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Design and analysis of a multi-sensor deformation detection system

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Abstract. Development of new technologies for monitoring structural and ground deformations puts new demands on the design and analysis of the multi-sensor systems. Design and analysis of monitoring schemes require a good understanding of the physical process that leads to deformation. Deterministic modelling of the load-deformation relationship provides information on the magnitude and location of expected critical deformations as well as delineates the deformation zone. By combining results of deterministic modelling with geometrical analysis, one can find the deformation mechanism and explain the cause of deformation in case of irregular behaviour of the investigated object. The concept is illustrated by four practical examples.

Keywords. Monitoring, multi-sensor, deformation, deterministic modelling.

1. Introduction

Rapid progress in the development of new technologies for monitoring structural and ground deformations has significantly increased the assortment of geodetic and geotechnical instruments being available for the automated monitoring schemes. This puts new demands on the design and analysis of the multi-sensor systems. In order to make intelligent decisions on the selection of the optimal combination of the sensors, their optimal location and density, the design must be based not only on the geometrical strength and sensitivity of the monitoring network, but also on a good understanding of the physical process which leads to deformation. For example, the location of the sensors or the observed targets must include points where maximum or critical deformations are expected (Chrzanowski 1993) while the location of reference stable points must be based on the knowledge of the boundaries of the deformation zone. Thus, the investigated deformable object must be treated as a mechanical system, which undergoes deformation according to the laws of continuum mechanics (Szostak-Chrzanowski et al. 2005). This requires the causative factors (loads) of the process and the physical characteristics of the object under investigation to be included in both the design and analysis of the deformation. This is achieved by using deterministic modelling of the load-deformation relationship using e.g., the finite element method (FEM).

Analysis of deformations of any type of deformable body includes geometrical analysis and physical interpretation. Geometrical analysis describes the change in shape and dimensions of the monitored object, as well as its rigid body movements (translations and rotations). Physical interpretation is based on the integrated analysis in which the deterministic and the geometrical models of deformations are combined. The integrated analysis helps in explaining causes of deformation and supplies information on the deformation mechanism (Chrzanowski et al. 1994). The combined analysis may also be implemented in verifying the designed geomechanical parameters (e.g., Chrzanowski et al. 2002). This paper gives a brief review of the geometrical and deterministic modelling of deformations followed by practical examples from four different projects.

2. Revisiting generalized method of geometrical analysis

The goal of the geometrical analysis is to determine the displacement and strain fields in the space and time domains for the whole deformable object. As a part of the activities of the FIG Working Group 6.1, a Generalized Method (GM) of geometrical modelling was developed in early 1980s (Chen 1983, Chrzanowski et al. 1983, Chrzanowski 1993). Though the method is not new, it is revisited in this presentation in connection with the growing demand for the multi-sensor monitoring and integrated analyses of deformations.

GM analysis accepts from the principles of continuum mechanics that the deformation of an investigated object's shape and dimension is fully described if 6 strain components (3 normal strains and 3 shearing strains) of the strain tensor and 3 differential rotations at every point of the body are determined. These deformation parameters can be calculated from strain-displacement relations if a displacement function representing the deformation of the object is known. Since, in general, deformation surveys are performed at discrete points, the displacement function must be approximated through some selected deformation model which fits the observed displacements, or any other types of observables, in the statistically best way. For example, the displacement function $d(x, y, z, t) = [u(x, y, z, t), v(x, y, z, t), w(x, y, z, t)]^T$ with u, v, and w being components of the displacement in x-, y-, and z-directions, respectively, may be determined through a polynomial (or other functions) approximation of the displacement field. The displacement function can be written in matrix form as

$$d(x, y, z, t) = \mathbf{B}(x, y, z, t)\mathbf{c}, \qquad (1)$$

where $\mathbf{B}(x, y, z, t)$ is the deformation matrix with its elements being some selected base functions, and $\mathbf{c}$

