Proceedings, 11th FIG Symposium on Deformation Measurements, Santorini, Greece, 2003.

USE OF GEODETIC MONITORING MEASUREMENTS IN SOLVING GEOMECHANICAL PROBLEMS IN STRUCTURAL AND MINING ENGINEERING

Anna Szostak–Chrzanowski[1], Adam Chrzanowski[1], and Michel Massiéra[2]

[1]Canadian Centre for Geodetic Engineering, University of New Brunswick, Fredericton, N.B., E3B 5A3 Canada
[2]Faculté d' Ingénierie (Génie Civil), Université de Moncton, Moncton, E1A 3E9; Canada

Abstract

Analysis of deformations of any type of a deformable body includes geometrical analysis and physical interpretation. The ultimate goal of the geometrical analysis is to determine in the whole deformable object the displacement and strain fields in the space and time domains. The latter may be obtained by deterministic modelling of deformations using, for example, finite element method (FEM). Physical interpretation is to establish the relationship between the causative factors (loads) and the deformations. By comparing the geometrical and deterministic model of deformations, one can verify the designed behaviour of the deformable object. In addition, with properly designed monitoring surveys, one may also determine the actual deformation mechanism and explain causes of deformation in a case of unexpected behaviour of the investigated object. Thus, the role of deformation monitoring surveys becomes much broader than just the conventional determination of the geometrical status of the deformable object. In this presentation two examples are given on the use of geodetic monitoring surveys in
(a) determination of effects of hydrological changes on ground subsidence in a potash mine in Canada and
(b) verification of geomechanical parameters of a large earth dam in California during filling up the water reservoir.

1. Introduction

Analysis of deformations of any type of a 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). The ultimate goal of the geometrical analysis is to determine in the whole deformable object the displacement and strain fields in the space and time domains (Chrzanowski et al., 1983; Chrzanowski et al., 1986).
Physical interpretation is to establish the relationship between the causative factors (loads) and the deformations (Chen and Chrzanowski, 1986). This can be determined either by statistical method, which analyses the correlation between the observed deformations and loads, or deterministic method, which utilizes information on the loads, properties of the material, and physical laws governing the stress-strain relationship.
The deterministic modelling requires solving differential equations for which closed form solutions may be difficult or impossible to obtain. Therefore, numerical methods, such as the Finite Element Method (FEM) are used. In case of rock and soil materials, the in-situ geomechanical properties may significantly differ from the laboratory values. This must be taken under consideration when performing deterministic modelling of deformation.
By comparing the geometrical model of deformations, derived from the observed deformation quantities, with the designed deformations obtained from FEM, one can verify the designed geomechanical parameters (e.g., Szostak-Chrzanowski et al., 2000). 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. Thus, the role of deformation monitoring surveys becomes much broader than just the conventional determination of the geometrical status of the deformable object. The role of combined analysis of deformation monitoring surveys and physical interpretation has impact on:
1.Redesign of the operation of the investigated structure
2.Safety
3.Economy
4.Environment
5.Gaining experience for the future.
In this presentation two examples are given on the use of geodetic monitoring surveys and physical interpretation:
(a) determination of effects of hydrological changes on ground subsidence in a potash mine in Canada and
(b) verification of geomechanical parameters of a large earth dam in California during filling up the water reservoir.

2. Analysis of ground subsidence at PCS mine in Sussex, N.B.

Potash Corporation of Saskatchewan (PCS) has carried out mining of a large deposit of high-grade sylvinite in New Brunswick since the mid 1980s. 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 (Figure 1). A strong, arch shaped, caprock provides an excellent natural support for the overlain brittle rocks. Potash is mined by using a mechanized cut-and-fill method with up to 100% extraction in the 1000 m long and about 150 m high stopes. Unsupported openings are up to 25 m wide. The potash deposit is structurally complex with a variable dip and width. Salt mining is by multi-level room-and-pillar method. Trans Canada Highway runs along the longitudinal axis of the mine and is affected by ground subsidence.
Annual monitoring of ground subsidence over the PCS mining operation near Sussex, N.B., has been carried out by the Canadian Centre for Geodetic Engineering (CCGE) since 1989. Fig. 2 shows the layout of the mining workings and the location of points of monitoring surveys consisting of precision levelling, traversing with total stations, and GPS surveys. In 1995, a finite element analysis was performed to model the maximum expected subsidence along a selected cross-section (line A-A in Fig. 2). A summary of the results was presented in (Chrzanowski et al. 1998). The expected subsidence profile was to follow a regular shape with its maximum subsidence located above the room-and-pillar salt extraction (approximately above the centre of the salt dome).
Since 1997, a significant increase in water inflow to the mine was noticed at lower levels of potash extraction near the investigated cross-section and a secondary subsidence basin started occurring on the surface at the north end of the investigated cross-section. In 2001, a new FEM analysis of ground subsidence was undertaken using the S-C method (Chrzanowski at al. 2000) to explain whether the water inflow from an unknown aquifer could cause the development of the secondary subsidence basin.
The following two basic models have been analysed:
(a) analysis of ground subsidence as caused only by extraction of potash and salt, and
(b) analysis of ground subsidence as above, with an addition of possible effects of hydrological changes in a hypothetical aquifer.
Deformation of the soil layer of the aquifer is mainly due to water head change. The deformation may be calculated using the theory of consolidation. Subsidence model derived by Bravo et al. (1991) uses the principle of relationship of elastic compaction of soil and ground water piezometric head. For example, Riley (1984) shows that a 24 m change of water level gives 0.076 m subsidence on the top of the aquifer.

