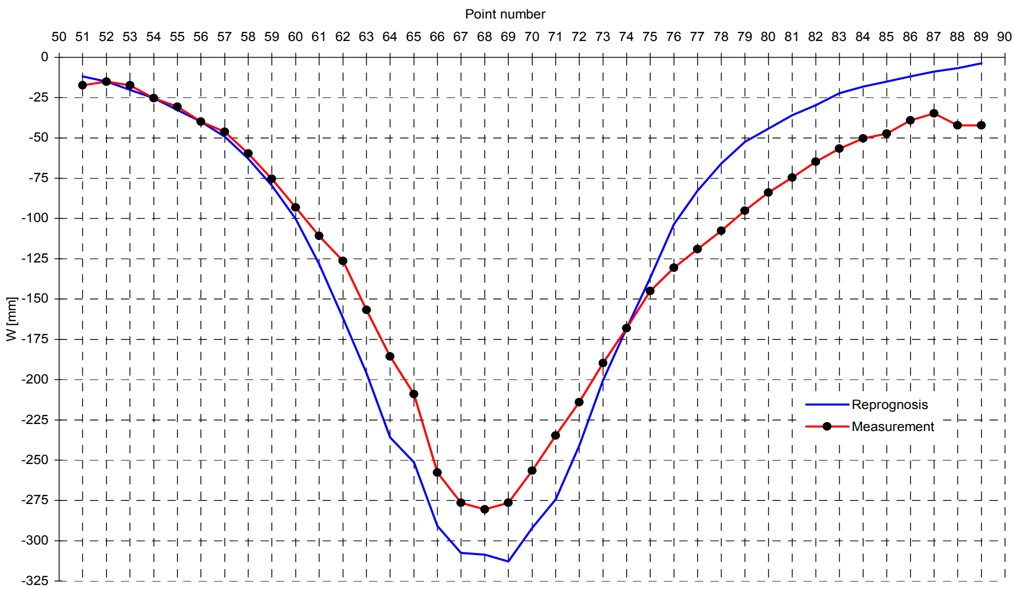

Fig. 3. The comparison of the results of prognostic calculations and geodesic measurements on the 51-89 line

activated, causing damage to the building of nearby Primary School No. 1. Probable causes of subsidence (larger by approx. 40 mm from the forecasts) in the section from 75 to 87 point (Fig. 3), are a substantial slope of seams and the presence of old workings in the seams lying higher up. These abandoned workings, as an activating factor, cause further subsidence on the lift side of the rock mass layers. Nevertheless, the prognosis presented in this section does not include the influence of faults and exploitation relics in the form of abandoned workings of the seam 502wd.

4. Model of rock mass

For a computer simulation of rock mass movements in the area of the longwall 225, a flat numerical model was developed with the base dimensions of 2000 m × 1200 m (Fig. 4), in which the most important structural elements of rock mass from the area of the analysed exploitation were incorporated. At a depth of 580 m to 380 m a coal seam 502 and a coal seam 504, located 18 m below 502, were modeled. Roof and floor layers were modeled on the basis of the profile from the "Wanda" mineshaft located in the distance of 300 m from longwall 225 penel borders.

The adopted model was located perpendicularly to the "Saara Południowa" and the "Saara Północna" fault planes (Fig. 1). This kind of location will allow only for a qualitative estimation of faults and exploitation relics influence on rock masses and area surface deformation.

In terms of a mathematical description, it was assumed that all layers creating a rock mass model are described by the ubiquitous joint medium. This model is an anisotropic elasto-plastic model, which contains weakness planes with a specific orientation (Wesołowski, 2014). In the model, a Coulomb – Mohr strength (plasticity) condition has been implemented. The plasticity may occur both within weakness planes and in the rock mass. Planes of isotropy and weakness planes can be inclined at any angle a to the *X*-axis direction (Itasca Consulting Group, Inc., 1992).

