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Ground subsidence modeling based on stress redistribution in rock mass

Abstract

Safety of underground mining operation and its effects on the surface infrastructure depend mainly on the redistribution of stresses in the surrounding rock mass. Therefore, more attention must be given to the use of deterministic modeling methods based on the knowledge of causative factors (loads), in-situ rock parameters, and physical laws governing the constitutive stress-strain relationship. Deterministic modeling of rock poses many challenges in large scale problems such as in the determination of the whole rock mass deformation in ground subsidence studies. The main problem comes from the fact that the rock mass in its natural geological state is largely discontinuous, anisotropic, and inhomogeneous.

Modelowanie osiadania terenu w oparciu o zmianę rozkładu naprężeń w górotworze

Streszczenie

Bezpieczeństwo podziemnych robót górniczych i ich wpływ na infrastrukturę powierzchni zależą głównie od zmiany rozkładu naprężeń w otaczającym górotworze. Dlatego należy zwrócić większą uwagę na zastosowanie metod deterministycznego modelowania w oparciu o znajomość czynników przyczynowych (obciążeń), parametrów skał *in situ* oraz praw fizycznych rządzących istotną zależnością naprężenie-odkształcenie. Modelowanie deterministyczne skał stawia wiele wyzwań w problemach na dużą skalę, takich jak określenie całkowitego odkształcenia górotworu w badaniach osiadania terenu. Główny problem wynika z faktu, że górotwór w swoim naturalnym stanie geologicznym jest w dużym stopniu nieciągły, anizotropowy i niejednorodny.

1. INTRODUCTION

Safety of underground mining operation and its effects on the surface infrastructure depend mainly on the redistribution of stresses in the surrounding rock mass. In cases of simple geology and geometry of mining method, modeling of ground subsidence may be based on empirical geometrical methods, e.g. methods based on empirical influence functions. They do not fulfill all the requirements for either an assessment of the safety of the mining operation or for physical interpretation of ground deformation. Therefore, more attention must be given to the use of deterministic modeling methods based on the knowledge of causative factors (loads), in-situ rock parameters, and physical laws governing the constitutive stress-strain relationship. Numerical methods, for example, the finite element method (FEM), are used in solving differential equations in the deterministic model. Powerful software packages for FEM are commercially available.

Deterministic modeling of rock deformation is commonly used in solving small scale problems in rock mechanics in determining stress redistribution in the vicinity of underground openings. It still poses, however, many challenges in large scale problems such as in the determination of the whole rock mass deformation in ground subsidence studies [21, 5, 23]. The main problem comes from the fact that the rock mass in its natural geological state is largely discontinuous, anisotropic, and inhomogeneous.

The rock mass characteristics include such parameters as: Young's modulus, compressive strength, shear strength, tensile strength, cohesion, angle of friction, post-failure modulus,

bearing capacity, and coefficient of thermal expansion. The in-situ mechanical rock mass parameters, particularly Young's modulus and strength, significantly differ from laboratory values which are obtained from small rock samples. The mining activity further changes the rock mass properties through the redistribution of stresses. When the detailed in-situ information on the rock material parameters and its stress is not available, the use of rock mass classification schemes may supply additional information [12, 10]. A number of rock mass classification systems have been developed.

Combination of 3-D monitoring results with deterministic modeling of deformations is essential for studying the processes occurring in the rock mass. Through a comparison of predicted deformations with the actual deformations, a better understanding of the mechanism of the deformations is achieved. On the other hand, the prediction models supply information on the expected deformation, which facilitates the design of the monitoring scheme.

The authors have been involved in deterministic modeling of rock mass behavior for many years and still are searching for better solutions, particularly in complex geological and mining conditions. Currently, they are developing a prediction model of rock mass behavior in a potash mining and gas withdrawal operation in eastern Canada. This paper reviews some problems and challenges of deterministic modeling of rock mass behavior followed by an outline of modeling approach in the area of the combined potash mining and gas withdrawal area.

2. REVIEW OF PROBLEMS IN MODELING ROCK MASS BEHAVIOR

2.1. Definition of Rock Mass

Rock mass in its natural geological state is largely discontinuous, anisotropic, and inhomogeneous material. Rock mass may be presented as an assemblage of intact rock blocks, called rock material, separated by various types of geological discontinuities. Behavior of the continuous rock mass can be analyzed using a model based on continuum mechanics, while a discontinuous model, such as the one proposed by Cundall [6], may be used to analyse the jointed rock mass. However, since it is almost impossible to define in practice all the joint blocks, one can assume that this type of rock mass may behave, in a global sense, like a continuous body. Therefore, a continuum mechanics deterministic model can be used with the effect of discontinuities adequately considered in the model. This is achieved by a large-scale approach, where equivalent geomechanical properties of the rock mass are derived based on the geometry of the contained fracture system and physical properties of the intact rock mass and the fractures.

The input information needed in the deterministic methods generally include geological characterization of rock mass, evaluation of initial state of stress, and the mechanical properties, which characterize the rock mass in in-situ stress conditions. The rock parameters may be obtained either from in situ testing, laboratory testing, or through a calibration based on the combination of a deterministic model with results of monitoring rock behavior.

The physical values obtained from laboratory testing require scaling in order to represent the rock mass. The problem of scale-dependent properties is a main problem in modeling rock behavior [4, 9]. There are a number of scaling techniques, which can be used for relating values of rock properties obtained from laboratory testing to rock mass in-situ values. The techniques are based on correlation numbers, which can be determined from empirical knowledge or from a selected rock classification system.

2.2. Rock Mass Classification

Rock mass classifications are the basis of the empirical design in rock mass. A number of rock mass classification systems have been developed to provide general information on the properties of rock mass. A general rock classification is based on the quality of the rock and is named Rock Quality Classification (RQC). Based on the general RQC classification, the very good quality hard rock mass [13] behaves as an elastic brittle material. In the case of an average quality rock mass, the post-failure characteristics can be estimated by reducing the Geological Strength Index (GSI) value from the in situ value to a lower value which characterizes the broken rock mass. A very poor quality rock mass may behave as a plastic material in certain loading conditions. Two most commonly used rock mass classification systems today are the Rock Mass Rating (RMR) classification [2] and the Q-system [1]. These classifications include information on the strength of the intact rock material, spacing, number, and surface properties of the structural discontinuities as well as allowances for the influence of subsurface groundwater, in situ stresses, and the orientation and inclination of dominant discontinuities.

2.3. Mechanical Parameters of the Rock Mass

One of the most important problems in rock mechanics is determining Young's modulus values, which vary through the in-situ rock mass. Generally, Young's modulus of in situ rock mass is smaller than the values obtained from laboratory testing [4, 18]. Studies by Bieniawski [3] and Heuse et al. [5] show that on average, Young's modulus of rock material measured in the laboratory is 2.5 higher than the in situ Young's modulus of rock mass. The ratio ranges from 1.7 to 5. The ratio depends on Rock Quality Designation (RQD) index of the rock mass. The correlation between Young's modulus of rock mass and Rock Mass Rating (RMR) classification is based on case histories [4]. [19] defined a correlation between Young's modulus of rock mass and Rock Mass Rating (RMR) classification. Young's modulus of rock is defined as a correlation to Geological Strength Index (GSI) by [14].

Estimating the strength of the rock mass poses another major problem in rock deformation modeling. The rock strength decreases with the size of the model where large fractures are predominant. Determination of the strength of an in situ rock mass by methods used in laboratory testing is generally not practical because the tests are made on the rock samples. The strength should be estimated and scaled from geological observations and from test results on individual rock pieces or rock surfaces, which have been removed from the rock mass. The laboratory strength of the rock mass also must be scaled in order to give in-situ values. The strength reduction is dependent on the type of rock and the state of stress. The strength reduction number in weak and poor quality rock is larger than in strong and good quality rock. In the case of tensional stresses, the tensile strength is reduced almost to zero due to the opening of the cracks in the rock mass. Therefore, brittle rock behavior can be assumed as the behavior of a non-tension material. The strength of the rock mass can be determined from the laboratory testing using reduction formula given by [17]. The different range of scaling coefficient values was determined for compressive or tensional strength reduction as a function of rock material strength. The rock mass strength can be estimated using the Rock Mass Strength (RMS) value [20].

