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100 Years of Ground Subsidence Studies

Adam Chrzanowski
University of New Brunswick, Fredericton, N.B.
Anna Szostak-Chrzanowski
University of New Brunswick, Fredericton, N.B.
David J. Forrester
CANMET Sydney Laboratory, Sydney, N.S.

ABSTRACT

Monitoring and analysis of ground subsidence were initiated about 100 years ago in populated mining areas in central Europe. Various empirical methods for modeling and prediction of subsidence were developed in central Europe in the first half of this century. The empirical methods, though still used in many parts of the world, including some adaptations to North American mining conditions, are being replaced by deterministic modeling using numerical methods. The subsidence models help in developing safer and more economical mining operation. New monitoring techniques help in verifying deterministic models of rock behavior in various geological and mining conditions. Significant contributions to the development of new monitoring techniques and numerical modeling and prediction of ground subsidence have been made in Canada. They include development of a telemetric monitoring system, pioneering use of the satellite Global Positioning System, development of a numerical method for deterministic modeling of ground subsidence in brittle and saltrocks, and use of hydrographic surveys in offshore monitoring. Applications of the new developments are discussed in case studies of monitoring subsidence in offshore coal mines in Nova Scotia, in coal mines in Sparwood, B.C., and in potash mines in New Brunswick.

INTRODUCTION

Extraction of underground solids, liquids, and gases causes the ground surface to subside. The ground displacements result in development of tilts and tensile strains which may cause damages to the surface properties and buildings, and changes to the ground water level. It may also result in opening pathways which may link major surface water bodies to the underground workings, with potentially catastrophic results. Already in the middle of the last century, the railway companies in the Ruhr coal mining district were taking ground leveling measurements in order to bring evidence of the lowering of their trucks in the event of disputes about mining damage (Kratzsch, 1983). Since the 1870s, a number of scientific publications have appeared on ground movements in mining areas and on mathematical formulation for the prediction of ground subsidence in Germany and in other European countries.

Most of the early prediction theories were developed by mine surveyors who had always been highly respected in European mines and who had first-hand access to the monitoring survey data. This tradition continues and, currently, the International Society for Mine Surveying (ISM) with its very active Commission 4 on Ground Subsidence is, perhaps, the leading international society dealing with the problems of ground subsidence. One should note that Canada hosted a meeting of the organizing committee of ISM during the Second Canadian Symposium on Mining Surveying and Rock Deformation Measurements which was held at Queens University in 1974. Canada was also one of 14 countries who founded ISM in 1976 in Leoben, Austria. The International Society for Rock Mechanics (ISRM), International Association of Hydrological Science (IAHS), and Commission 6 of the International Federation of Surveyors (FIG) are three other international bodies involved in ground subsidence studies. This indicates that the century of research and development have not been enough to solve all problems in modeling and prediction of ground subsidence. On the contrary, over the past twenty years, many mines have started recognizing that new monitoring techniques and sophisticated numerical modeling of ground surface subsidence are useful not only for legal liability and environmental control purposes but they may give a better understanding of the mechanism of rock strata deformation leading to the development of safer and more economical methods.

Canadian mines, with an exception of a few coal and potash mines, have never been too preoccupied with the problems of ground subsidence. Most of the 140 or so underground mines are either in unpopulated areas or belong to the hard rock types in which the surface effects due to mining are comparatively small. Until the early 1960s, ground subsidence monitoring and prediction were rather primitive. In the late 1960s, some improvements started taking place. 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 creation of the Committee on Engineering and Mining Surveys of the Canadian Institute of Surveying and Mapping. A few years later, the Canadian Center for Mineral and Energy Technology (CANMET) was established and became active in ground subsidence studies. By the early 1990s, Canada, despite the comparatively small number of mines engaged in ground subsidence monitoring, gained an international recognition as one of the most advanced countries in developing new monitoring techniques and numerical modeling methods.

On the occasion of the Centennial Meeting of CIM, a sample of the centennial Canadian contributions are reviewed in this paper. They include contributions to the development of a method of numerical modeling of ground subsidence and three case studies involving a pioneering use of hydrographic surveys in offshore subsidence studies in Nova Scotia; development and application of a telemetry monitoring system in a coal mine in British Columbia; and monitoring and modeling of ground subsidence in potash mines in New Brunswick. A full review of all Canadian developments would be impossible to cover in this short presentation. The authors apologize for it. Even some of the authors' own developments have been omitted, for example:

- development of the Generalized Method of Deformation Analysis (integration of geodetic and geotechnical measurements, scattered in space and time, in a simultaneous integrated analysis), (Chen, 1983; Chrzanowski et al. 1986);
- pioneering use of the satellite Global Positioning System (GPS) in ground subsidence studies (Chrzanowski et al. 1989);
- identification of unstable reference points in deformation surveys (Chen et al. 1990).

DEVELOPMENT OF SUBSIDENCE PREDICTION METHODS

Geometrical vs. Deterministic Modeling of Ground Subsidence

All currently used prediction theories are based either on geometrical or deterministic (mechanistic) modeling of subsidence. The geometrical models are derived from a relationship between the geometry of the subsidence trough and dimensions and depth of the underground openings through some empirically determined parameters of the function describing the relationship. The deterministic models are derived from the a priori known mechanical properties of rocks, from mechanical relations between the loads (surface and body forces, initial stresses) and internal stresses, and from the physical laws governing the stress-strain relation. Excellent review of prediction theories and mechanism of rock strata deformation is given by Kratzsch (1983).

Among the geometrical methods of subsidence modeling, one can distinguish those based on an 'influence function' and those based on a 'profile function'. The 'influence function' describes the distribution of the subsidence above a differentially small element of opening. Through the integration of the function over the whole area of the opening, the subsidence trough is determined. In the 'profile function' methods, the profile of the subsidence is determined through the best fit (regression analysis) of a selected function.