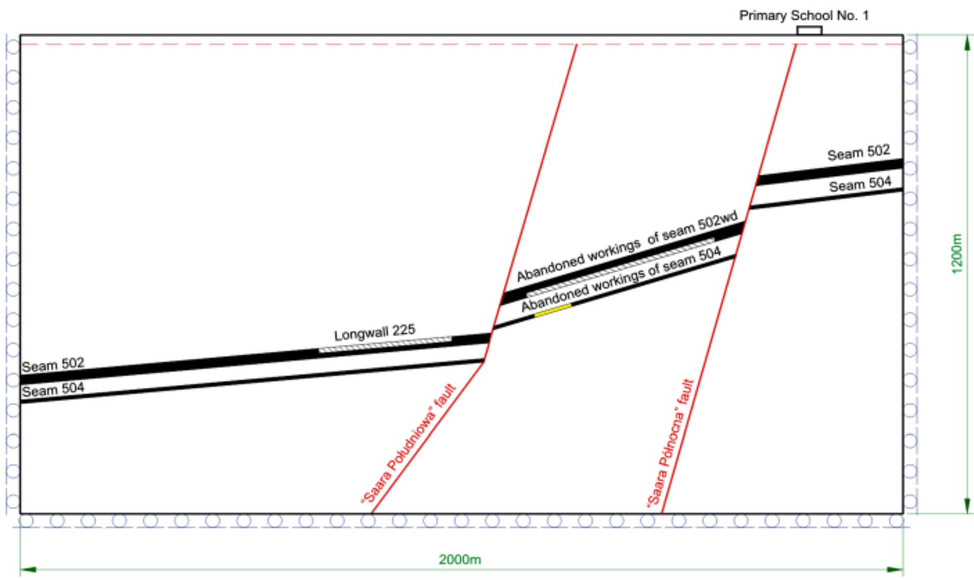

Fig. 4. A scheme of the computational model

Strength and strain parameters of layers were adopted on the basis of mine data and literature (Kidybiński, 1982, Prusek & Bock, 2008). The basis for determining the values of parameters of weakness planes was a case described in (Sainsbury et al., 2008). The variability range of the ubiquitous joint model rock layers material parameters adopted for the calculations are presented in Table 1.

In terms of tectonics, the adopted calculation model has been divided by the "Saara Południowa" and the "Saara Północna" faults into three theoretical parts:

- the left part is the exploitation area of the longwall 225 in the seam 502wg,
- the middle part (an inter-fault one) contains fragments of the backfilling and caving exploitation in the seam 504 and abandoned workings of the seam 502wd,
- the right part is an area in which there are no mining activities.

The Saara Południowa" and "Saara Północna" faults were presented as two co-operating planes joined by contact elements. This is an oversimplification, because in this way, the secondary faults zone, often occurring in the area of large tectonic dislocations, is omitted. The value of the material constants, characterizing the mechanical properties of fault cracks, are summarized in Table 2. Due to the lack of data concerning the properties of the fault crack filling material, the values of the parameters characterizing the fault have been selected on the basis of literature (Kwaśniewski & Wang, 1994).

TABLE 1

Calculations parameters of layers within the ubiquitous joint model

Parameter	Unit	Overburden	Mudstone	Sandstone	Seam
Parameters of rock mass					
Shear modulus G	[MPa]	114	2680	4350	864
Bulk modulus K	[MPa]	247	2630	4760	1830
Cohesion c	[MPa]	0,46	10,7	20,75	6,26
Angle of internal friction ϕ	[deg]	24	24	35	25
Tensile strength Rr	[MPa]	0,1	5,25	9,50	1,6
Volumetric density ρ	[kg/m^3]	1950	2610	2450	1400
Weakness planes parameters					
Cohesion c	[MPa]	0,0046	0,1	0,2	0,06
Angle of internal friction ϕ	[deg]	24	24	24	24
Tensile strength Rr	[MPa]	0,001	0,05	0,1	0,01
Planes angle α	[deg]	0	8 (17*)	8 (17*)	8 (17*)

