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ORIGINAL PAPER

GEOMECHANICAL MODELING OF SUBSIDENCE RELATED STRAINS CAUSING EARTH FISSURES

Agnieszka A. MALINOWSKA [1)], Rafał MISA [2)] and Krzysztof TAJDUŚ [2)]

[1)] AGH University of Science and Technology, Faculty of Mining Surveying and Environmental Engineering, Department of Mining Areas Protection, Geoinformatics and Mining Surveying, Al. A. Mickiewicza 30, 30-059 Kraków, Poland
[2)] Strata Mechanics Research Institute of the Polish Academy of Sciences, ul. Reymonta 27, 30-059, Kraków, Poland

**Corresponding author's e-mail:* amalin@agh.edu.pl

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ABSTRACT

The research is focused on the feasibility analysis of a numerical model describing the field of strains generated by mining-induced subsidence caused by a deep underground coal extraction, which may contribute to the formation of Earth fissures. The finite elements method and Knothe's theory were used in the research. The geomechanical modeling was applied for defining zones of strains and maximum horizontal deformations of the terrain. Knothe's theory was employed for defining boundary conditions of the geomechanical model. The parameters of the empirical and geomechanical models were scaled out on the basis of geodetic surveys in the mining area.
The results of geomechanical modeling were compared with the geodetic surveys to select the best model. The presented research confirmed high congruence between the results of modeling with the finite elements method and observations of vertical movements on the surface. The results of modeling also confirmed the assumed highest stress in areas where earth fissures were observed. The proposed solution may be a new research tool applicable to areas where earth fissures potentially occur.

1. INTRODUCTION

A correct evaluation of the risk of occurrence of discontinuous deformations on the surface is one of the major problems of underground mines operating on highly urbanized areas. The presently applied methods of assessing or predicting the risk of occurrence of discontinuous deformations can be used to preliminarily define the areas prone to sinkholes occurrence. The methods are mostly based on simple geomechanical conditions, where the volume of damaged rocks over the extraction is determined and this value is compared with the depth of the existing or planned underground void.

The problem of determining occurrence and magnitude of earth fissures is more serious. Number of studies was devoted to the cause-and-effect analyses of factors initiating that phenomenon (Chudek et al., 1998; Delle Rose et al., 2004; Fenk, 1981; Janusz and Jarosz, 1976; Kowalski, 2005; Liu, 1981; Malinowska and Dziarek, 2014, Malinowska and Matonóg, 2016, Whittaker and Reddish, 1989). This research allows one to better understand the process in which linear discontinuities are generated. The existing solutions which are based on expert methods, artificial intelligence or clusters can be used for identifying zones where surface linear discontinuities are generated (Blachowski and Ellefmo, 2012; Malinowska and Dziarek, 2014; Taheri et. al., 2015; Malinowska and Matonóg, 2016). However they cannot be used for determining places of occurrence of earth fissures. Considering the state of the art, one may conclude that the prediction of linear discontinuous effects is a challenge and no satisfactory solution has been worked out yet. Knothe theory is broadly applied in Poland for prediction of ground deformation (Hejmanowski and Malinowska, 2009; Malinowska and Hejmanowski, 2010; Malinowska and Hejmanowski, 2016; Knothe, 1953). Modified Knothe's model has been applied not only for prediction subsidence above coal extraction, but also copper and salt mining. Basic assumption of the theory has been presented in many articles (Hejmanowski and Malinowska, 2009; Malinowska and Hejmanowski, 2010). This paper presents research works focusing on a method for assessing zones hazarded with earth fissures. The research was based on a geomechanical numerical model and Knothe's geometrical-integral theory, supported by the results of geodetic surveys.

2. STUDY AREA

The numerical analysis of the state of strains in the ground surface in the neighborhood of underground excavation was performed in an

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exemplary area of underground coal mine. Multilevel coal extraction with a longwall system and water pumping are the main root causes of subsidence in that region (Fig. 1). In the pre-selected study area, coal was extracted from a coal bed 382 along two longwalls 10/l and 9/l at a depth of about 920 m, and maximum 2.6 m high. The average rate of progress of the mining front was about 6 m/24 hrs.

The geological conditions in the study area are relatively uncomplicated. The extracted coal bed is horizontal the same as only in geological layers. Clays and sands dominated in the near-surface zone and reached a depth of about 30 m. Underneath there was a ca. 10 m thick layer of clay and then limestones.

