Canadian Contributions to Monitoring and Physical Interpretation of Ground Subsidence

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ABSTRACT :

Most of the currently active 150 underground mines in Canada are in hard rocks and are located in sparsely populated areas. Therefore, the effects of mining on the surface infrastructure have never been of a major concern. However, most of Canadian mines recognize the importance of improving their monitoring and interpretation techniques for safety and economy of their operation and environmental protection. Since 1970s significant contributions have been made to the development of new monitoring techniques and numerical modeling and prediction of ground subsidence. They include a pioneering development of a telemetric monitoring system in the1970s, pioneering use of GPS in the 1980s, development of a generalized method of deformation analysis, development of a numerical method for deterministic modeling and prediction of ground subsidence, development of the concept and methodology for the integrated analysis of rock deformation, a current development of the DDS-ALERT, an automated Deformation Detection System, and a Precise Position Monitoring System (PPMS) for fully automated GPS data processing.

1   Introduction

Canada is one of the world's largest exporters of minerals and mineral products. In 2003, the mining and mineral processing industries contributed $41.1 billion to the Canadian economy, an amount equal to 4.1% of the national Gross Domestic Product (Natural Resources Canada, 2005). In 2002 the five most important minerals were gold ($2.3 billion), nickel ($1.9 billion), potash ($1.6 billion), copper ($1.4 billion), and cement ($1.4 billion). Canada ranks first in the world in the production of potash and uranium, and ranks in the top five for the production of nickel, asbestos, zinc, cadmium, titanium concentrate, aluminum, platinum group metals, salt, molybdenum, copper, gypsum, cobalt and diamonds. Out of a total land area of 1.01 billion ha (hectares), less than 0.40 million ha (0.03%) of Canada land area are used for mining.

There are several hundred mining sites where extraction has occurred, plus thousands more subjected to underground or surface exploration activity (Betournay and Udd, 1997). The problem with inactive (closed) mines is that most of them had no good plans and maps. Therefore, the cause (location and dimension of mining openings) and size of subsidence affected area is very often not known. Damage or threat of damage by subsidence in Canadian residential areas has occurred primarily in areas of abandoned mines or at old operating mines that have since closed. Notable cases of subsidence caused by rock mass failure have occurred in the municipal areas of Cobalt, Timmins and Windsor, Ontario, the Pictou County, Nova Scotia (Mackasey, 2002), and Sydney, Nova Scotia (Forrester and Courtnay,1996).

At present, the operating mines when reaching the decommissioning stage must store the plans data in GIS data system established in each province. Government mining agencies have begun creating databases to provide easier public access to information on mining lands. Municipalities are thus aware of zones not suitable for town development. Residential constructions are now built at sites remote from the mining operation.

Most of the 150 currently active underground mines are in hard rocks and are located in sparsely populated areas. Therefore, except a few coal and potash mines, effects of mining on the surface infrastructure have never been of a major concern. The leading geomechanical problem in conditions of Canadian mining has been to understand damage and failure around mining openings excavated in brittle rock mass under high in situ stresses (Castro, 1997). Till very recently, the main interest of Canadian research centers dealing with rock mechanics problems concentrated in monitoring and analysis of displacements and stresses in vicinity of mining openings rather than in modeling and prediction of surface subsidence.

In the late 1960s, due to the growing awareness in environmental protection some improvements in ground subsidence monitoring and modeling started taking place particularly in coal and potash mining. In 1965, the Department of Surveying Engineering at the University of New Brunswick (UNB), initiated a specialization in mining surveying at the undergraduate and postgraduate levels including research on monitoring techniques and prediction theories. In 1969, the First Canadian Symposium on Mining Surveying and Rock Deformation Measurements was organized at UNB. The symposium resulted in a creation of a Committee on Engineering and Mining Surveys of the Canadian Institute of Surveying and Mapping (presently the Canadian Institute of Geomatics). A few years later, Canada Mineral and Energy Technology (CANMET) was established and became active in ground subsidence and rock deformation studies. In 1974, Canada hosted the organizing meeting of the International Society for Mine Surveying (ISM) during the Second Canadian Symposium on Mining Surveying and Rock Deformation Measurements. Two years later, Canada was one of the 14 countries, who signed the foundation of ISM in Leoben, Austria, in 1976.