2.4. Behavior Model of Rock Mass

Another important problem in deterministic modeling is the selection of the rock material behavior. The model of linear elasticity is still most widely used in modeling behavior of rocks, especially hard rock [15]. More sophisticated constitutive models used in rock mechanics are, for example, a transversely isotropic elasticity [24], anisotropic elasticity, plasticity, elasto-

plasticity, and visco-elasticity. Plasticity and elasto-plasticity models used in rock mechanics are typically based on Mohr-Coulomb and Hoek-Brown failure criteria [12]. The transversely isotropic elasticity model is extensively used in modeling behavior of brittle rock mass [25]. The model is presented in Figure 1. Visco-elastic models are used in salt rock or other weak rocks and may be based on a rheological model [16]. Salt rock is also modeled as a non-Newtonian liquid [8]. Use of more sophisticated constitutive models in rock mechanics may be limited by a difficulty in obtaining necessary parameters. Therefore, their use may be not practical.

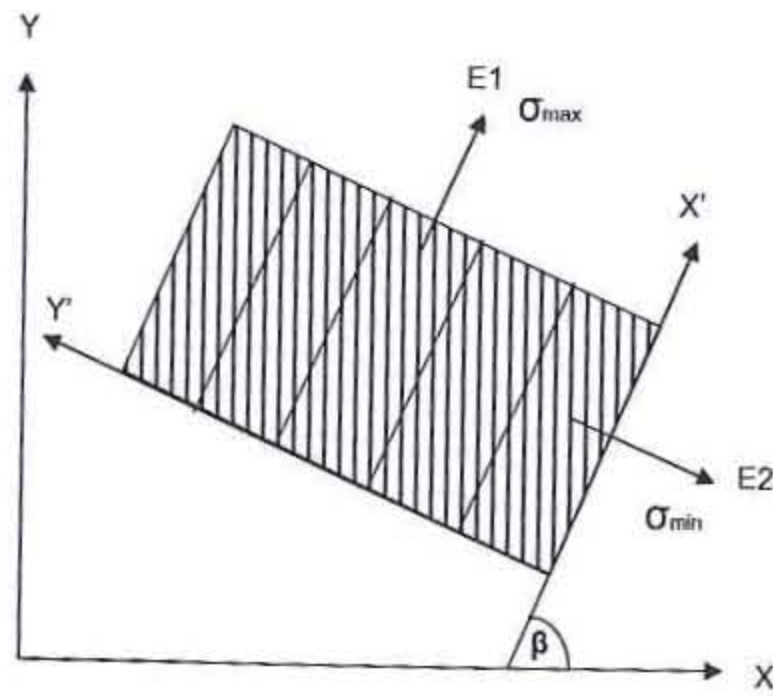


Fig. 1. Transversely isotropic model

3. BEHAVIOR OF ROCK MASS DISTURBED BY UNDERGROUND MINING

3.1. Redistribution of Stress

Before starting the mining activity, initial conditions such as geological characterization of brittle rock mass, initial state of stress, and the initial geomechanical properties should be defined. In the initial state of stress, the rock mass is subjected to compressive stresses such that:

$\sigma_{\max} > 0$ and $\sigma_{\min} > 0$, where: σ_{\max} is maximum stress and σ_{\min} is minimum stress.

In most cases, the intact rock mass may be modeled using the linear elastic model. The brittle rock behavior can be assumed as the behavior of a non-tension material.

The introduction of an underground mining opening causes a stress redistribution.

In extreme conditions, three zones of stress configuration may be identified:

- 1) tensional zone immediately over the mining opening with $\sigma_{\max} < 0$ and $\sigma_{\min} < 0$;
- 2) transversely isotropic zone with: $\sigma_{\max} > 0$ and $\sigma_{\min} < 0$, and
- 3) compressive zone with $\sigma_{\max} > 0$ and $\sigma_{\min} > 0$.

The new state of stress and location and size of the zones can be determined from the FEM initial solution with mining opening using linear elastic model. In the next solution, the zone (1) will be modeled as a zone with reduced strength and reduced Young's modulus. The zone (2) will be modeled using the transversely isotropic model shown in Figure 1. The zone (3) will be modeled using linear elastic model if it does not exceed a given criteria. One of the problems of modeling zone (2) is selection of reduction coefficient c , which determines the ratio between E_1 and E_2 (Fig. 1):

$$c = E_1 / E_2,$$

where: E_1 and E_2 are in directions of σ_{\max} and σ_{\min} respectively. The angle β between x, y and x', y' coordinate systems (Fig. 1) may be determined from the FEM solution as an orientation of principal stresses.

3.2. Sensitivity of Surface Deformation to Changes of Rock Mass Parameters

To illustrate the sensitivity of the modeled deformations to the changes of the model parameters, a simplified mining example of a long wall coal extraction with caved-in roof has been used as shown in Figure 2. Tables 1 and 2 give the geometrical data and initial geomechanical parameters taken from [24]. For the purpose of the test, the delineation of the three post-mining zones has been arbitrarily selected as given in Figure 2.

The given examples relate only to the effects of changes of coefficient c and changes in angle β in the transversely isotropic zone.

Table 1. Geometry and geological strata of the test mine

Rock mass layers in the region of excavation	Rock mass layers thickness (m)	Depth (m)
Trias	90	90
Clay shale	65	155
Sandstone	75	230
Clay shale	18	248
Sandstone	40	288
Clay shale	18	306
Sandstone	11	317
Clay shale	13	330
Coal	3.0	333
Sandstone	120	453

Table 2. Initial parameters

Rock mass	Rc (MPa)	E (GPa)	ν
Trias layers	12.2	1.900	0.25
Clay shale	18.0	1.600	0.25
Sandstone	12.6	1.300	0.25
Clay shale	21.6	1.600	0.25
Coal	10.0	0.900	0.25

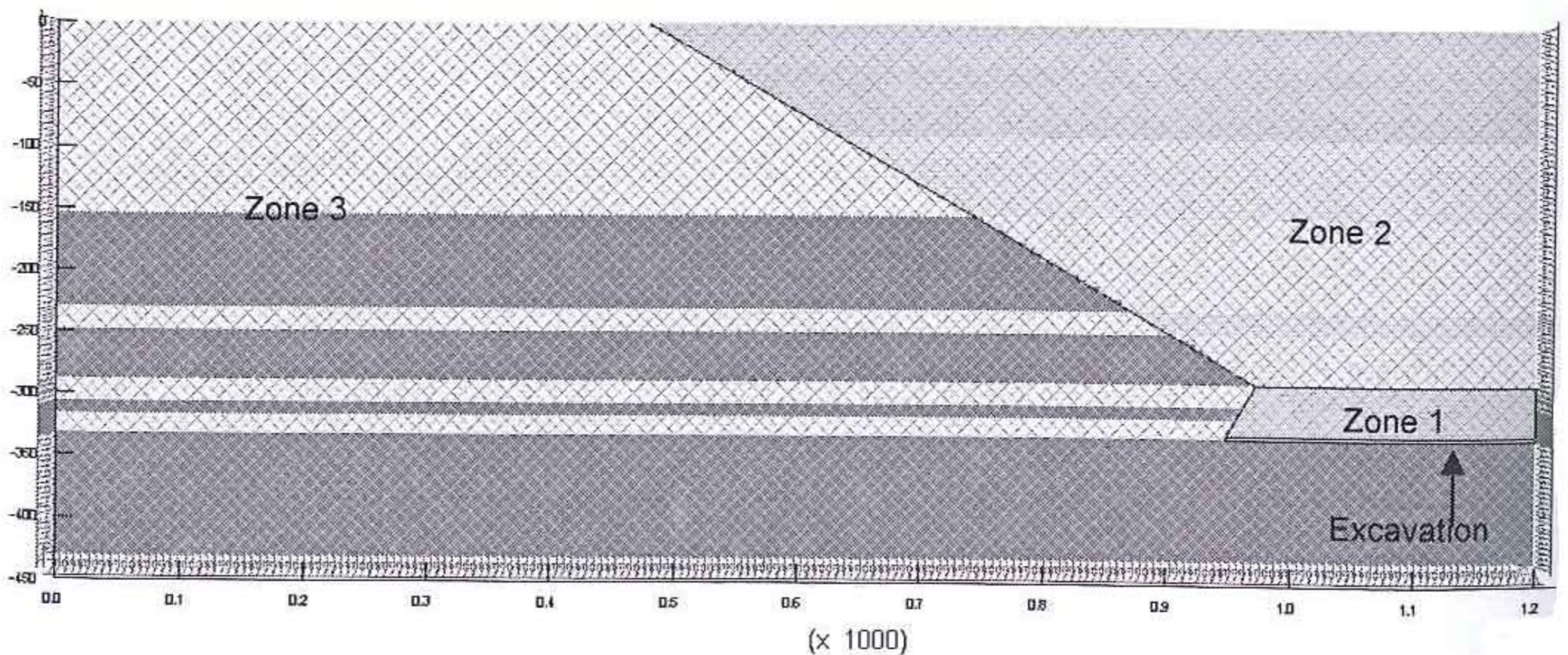


Fig. 2. Excavation and three post-mining zones: caved-in (Zone 1), transversely isotropic (Zone 2) and isotropic compressive (Zone 3)

3.2.1. Sensitivity of Surface Deformation to Changes of Coefficient 'c'

Changes of parameter c values from 1 to 100 were introduced to FEM analysis of surface deformations. In all analyses, the angle β was accepted as 90° . Figure 3 and Figure 4 show changes to the horizontal and vertical surface displacements as a function of coefficient c . As one can see, when using the transversely isotropic material model of zone 2, the horizontal displacements for linear elastic solution ($c = 1$) are twice smaller, then in the case of $c = 10$. In case of vertical surface displacements, the changes in the value of c significantly affect the shape of the subsidence curve.