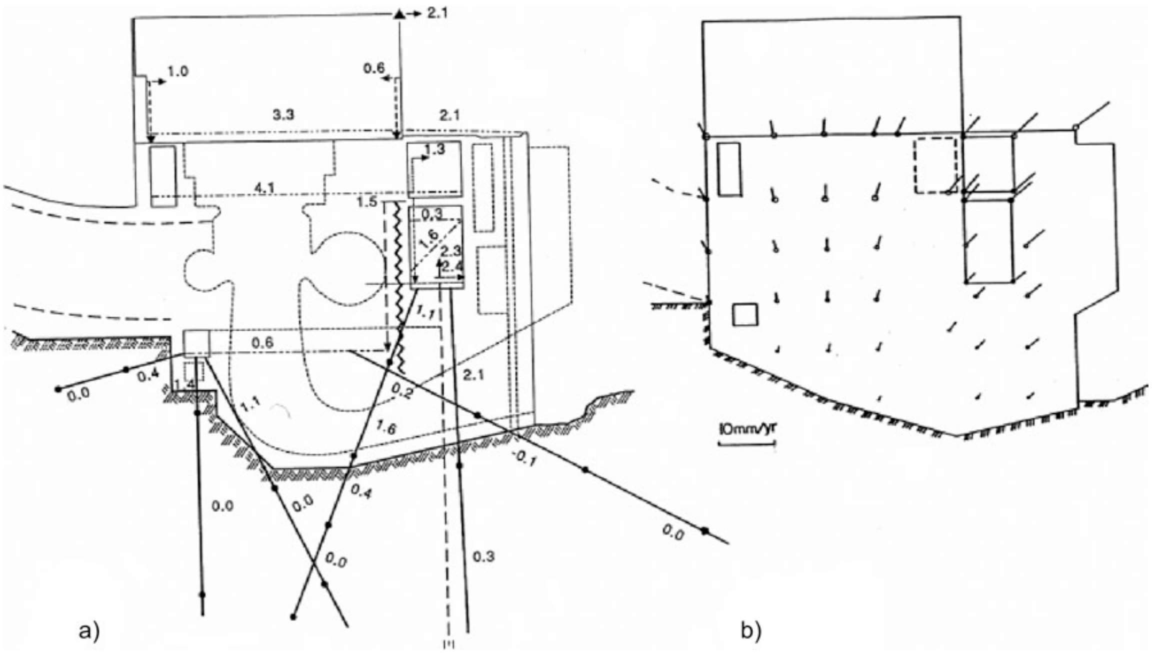

Figure 1: Application of the Generalized Method of geometrical analysis (after Chrzanowski 1993): a) observed rates of deformation (mm/y), b) derived displacement field.

is the vector of unknown coefficients. A vector $\Delta\mathbf{l}$ of changes in any type of deformation observations, for instance, changes in tilts, in distances, or in strain, can always be expressed in terms of the displacement function (Chen 1983). In matrix form, the relationship is written as

$$\Delta\mathbf{l} = \mathbf{A}\mathbf{B}_{\Delta\mathbf{l}}\mathbf{c}, \tag{2}$$

where $\mathbf{A}$ is the transformation matrix relating the observations to the displacements of points at which the observations are made, and $\mathbf{B}_{\Delta\mathbf{l}}$ is constructed from the above matrix $\mathbf{B}(x, y, z, t)$ and related to the points included in the observables. If redundant observations are made, the elements of the vector $\mathbf{c}$ and their variances and covariances are determined through the least-squares approximation, and their statistical significance can be calculated. One tries to find the simplest possible displacement function that would fit to the observations in the statistically best way.

Figure 1 shows as an example the application of the GM geometrical analysis at a power house of the Mactaquac hydro-electric power station in eastern Canada. Due to irregular behaviour and fracturing of the structure, geodetic techniques (trilateration and levelling) and dozens of various geotechnical instruments (borehole extensometers, plumb-lines, tape extensometers and jointmeters) have been used to explain the mechanism and cause of deformations.

Figure 1a shows a sample of observed rates (mm/y) of absolute and relative displacements in a cross-section of the structure. Several different functions (full or partial polynomials) were attempted in fitting the observation data, including relative rotations and translations between the structural blocks and different deformations in each block. After eliminating all the statistically insignificant coefficients of the selected displacement functions, the final displacement field (Figure 1b) appeared to be quite simple with the whole cross-section of the power house undergoing the deformation described by the horizontal (dx) and vertical (dy) displacement functions (rates per year):

$$\begin{aligned} dx(x, y) &= a_1 x + a_3 xy + a_4 x^2, \\ dy(x, y) &= b_2 y \end{aligned} \tag{3}$$

in which the values of the a_i and b_i coefficients were determined through a least squares fitting to the observed deformations.