Most of the geometrical theories for predicting subsidence have been developed in central Europe and the United Kingdom. First theories based on the 'influence function' were developed by Keinhorst (1925), followed by Bals (1932) in Germany where systematic and accurate monitoring surveys have been conducted in mining areas for several decades. Within that group of theories, Knothe's (1957) 'influence function' theory, developed in Poland, has gained the most popularity and has been used (sometimes with modifications) till now in many countries, including adaptations in the USA (e.g., Luo and Peng, 1993), in P.R. China, and many other places. Knothe's influence function is derived from the normal (Gaussian) distribution curve. Among the 'profile function' theories, the British theory (NCB, 1975) has found many applications in call mines with long wall mining. The NCB theory is based on a graphical presentation of the relationship between width and depth of the long walls.

In both, the 'influence function' and 'profile function' models, some parameters (coefficients) of the functions must be determined (calibrated) empirically through a comparison with the observed subsidence. Since other parameters, such as mechanical properties of the rock and tectonic stresses, are not taken into account, the prediction theories are applicable only to the areas where the mining, geological, and tectonic conditions are the same or very similar to the area where the empirical data for the theory had been collected. Since the conditions in different areas are never the same, any attempt to adapt, for instance, the European geometrical methods for ground subsidence prediction on the North American continent requires the calibration of the model parameters through many years of comparisons with the observed deformations in the new area. Usually, this approach is unrealistic because very few mines in North America have a well organized and systematic program of monitoring surveys. It should be also stressed that the geometrical theories are generally not reliable in cases of complicated geometry of mined deposits, in the presence of faulting, and in areas of previous extensive mining operations.

For the above reasons, the UNB group, in their research on the development of a prediction theory concentrated on the use of deterministic modeling of ground subsidence, rather than on adaptation of empirical geometrical models from other areas to North American conditions. The deterministic methods are definitely more universal than the empirical theories because they can be applied in any geological and mining conditions and they provide information not only on the surface subsidence but also on deformations within the rock masses and within the mining workings. However, the deterministic methods require reliable information on the in-situ properties of rocks, initial stresses, and tectonics of the area. Since the deterministic modeling involves complex differential equations, early applications (e.g. Salustowicz, 1953) to ground subsidence modeling were possible only for very simplistic models of the rock behavior such as elastic bending of the roof strata. Development of computers brought a rapid development of numerical methods in deterministic modeling of rock mass deformations and surface subsidence. In case of mining subsidence, the finite element method (FEM), is considered as the most suitable. Among the first applications of FEM were works by Zienkiewicz et al., (1968), by Brown (1968), and Dahl (1969), followed by many other researchers in various research centers.
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In deterministic modeling, the in-situ mechanical properties of rocks are of a particular importance. They are difficult to be determined and they change in time according to the progress of the mining activity. It is the main reason that despite an intensive research performed at various research centers over the past thirty years, not much success has been reported in predicting ground subsidence when using deterministic modeling alone. In the mid-1980s, Szostak-Chrzanowski (1988) at UNB combined iterative finite element method with the global empirical knowledge on the mechanism of the rock strata deformation. The method, known as the S-C method (S-C from Sequential Computations), has successfully been implemented in modeling and prediction of ground subsidence in coal, copper, lead and zinc mines (Szostak-Chrzanowski and Chrzanowski, 1991) and, recently, in salt rocks (Chrzanowski et al., 1997). The basic principles of the S-C method and its recent adaptation to modeling subsidence in saltrocks are discussed below.

S-C Method of Subsidence Modeling and Prediction

The main goal of the S-C method is to determine the final (static) state of deformation when the mining process has been completed and a new state of equilibrium of forces has been achieved after a long enough period of time. The problems of time dependency and non-linearity of the material are solved through sequential linear elastic solutions with iterative updating of the modulus of elasticity, E, using the finite element method (FEM). The method is supported by software FEMMA, developed at UNB, for 2-D and 3-D analyses.

Following Zienkiewicz et al. [1968], the method accepts the in-situ 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 as shown in Figure 1. The 'weak zone' is delineated by the FEM elements in which the maximum shearing stresses develop at the boundary between the zone of rocks subjected to tensional stresses above the underground opening and the surrounding rocks subjected to compressive stresses. The boundary surface of the maximum shearing stresses had been identified by Kratzsch [1983] as a slippage surface of rocks which reduces transferring of the tensional stresses beyond the boundary. The introduction of the 'weak zone' produces a pronounced downward bend of the subsidence trough above the zone and decreases the diameter of the mining influence in comparison with effects expected from a purely elastic bending of the rock strata. The limitation of the transfer of tensional stresses beyond the weak zone is achieved by dividing the initial value of E of the rocks within the zone by an empirical parameter 'c'. Based on experience gathered from several practical applications of the method in various mines (coal, copper, lead, and zinc) of various depths, one can take c = 3 in shallow mines (say up to 200 m) decreasing to c = 1 at the depth of about 1000 m.

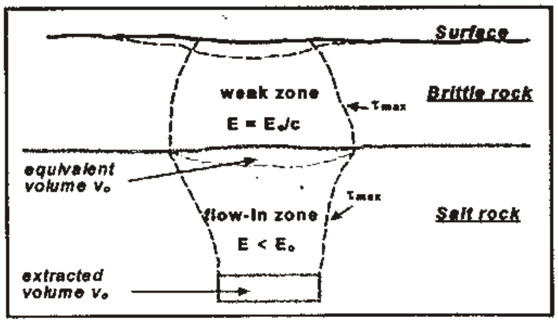

Figure 1. Modelling of ground subsidence (S-C Method)

Once the weak zone is introduced into the FEM model, the basic task is to change sequentially the values of E in individual FEM elements according to a criteria based on the critical tensional stresses. In the case of elements in which both principal stresses (in two-dimensional analysis) exceed the critical value, the value of E = 0 is placed in the given elements. In cases of only one principal stress being tensional, the material is assumed to be anisotropic with E = 0 in the direction of the critical principal stress and the constitutive matrix is changed to reflect the transversely isotropic material. The FEM analysis is repeated until no more elements are identified as having developed critical tensional stresses.