* The angle of inclination value of the weakness planes in the inter-fault area

TABLE 2

Mechanical parameters of the fault, adopted for calculations

Parameter	Unit	Value
Normal stiffness coefficient (K_n)	[MPa/m]	120
Tangential stiffness coefficient (K_s)	[MPa/m]	45
Friction angle (ϕ)	[deg]	28
Cohesion (c)	[MPa]	0,4
Tensile strength (σ_T)	[MPa]	0

The presented model is described by a difference mesh and thus the shield was divided into zones with approximately rectangular shapes. Due to the lack of knowledge about the tectonic residual stress values, it was assumed that the value of initial stresses in the rock mass came only from gravitational forces. The value of the initial horizontal stress σ_x has been determined in the preliminary numerical calculations process (Kołodziejczyk & Wesołowski, 2010; Tajduś, 2010).

The mining exploitation is simulated by cyclic removal of a finite difference mesh in the individual zones, in order corresponding with mining of the longwalls. At the same time contact elements, (a division plane), were introduced between the roof and the floor layer, which prevents interpenetration of the roof and the floor of the seam. This method of mining exploitation simulation eliminates the need for any additional parameters attributed to caving zones. Simulation of rock mass displacements corresponds with the quasi-static model, in which the influences caused by the exploitation (removal) of the following element of the seam, reveal instantaneously. There are no viscous elements here and the notion of time does not exist. Nevertheless, because of the plastic properties of a medium, the sequence of removal (exploitation) of specific zones of a mesh is important. Simulation of the backfilling exploitation will be arranged as changing strain parameters for zones located within the abandoned workings. In this case of exploitation, it was assumed that the values of shear modulus and bulk modulus will be equal to G = 123 MPa; K = 260 MPa respectively.

For the detailed evaluation of the exploitation relics in the 502wd seam and the fault planes influence on the rock mass deformations in the discussed area of exploitation, additional simulations were preformed on comparative models. In this part, the following models were analysed:

1. The model without fault planes and with exploitation relics in seams 502 and 504.
2. The model with fault planes and without exploitation relics in seams 502 and 504.

The remaining structural elements as well as strain and strength parameters for all models are virtually the same. This will allow for a full comparative analysis of these models.

5. Interpretation of the results of numerical calculations

After mapping the initial state of stress in the modeled rock mass shield and after creating the so-called zero model, the simulated mining exploitation in the discussed area was then started. This part of the computer simulation was divided into the following steps:

- exploitation of part of the seam 502wd, located within the model. The extracted part of the seam is located between the „Saara Południe" and the „Saara Północ" faults. It is the caving exploitation with the height of approx. 3 m, that was conducted in the years 1948-1951. Due to the time elapsed since the end of the exploitation to the period of measuring points stabilization, it has been omitted in the previous prognoses.
- simulation of caving and backfilling exploitation in the inter-fault part of seam 504, conducted in the years 1990-1992. This exploitation was carried out before the zero measurement on measuring lines was performed;
- extraction of the longwall 225 in the seam 502wg.

The results of the numerical calculations, performed for respective stages of the computer simulation, are shown as graphs in Figures 5 and 6. In addition, in Figures 7 to 9, maps of subsidences and damage zones in the model are provided.

The results of the numerical calculations lead to the following conclusions:

1. For all the analysed models, a numerically simulated mining exploitation in the longwall 225 of the seam 502wg has created a subsidence trough, for which the maximum value of sinking is approx. 620-640 mm (Fig. 5). This value is slightly larger than the value measured on line 1-43, stabilized along Czarnoleśna Str. (Fig. 1). At the same time it should be emphasized that the discussed measuring line does not run over the central part of a subsidence trough, so the measurements do not represent the maximum subsidence values. It can therefore be assumed that the numerical model correctly reflects the range of subsidence over the extracted panel of the longwall 225.
2. The simulated mining exploitation also resulted in a 50 mm subsidence increase in the inter-fault area, which was confirmed by geodetic observations. Let us remind ourselves that these very distant subsidences were the main cause of discrepancies in prognoses performed with the use of geometrical and integral methods. The factors that caused an increase of subsidence in that area are exploitation relics in the seam 502wd in conjunction with the activation of the "Saara Południowa" fault plane. This is confirmed by the results of computer calculations, performed for a comparative model, in which these relics have been omitted (Fig. 5).