The surface in the mining area was not intensely developed. In the zones of earth fissures occurrence a few rural buildings were located along the road. In the study site three NS earth fissures were observed. The maximum earth fissure length was about 150-180 m and the width of opening reached 6 cm (Fig. 2a). The fissures were about 100-150 meters from the edge of the long wall mining panel (Fig. 2a, orange polygon). One of the earth fissures occurred in densely build-up area and it caused construction damage in one building (Fig. 2b). The foundations of that building was torn causing sever endanger for its. That event became a reason for further investigation of the possible key factors of earth fissure occurrence in that region.

3. NUMERICAL MODELING OF THE STATE OF STRESS AND STRAIN IN A GIVEN MINING AREA

The main assumption of presented solutions was a simulation of the state of stresses and strains in the extraction area. A numerical model based on finite elements method and pre-processor Abaqus CAE 2016 was worked out (Simulia, 2016). The geomechanical calculations were based on linear elastic model and Coulomb-Mohr constitutive model (elasto-plastic), and used for simulating of mining extraction influence to the surface and near surface layers. Accordingly, numerical calculations were performed for the assumed geomechanical parameters of rock masses (Tab. 1). It should be noted that the calculations had a qualitative character, parameters were taken from available literature and materials imparted by coal mine (Wasil, 2002; Tajduś, 2009b). Numerical calculations were carried out with use of Abaqus Standard module. Moreover additional software for simulating mining-induced strains was developed and applied in the research (Tajduś, 2009a; Lutz, 2010; Simulia, 2016). Basic information about boundary conditions of the model was defined on the basis of Knothe's model. Additional assumption about physico-mechanical properties of the rock masses was defined before modelling. Verification of the obtained outcomes was done by comparing the modelling results with measured ground movement. Below each research phase was presented step-by step.

3.1. DEVELOPMENT OF MATHEMATICAL-PHYSICAL MODEL

The first phase of the investigation was definition of boundaries of numerical model. Based on information about geological and mining conditions in the study area the theoretical model of rock masses deformation and its influence to the ground subsidence was analyzed. The modeled mining operation was carried out at a depth of 920 m. The calculations were performed for depleted longwalls *10/l* and *9/l* in coal bed 382 of Bogdanka coal mine. The size of the mining panels*10/l* and *9/l* is presented in Figure 3. The subsidence on the surface was defined for these longwalls according to Knothe's theory. Based on ground deformation measurements done in the study area Knothe's theory parameters was established (Tajduś, 2009b). The angle draw was $\beta=62.24°$ and extraction coefficient $a=0.9$. The measured average thickness of extracted layer totaled to 2.6 m.

Based on defined theory parameters preliminary boundary conditions of the numerical model were defined. Mainly, the angle of draw parameter support the analysis of the extend of influence the mining extraction to the surface. That constitute basis for the assumption about the dimension about geometrical model (Fig. 4b).

Final geometrical model dimension was 900 m x 900 m at the base, and 20 m high (Fig. 4b). For the sake of reducing the time of numerical simulation the analysis were carried out in for a certain region above the mining extraction. That is why layer with the thickness up to 20 m below the ground surface was main object of the simulation.

3.2. DEVELOPMENT OF NUMERICAL MODEL

The second stage of the study was defining the numerical model the rock masses. The spatial discretization of the geometrical area was performed with the finite element method (FEM). Cubic eight-node linear finite elements were applied for the model (Fig. 5). The final numerical model consisted of 1,000,000 finite elements, and the structure of equations had over 3,500,000 variables.

Using a special script on the edge of the modeled area (sides and bottom of the model), displacement boundary conditions were applied, simulating the formation of the mining trough according to the equations of Knothe's theory. At each node, three displacement values were assigned (in 1, 2 and 3 direction).

3.3. NUMERICAL MODEL PARAMETERS ESTIMATION

The investigation on rock mass properties in the vicinity of the study area leads to evaluation strength properties of geological layers (Rak and Stasica, 2005). Availability of leveling results in the study area enables authors to verify geomechanical parameters. Three geomechanical models were tested (Table 1).

Table 1 Parameters assumed for 3D numerical calculations.

Material of the rock mass	***Assumed model***	***E [GPa]***	***n [-]***	***r [kg/m³]***	***φ [°]***	***c [kPa]***
Model 1	Coulomb-Mohr	2.50	0.25	2300	35	0
Model 2	Coulomb-Mohr	0.45	0.35	1900	30	0
Model 3	Linear-elastic	3.00	0.20	2400	-	-

Table 2 Parameters assumed for 3D numerical calculations.