Over the past few years, the UNB Group in cooperation with the Potacan Mining Company and the New Brunswick Division of the Potash Corporation of Saskatchewan (PCS), made the first attempt to expand the S-C method to model ground subsidence in salt rock using, as an example, PCS and Potacan salt and potash mines in New Brunswick.

In the S-C method, the salt rock is considered as a non-Newtonian liquid with high and not constant viscosity (Mraz et al., 1987). As a liquid, the intact salt rock deposits are under isotropic lithostatic stress conditions which are characterized by all stress components being equal to each other and equal to the overburden stress. Therefore, the shear stress in intact salt rock is equal to zero. Development of shearing stresses due to mining activity causes the flow of the salt mass into the excavated areas in order to achieve a new equilibrium state of stresses. The 'flow-in' zone is determined by the FEM elements in which maximum shearing stresses are developed by introduction of the mining opening. Figure 1 summarizes the propagation of rock strata subsidence above the excavated area. In modeling the final maximum subsidence at the top of the salt formation, the original value of E in the 'flow' zone is decreased to give the same volume of the subsidence basin (under the cap rock) as is the volume of mining openings (minus the volume of the compacted backfill) which will be filled up by the salt rock convergence. The initial stress in the intact salt rock is assumed to be isotropic lithostatic. Once the equivalent subsidence trough at the top of the salt is determined, the response of the brittle rock is modeled as described above.

A CENTURY OF SUBSIDENCE OBSERVATION IN CAPE BRETON, N.S.

During the nineteenth century, underground coal mining developed in parts of the Nova Scotia coalfields, especially in Cape Breton. In developed areas, mining subsidence created surface property damage and, as claims for compensation for mining subsidence damage arose, companies began to take measurements and keep records of surface damage. In Cape Breton, this became routine throughout most of this century. For example, in the town of Glace Bay, which was undermined by workings in up to 4 seams, most houses and buildings in the town were regularly surveyed. In fact it was a common feature to have a "crow's foot" bench mark on a lower shingle of most houses.

Much of this data has since been lost in time and technical papers have not been found. However, one example of this routine subsidence monitoring has survived. Figure 2 shows a survey line along West Main Street in Glace Bay from Wallace Road to Nolans Lane. Subsidence from 1904 to 1916 is compared with that observed in 1949 and with a more recent subsidence prediction estimate using an influence function model "SUBCALC" from Nottingham University in England (Jacques Whitford & Assoc., 1993).

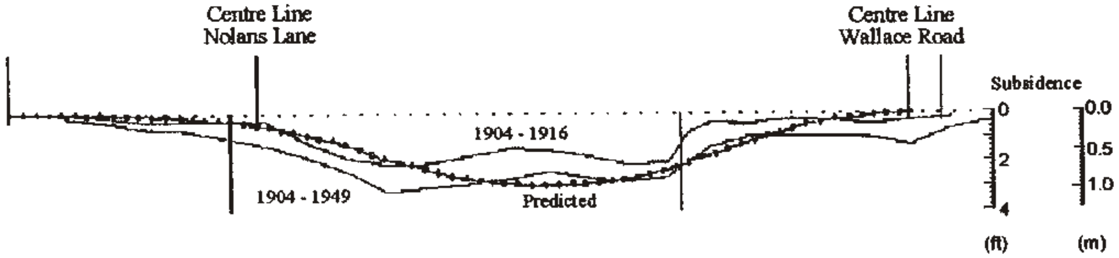

Figure 2. Subsidence in Glace Bay, N.S., 1904-1949

Throughout the twentieth century, mine after mine in the Sydney Coalfield in Cape Breton exhausted economic reserves under land and followed the seams out under the sea. The operation of any mine under large bodies of water brings with it the need for careful design of extraction operations. This is especially true of coal mines, which are characterized by extensive areas of extraction beneath weak, stratified rock and overburden. In fact, this undersea coal mining started in the mid nineteenth century and provisions were made in Nova Scotian coal mining law as early as 1877, based on a report by Mr. H. S. Poole, then the Chief Inspector of Mines. These included: minimum solid rock cover between the seam and seafloor, barrier pillars between workings, restrictions on mine layouts below 500ft (150m) and pre-approval of mine plans. These provisions were modified in 1908 and again, in subsequent N.S. legislation updates, in 1967 and 1997.

Since the 1970's all workings in the Sydney Coalfield have used longwall production methods and are under the ocean. Ground movement above the caved area behind the longwalls is typically characterized on the overlying ocean floor by shallow trough-shaped subsidence depressions. Such subsidence movements on the seafloor are masked from view by water and seafloor sediment, thus any potential for the development of a field data base of subsidence measurements is severely constrained. Precise knowledge of the magnitude and extent of such subsidence is critical to the optimization of mine design to ensure safe and successful operations.

Since 1983, CANMET's Sydney Laboratory and the Cape Breton Development Corporation (CBDC) have jointly researched the measurement of this seafloor subsidence. By observing seafloor topography before and after mining, comparisons can be made to reveal the subsidence troughs. Mapping the ocean floor has been facilitated recently by the implementation of wide-swath multi-beam sonars arising from improvements in acoustic transducer design, coupled with a dramatic acceleration of digital processing capability (Dinn, et al, 1996). The application of this technology to the measurement of the seabed subsidence over an actively worked colliery has both initiated the development of new techniques for acoustic sounding analysis and confirmed its application to monitoring the changing depth to the seabed over time.