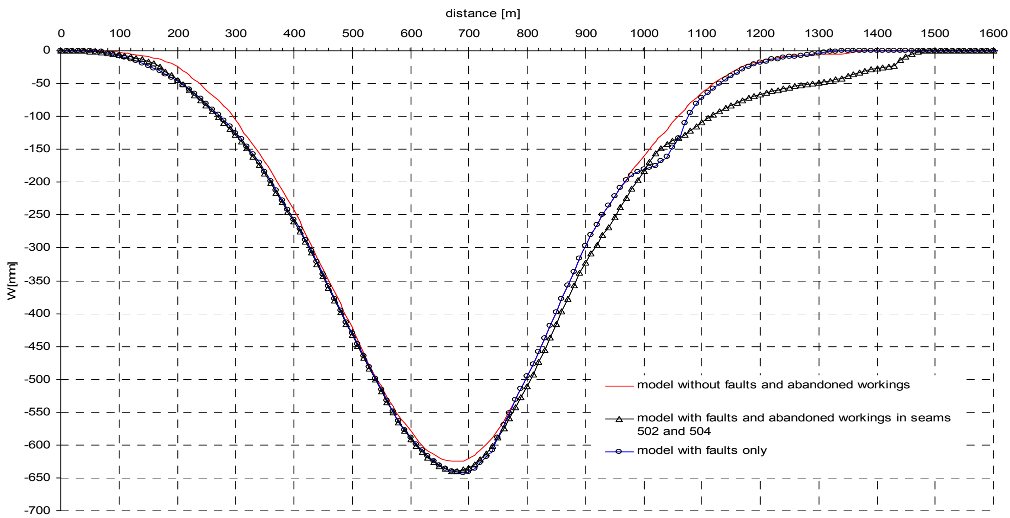

Fig. 5. Subsidences determined on the basis of a numerical model

3. The extraction of the longwall 225 produced horizontal deformations whose extreme values over the undisturbed strata (on the dip side) amount to +1.5 mm/m over the undisturbed strata and -3,1 mm/m over the extracted space (Fig. 6). Such deformations were determined for all of the analysed numerical models.
4. Significant differences occurred in the models with fault planes included (Fig. 6). For these models some changes occurred, which were a sign of the activation within the fault planes and an abrupt increase of strains appeared in the outcrop areas of the fault planes. The largest deformation increase (up to 4.8 mm/m) in the area of the "Saara Południowa"

fault occurred in the model, which did not include the abandoned workings of the seam 502wd. In the case of the model with abandoned workings included, only a slight increase of strains occurred (up to 2.7 mm/m) in the area of the "Saara Południowa" fault outcrop and a much larger one (up to 3,8 mm/m) in the area of the "Saara Północna" fault. This suggests that activation of the abandoned workings at the seam 502wd and the "Saara Północna" fault caused damage to the building of Primary School No. 1.