Due to a lack of information on the time dependent effects of mineral extraction and hydrological changes in the aquifer, the identification of the best model had to be based only on a qualitative analysis by comparing the shape of the FEM calculated subsidence profile with the observed subsidence curve.

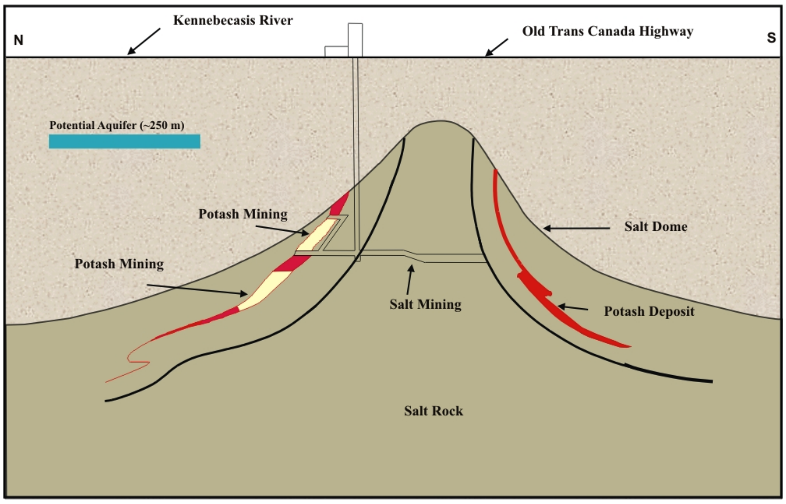

Figure 1. Cross-section of the PCS potash and salt mine in New Brunswick

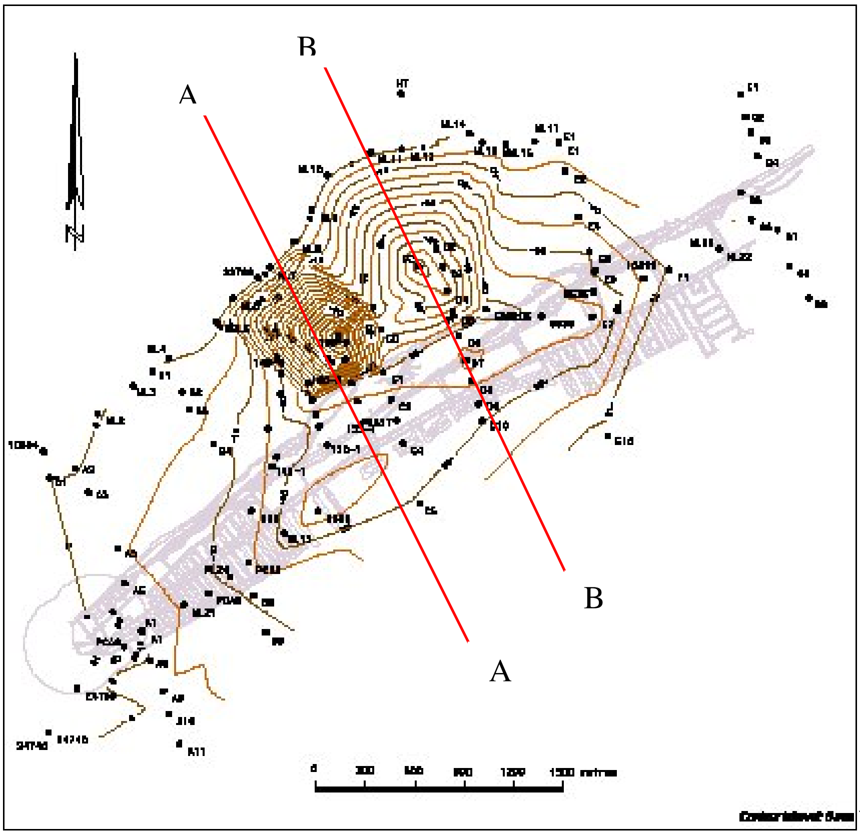

Figure 2. Mine layout and the subsidence isolines (2002).