Between 1994 and 1997, a series of three marine surveys were conducted over the Prince Colliery in Cape Breton, to determine the ground subsidence over actively worked panels. The active panels of the Prince Colliery are presently located some 5 km offshore, working the Hub Seam at some 150-300 m below the seabed. The average water depth over the active panels is around 45 m. This presentation summarizes the results of the 1994 and 1995 surveys which have been discussed in more details by Forrester and Courtney (1996).

Soundings were made from a specially designed SWATH (Small Water Area - Twin Hull) type vessel, F.G. Creed, owned by the Canadian Hydrographic Service. A Simrad EM1000 multi-beam sounder was used during the three surveys; it can take 60 simultaneous and individual soundings of the seabed over a spreading 150° fan-like pattern as it traverses over a survey area. In 45 m of water, the sounding width on the seafloor would be 250 m with roughly 4 m between beams. The precise location of each of the soundings on the seafloor depends critically on the exact orientation (including heave, roll, and pitch) of the survey vessel in space; the Creed employs an inertial motion sensor (Applied Analytic POS-MV) to measure these motions and to correct data. The earth centered position of the vessel was determined using the Global Positioning System (GPS) with real time differential corrections telemetered from a shore base station via a radio link, yielding horizontal positional accuracies of better than one metre.

In the summer of 1994, the first reference survey over Prince Colliery provided over 10,000,000 soundings across 50 km^2 of seabed during 3.5 days. Software was developed to correct second order sound velocity refraction and related errors. From the data projected onto a grid, a digital terrain model (DTM) of the seabed over the colliery was obtained. Contour maps and a sun illuminated relief depiction were produced from DTM for further interpretation.

The second survey was performed in the summer of 1995. Since the gridded data were georeferenced, it was a simple matter to subtract the two grid sets to calculate the subsidence (Fig. 3) in selected profiles across the panels completed over the year. The maximum subsidence, for example, over the 13 West panel with 2.4 m seam thickness, reached 1.2 m over one year. The measurement error (standard deviation) was estimated to be less than 0.010 m (Forrester, 1997). These estimates have been used to aid the planning and to initiate development of a prediction subsidence model for new panels for future colliery expansion.

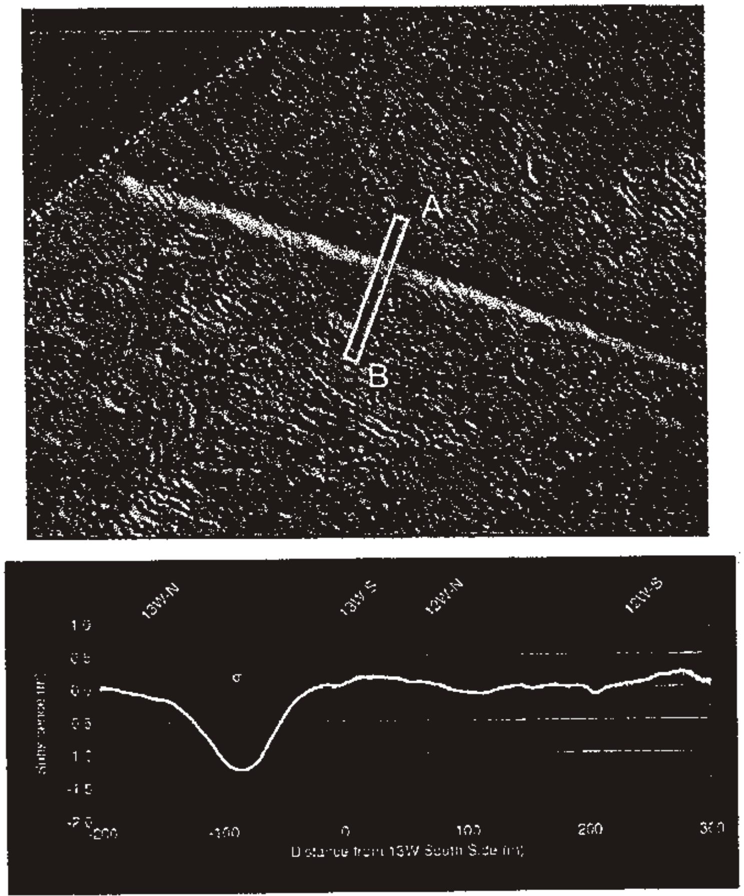

Figure 3. Computer image of an observed seafloor and derived subsidence profile

The multi-beam method has proved to be a useful tool for measuring seabed subsidence over working collieries. It can provide both subsidence information and, also, geologic information about the outcrop of the hosting rock of the seafloor. In two surveys completed near to the Prince area, fault systems can be recognized on the seafloor crosscutting the Carboniferous bedding. The extent to which these features affect mining is a subject of future work.

DEVELOPMENT AND APPLICATION OF A TELEMETRY MONITORING SYSTEM

In the early 1970s, CANMET initiated a project on developing automatic monitoring systems with telemetry data acquisition which could be used year-round in the harsh climate and rugged terrain conditions of some mines in Western Canada. B. C. Coal's (formerly known as Kaiser Resources Ltd.) underground mining operation, located near the town of Sparwood in southeastern British Columbia, was selected as a test ground for new monitoring systems.

The coal bearing strata in the Sparwood area are extensive and contain vast reserves of good quality coking coal. The thickness of the coal seam varies from 12 m to 16 m with a dip of 30° to 50°. The surface topography is very rugged. The ground rises from the outcrop and over the working panels as shown in Figure 4.