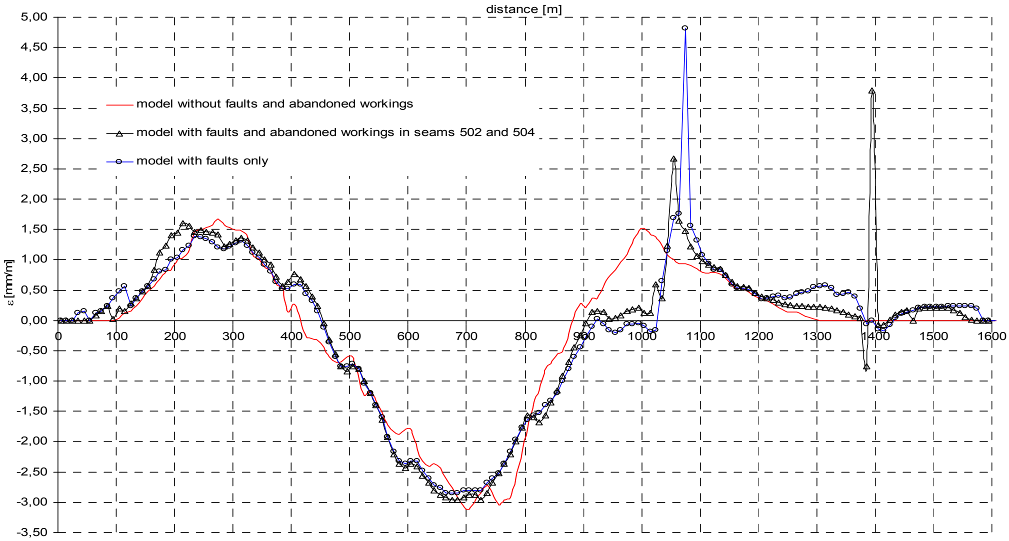

Fig. 6. Horizontal strains of the subsidence trough profile

The analysis of a rock mass model without fault planes and abandoned workings in the seams 502 and 504 shows that isolines of subsidences are in most cases distributed regularly and symmetrically to the exploitation panel of the longwall 225 (Fig. 7). Only in the case of outer isolines of displacement, a slight increase in the range of exploitation influence on the lift side of seam can be seen. The reason for this is the high slope of the model layers in its central part. The analysis of plasticity zones shows that the main damage of the rock structure were located in the roof and subsurface layer over the panel of the longwall 225. Such a large range of plasticity zones (especially in the subsurface layers) is due to the small size of the longwall 225 panel and the interaction of influences of both exploitation edges.

The inclusion of fault planes and abandoned workings of the seams 502 and 504 in the model resulted in a significant increase of exploitation influence range in the inter-fault zone (Fig. 8). The isoline shift within the "Saara Południowa" fault and on the border of abandoned workings in the seam 502wg., shown in the aforementioned figure, is the cause of additional subsidence, which was a main cause of discrepancies in prognoses made with the use of geometrical and integral methods.

The assessment of the size and range of plasticity zones in the model has also shown that an activation of the "Saara Południowa" and the "Saara Północna" fault planes took place, which caused an abrupt increase of tensile strains in the areas of their outcrops.