	Model 1	Model 2	Model 3
Standard deviation [m]	±0.04	±0.10	±0.14

The first and the second models were constructed on the base of Coulomb-Mohr theory. The third model was constructed applying linear elastic model. The selection of these models was done in regard to a previous investigation conducted by the authors in this study area (Tajduś, 2009a).

The accuracy of the models was evaluated on the basis of comparison simulated ground subsidence to results of geodesic measurement conducted at Dratów-Uciekajka measurement line (Fig. 6). The results obtained for the model 2 and 3 were underestimated. Comparison the results of simulation done with the application of the Model 1, to the measured values reveled that high accuracy of that model. In the area where the most significant values of ground movements had occurred application of 1 model provided the best accordance between simulated to measured subsidences (Fig. 6).

Measure of variability of first predictive model was the lowest. Standard deviation for that model was ±0.04 m (Table 2). Standard deviation was analyzed only on the section where the measurements were provided.

4. PRESENTATION OF RESULTS OF 3D NUMERICAL CALCULATIONS

Constructed models enable simulation distribution of vertical displacements, normal, principal, maximal stress and strains. Modeled distribution of ground deformation has not been analyzed in time. The static state has been result of the simulation. Subsidence which occurred above mining panel and it reached 2.35 m (Fig. 7). The analysis of distribution of principal stress reveals that concentration of compressive stress is above the center of mining panel and it reached -2.78E-06 Pa. Outside of edge of mining extraction zones subjected to tensile stress occurred. Approximately 150 meters from mining panel edge it reached its maximal value which had been around +6.03E-06 Pa (Fig. 8).

The distribution of normal stressσ_{11} is corresponding to distributions of maximum principal stress. Outside the mining panel normal stress reached +4.93E-06 Pa. The area where the maximum normal stress caused the highest tension to the surface was parallel to mining panel edge (Fig. 9a). Figures 9b and 9c presented a section along the vertical cut to show the variability of strain in vertical direction.

Further analysis were focused on simulation of distribution of maximum strains ε_{max} above the extraction field (Fig. 10). The zone of maximum concentration of compress deformations is visible. This place coincides with the localization of concentration of maximum stresses.

The distribution of linear horizontal strains ε_{11} is presented in Figure 11.

Those areas where the maximum values of strains are simulated the ground surface is prone to earth fissure occurrence. Also in this case the zone of expected earth fissures is visible. Besides, the localization of that site is very similar to the actual place where such deformations occur.

The modeled situation illustrates the static state, after the coal bed has been extracted. Despite the observable concentrations of tensile stress, attention should be paid to the fact that with the advancing front, zones of tensile stress, compressive stress and again tensile stress occur on the surface. The rock mass constantly operates, and discontinuous deformations may be probably generated in the zones of biggest concentration of compression and tensile stress, being a result of constant inner changes and the lack of equilibrium.

The analysis of distribution of strains ε_{11} reveals that discontinuous deformations may occur in the near-surface layers of the rock mass and their magnitude depends on the type and quality of ground in the near surface zones.

5. CONCLUSIONS

The analysis of the obtained results shows that the zones of high concentration of stresses and strains are very likely to occur in the neighborhood of the analyzed extraction, both on the surface and in the near-surface zones. They clearly indicate the potential places of sinkholes occurrence. The analysis of literature (Grün, 1995; Sroka, 2007 and 2008) reveals that the places of mining-induced deformations may coincide with sites defined by numerical spatial analyses. Available literature mainly focuses on designing the extraction, i.e. minimizing the activity of earth fissures – existing and the new ones. German experience clearly shows to the importance of the advancing mining front, and whether or not the extraction is realized continuously or with weekends off. Optimally the extraction should be continuous (7 days per week) at approximately constant rate.

When making numerical analyses one should be aware that the influence of mining works (excavations) on the surface and near surface layers is complex and depends on a number of factors. Not all factors can be accounted for in numerical modeling as there is no accurate method of determining parameters, which characterize the rock mass accurately and in detail. Hence, the qualitative and mainly quantitative analysis of movement of the surface under the influence of underground mining activity is practically impossible. In such conditions one should have enough data to predict the surface deformation with sufficient accuracy to help engineers work out appropriate preventive solutions minimizing the mining impact.