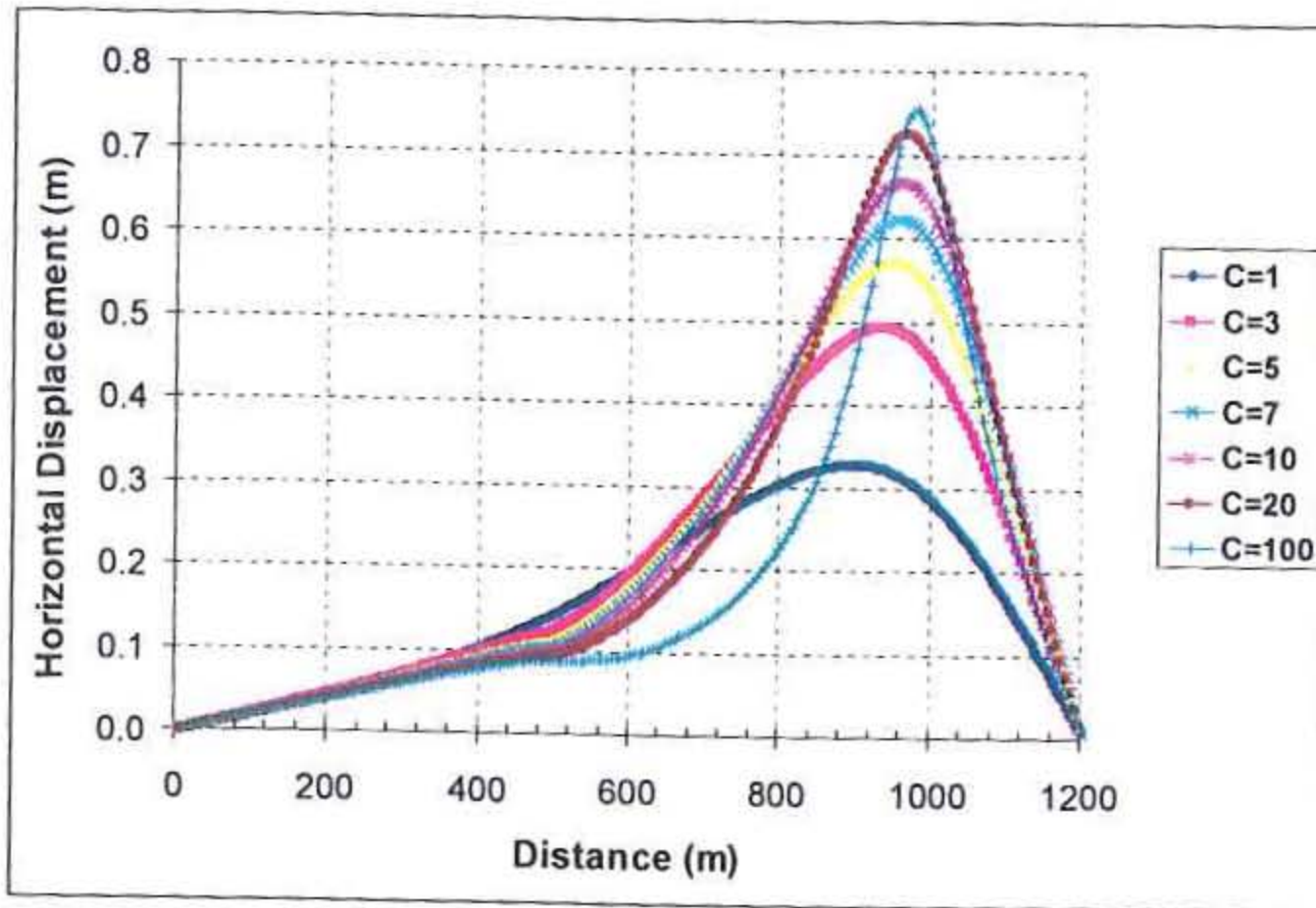


Fig. 3. Horizontal displacements

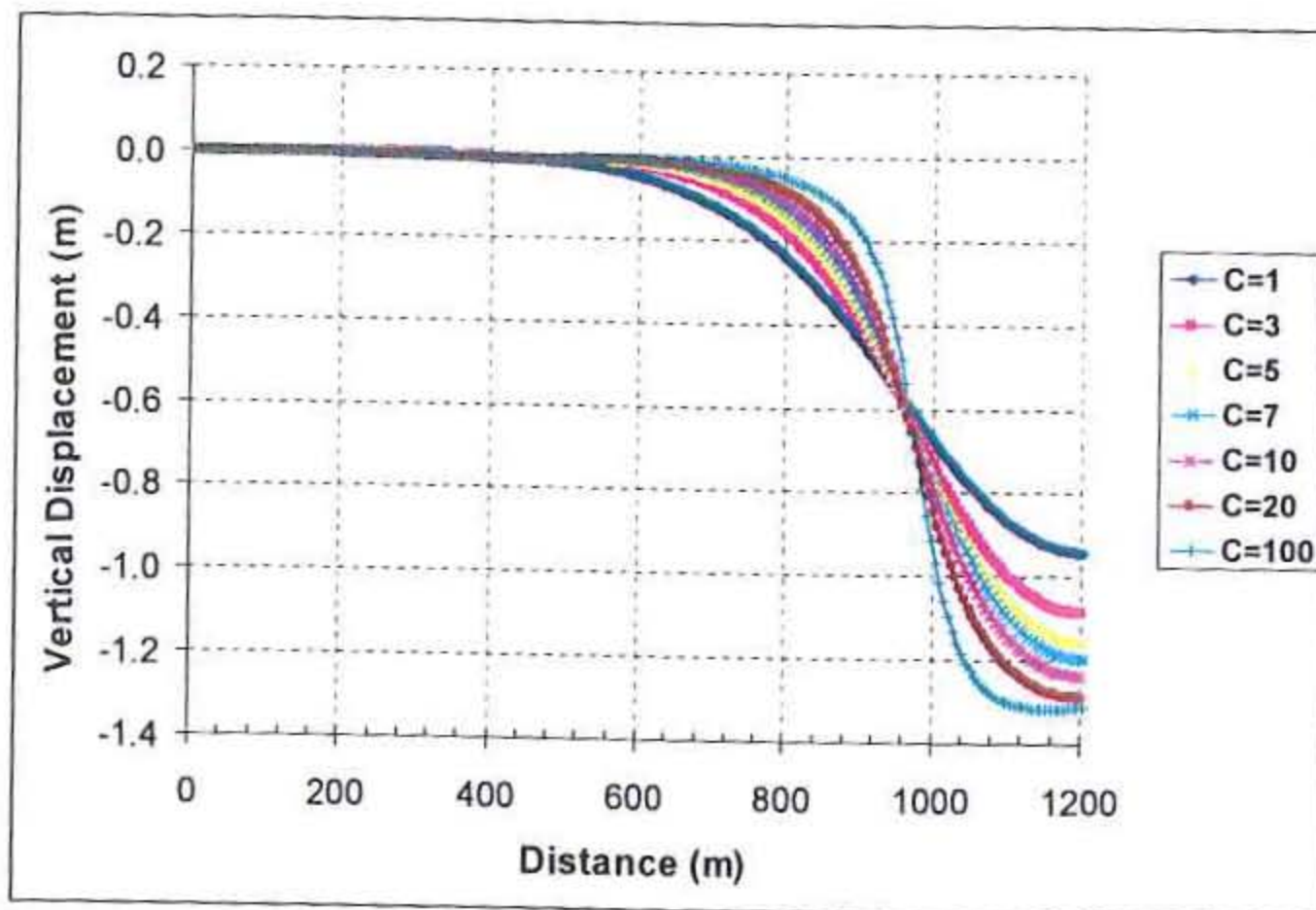


Fig. 4. Vertical displacements

3.2.2. Sensitivity of Surface Deformation to Changes of Angle β

The test was performed for 5 values of angle β between: $\beta = 0^\circ$ and $\beta = 90^\circ$. The changes were uniformly introduced in the whole zone 2. An additional test was made by dividing zone 2 into three layers with $\beta = 0^\circ$ in the lowest layer, $\beta = 45^\circ$ in the middle and $\beta = 90^\circ$ in the

upper layer. In all analyses, the parameter c was accepted as $c = 5$. Figure 5 and Figure 6 show changes to the horizontal and vertical surface displacements as a function of angle β . As expected, the value of β has very significant effect on both horizontal and vertical surface displacements.