In the first model, the Young modulus in salt rocks over salt and potash excavations was selected in the FEM analysis to give the calculated maximum subsidence the same as the observed maximum subsidence for the observation period 1995-2001. Figure 3 shows the FEM calculated profile of the surface subsidence in comparison with the observed subsidence. The irregular observed subsidence could not be caused by the mineral extraction alone. Therefore, the second model with an effect of hydrological changes in the assumed aquifer (Fig. 1) was analyzed.

Three analyses were performed for three assumed depths of the aquifer: 350 m, 250 m, and 150 m. In each analysis, it was assumed that the centre of the aquifer is located under the point of the maximum subsidence of the secondary subsidence basin and that the compressibility value in the aquifer is such that the effect on the surface subsidence is approximately equal to the observed maximum subsidence of 0.3 m. The dimensions of the aquifer were arbitrarily taken as having the width of 330 m and thickness of 40 m. The analysis of the aquifer at the depth of 150 m gave the best agreement between the observed and modeled subsidence curve (Fig.4).

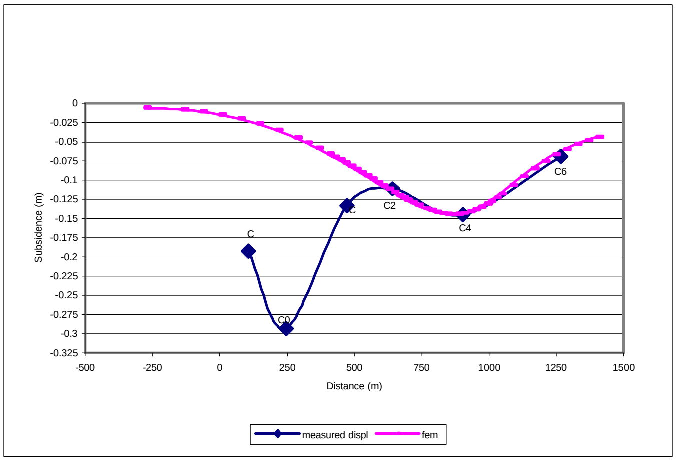

Figure 3. Measured subsidence along A-A Line and calculated (FEM) subsidence due to mineral extraction

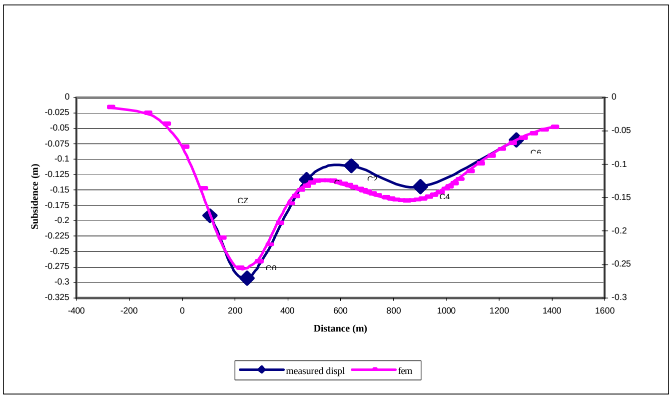

Figure 4. Measured subsidence along A-A Line and calculated (FEM) subsidence with aquifer at 150m depth.

In 2002 a second secondary subsidence basin started to develop north of the mining openings, as shown in Figure 3. Significant increase in water inflow to the mine was noticed at top levels of potash extraction. Exploratory and mitigative drillings from underground workings revealed that the cap rock and rock strata above potash mining are much weaker than previously estimated, showing multiple cracks and a significant void.

The fact that water started to intrude the mine at the top level of potash mining has confirmed the 2001 conclusion that the aquifer is at 150 m or shallower. After several iterative analyses in cross-sections A-A and B-B (Fig.2) with various dimensions of the aquifer, a good agreement of the observed and calculated subsidence was obtained when the aquifer was extended further north.

The measured and calculated subsidence for 2001-2002 epoch is shown on Figure 5. The analysis permitted also to determine approximate boundaries (shape) of aquifer (Fig. 6).

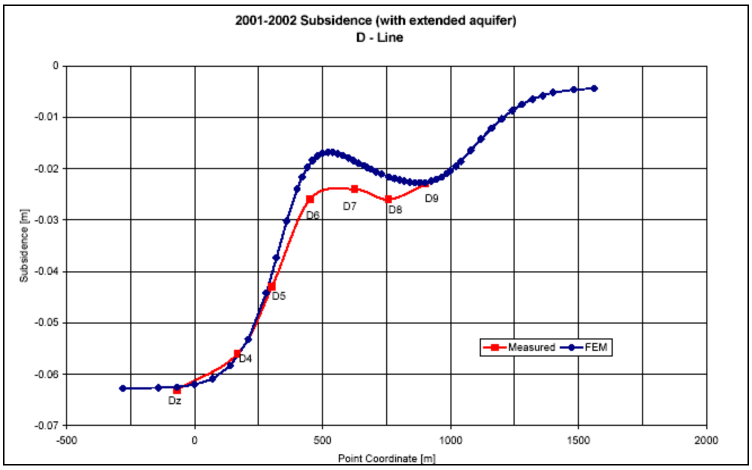

Figure 5. 2001-2002 subsidence with extended aquifer.