ACKNOWLEDGEMENTS

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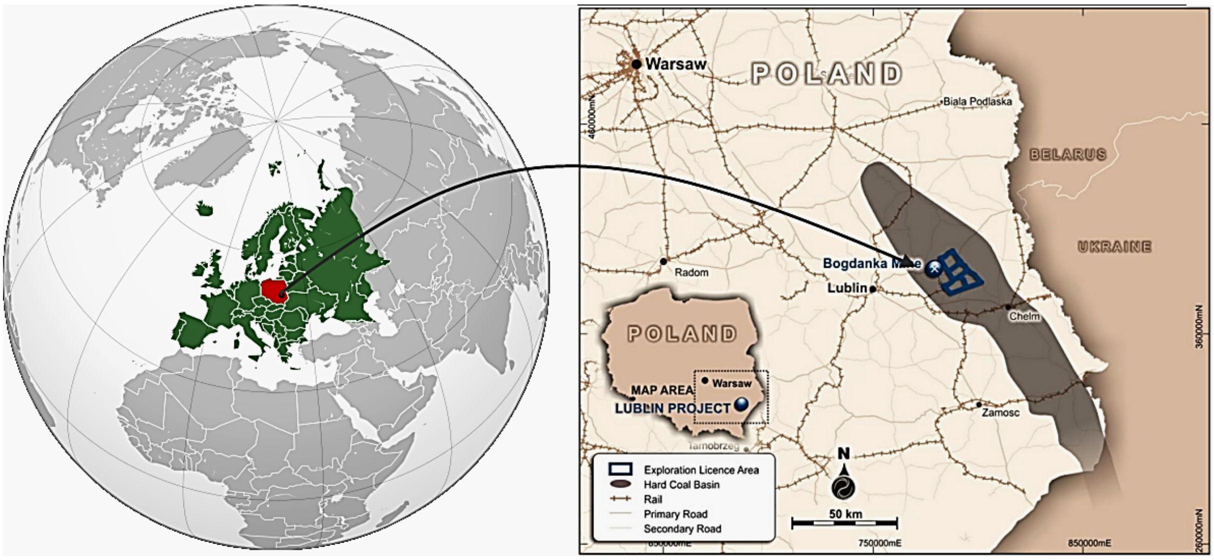
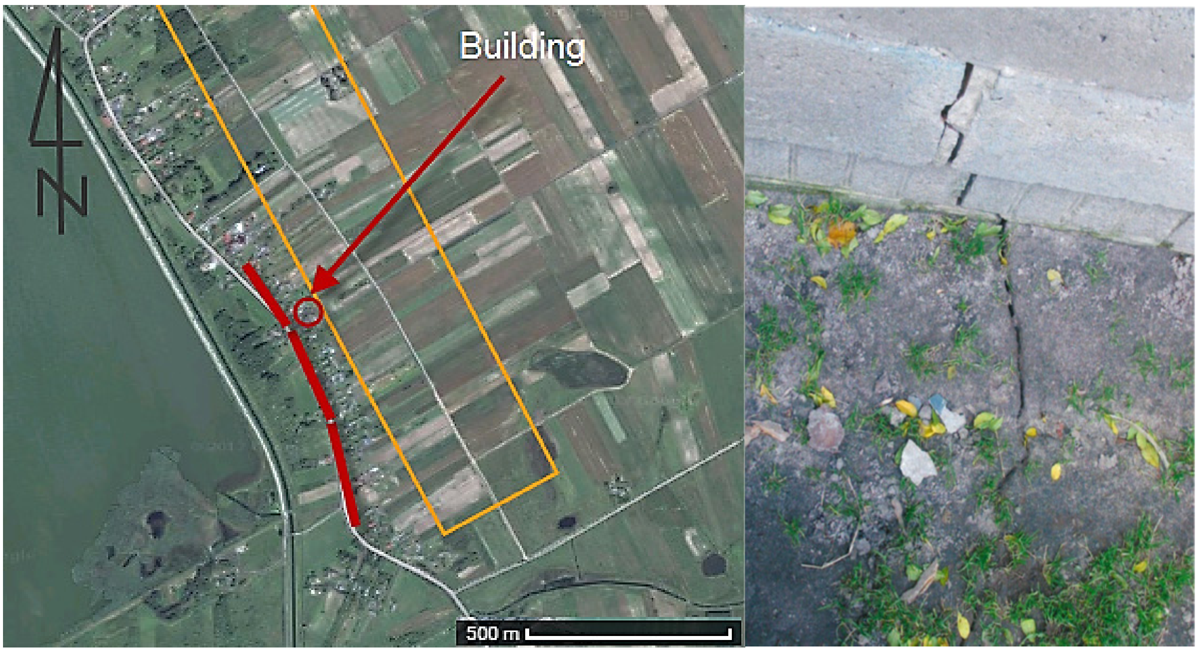


Fig. 1 Area of investigation (after google maps, 29.04.2017).