Over the past 30 years, most Canadian mines have started recognizing the importance of improving their monitoring techniques and methods of modeling and prediction of rock strata deformation not only for safety and environmental protection purposes but first of all for a better understanding of the mechanism of rock strata deformation leading to the development of more economical and safer mining methods. Intensive research programs were established at a few Canadian universities and at CANMET, to develop new techniques and methods for monitoring, modeling, and prediction of rock strata deformation and stress redistribution in both underground and open pit mines. The new developments focused mainly in two areas:

(1)   automation of monitoring techniques and
(2)   development of methods for deterministic modeling of ground subsidence and rock strata deformation.

Now, despite the late start, Canada is recognized as one of the most advanced countries in developing new monitoring techniques and new methods for modeling and prediction of rock strata deformation within the rock mass and on the surface. This paper presents a short review of Canadian developments of automated monitoring techniques and new methods for modeling, and prediction of rock strata deformation focusing on recent developments at the Canadian Centre for Geodetic Engineering (CCGE).

2   Contributions to the Development of Deformation Monitoring Techniques

2.1   Summary of Developments (1979 – 2008)

Major Canadian contributions are presented in the chronological order.

1979- 1982: Pioneering development of a fully automated telemetry data acquisition system (Chrzanowski et al. 1980; Fisekci et al., 1981; Chrzanowski and Fisekci, 1982); for year-round continuous monitoring of ground subsidence using electronic tiltmeters (bi-axial servo-accelerometers). The system was used in monitoring a slope stability over a hydraulic mining extraction of a 12 m thick coal panel in the harsh climate conditions (temperatures down to -25°C and snow cover of 5 m) of Rocky Mountains (Fig.1 and Fig.2).

1981 – 1983: Development of the concept of integrated monitoring and analysis of structural and ground deformations using terrestrial and space geodetic techniques combined with geotechnical instrumentation (Chrzanowski et al., 1986).

1980 – 1983: application of aerial photogrammetric surveys (Armenakis and Faig, 1982) in integrated monitoring of ground subsidence in mountainous terrain.

In *1983 – 1985*: development of a motorized trigonometric height traversing technique and its implementation in geodetic levelling of high precision (Chrzanowski, 1989). In *1986 -1988*: Pioneering application of GPS combined with geometrical levelling in ground subsidence studies in oil fields in Venezuela (Chrzanowski et al., 1989).

In *1994 – 1997*: Application of wide-swath multi-beam sonars in monitoring seafloor subsidence over offshore extraction of coal seams in Nova Scotia (Forrester and Courtney, 1996; Chrzanowski et al. 1998).

In *1995*: launch of Radarsat satellite by the Canadian Space Agency. Radarsat images contribute to the worldwide applications of the Interferometric Synthetic Aperture Radar (InSAR) in ground subsidence studies. An enhanced RADARSAT 2 satellite has been launched in 2008

(http://www.radarsat2.info/). In *1996 +*: Development of EarthView-InSAR software by Atlantis Scientific Inc.
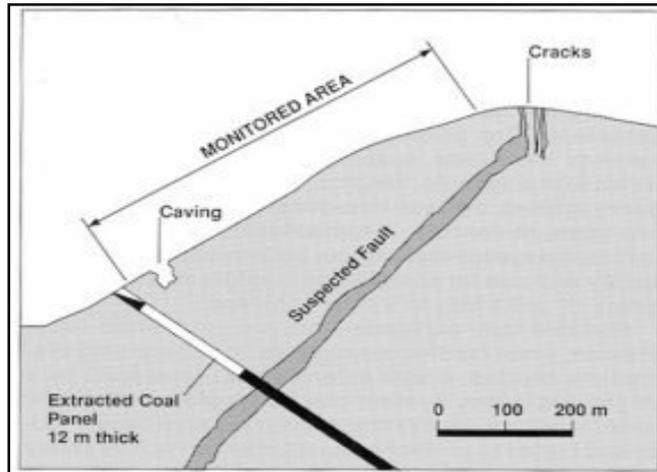
Fig.1:   Coal mining in Sparwood

Fig. 2:   Installing tiltmeter station

In *2000 – 2008*: Development and implementation of ALERT system (Lutes et al., 2001; Wilkins et al. 2004, Chrzanowski and Wilkins, 2005) for a fully automated data acquisition, data processing and deformation analysis using robotic total stations (RTS) linked with other sensors. See section 2.2 for more details.