Figure 1b shows a graphical display of the derived displacement field that indicates a volumetric expansion of the whole structure. The results of the GM analysis have supported the postulated earlier hypothesis about possible swelling of concrete due to the alkali-aggregate reaction.

3. Deterministic modelling

Deterministic analysis of deformation is based on principles of continuum mechanics, in which solving differential equations of equilibrium of forces is the main problem. In many cases closed form solutions of the equations may be difficult or impossible to obtain. Consequently, numerical methods, such as the finite element method (FEM) are used.

The deterministic method establishes relation between the causative factors (loads) and the deformation by forming equations of equilibrium, kinematic relation between strain and displacement, and using

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relation between strain and stress through constitutive matrix. The ultimate goal of the deterministic modelling of deformations is to develop a prediction model for the given type of the investigated object, given properties of the material, and assumed mathematical model of stress-strain relation. Once the prediction model is developed, it may be used for the design of the monitoring scheme. On the other hand, using the back analysis (Szostak-Chrzanowski et al. 1994), the results of the properly designed monitoring observations may be used to enhance the deterministic model (e.g. by correcting the material parameters of the observed object). In addition, with properly designed monitoring surveys one may also determine the actual deformation mechanism (Chrzanowski and Szostak-Chrzanowski 1993, 1995) and explain the causes of deformation in case of an abnormal behaviour of the investigated object.

The most critical problem in modelling and predicting deformations, particularly in rock or soil material, is to obtain real (in-situ) characteristics of material. Collection of in-situ characteristics is very difficult and very costly and the data is often incomplete. In laboratory testing, the selected samples may differ from one location to another, they may be disturbed during the collection, or the laboratory loading conditions may differ from natural conditions. The physical values obtained from laboratory testing require scaling in order to represent a rock mass. The problem of scale-dependent properties is a main problem in modelling rock or soil behaviour (Glaser and Doolin 2000).

A large-scale approach has been developed at Canadian Centre for Geodetic Engineering (CCGE) in which equivalent material properties are identified in the whole rock mass or in blocks of the material as a function of geometry of fractures and stress distribution including effects of tectonic initial stresses and stresses redistributed, for example, by mining activity. The approach has successfully been used in ground subsidence studies in mining areas (Chrzanowski and Szostak-Chrzanowski 2004) and in modelling deformations of large earth dams (Szostak-Chrzanowski et al. 2007).

4. Deterministic modelling as an aid in designing monitoring schemes

4.1. *Example 1: Concrete face rock-fill dam*

Deterministic modelling of expected deformations has been applied to Shuibuya Concrete Face Rockfill Dam (CFRD) in China (Szostak-Chrzanowski et al. 2008). Shuibuya CFRD is presently the highest of its kind in the world. It is 233 m high and 608 m long, and is resting on bedrock. Figure 2 shows expected horizontal and vertical displacements caused by filling the reservoir.

As one can see from the modelled displacements, the largest displacements are expected to occur at the upstream face of the dam, which is covered by a concrete slab. It is the most crucial area for monitoring the deformation. Since the upstream face is under water, the monitoring scheme should be designed to have geotechnical instruments such as fibre-optic strainmeters and arrays of micro-machined tilt sensors based on MEMS technology (Danish et al. 2008) embedded in the concrete slab. The rest of the dam could be monitored by geodetic methods using, for example, robotic total stations and GPS (Chrzanowski et al. 2007). Besides the deformation sensors, various physical geotechnical sensors must also be used, for example piezometers, seepage gages, and others. Final details of the design including the density of the instrumentation, accuracy requirements and frequency of observations require additional information. For example, by modelling the expected deformation at various water level stages in the reservoir, one can obtain information on the velocity of deformations. The deformations gradients are calculated using the calculated deformation and the time interval between each stage of water level. This would aid in determining the required frequency of repeat surveys.