(a) (b)

Fig. 2 Places of occurrence of discontinuous deformations: earth fissures marked with red line, geometry of mining panels marked with orange line (a), damage caused by earth fissure to the building (b).

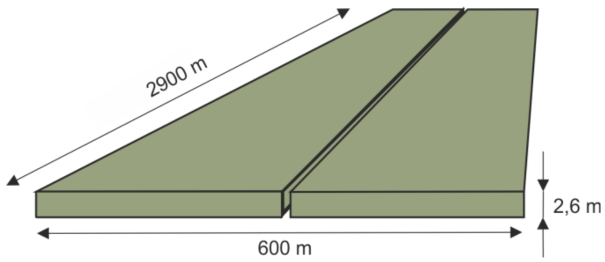


Fig. 3 Selected longwalls 10/l and 9/l of coal bed 382, Bogdanka coal mine.

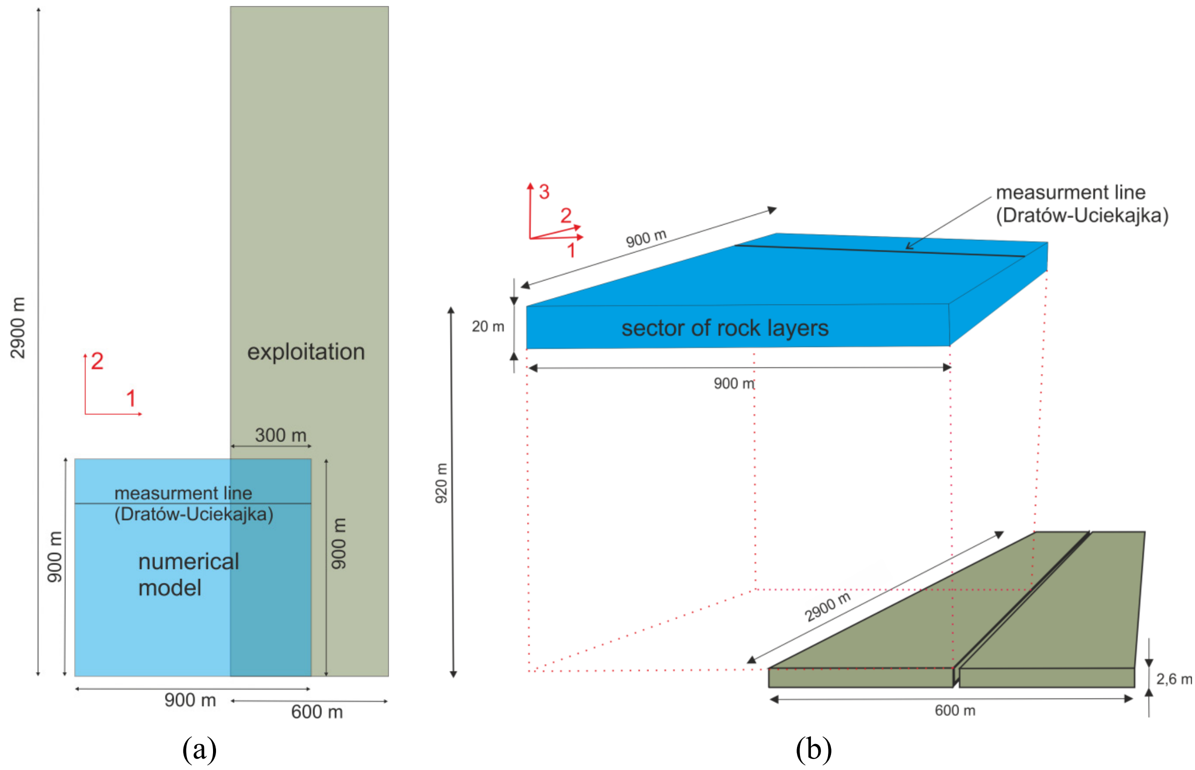


Fig. 4 Schematic of analysis: (a) ground plan, (b) spatial view.