In *2005 – 2008*: development of GPS software for deformation monitoring in harsh environment conditions have resulted in the emergence of the fully automated Precise Position Monitoring System (PPMS) (Bond et al., 2007a). See Section 2.3 for more details.

In *2008 +*: fusion of geodetic sensors with sensors of acceleration, tilt, bending, and vibrations based on the Micro Electro-Mechanical Systems (MEMS) (Danish et al., 2008).

2.2   Development of ALERT Deformation Detection System

 In 1999-2003, the Canadian Centre for Geodetic Engineering developed ALERT software suite for fully automated data collection, data processing, and displacement analysis (Lutes et al., 2001; Wilkins et al. 2004; Chrzanowski and Wilkins, 2005). Initially, ALERT was designed for monitoring surveys only with robotic total stations (RTS) that are equipped with the automatic

target recognition (e.g. Leica TCA 1800). Currently, the ALERT system is being expanded into a multi-sensor Deformation Detection System (DDS), which will accommodate any type of deformation sensors. The software suite is composed of a series of modules that automate surveying tasks, handle database management, and provide graphical user interfaces. The software's observation and processing tasks are automated according to any desired schedule.

An alarm system has been incorporated into the DDS-ALERT software, which can be triggered either by individual point or group of points, when their movement reaches a predefined threshold value of either displacement, or velocity, or acceleration. Plotting utilities allow rapid visualization of displacement and velocity trends, vectors of displacements and their confidence regions, and displacement fields in the form of isolines.

DDS-ALERT has three very unique features:
- fully automatic identification of unstable reference section stations using the Iterative Weighted Similarity Transformation (IWST) of displacements (Chen et al., 1990),

- capability of automated handling of multiple-RTS networking with simultaneous observations between the RTSs and observations of object targets by more than one instrument,

Since 2000, ALERT and DDS-ALERT systems have been implemented in monitoring stability of bench walls in large open pit mines and stability of large earthen dams in several projects in Canada, USA, Venezuela, and Chile. Fig. 3 shows a typical observation shelter of ALERT system in an open pit mine.

Fig. 3: Typical observation shelter

2.3   Development of PPMS for Automated GPS Data Collection and Processing

Recent efforts at CCGE to develop GPS software for deformation monitoring in harsh environment conditions have resulted in the emergence of the Precise Position Monitoring System (PPMS) (Bond et al., 2007a). PPMS utilizes a delayed-state Kalman filter to process GPS triple-differenced (differencing consecutive double-differenced observations) carrier phases. Implementing GPS for deformation monitoring poses challenges. Displacements encountered in deformation monitoring

are frequently at the sub-centimetre level. Since the practical resolution of an undifferenced GPS carrier-phase measurement is approximately 2 mm (1% of the L1 carrier wavelength of 0.190 m), monitoring millimeter level displacements in near real-time pushes the limits of the system. Achieving reliable, millimetre level precision in 'real-time' using GPS is not easy in favorable monitoring conditions, let alone in the harsh environments frequently encountered in deformation monitoring projects.

Test results have indicated that the software is capable of detecting millimetre level displacements without having to solve for ambiguity terms. The ability to provide high precision solutions that are independent of ambiguities makes PPMS desirable for deformation monitoring since it is less susceptible to false alarms caused by cycle slips than traditional double-differenced processing methods. The trade-off in using the triple-differenced approach is a longer convergence time than for double-differenced methods. This is generally not a concern, however, for deformation monitoring applications where long term structural behaviour is of interest.

The PPMS software has recently been expanded to include fully automated data collection and processing of pseudolite (PL) signals (Bond et al. 2007a).