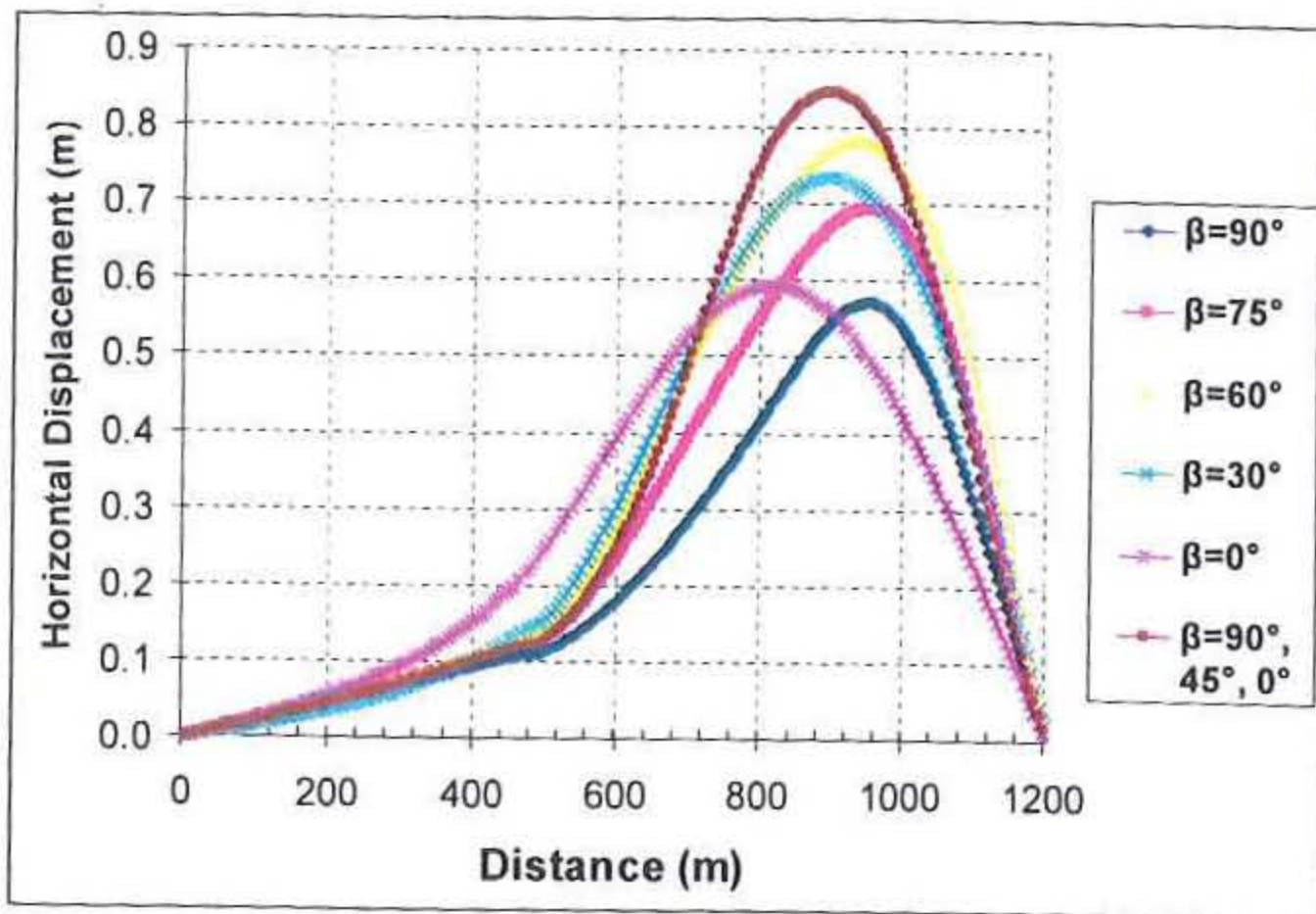


Fig. 5. Changes of horizontal displacements

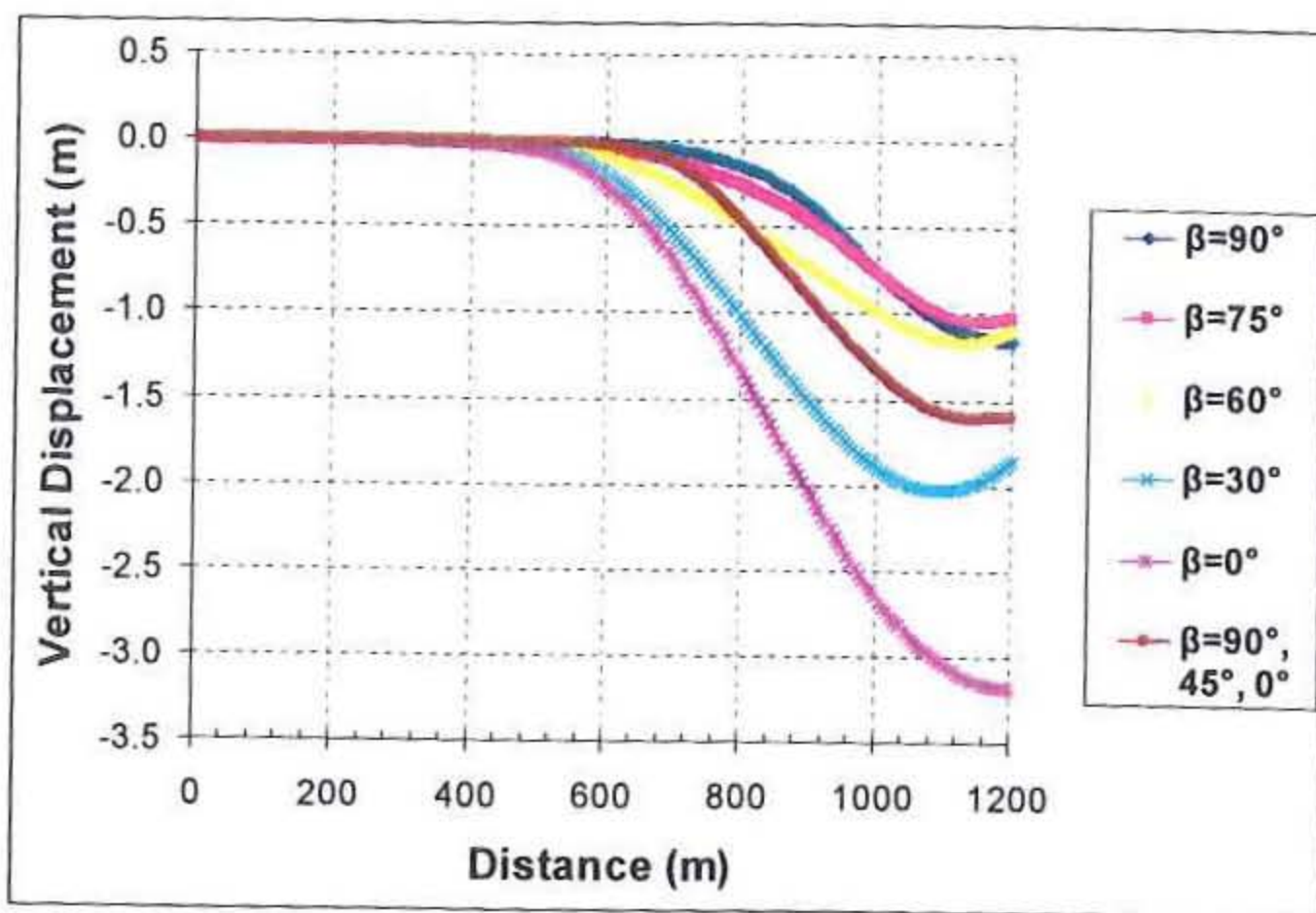


Fig. 6. Changes of vertical displacements

3.3. Determination of Surface Deformation Based on Stress Redistribution

In the presented deformation analysis based on redistribution of stresses the same mining example of a long wall coal extraction with caved-in roof has been used as shown in Figure 2. Tables 1 and 2 give the geometrical data and initial geomechanical parameters. The analysis is based on determination of the redistribution of stresses in the rock mass produced by the mining activity. The delineation of the three post-mining zones has been based on the actual stress distribution (Figure 7). Figures 8 and 9 show resulting horizontal and vertical surface displacements when applying reduction coefficient $c = 20$ in the caved-in zone (zone 1) and $c = 5$ in the transversely isotropic zone (zone 2).