4.2. *Example 2: Open pit mine*

Analysis of an open pit mine (Figure 3) of a 2 km diameter at the surface was performed to calculate effects of additional extraction of 75 m at the bottom

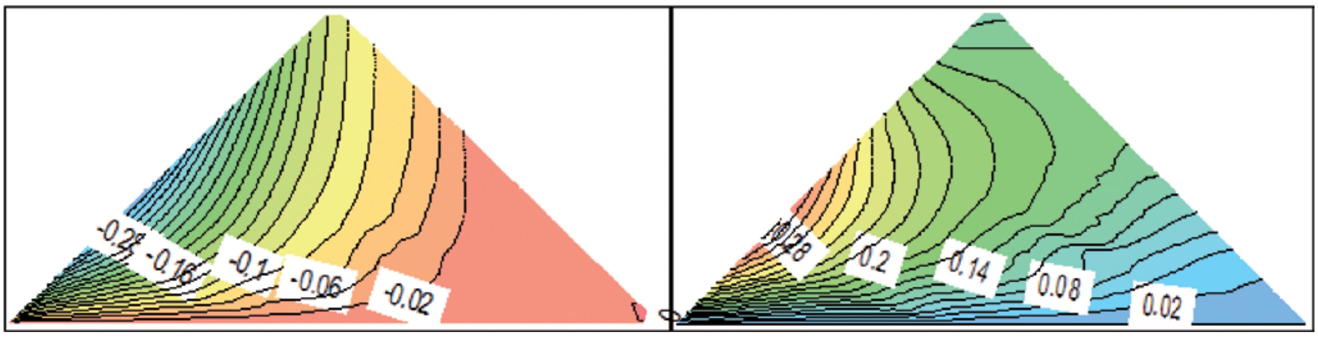

Figure 2: Predicted displacements [m] after filling the reservoir. a) vertical displacements, b) horizontal displacements.

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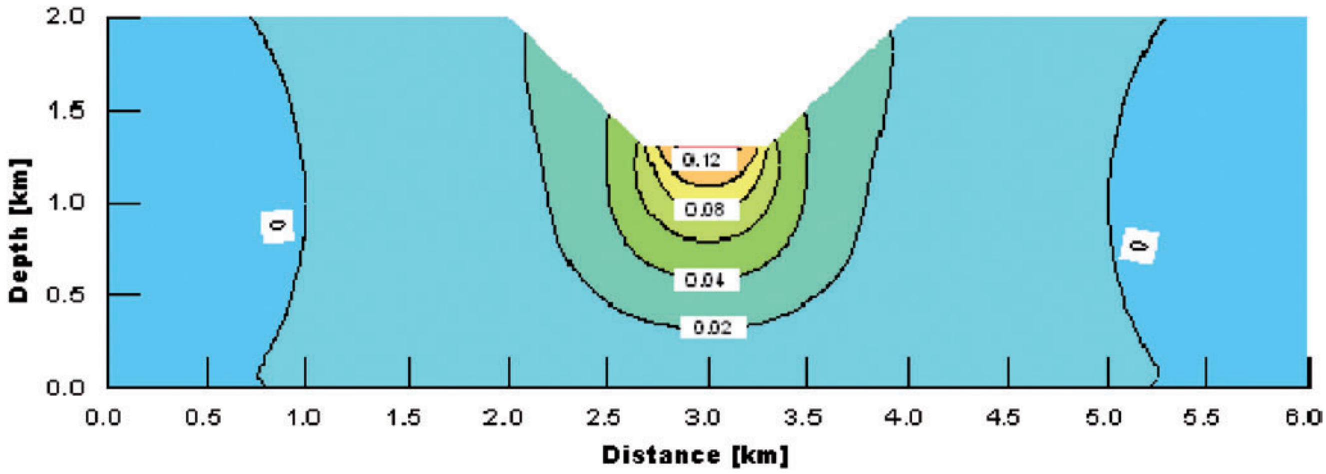

Figure 3: Vertical displacement [m].