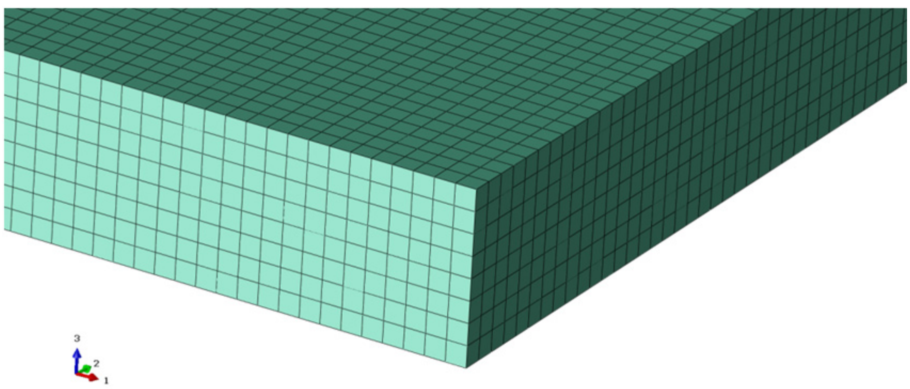


Fig. 5 Fragment of assumed grid of finite elements.

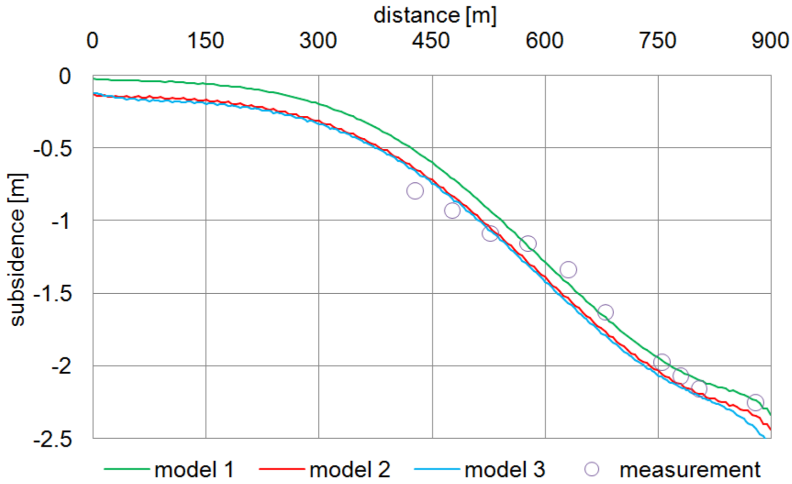


Fig. 6 Subsidence for 3 models and comparison with the results of measurements at Dratów-Uciekajka measurement line.

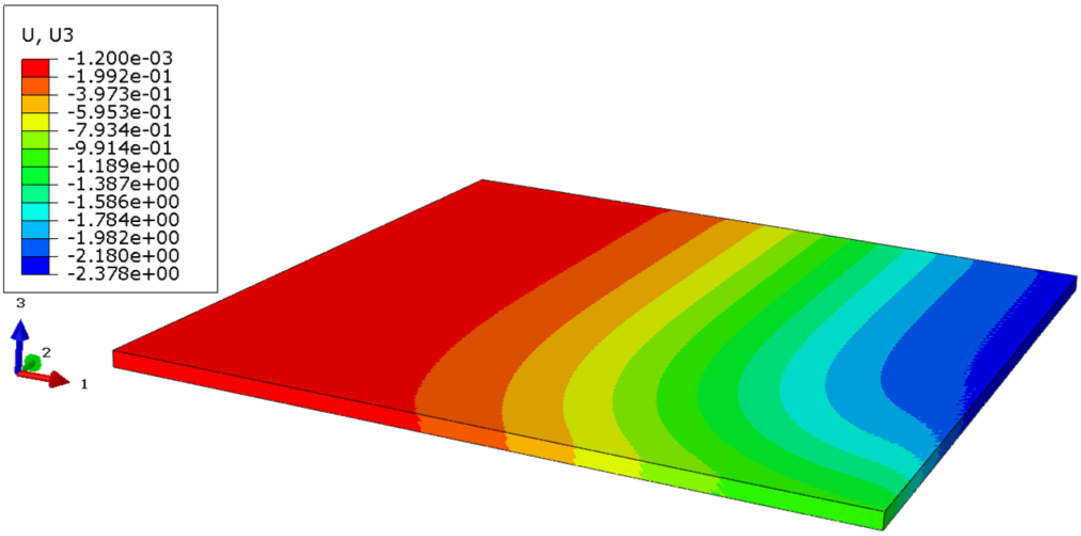


Fig. 7 Distribution of vertical deformations m, black polygon is mining panel egdes.