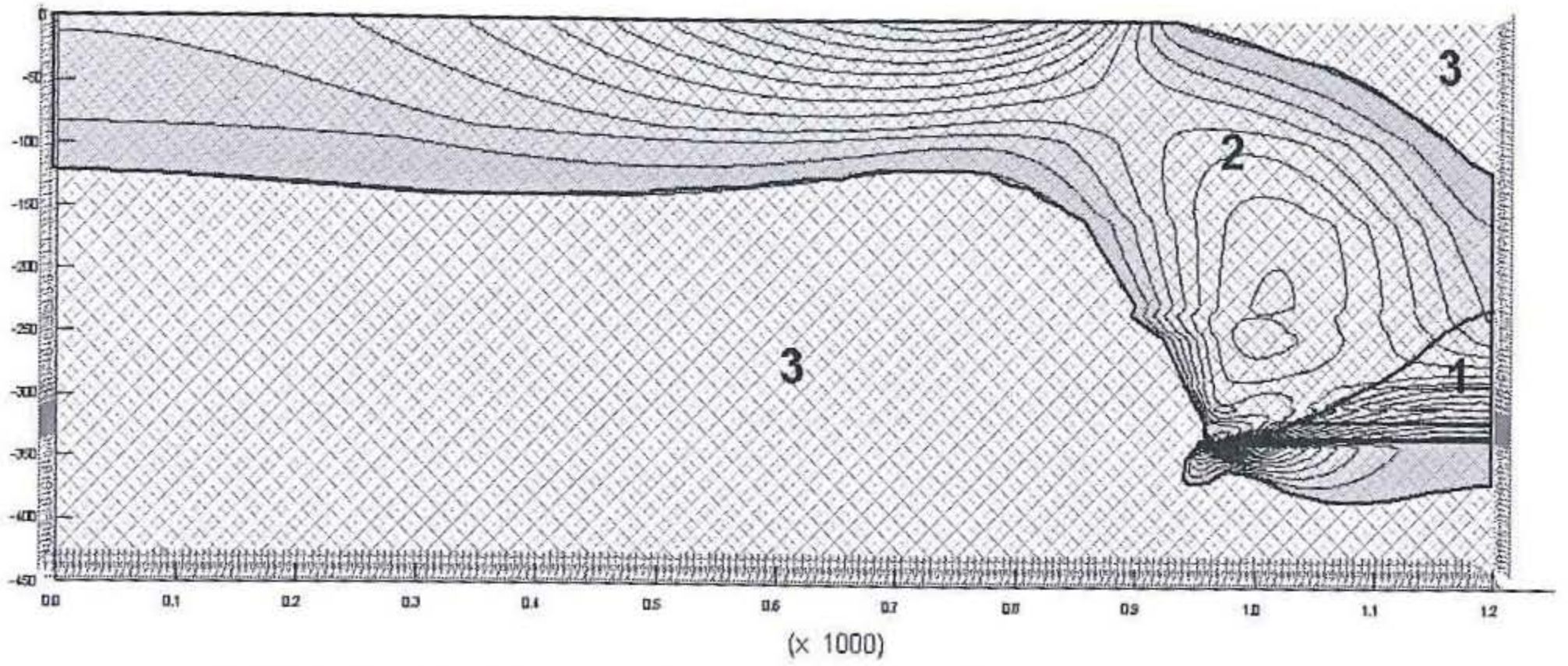


Fig. 7. Delineation of the zones: 1 – caved in, 2 – $\sigma_{\min} > 0$, 3 – compressive stresses