3 Contributions to the Development of New Methods for the Analysis and Prediction of Rock Strata Deformation

3.1 Development of a Concept o the Integrated Deformation Analysis

The analysis of deformation surveys of any deformable object includes geometrical analysis and physical interpretation which consists of: (a) a statistical (empirical) method and a deterministic method. By comparing the geometrical model of deformations, derived from the observed deformation quantities, with the designed deformations obtained from the deterministic model one can verify the designed geomechanical parameters (Szostak-Chrzanowski et al., 2002) of the material. In addition, with properly designed monitoring surveys one may also determine the actual deformation mechanism (Chrzanowski and Szostak-Chrzanowski, 1993; Chrzanowski and Szostak-Chrzanowski, 1995) and explain the causes of deformation in case of an abnormal behaviour of the investigated object. The combined (integrated) analysis of deformation plays an important role in the eventual redesign of the operation of the investigated structure, safety, economy, and environmental protection.

3.2 Developments in the Geometrical Analysis of Deformation Measurements

Within the geometrical analysis, the Canadian contributions include:
(1)   Development (1982-1985) of a Generalized Method of Deformation Analysis (Chrzanowski et al. 1982; Chrzanowski et al. 1983; Chrzanowski et al. 1986). The method permits a simultaneous analysis of deformations from any type of geodetic and geotechnical/structural observations of displacements and deformations even if the observations are scattered in space and in time. Through an iterative least squares fitting of a selected displacement function to the observed displacements at discrete points, the displacement and strain fields are determined in the whole deformable body.
(2)   Development of a methodology for the identification of unstable reference points. The identification is based on an iterative weighted similarity transformation of observed displacements (Chen et al. 1990).

3.3   Summary of Developments in Deterministic Modeling of Rock Strata Deformation

The deterministic methods require reliable information on the in-situ properties of rocks, initial stresses, and tectonics of the area. The in-situ geomechanical properties may significantly differ from the laboratory values (Bieniawski, 1984) mainly due to scale factor (Jing, 2003). This must be taken under consideration when using laboratory data in deterministic modeling of deformations.

Canadian developments in a deterministic modeling are summarized below in a chronological order.

In *1975:* the first research work in Canada sponsored by Mining Research Laboratories of CANMET A numerical FEM model was developed to calculate subsidence in flat and steep dipping ore bodies (Vongpaisal and Coates, 1975) and applied to Falconbridge (Sudbury) mining operation.

In *1980-1987*: Hoek and Brown (1980) proposed a method for obtaining estimates of the strength of jointed rock masses. This method was modified over the years in order to meet the needs of users who were applying it to problems that were not considered when the original criterion was developed (Hoek and Brown 1988).

In *1985:* FEM code was developed to model stress distribution in potash mines (Fossum et al, 1985). The developed methodology was also applied to model seafloor subsidence over offshore coal mining in Nova Scotia. At the same time, CCGE at UNB, initiated research on the development of a deterministic model of deformations and stress distribution in rock mass using also FEM (Szostak-Chrzanowski, at al, 1988).

In *1985 – 1990*; a method, known as the S-C method (S-C from Sequential Computations) was developed at CCGE for modeling brittle rock deformation (Szostak-Chrzanowski and Chrzanowski 1991b). The method combines iterative finite element method with the global empirical knowledge on the mechanism of the rock strata deformation. The method is supported by software FEMMA, developed at UNB, for 2-D and 3-D analyses (Szostak-Chrzanowski and Chrzanowski, 1991a).

In *1986 – 1995*: the S-C method was successfully implemented in modeling and prediction of ground subsidence in several coal, copper, lead and zinc mines (Szostak-Chrzanowski et al., 1988; Szostak-Chrzanowski and Chrzanowski, 1991b) including: modeling seafloor subsidence over offshore coal mining in Nova Scotia in cooperation with CANMET; modeling of ground subsidence and identification of a fault over a steeply inclined coal seem (Fig. 1) near Sparwood, B.C., (Szostak-Chrzanowski and Chrzanowski, 1991b).

In *1980s/1990s*: Research continued at several institutions on the development of deformations and stresses around mine openings using numerical modeling (Udd and Yu, 1993). At the University of Toronto, the boundary element method was developed to analyze stresses around mine stopes (Corkum et all, 1991); at INCO Ltd., the boundary element method code was developed to model a large backfilled stopes at depth. At CANMET, the finite element method code was developed to model stresses of mine structures; at McGill University, seven codes were developed based on FEM and boundary element method for variety applications (Rizkalla and Mitri, 1991; Suriyachat and Mitri, 1991); and at the University of New Brunswick, CCGE developed FEM methodology to determine the relation of the development of critical stresses around mining opening as a function of a mining sequence (Szostak-Chrzanowski and Planeta, 1997).