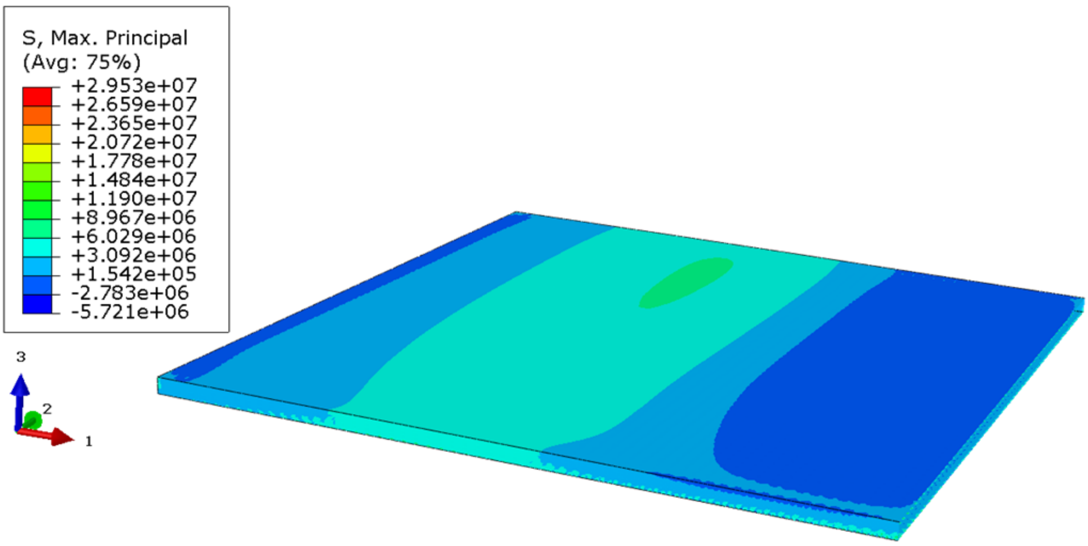


Fig. 8 Distribution of maximum principal stress σ_{max} Pa, black polygon is mining panel egdes, red line is a observed earth fissure.