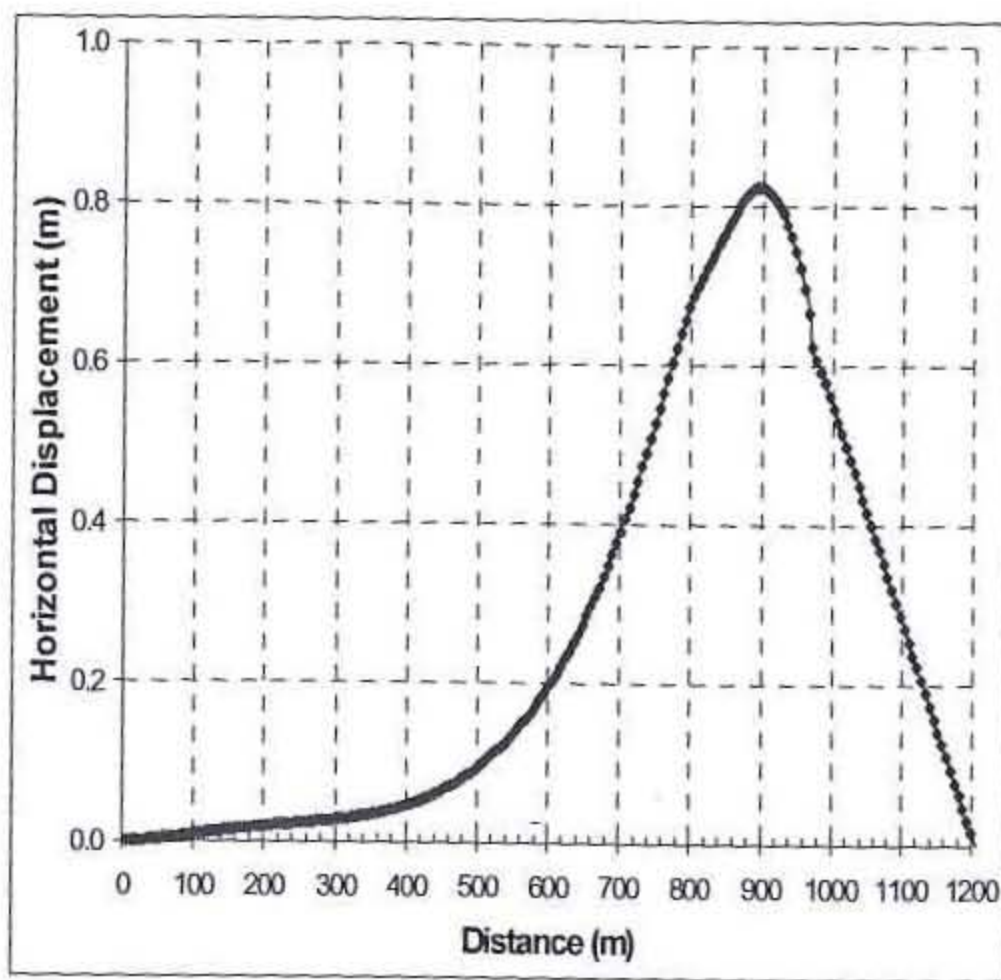


Fig. 8. Surface Horizontal Displacements

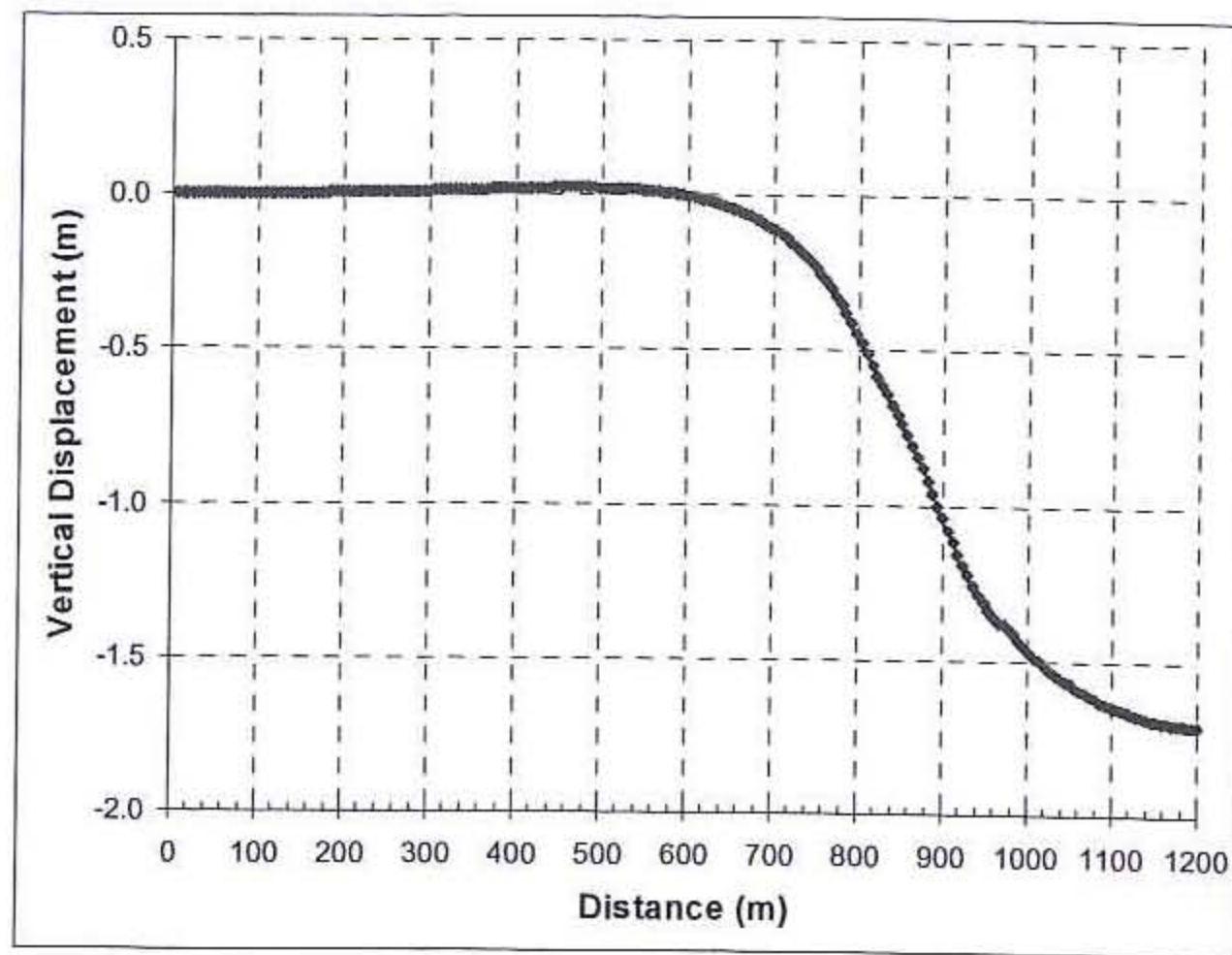


Fig. 9. Surface vertical displacements

4. MODELING OF GROUND DEFORMATION DUE TO POTASH AND NATURAL GAS WITHDRAWAL

Mining of a large deposit of high grade sylvinite in New Brunswick, Canada, has been carried out since the mid 1980s. Potash and salt mining takes place at depths between 400 m to 700 m within a 25 km long dome-shaped salt pillow in which the potash is preserved in steeply dipping flanks (Fig. 10).

The potash deposit is structurally complex with a variable dip and width. A strong, arch shaped, cap rock provides a natural support for the overlain brittle rocks. Potash is mined by using a mechanized cut-and-fill method with up to 100% extraction in the 1000 m long and about 150 m high stopes. Salt mining is by multi-level room-and-pillar method with unsupported openings up to 25 m wide. Currently, the mine in New Brunswick expands its activity to Picadilly field (Fig. 11), which will become operational in 2012 and will triple the potash production. The existing mine is subjected to significant water inflow that produces hydrological changes in the rock mass.

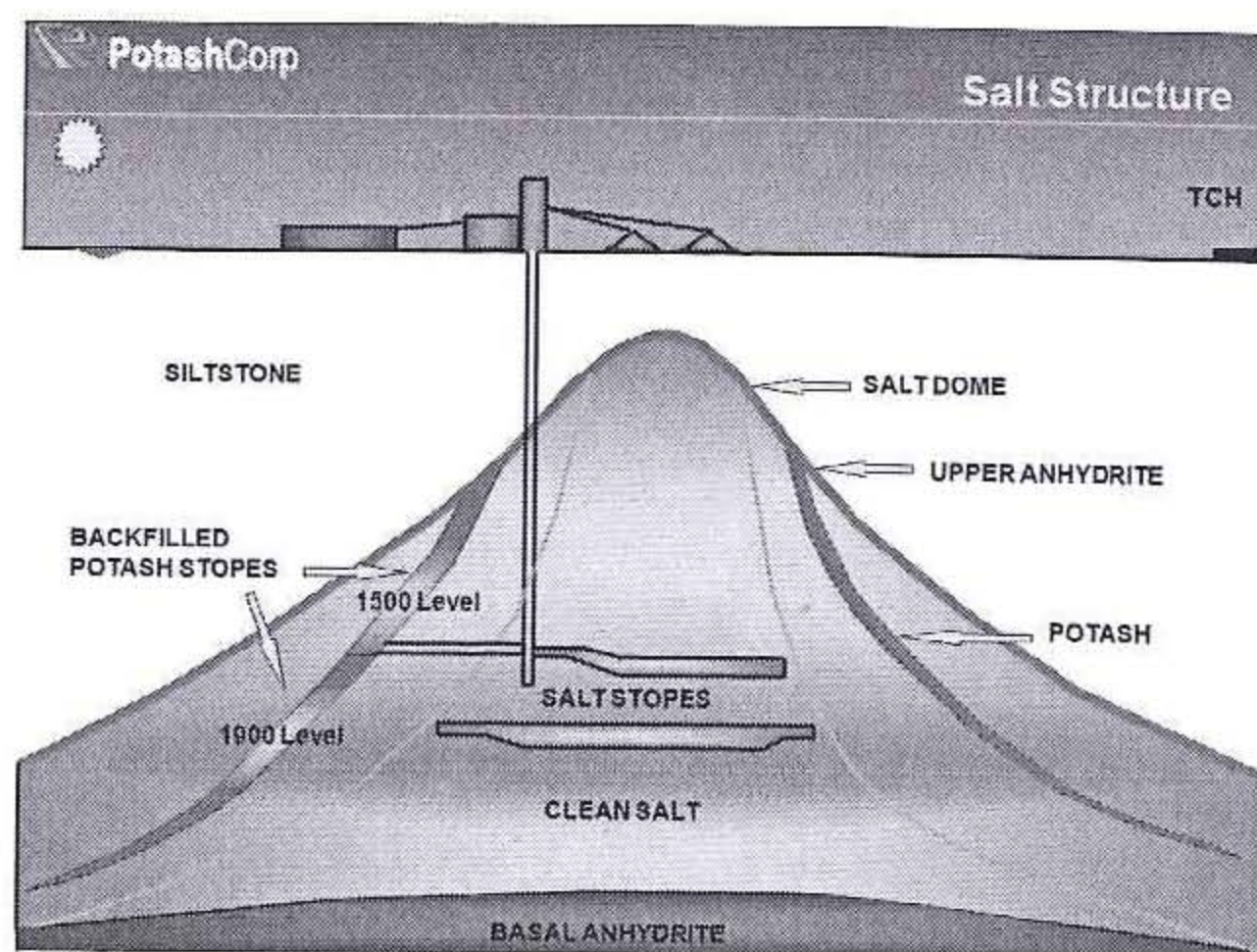


Fig. 10. Schematic cross-section of the potash and salt formation (courtesy of PCS-NB Division)

In 2007, extraction of natural gas was initiated from McCully gas deposit located below the salt pillow at a depth of 3000 m. Gas is withdrawn by using multi-stage fracturing method (Fig. 12). Preliminary estimation of the gas-in-place resources amounts to 59 trillion cubic feet. Recent exploration indicates that more gas and possible oil may be located in the area at depths ranging from 1700 m to 3000 m.