In *1993*: Development of a method for the analysis of propagation of random errors in FEM (Szostak-Chrzanowski et al., 1993) based on a rigorous propagation of variances and covariances of the material parameters that are treated as random variables. This approach is particularly important in any rock mechanics problems where mechanical properties of the same type of rock may be significantly changing from one location to another due to inhomogenities and discontinuities in the rock material.

In *1995*: the S-C method was expanded to model deformations in salt rocks (Chrzanowski et al., 1997). The method has been applied to prediction of ground subsidence in potash and salt mining at two mines in New Brunswick (Chrzanowski and Szostak-Chrzanowski, 1997; Chrzanowski and Szostak-Chrzanowski, 2004).

In *1997*: Development of a new classification of the rock masses based on (Hoek et al., 1992) called the Geological Strength Index (Hoek et al., 1995; Hoek and Brown 1997).

In *2000 - 2008*: application of numerical modeling using FEM and S-C method to the PCS potash mine in New Brunswick to identify hydrological changes (Chrzanowski and Szostak-Chrzanowski, 2004). See Section 4 for details.

In *2000*: Development of integrated analysis of stress accumulation by combining surface subsidence measurements and S-C method. Following Zienkiewicz et al. (1968), the method accepts the in-situ brittle rock masses as a 'no-tension' material, particularly in the rock layers in the immediate roof of the mining opening. The most important concept of the S-C method is an introduction of the 'weak zone' in the qualitative model of ground subsidence. In the method, the salt rock is considered as a non-Newtonian liquid with high and not constant viscosity (Dusseault et al., 1987). As a non-Newtonian liquid, the intact salt rock deposits are under isotropic lithostatic stress conditions. The method was applied to coal, lead and zinc mines in Canada, USA, and Poland; KGHM Polish Copper mines (Chrzanowski et al., 2000).

In *2003*: development of simple and practical FEM software for stress analysis of mine openings at McGill University. The software is addressing needs of practicing engineers particularly involved in hard rock excavations and includes modeling rock supports such as e.g. rockbolts (Mitri and Tang, 2003).

In *2005- 2006*: Identification of the source of deformation and modeling of ground subsidence caused by fluid extraction combining Knothe's empirical method (Szostak-Chrzanowski et al., 2006) and FEM modeling at CCGE.

In *2006-2007*: use of deterministic modelling (FEM) in the design of a geodetic deformation monitoring scheme in open pit mine at various stages of mining sequence (Bond et al., 2007b).

4   Example of Integrated Analysis of Deformations and Stresses

The concept of a combined geometrical and deterministic analysis of ground subsidence has been applied to a salt and potash mine. 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.4). Annual monitoring of ground subsidence over the potash and salt mining operation has been carried out by CCGE since 1989.