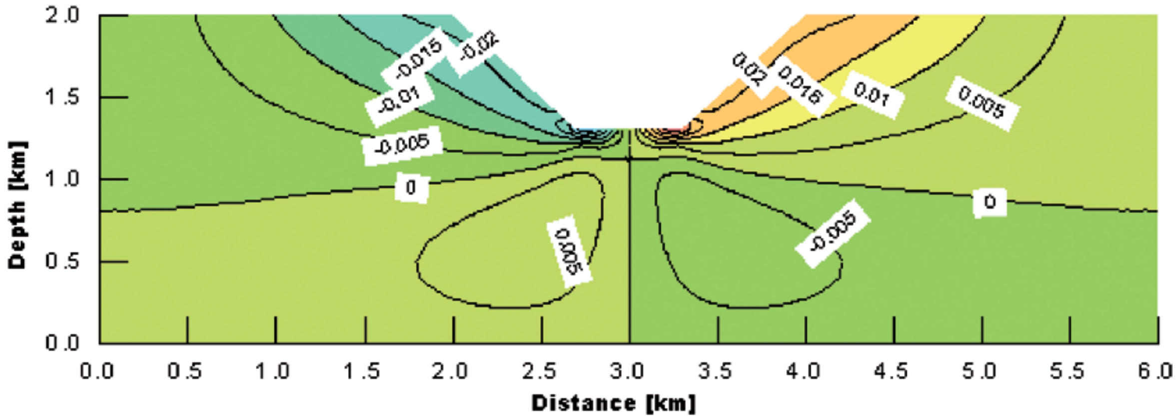

Figure 4: Horizontal displacement [m].

of the mine from the existing depth of 625 m to the depth of 700 m. The main purpose of the analysis was to estimate the magnitude of the expected deformations and localize stable area for placing the reference points for geodetic monitoring surveys. FEM analysis of the expected deformations was performed for various stages of the mining sequence and various distributions of possible discontinuities, for example faults, in the rock mass. Here, only accumulated displacements are discussed in the case of homogenous rock strata. Figures 3 and 4 show vertical and horizontal displacements, respectively. The floor of the mine is expected to undergo uplifts of up to 0.12 m while displacements on the bench walls may reach about 0.04 m. The surface points may still show 5 mm horizontal displacements at distances 1.5 km from the rim of the mine.

Since large open pit mines require continuous or very frequent (several results per day) monitoring of a large number of points, robotic total stations (RTS) with automatic target recognition would be the most economical solution. In order to minimize effects of atmospheric refraction (Chrzanowski and Wilkins 2005), RTSs should be located as close as possible to the monitored targets; i.e., RTSs would have to be located within the deformation zone while stable reference points would have to be located about 2 km beyond the rim of the mine. Therefore, RTSs should be combined with GPS, which would supply positional corrections to the RTSs. This whole process could be run in a fully automated mode by using, e.g. ALERT-DDS and PPM software developed at CCGE (Danish et al. 2008, Chrzanowski et al. 2007).

One should note that in case of identified discontinuities in the rock mass, the effects of mining on the surface would decrease because discontinuities, e.g. faults, reduce the transfer of tensional stresses. This has further important implications. Knowing that a discontinuity limits the extent of the region of instability, geodetic monitoring results can be used to locate fault zones. For example, if a monitored point shows stable behaviour in a region thought to be active, this may suggest that a fault exists somewhere between the monitored target and the area of mining activity. Both the FEM results and actual measurement values should therefore be used to complement each other in the overall physical interpretation process.

5. Example of integrated deformation analysis

The concept of combined geometrical and deterministic analyses of ground subsidence has been applied to a salt and potash mine in eastern Canada. Mining of a large deposit of high grade sylvinite 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 (Figure 5). Annual monitoring of ground subsidence over the potash and salt mining operation has been carried out by CCGE since 1989. The multi-sensor monitoring scheme includes GPS, robotic total stations, and leveling.

In 1997, a secondary subsidence basin started developing on the surface at the north end of the mine area and an increase in water inflow to the mine was noticed at lower levels of potash extraction. It was assumed that hydrological changes were causing the secondary subsidence. At the same time, exploratory and mitigative drillings from underground workings revealed that the caprock and rock strata above potash mining are much weaker than previously expected. Figure 6 shows the accumulated subsidence profile between 1996 and 2006.