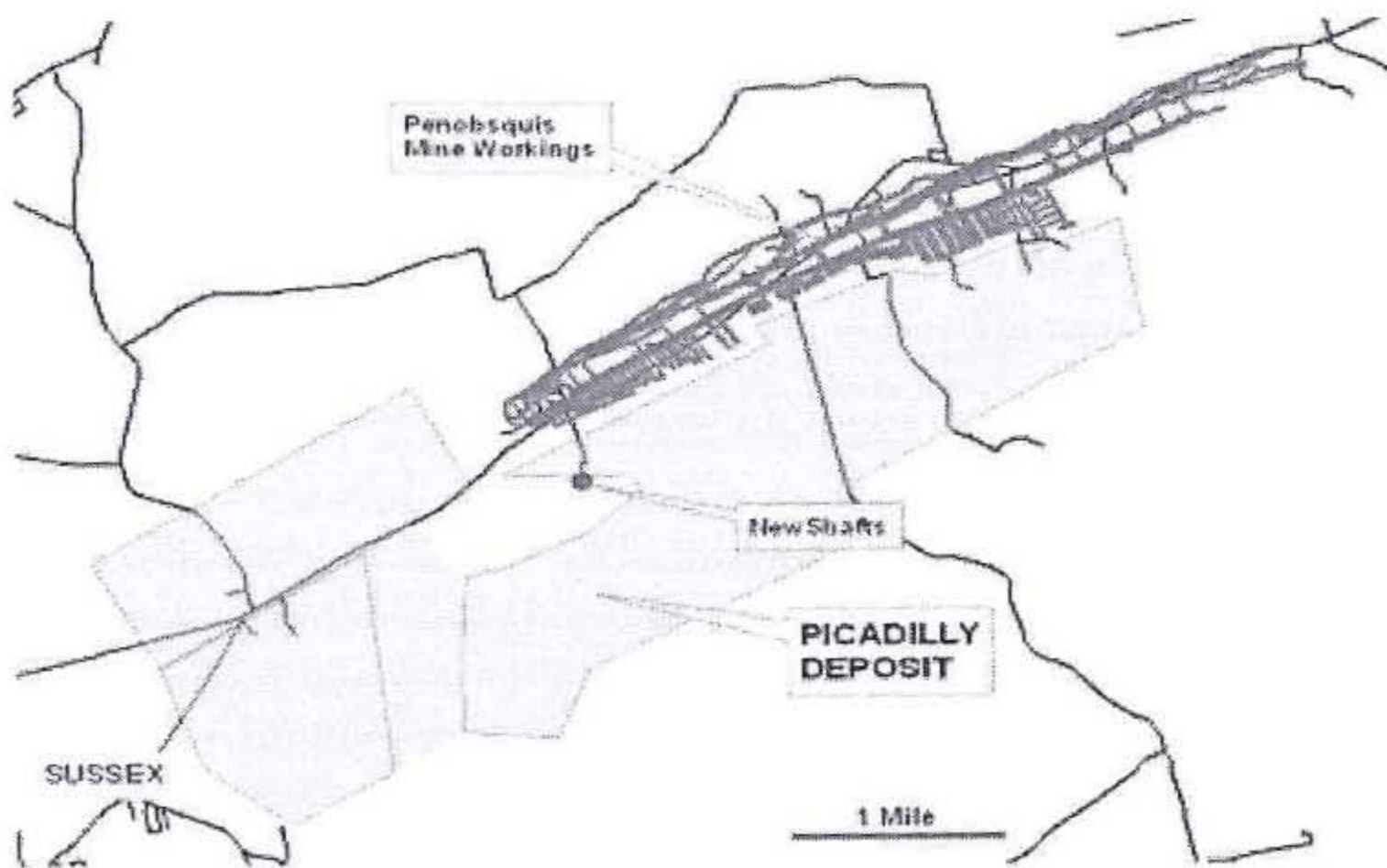


Fig. 11. Current mining workings (marked red) and the planned Picadilly expansion (shaded area)

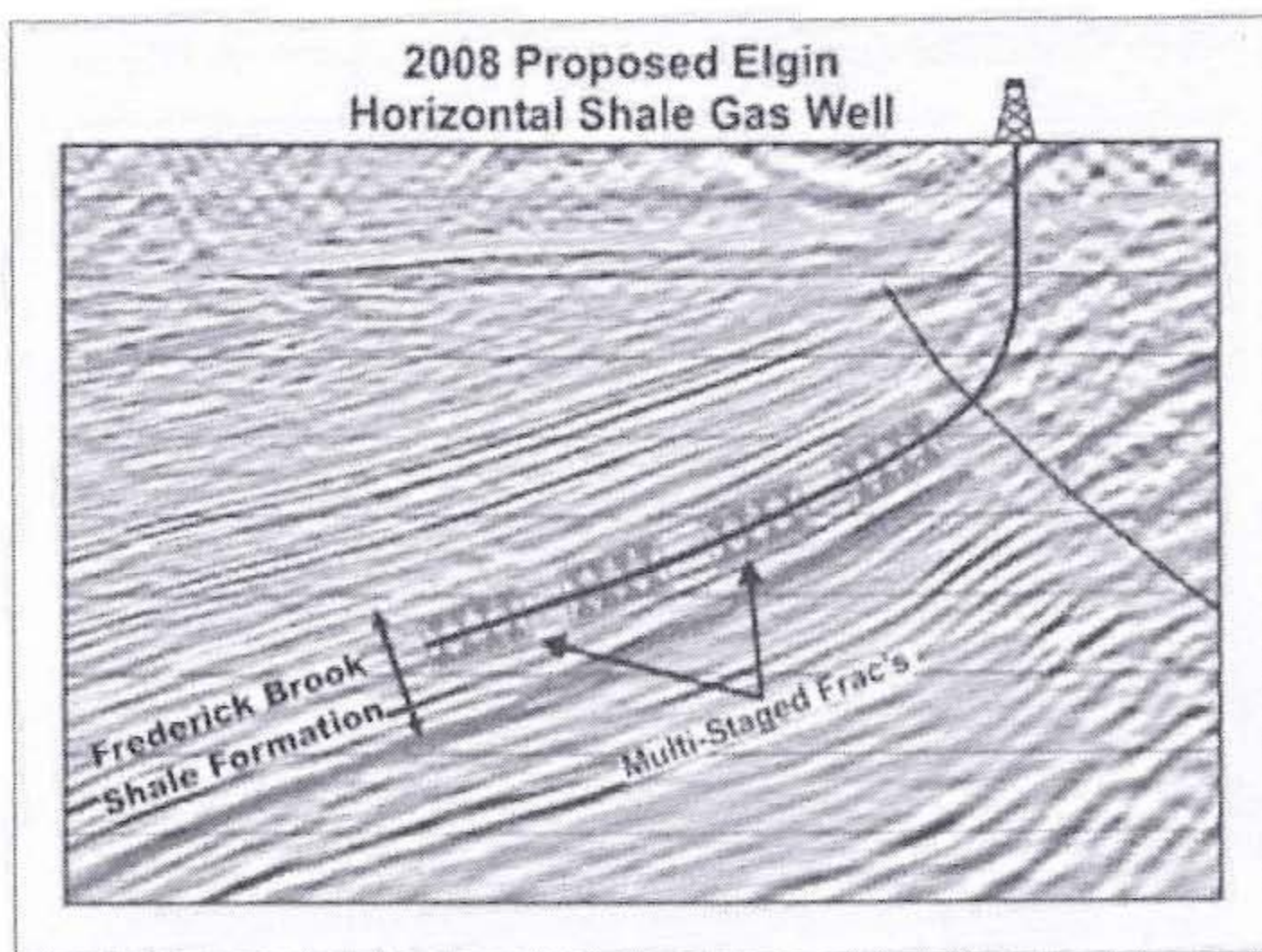


Fig. 12. Multi-stage fracturing method of gas extraction

New development of potash mining in Picadilly field and development of gas extraction project requires the enhancement of the deterministic modeling of subsidence and development of a prediction model for the Picadilly area. The objective of modeling is to determine the combined effects of:

- (1) existing and new potash mining operation,
- (2) hydrological changes, and
- (3) natural gas withdrawal.

Monitoring of ground subsidence has been conducted annually since 1989. Currently, a three-dimensional monitoring system covers an area of 30 km². It consists of first-order geodetic leveling, a GPS network of 30 points, and traversing with robotic total stations. During the summer of 2011, the monitoring network will be significantly expanded to cover the area of the new mining and gas extraction operation in Picadilly field (Fig. 11). In 2010, the maximum subsidence reached 0.7 m and horizontal movements reached 0.3 m.