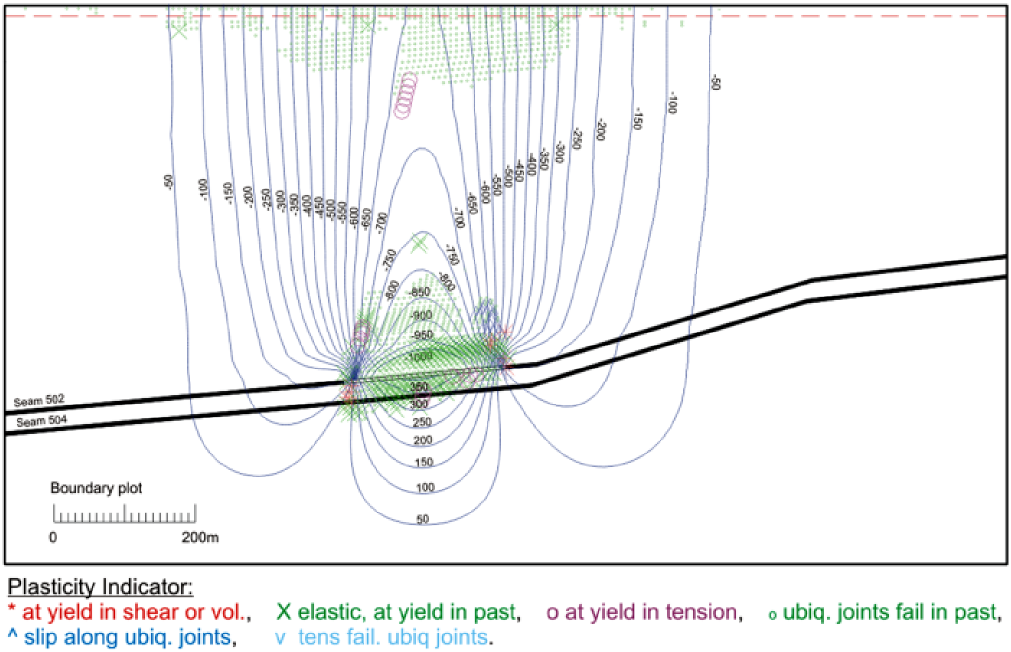

Fig. 7. Subsidences and plasticity zones in a model without faults and abandoned workings

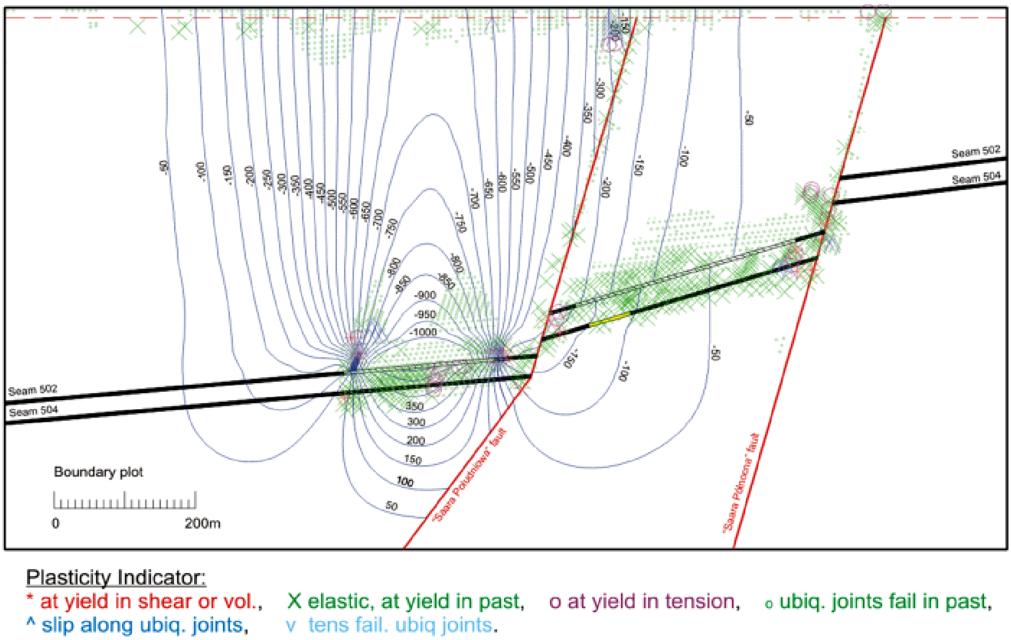

Fig. 8. Subsidences and plasticity zones in a model with faults and abandoned workings in seam 502 and 504

The numerical calculations conducted for a comparison model (Fig. 9), also show that the lack of additional influence resulting from the reactivation of the abandoned workings in the seam 502wd would cause a significant reduction in the range of exploitation influences in the inter-fault zone and probably a formation of a threshold on the border of the "Saara Południowa" fault. The plasticization zones formed in this case clearly end within the "Saara Południowa" fault plane. This is also confirmed by the lack of damage zones in the area of the "Saara Północna" fault plane. As in the previous case, the activation of the "Saara Południowa" fault planes will cause an abrupt increase of tensile strains in the area of this fault's outcrop.