In 1997, a significant increase in water inflow to the mine was noticed at lower levels of potash extraction and a secondary subsidence basin started occurring on the surface at the north end of the investigated cross-section. An underground aquifer located above the potash mining in the area of the secondary subsidence was suspected to be a source of inflowing water. 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, showing multiple cracks and a significant void of about 20 m width and 180 m height. Fig. 3 shows the accumulated subsidence profile along C line between 1996 and 2006.
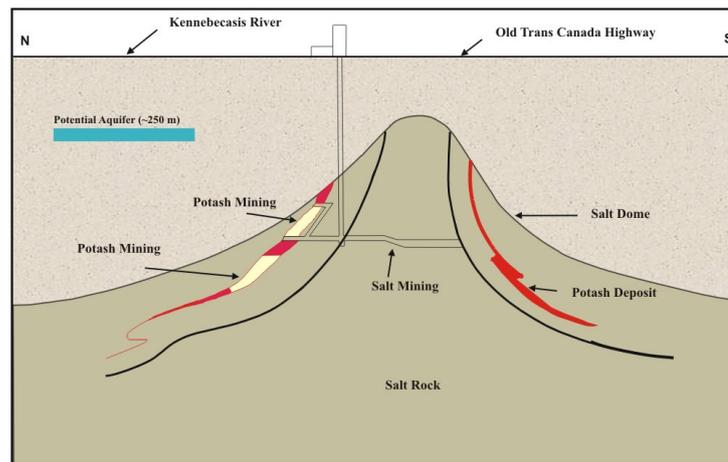
Fig. 4: Geological cross-section
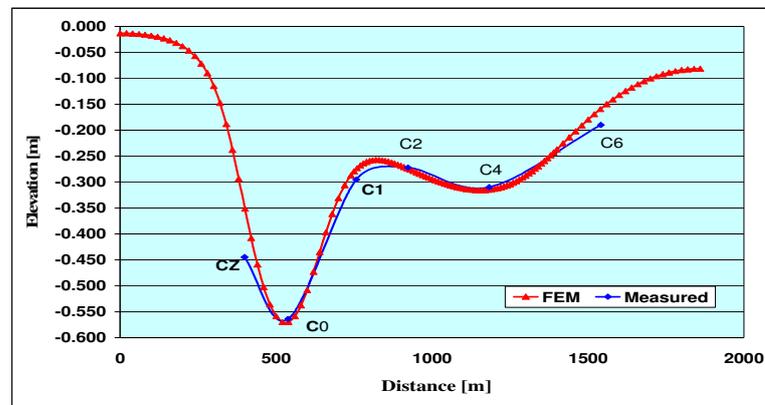
Fig. 5: Measured and FEM Surface Subsidence

The FEM analysis of ground subsidence was performed to explain whether the water inflow from an unknown aquifer and its compaction, or the weaker rock strata and the creation of the void could cause the development of the secondary subsidence basin. The combined geometrical and FEM analyses indicated that the aquifer at the depth 150 m would be the main cause of the secondary subsidence (Chrzanowski and Szostak – Chrzanowski, 2004).

FEM analysis of the rock mass response to the mining activity and to the hydrological changes addressed the redistribution of stresses in the rock mass and determination of zones with the maximum stress values. The redistribution of stresses (Fig. 6.) explains the mechanism of response of the rock mass to the mining activity and to the hydrological changes.
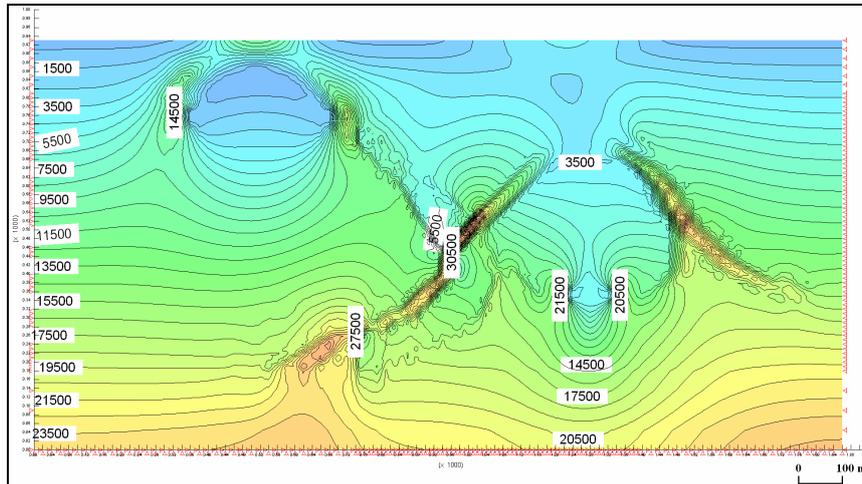
Fig. 6: Distribution of Maximum Stress (MPa)

5   Example of the Design of Deformation Monitoring Schemes Using Deterministic Modeling

Finite element method was applied to the analysis of an open pit mine to predict the displacement fields at various stages of mining sequence. The predicted displacement field delineates the deformation zone so that suitable locations for stable reference points can be chosen; supplies information about sensor placement to capture displacements of interest; and provides information for predicting global deformation. The actual values of the displacements may significantly vary from one open pit mine to another. For example, two open pit mines of Highland Valley Copper in Western Canada, though only 2 km apart, represent very different conditions for possible wall failure (Newcomen et al., 2003). Where 50 mm/day displacements may be categorized only as a "watch" category in one mine, a displacement rate of 10 mm/day may already been considered as the "Alert" category in the second one. Thus, the required accuracy of monitoring may differ significantly from one mine to another.