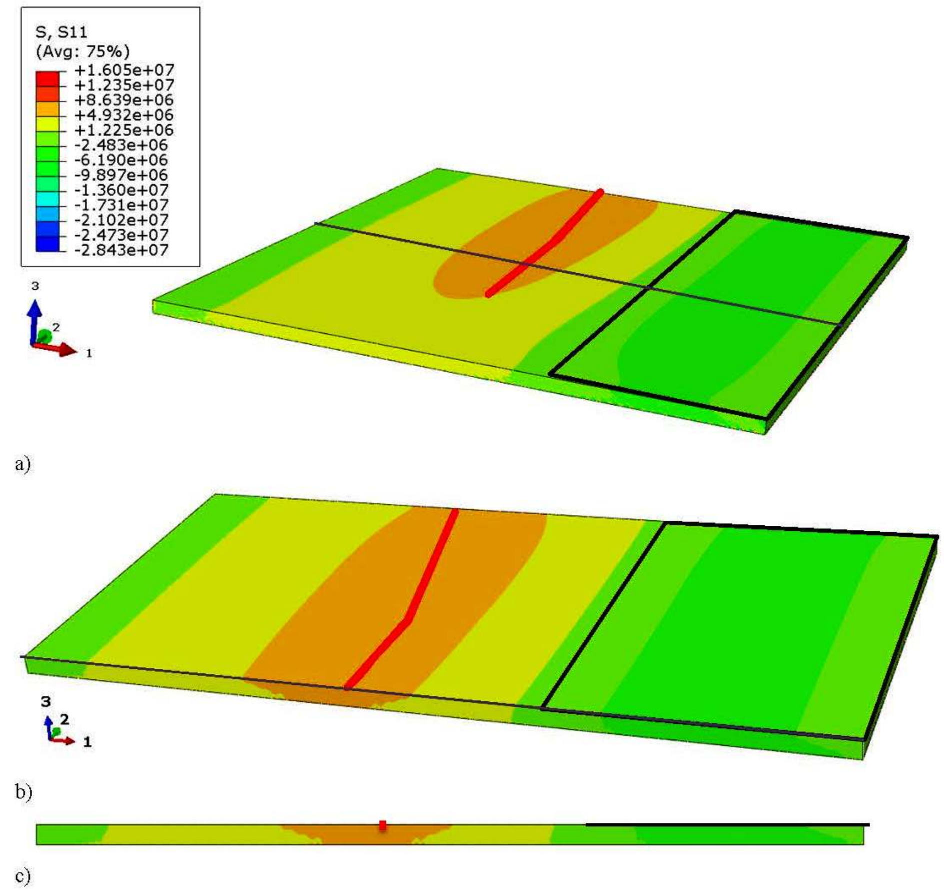


Fig. 9 a) Distribution of normal stress σ_{11} [Pa] for the surface, black polygon is mining panel egdes, red line is a observed earth fissure,
b) cut of the model to present the variability of strain in vertical direction,
c) section along the vertical

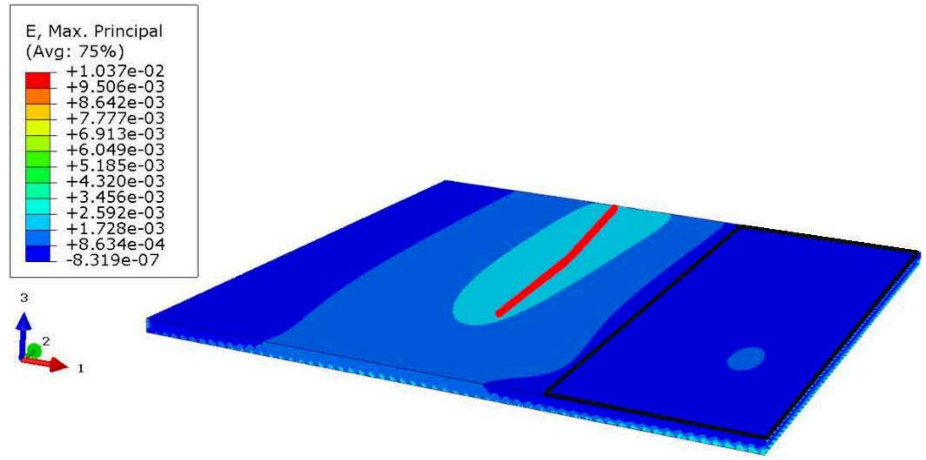


Fig. 10 Distribution of maximum strains ε_{max} [mm/m], black polygon is a mining panel egdes, red line is the observed earth fissure.

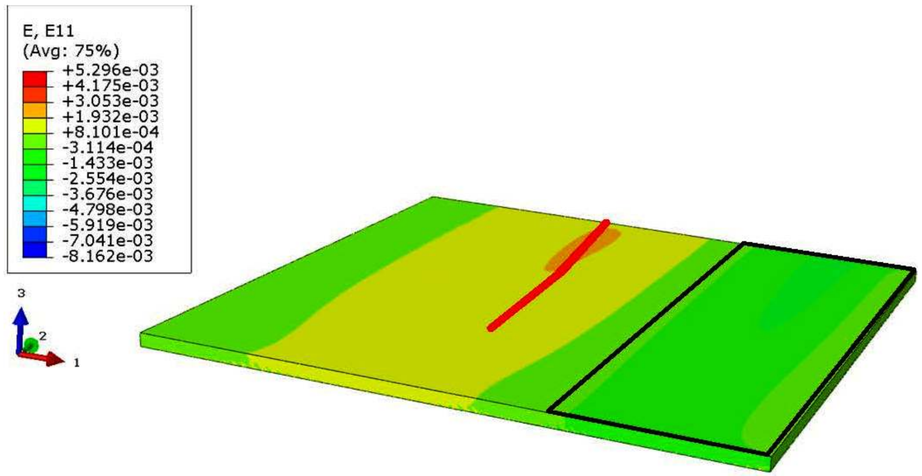


Fig. 11 Distribution of linear horizontal strains ε_{11} [mm/m] for terrain surface, black polygon is mining panel egdes, red line is the observed earth fissure.