Late in 1969, the hydraulic mining method with roof caving was introduced in steeply inclined extraction panels of about 250 m x 700 m separated from each other by narrow pillars. No previous knowledge on the behavior of the rock strata in similar mining and topography conditions had been available and no case histories had been documented which could been used for a comparison or prediction of the subsidence in the area.

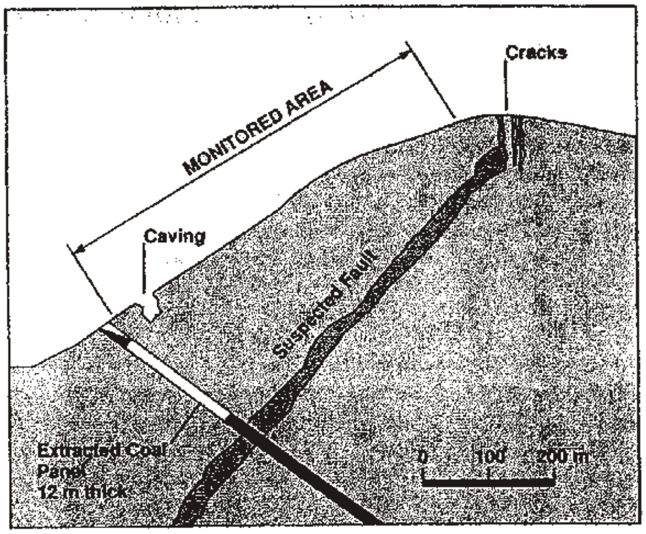

Figure 4. Cross-section of the subsidence area

The first subsidence effects in the area were noticed in the fall of 1975. At that time only the conventional geodetic methods with angle and distance measurements were available for monitoring the ground movements. The subsidence surveys were not easy. Temperatures down to -40°C and snow cover up to 5 m made access and visibility to the targets practically impossible between October and mid-June. The geodetic surveys during the short summer season could not supply sufficient information on the time dependent behavior of the rock strata. Between 1975 and 1978 CANMET attempted to develop a continuous monitoring system based on a 33 m long strain sensor with a telemetry data acquisition (Fisekci et al., 1981) powered by solar photocells. However, the first fully successful telemetry system with a continuous data acquisition was developed only in 1980 (Chrzanowski et al. 1980; Chrzanowski and Fisekci 1982) in cooperation with UNB using electronic tiltmeters (bi-axial servo-accelerometers) as ground movement sensors. The telemetry monitoring system utilized the most advanced, at that time, microprocessor technology and data communication principles. The system consisted of 'slave' units which were directly linked with the tilt sensors and a 'master' unit which served as a controller and handled the acquisition of sensor data from the Slaves at preprogrammed time intervals. In order to ensure that the unit's power base (gel-cell batteries) would last through the winter, the system was designed to turn itself off to a stand-by-mode after interrogation by the Master. The design allowed for up to ten interrogations per day for one year in temperature of -25°C without recharging the batteries.

The telemetry system with five slave units was utilized together with conventional geodetic surveys (using total station AGA 700 and 15 permanently mounted prisms) and with aerial photogrammetric surveys (Armenakis and Faig, 1982) in an integrated monitoring of deformations over one of the extraction panels. The panel of a 12 m thick coal seam with a 30° dip, was extracted between 1980 and 1981. The integrated monitoring started just before the commencement of the extraction and was continued until 1983.

The panel extraction between 1980 and 1981 produced ground displacements of up to 2.5 m with surface cavings near the coal outcrop and long north-south cracks near the mountain ridge. The telemetry system, which successfully operated through three winters gave useful information on the progress of ground movements in time (Fig.5).

The geodetic, photogrammetric, and tiltmeter measurements were used in a simultaneous analysis of the slope deformation employing the aforementioned UNB Generalized Method of Deformation Analysis. Through the least squares fitting of selected deformation models and statistical testing, a final deformation model (Fig. 6) has been obtained (Chrzanowski et al. 1986).

The obtained model has been compared with a 2-D non-linear elastic finite element analysis (Chrzanowski and Szostak-Chrzanowski 1986) using an earlier version of the S-C method. The finite element analysis was made mainly for the purpose of confirming the existence of the suspected fault (Figure 4). Several analyses with and without the fault were performed. The analyses with the fault gave a very good agreement with the observed

displacements. The results of monitoring and findings of the integrated analysis led to the closure of the mining operation to prevent a potential slope failure.