Analysis of an open pit mine (Fig.7) of a 2 km diametre at the surface was performed to calculate effects of enlarging the mine from the existing depth of 600 m to the depth of 650 m by extracting the left wall and the bottom. 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 homogeneity of the rock mass (with and without faults). Figure 7 shows expected accumulated displacements for the simplest model of the homogenous rock strata. The maximum displacements (uplifts) of up to 40 cm are expected to occur at the bottom of the pit. The effects of mining reach several kilometres beyond the rim of the mine with 5 mm displacements still possible at a distance of 4 km to the left of the extracted wall and 2 km beyond the rim at the right hand side of the mine.

Figure 8 shows schematically the proposed monitoring scheme for the above case. The scheme would include robotic total stations (RTS) placed on the right wall that would be connected to stable reference points by GPS. Since the RTSs are located within the deformation zone, their positions (coordinates) would be automatically updated by GPS using the discussed earlier ALERT/PPMS software suite.
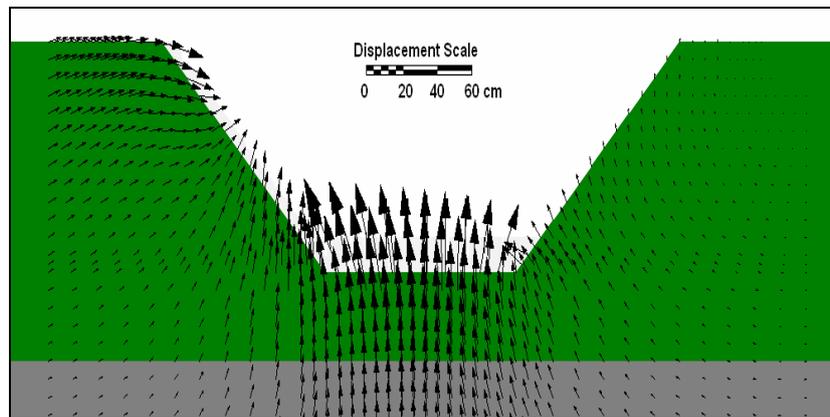
Fig.7: Cumulative Displacement Field after all Excavations
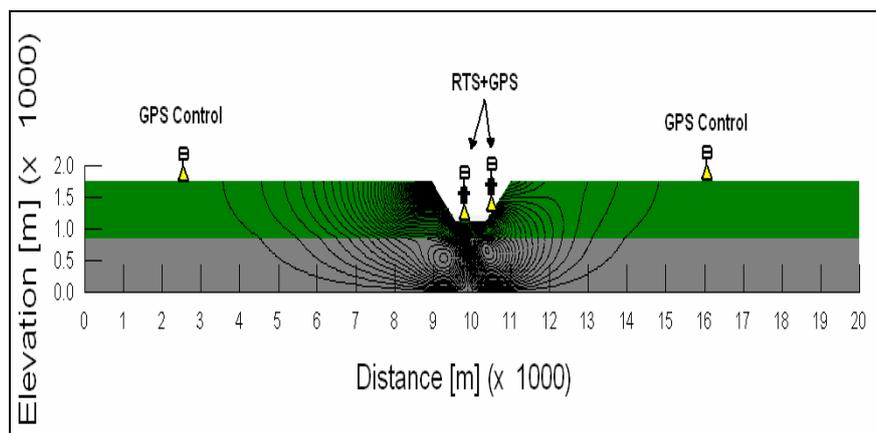
Fig. 8: A Geodetic Deformation Monitoring Scheme based upon deterministic modelling

As expected, the FEM analysis of the models with introduced in-homogeneities in the above example (Bond et al. 2008). showed much shorter distance to the expected stable area because discontinuities,e.g. faults, reduce the transfer of tensional stresses. This has further important implications. Knowing that a fault 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   Conclusions

The Canadian contributions to both monitoring technology and methods of modeling rock deformation analysis are significant and they have found worldwide applications. The research and development at Canadian research centres concentrates on the automation of integrated monitoring systems and on the deterministic modeling of ground subsidence and rock mass deformation.

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