Till 1997, the observed subsidence followed a regular bell-shaped pattern with the maximum subsidence occurring above the centre of the salt dome. Since 1997, water inflow to the mine was noticed at lower levels of potash extraction and a secondary subsidence basin started occurring on the surface outside the estimated effects of mining. Exploratory and mitigation drillings from underground workings revealed that the caprock and rock strata above potash mining were much weaker than previously expected. The exploration drillings also show multiple cracks and significant voids, with complex geometry, in the strata overlying potash workings.

In 2001, FEM analysis was performed to explain whether the water inflow from a postulated aquifer (Fig. 13) could cause the development of the secondary subsidence basin. The salt rock behavior was modeled as a non-Newtonian liquid and the overlying brittle rock was modeled as a non-tension material. The modeled vertical displacements gave very good agreement (Fig. 14) with the results of monitoring surveys when a postulated aquifer was introduced at a depth of 150 m. However, the existence of the postulated aquifer requires farther investigation, because the observed horizontal displacements showed about twice larger values than the FEM derived displacements. Currently, research is in progress on improving the deterministic model by using the presented methodology based on the redistribution of stresses due to the potash mining and gas withdrawal.

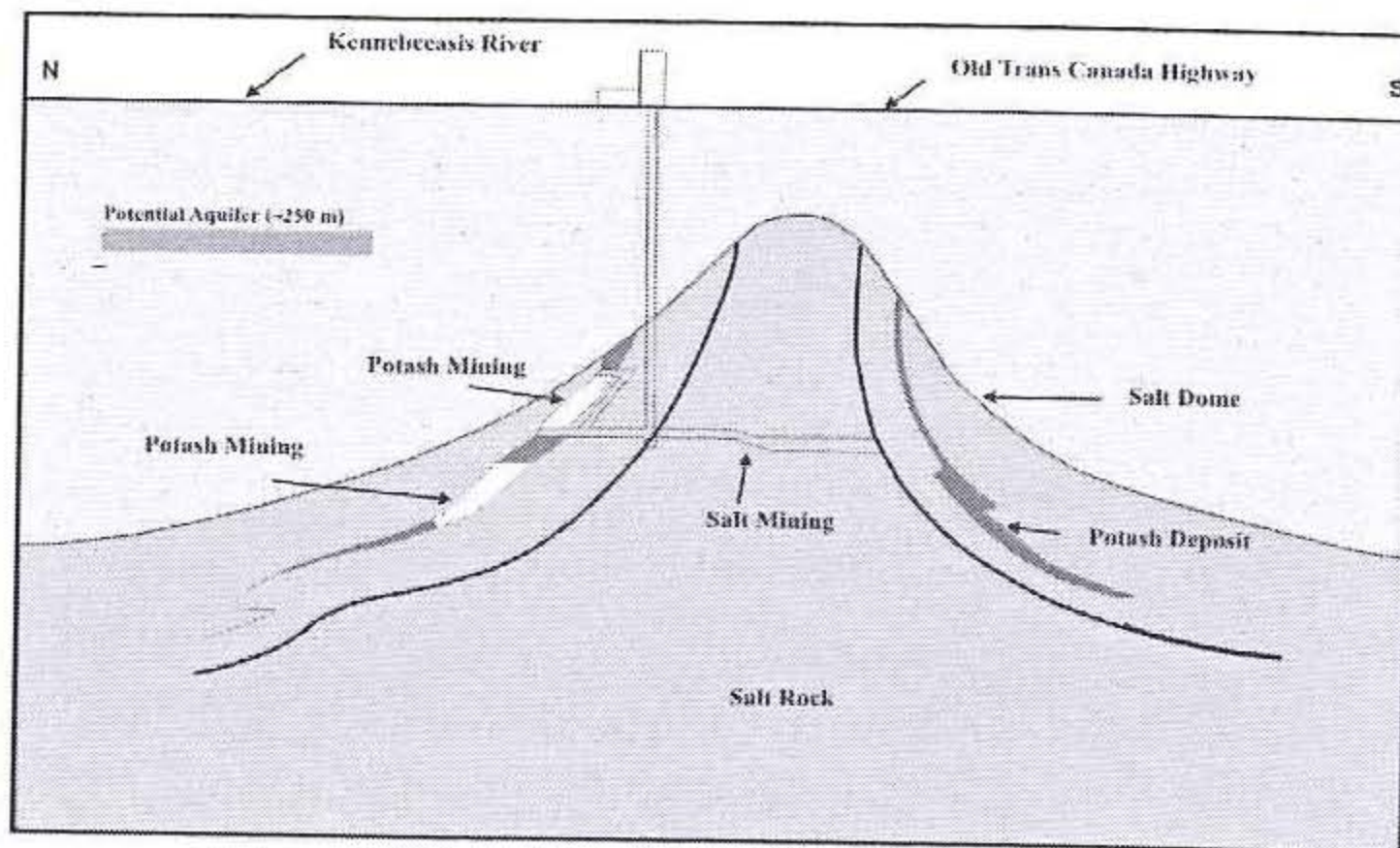


Fig. 13. Location of the postulated aquifer

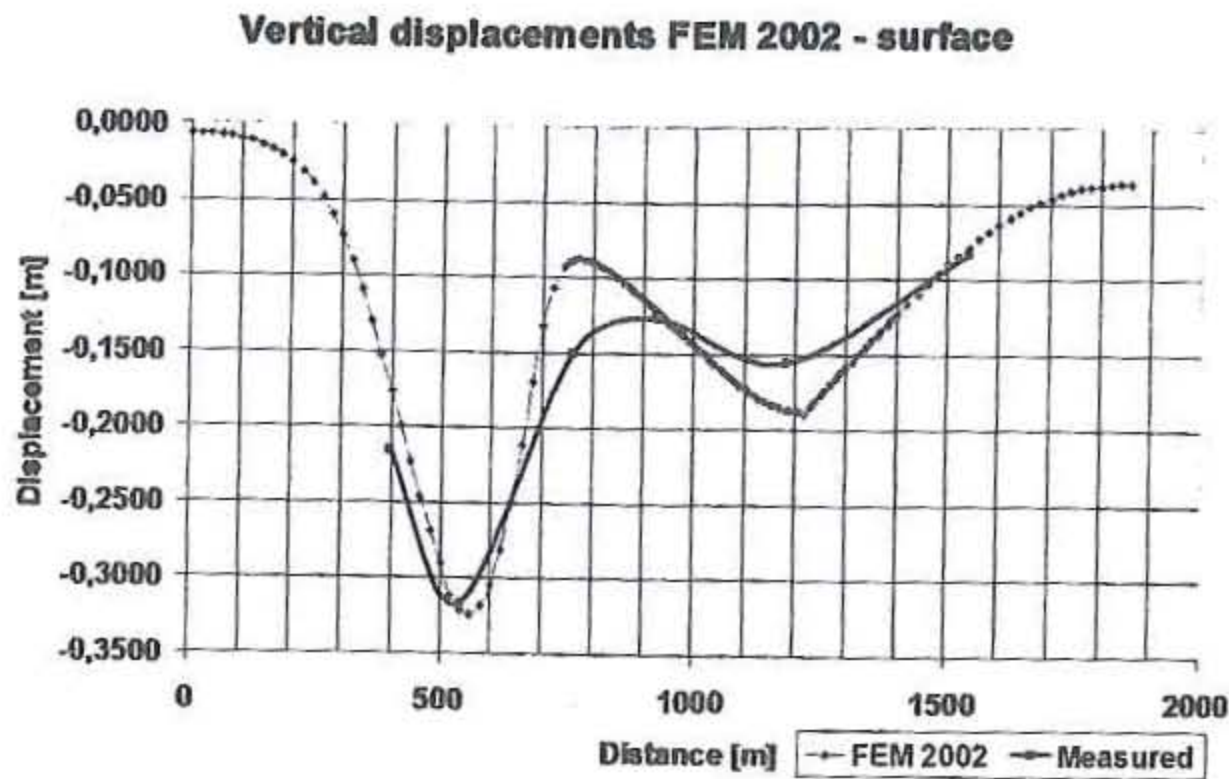


Fig. 14. FEM and observed vertical displacements in potash mine

5. CONCLUSIONS

In simple geological and mining conditions, either empirical or deterministic methods may be used in modeling and predicting ground deformations. However, in cases of complex geology and mining conditions, deterministic methods must be used. In all cases, the deterministic methods give an advantage of supplying information on the stress redistribution within the rock mass. Application of deterministic methods requires very careful scaling of the rock mass parameters and systematic investigation of the model sensitivity to changes of the parameters. Physical interpretation of ground deformations must be based on an integration of modeling results with the results of 3-D monitoring of displacements.

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