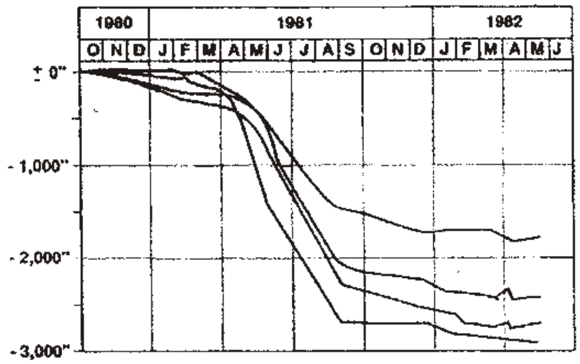

Figure 5. Record of the slope tilt changes, 1980-1982

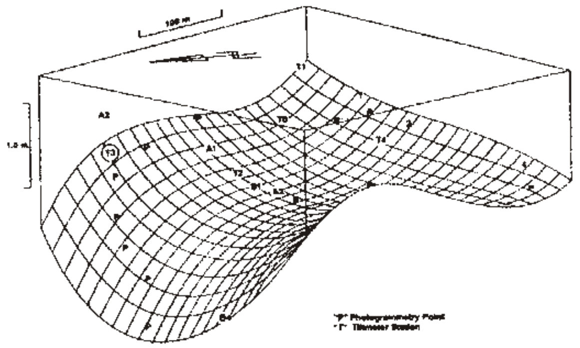

Figure 6. Derived subsidence model

GROUND SUBSIDENCE STUDY IN POTASH MINES IN NEW BRUNSWICK

Mining of two large deposits of high grade sylvinite in New Brunswick started in the mid 1980s. Until 1997, Potash Corporation of Saskatchewan (PCS) and Potacan Mining Company carried on mining in two mines which were located about 30 km apart. Since 1997, only PCS continues the mining operation while Potacan mine had to be closed due to an uncontrolled water inflow. It is interesting to note that despite their proximity, the geological and mining conditions in the two mines are quite different. Potash and salt mining at PCS 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. A strong, arch shaped, caprock (E = 31 GPa), provides an excellent natural support for the overlain brittle rocks.

At the Potacan mine, the ore body is tabular in shape, with the dip of 10° to 12° and the mining depth is between 850 m to 1100 m below the surface. Until 1997, room-and-pillar mining method was employed with delayed backfill. According to an overcoring test performed by Potacan, the geological formations in the mining area are subjected to a horizontal tectonic stress, s_h, with the ratio $s_h / s_v = 1.4$. The heights of the rooms varied from 4 m to a maximum of 35 m. Sylvinite is overlain by variable thickness of halite (only a few tens of metres) with a very weak cap rock (E = 0.44 GPa) and then a sequence of red beds.

Although a significant amount of research, including studies directly oriented towards the time dependent saltrock behavior and use of backfill at PCS (Beddoes et al., 1989) and at Potacan mines (Monahan and Munroe, 1990; Mraz et al., 1987), has been devoted to the problem of time dependency in the saltrock deformation, all the initial studies were performed in a comparatively short period (2 years) of time, mostly in laboratories. The results of those studies are of very limited use for modeling the time dependent global behavior of the salt and overlain brittle rock masses which could be applied for developing a global subsidence theory. The time dependency, in this case, has to be established only through long term monitoring of ground subsidence. Through a comparison of results of monitoring surveys on the surface and in the mining workings coupled with deterministic models of expected deformation, a better understanding of the mechanism of the deformations can be achieved.

Results of Monitoring Surveys

Potacan and PCS mines, in close cooperation with the UNB Group, started systematic monitoring programs in 1986 and 1989, respectively. Initially, monitoring in both mines included only geodetic leveling of first-order accuracy. In

1993, GPS was added to the monitoring schemes at both mines in combination with the high precision electronic total stations (Leica TC2002) to monitor also horizontal movements. Both the vertical and horizontal displacements could be detected with accuracy of ± 5 mm at the 95% confidence level. In 1997, each of the two mines extended over a similar area of approximately 5.5 km x 1.2 km and they were still expanding. Figure 7 shows the monitoring scheme (1996) and horizontal layout of Potacan mine. Table 1 summarizes the results of monitoring.

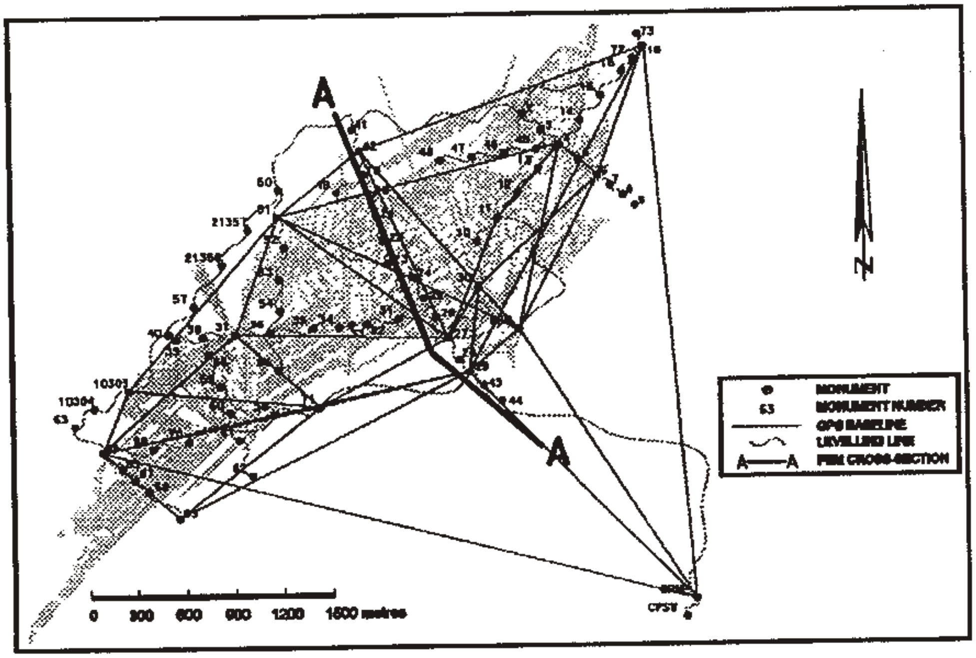

Figure 1. Mine layout and monitoring scheme at Potacan

TABLE 1. Summary of Monitoring Results

	PCS MINE 1989 - 1996	POTACAN 1986 - 1996
Maximum Subsidence:	127 mm	556 mm
Maximum Rate of Subsidence:	20 mm/y	124 mm/y
Maximum Rate of Horizontal displacements:	20 mm/y	60 mm/y

Information on the rate of subsidence is of particular importance because any deceleration or acceleration may indicate an unwanted accumulation or unpredicted release of stresses in the rock masses. Therefore, detection of a change in the rates of subsidence and horizontal movements is one of the most important aspects of monitoring surveys. At PCS mine, the subsidence has been almost linear with time. At Potacan, however, a significant acceleration was noticed in the eastern part in 1995 as shown in Figure 8. The acceleration was accompanied by audible micro-seismic events. It is very unfortunate that funds were not available for increased frequency or even continuous monitoring of that area as suggested by UNB Group. Annual monitoring surveys are inadequate in such case. In 1997, an intensive and uncontrolled water inflow into the eastern part took place forcing Potacan to close the mine. It is planned to continue the ground subsidence surveys to control effects of the underground water inflow on the surface.