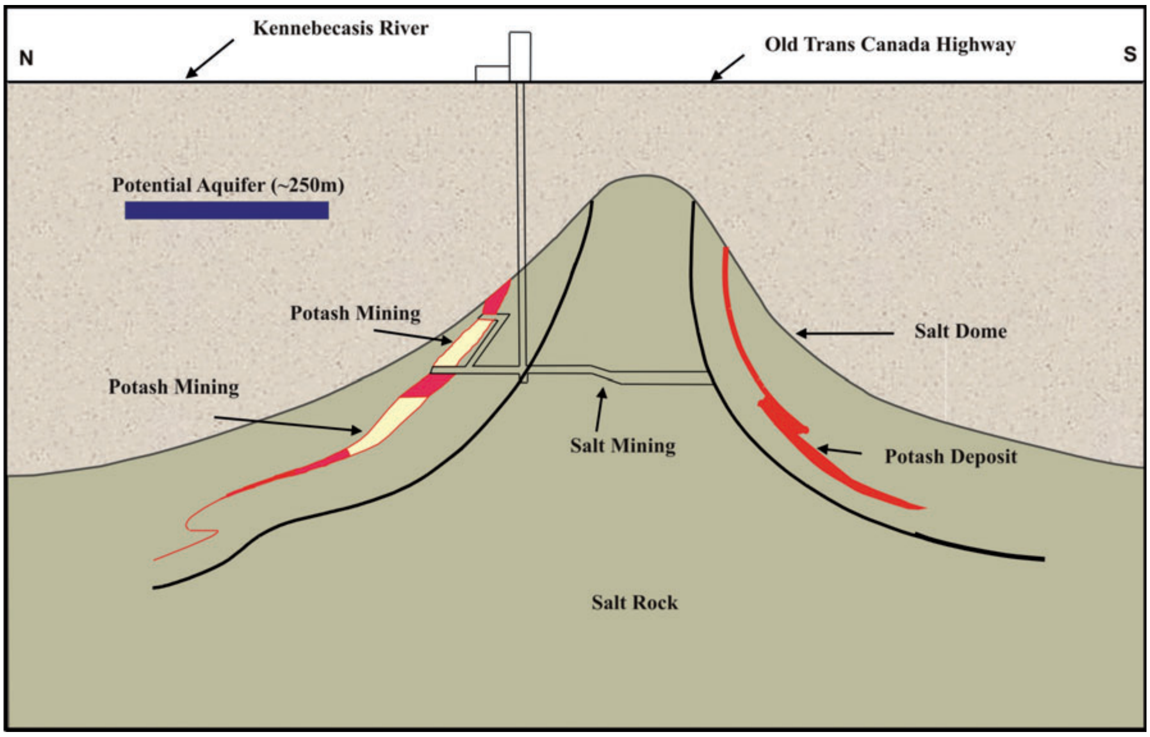

Figure 5: Geological cross-section.

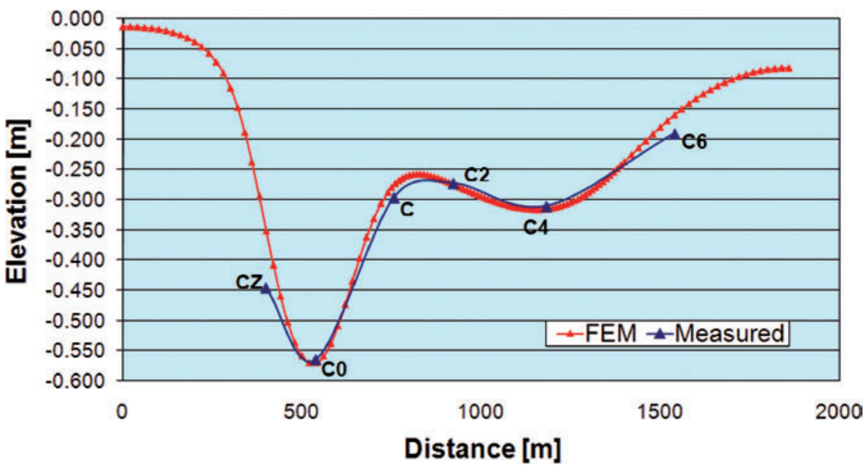

Figure 6: Measured and FEM surface subsidence.