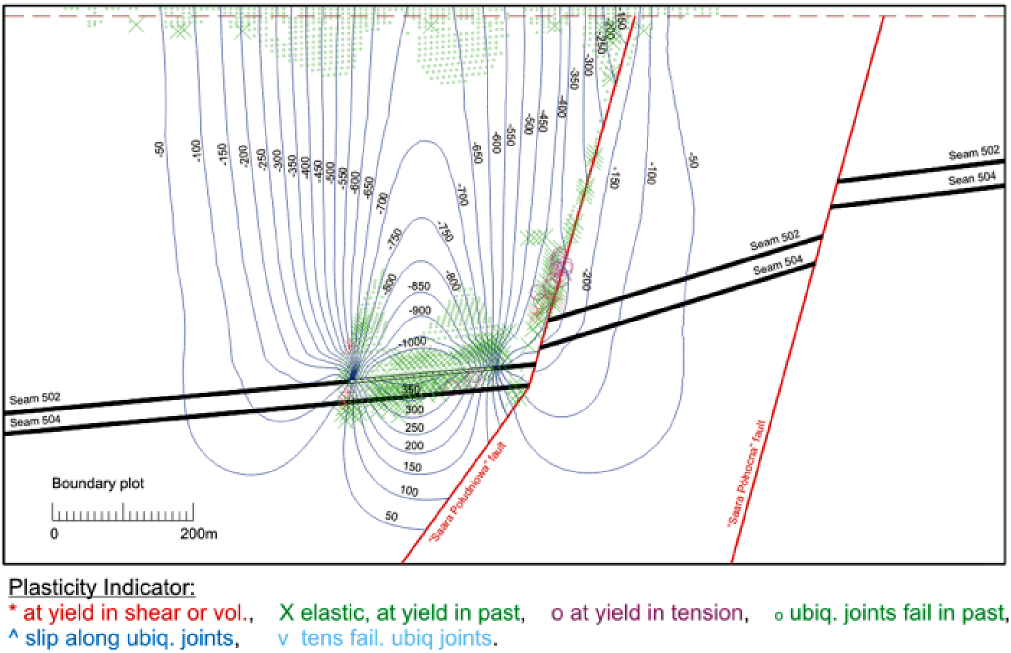

Fig. 9. Subsidences and plasticity zones in a model with faults and without abandoned workings in seam 502 and 504

6. Summary and final conclusions

This article is an attempt to determine the effect of the "Saara" fault and the influence of exploitation relics on the size and distribution of surface deformation within a mining area. As an example, the actual exploitation of the longwall 225 area in the seam 502 of the "Pokój" coal mine has been analysed. The results of numerical calculations allowed us to determine the following conclusions:

1. With the use of the finite difference program *FLAC,* it was shown that it is possible to determine the influence of fault planes and exploitation relics on the size and distribution of the mining area surface deformation. These factors are not recognized by the commonly used geometrical and integral theories in Poland.

2. On the basis of computer simulations, it can be ascertained that the main factor which causes additional area surface deformations are the abandoned workings in the seam 502wd. These workings have an activating function, causing additional subsidence, and also, due to a significant dip (here approx. 15 to 20 degrees), they constitute a layer at which the rock mass slides in the direction of the extracted space, which results in a significant increase of the area subsidence on the lift side of rock mass layers.
3. Numerical calculations for the comparison model show that the lack of additional influences resulting from the reactivation of the seam 502wd abandoned workings would probably cause a formation of an exploitation threshold on the border of the "Saara Południowa" fault.
4. The analysis of the possible influence of existing faults on additional surface deformations in the area of their outcrop showed a generally minor effect of the exploitation on these deformations. The factor that reduces the influence of faults on the model's surface deformation size is the slope and position of the analysed fault planes in relation to an ongoing mining exploitation.

References

Białek J., 2003. *Algorytmy i programy komputerowe do prognozowania deformacji terenu górniczego*. Wydawnictwo Politechniki Śląskiej, Gliwice.