Numerical Modeling and Prediction

The S-C method has been applied to a two-dimensional modeling of ground subsidence along selected cross section of the mines. In case of Potacan, the FEM analysis using the S-C method was made along the cross-section A-A (Fig. 7). Two analyses were performed. First, a global prediction model was developed to analyze the total expected final subsidence to be produced by the mining activity up to 1995. The second analysis was made to derive the subsidence model which would best fit the observed subsidence between 1987 and 1995 at the Potacan mine and between 1989-1995 at the PCS mine. Geological data and mechanical properties of rocks were supplied by the mines. At Potacan, the aforementioned horizontal tectonic stress has been accounted for in the analyses. The very weak caprock at Potacan was of a concern.

Results of the predicted subsidence are summarized in Table 2 and in Figure 9 for the Potacan mine. A good agreement with the observed subsidence 1986- 1995 has been obtained in both mines.

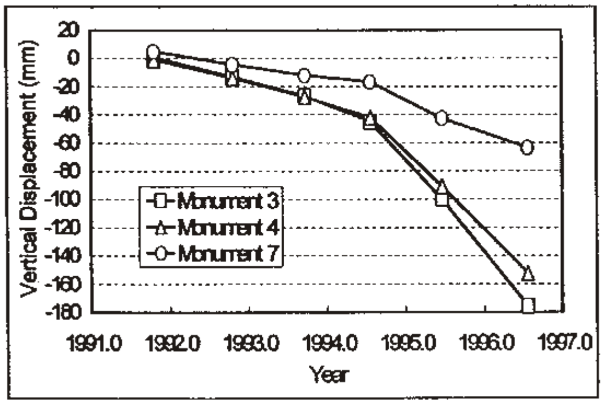

Figure 8. Subsidence at Potacan (east part)

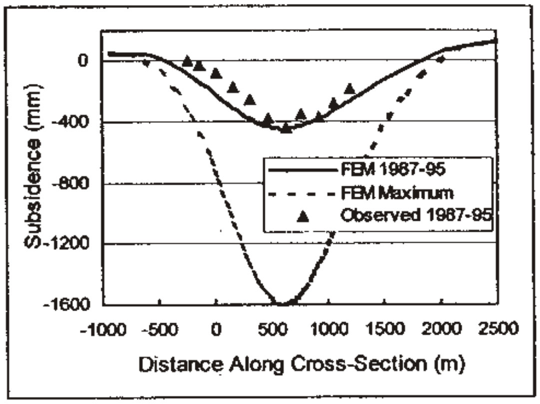

Figure 9. FEM modelled (1987-1995) and predicted total subsidence in cross-section A-A

TABLE 2. Predicted Ground Subsidence

	Potacan	PCS
Time to reach max. subsidence	40-50 years	12-15 years
Maximum predicted subsidence	1.6 m	0.35 m
Maximum horizontal movements	0.7 m	0.14 m
Max. rate of horizontal movements	20 mm/y	7 mm/y

As far as horizontal movements are concerned, the predicted rates of horizontal movements in both mines are 2-3 times smaller than observed (see Table 1). More details on modeling are given in Chrzanowski et al. (1997).

CONCLUDING REMARKS

As mentioned above, the discussed case studies do not cover all the Canadian contributions to monitoring and modelling of ground subsidence over the past 100 years. Though the progress has been good, there is still much work to be done. Hopefully, this presentation will contribute to a better than till now cooperation and exchange of information between all the research centers and mining industry. The surface subsidence and roof control in underground mines are so strongly correlated that through a combination of the expertise of both the survey engineers who observe the subsidence and rock mechanics engineers who design the openings, a faster progress could be made towards safer and more economical mining.

REFERENCES

ARMENAKIS, C. and FAIG,W., 1982
Subsidence monitoring by photogrammetry. Proceedings of the Fourth Canadian Symposium on Mining Surveying and Deformation Measurements, Banff, June, pp. 197-208.

BALS, R. 1931/32
Beitrag zur Frage der der Vorausberechnung bergbaulicher Senkungen", mitt. Markscheidew. 42/43, pp.98-111.

BEDOES, R.J., STREISEL, J.J., ROULSTON, B.V., 1989
Implementation of an Integrated Rock Mechanics Programme for Cut and Fill Potash Mining. Monograph published by Potash Company of America, Sussex, New Brunswick (Canada).

BROWN, R.E. 1968
A Multilayered Finite Element Model for Predicting Mine Subsidence. Ph.D. thesis, Carnegie Mellon University.

CHEN, Y.Q., 1983
Analysis of Deformation Surveys-A Generalized Method. Techn. Report 94, Dept. Geodesy & Geomatics Eng., Univ. N.B.

CHEN, Y.Q., CHRZANOWSKI, A., SECORD, J., 1990
A strategy for the analysis of the stability of reference points in deformation surveys. CISM Journal, vol.44, 39-46.

CHRZANOWSKI, A., FAIG, W., KURZ, B., MAKOSINSKI, A., 1980
Development, Installation and Operation of a Subsidence Monitoring and Telemetry. Final Report Submitted to Canada Centre for Mineral and Energy Technology (DSS File: 18 sq. 23440-8-0-16), pp. 148.