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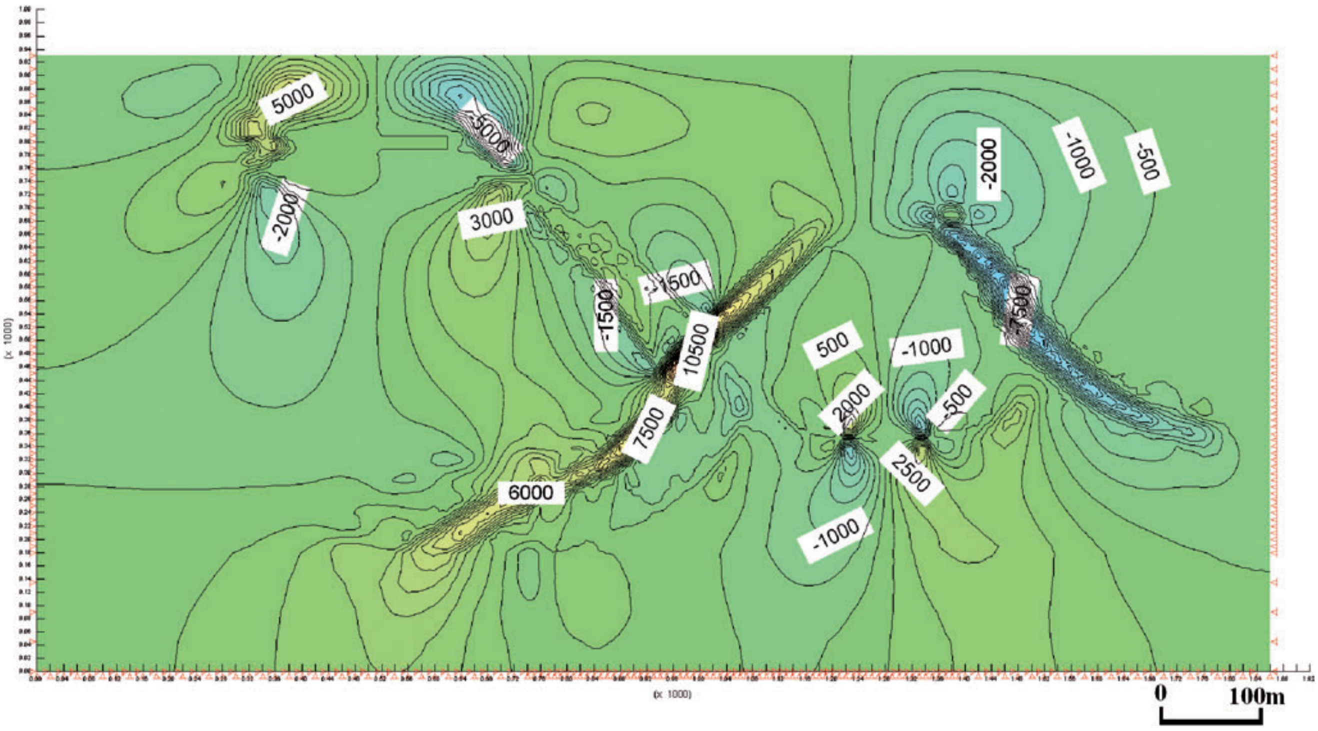

Figure 7: Distribution of maximum shearing stress [MPa].

The FEM analysis was performed to explain whether the hydrological changes, or weaker rock strata and the creation of the void or both could cause the development of the secondary subsidence basin. The combined geometrical and FEM analysis confirmed that the cause of the development of the secondary subsidence (Figure 6) were the hydrological changes and the development of voids in the rock strata (Szostak-Chrzanowski and Chrzanowski 2004).

The analysis of the rock mass response to the mining activity and to the hydrological changes gave information on redistribution of stresses in the rock mass and determination of zones where the maximum stresses develop. Figure 7 shows the redistribution of maximum shearing stresses. The redistribution of stresses gave additional information on the response of the rock strata to the mining activity and to hydrological changes.

6. Conclusions

The given examples of the combined geometrical and deterministic analyses of deformations indicate that the role of monitoring surveys is much broader than just serving as a source of information on deformation and strain field. Deterministic modelling provides information on deformation, strain, and stress fields. The integrated analysis permits to identify the deformation mechanism and to verify the in-situ parameters. The deterministic modelling significantly improves the design of monitoring schemes by giving information on the expected magnitude and location of maximum deformations and by delineating the deformation zone.

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