Białek J., Mielimąka R., Wesołowski M., 2002. *Ein linear, transversal-anisotropisches Gebirgsmodell zur Modellierung Abbaubedingter Gebirgsbewegungen. Schriftenreihe des Institutes fűr Markscheidewesen und Geodäsie der TU Bergakademie Freiberg*. Heft 1, 184-191.

Białek J., Wesołowski M., 2011. *Problematyka numerycznego modelowania ruchów terenu górniczego na przykładzie eksploatacji pokładu 354 w KWK "Chwałowice"*. Prace Naukowe GIG, XI Dni miernictwa górniczego i ochrony terenów górniczych. Kwartalnik nr 2/1, ISSN 1643-7608.

Budryk W., Knothe S., 1950. *Wpływ eksploatacji podziemnej na powierzchnie z punktu widzenia ochrony obiektów*. Przegląd Górniczy, nr 11,

FLAC User's Manual 1992. Itasca Consulting Group. Minneapolis.

Kidybiński A., 1982. *Podstawy geotechniki kopalnianej*. Wydawnictwo Śląsk, Katowice.

Kołodziejczyk P., Wesołowski M., 2010. *The influence of deformational parameters of a numerical model on the subsidence basin profile for chosen working dept*. Archives of Mining Sciences, Vol. 55, No 4, 775-781.

Kowalski A., Jędrzejec E., Gruchlik P., 2010. *Linear discontinuous deformations of the surface in the Upper Silesian coal basin*. Archives of Mining Sciences, Vol. 55, No 1, 331-346

Kwaśniewski M., Wang J,. 1994. *Symulacja komputerowa eksploatacji pokładu węgla systemem ścianowym z zawałem stropu, II. Zachowanie się uskoków poddanym wpływom eksploatacji*. Zeszyty Naukowe Politechniki Śląskiej, s. Górnictwo, z. 221, Wydawnictwo Politechniki Śląskiej.

Majcherczyk T., Szlązak N., Niedbalski Z., 2011. *Wpływ zrobów ścian zawałowych na chodniki przyścianowe projektowanej ściany w warunkach zagrożenia metanowego*. Górnictwo i Geologia: kwartalnik, Gliwice, t. 6, z. 3, s. 127-140.

Praca zbiorowa pod redakcją W. Konopko, 2013. *Bezpieczeństwo pracy w kopalniach węgla kamiennego*. t. 1, Główny Instytut Górnictwa Katowice.

Prusek S., Bock S., 2008. *Assessment of rock mass stresses and deformations around mine workings based on three-dimensional numerical modelling*. Archives of Mining Sciences, Vol. 53, No 3, 349-360.

Sainsbury B., Pierce M., Mas Ivars D., 2008. *Simulation of rock mass strength anisotropy and scale effects using a ubiquitous joint rock mass (UJRM) model*. Continuum and Distinct Element Numerical Modeling in Geo-Engineering, Detournay & Cundall (eds.) Paper: 06-02 Itasca Consulting Group, Inc., Minneapolis, ISBN 978-0-9767577-1-9.

Strzałkowski P., 2001. *New mathematical model for description of time-dependent surface subsidence*. Institute of Materials, Minerals and Mining, Mining Technology, A178-A182.

Strzałkowski P., 2010. *Forecasts of mine-induced land deformations in consideration of the variability of the parameter describing the process kinematics*. Archives of Mining Sciences, Vol. 55, No 4, 865-872.

Ścigała R., 2013. *Wpływ tektoniki złoża na rozkład deformacji terenu górniczego*. Wydawnictwo Politechniki Śląskiej, Gliwice.

Tajduś K., 2010. *Determination of approximate value of GSI index for the disturbed rock mass layers in the area of Polish mines*. Archives of Mining Sciences, Vol. 55, No 4, 879-890.

Wesołowski M., 2014. *Możliwości stosowania modeli numerycznych do opisu deformacji powierzchni terenu górniczego*. Przegląd Górniczy, nr 4.