CHRZANOWSKI, A. and FISEKCI, M.Y., 1982
Application of Tiltmeters with a Remote Data Acquisition in Monitoring Mining Subsidence. 4th Canadian Symposium on Mining Surveying and Deformation Surveys, Banff, June 6-9, Proceedings (The Canadian Institute of Surveying), pp. 321-333.

CHRZANOWSKI, A., CHEN, Y.Q., ROMERO, P., SECORD. J.M. 1986
Integration of geodetic and geotechnical deformation surveys in the geosciences. Tectonophysics 130, pp. 369-383.

CHRZANOWSKI, A. and SZOSTAK-CHRZANOWSKI, A. 1986
Integrated analysis of ground subsidence in a coal mining area: a case study. Deformation Measurements Workshop, Mass. Inst. of Technology, Oct. 31-Nov. 1, Proceedings (MIT), pp. 259-274.

CHRZANOWSKI, A.,MONAHAN, C., ROULSTON, B., and SZOSTAK-CHRZANOWSKI, A., 1997
Integrated Monitoring and Modelling of Ground Subsidence in Potash Mines. Int. J. Rock Mech. Min. Sci., vol.34, No. 3/4, p. 621 (abstract) and CDROM (full text)

CHRZANOWSKI, A., CHEN, Y.Q., LEEMAN, R., LEAL,J., 1989.
Integration of the Global Positioning System with geodetic leveling surveys in ground subsidence studies. CISM Journal, v.43, No.4, pp.337-386.

DAHL, H.D., 1969
A finite element model for anizotropic yielding in gravity-loaded rock. Ph.D. thesis, Pennsylvania State University.

DINN, D.F., HENDERSON, G., COURTNEY, R. and BRADFORD, J., 1996.
New Technologies for Nearshore Mapping, in Science Review 1994 and 1995 of the Bedford Institute of Oceanography, Department of Fisheries and Oceans, Maritime Region, Halifax, 151 pp.

FORRESTER, D. and COURTNEY, R., 1996
Monitoring Subsidence over Submarine Coal Mines in the Sydney Coalfield by Bathymetric Methods. Proc. of

the 15th International Ground Control, Division Report MMSL 96-111(OP), CANMET Natural Resources Canada.

FORRESTER, D., 1997
Mining Research in Undersea Coal Mines in Eastern Canada. *Proceedings* of the 3rd International Asia Pacific Workshop on Coal Mining Technology, (Japan Coal Energy Center), Tokyo, Oct. 16-17

FISEKCI, M.Y., CHRZANOWSKI, A., DAS, B.M. and LA ROCQUE, G., 1981
Subsidence Studies in Thick and Steep Coal Seam Mining." First Annual Conference on Ground Control in Mining, Morgantown, W.V., Proceedings, (ed. S. Peng, Univ. of West Virginia), pp. 230-238.

JAQUE WHITFORD & ASSOC. LTD., 1993
Evaluation of Mining Subsidence Field Data, Cape Breton, N. S. Dept. of Supply & Services Contract, Report #23440-1-9127, March 31, 1993.

KEINHORST, H. 1925
Die Berechnung der Bodensenkungen im Emschergebiet. 25 Jahre der Emschergenossenschaft 1900-1925, Essen, pp.347-350.

KNOTHE, S., 1957
Observations of surface movements and their theoretical interpretation. Proceedings of the European Congress on Ground Movement, Leeds, pp.27-38

KRATZSCH, H., 1983
Mining Subsidence Engineering. Springer-Verlag, Berlin.

LUO, Y. and PENG. S.S., 1993.
Using influence function method to predict surface subsidence caused by high extraction room and pillar method. Proceedings, 17th Int. FIG Symposium on Deformation Measurements and 6th Canadian Symposium on Mining Surveying (Canadian Institute of Geomatics), Banff, Alberta, May 3-5, pp. 342-353.

MONAHAN, C. AND MUNROE, S., 1990
Mining with salt backfill at Denison-Potacan: Numerical Modelling, Placement, Testing, and Monitoring. Proceedings of a Specialty Conference on Stresses in Underground Structures (Herget et al. Eds.) CANMET, Ottawa, October 2-3, 162-171.

MRAZ PROJECT CONSULTANTS LTD., DUSSEAULT, M. B., FORDHAM, C. and MUNROE, S., 1987
Use of Backfill in New Brunswick Potash Mines. Unpublished report submitted by Denison-Potacan Potash Company to CANMET.

NCB - NATIONAL COAL BOARD, 1975.
The subsidence engineers' handbook. Mining Department. London.

SALUSTOWICZ, A., 1953.
Profil niecki osiadania jako ugiecie warstwy na sprezystym podlozu. Arch. Gornictwa I Hutnictwa, (Poland) t.1, z.1.

SZOSTAK-CHRZANOWSKI, A.,1988
An iterative modelling of ground subsidence using non-linear elastic finite element analysis. 5th International Symposium on Deformation Measurements, Fredericton, 6-9 June, Proceedings (the Canadian Institute of Surveying and Mapping), PP. 524-529.

SZOSTAK-CHRZANOWSKI, A. and CHRZANOWSKI, A., 1991
Modelling and prediction of ground subsidence using an iterative Finite Element Method. In Land Subsidence, Proceedings of the 4th Int. Symp. on Land Subsidence, ed. A.I. Johnson, Houston, Texas, 12-17 May; International Association of Hydrological Sciences, IAHS Publ. **200**, 173-180.

ZIENKIEWICZ, O.C.,.VALLAPPAN, S., and KING, I.P., 1968
Stress analysis of rock as a 'no-tension' material. Geotechnique, Vol. 16, pp. 56-66.