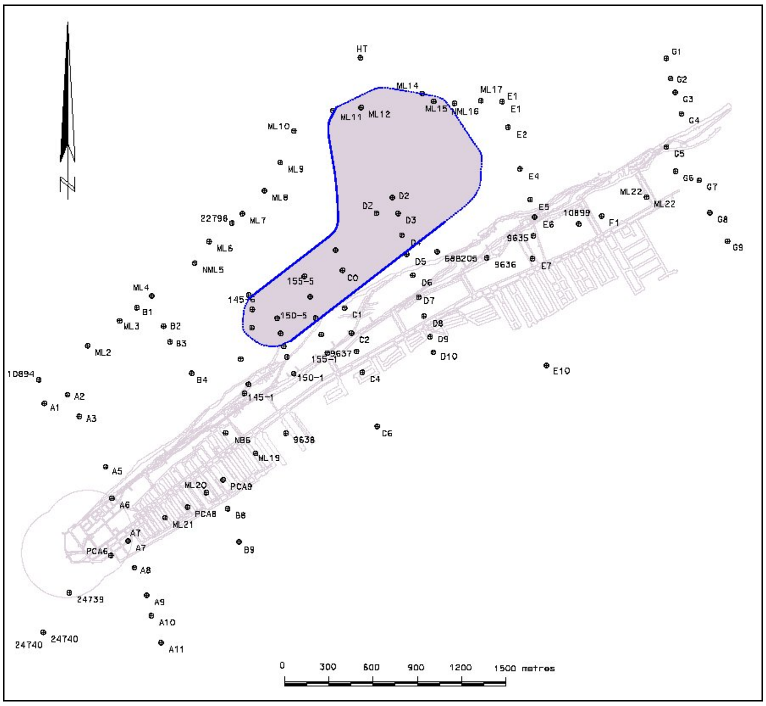

Figure 6. Location and shape of the aquifer.

3. Verification of geotechnical parameters of a large earth dam

In 2000, the Metropolitan Water District (MWD) of Southern California finished construction of Diamond Valley Lake (DVL), Southern California's largest water storage reservoir, with a capacity of nearly one billion cubic metres of water. This $2-billion project, located near Hemet, California (about 160 km southeast of Los Angeles), was designed to secure six months of emergency water for about 16 million inhabitants. It was created by enclosing a valley approximately 7.2 km long and 3.2 km wide with three large earth/rock filled dams of 2.9 km, 3.2 km and 0.8 km lengths and up to 85 m high. The filling of the reservoir began in December 1999 and is estimated to take between three and five years, depending on the availability of water throughout the western United States. At the time of writing this paper the filling was about 90 % complete.

Due to the dimensions of the project and its location within the earthquake prone area, an extensive monitoring program has been developed in order to provide a warning system and confirm that the dams and foundations are functioning as intended. The monitoring instrumentation includes an extended array of geotechnical instrumentation, strong motion accelerographs, active GPS stations, and a fully automated terrestrial geodetic system for Dam Deformation Monitoring (Duffy et al., 2001). The latter was designed to detect displacements of targeted points on the downstream faces of the dams with an accuracy of 10 mm at the 95% confidence level. Eight Leica TCA1800 robotic total stations (RTS), permanently installed in specially designed shelters, perform automatic measurements to 232 targets (prisms) at pre-programmed time intervals. All functions of RTSs, automatic data collection, and automatic data processing are controlled by software developed at the Canadian Centre for Geodetic Engineering (Lutes et al., 2001). Fig. 7 shows the distribution of RTS and GPS stations of the geodetic monitoring scheme.

At the stage of filling the reservoir, the main two effects must be considered: pressure of water and effect of wetting. Figure 8 shows a typical cross-section of the East Dam. During the process of wetting, the values of geotechnical material parameters and the derived values of Young modulus decrease. Young modulus of the material in the submerged sections of the structure becomes smaller and buoyancy force is developed producing dam deformation. In the process of filling the reservoir, the wetting of the dam material may cause significant changes to the material parameters. The rock mass on which the embankment dam is located may be assumed to behave as a linear-elastic material under the load of the weight of the dam and the weight of water in the reservoir.

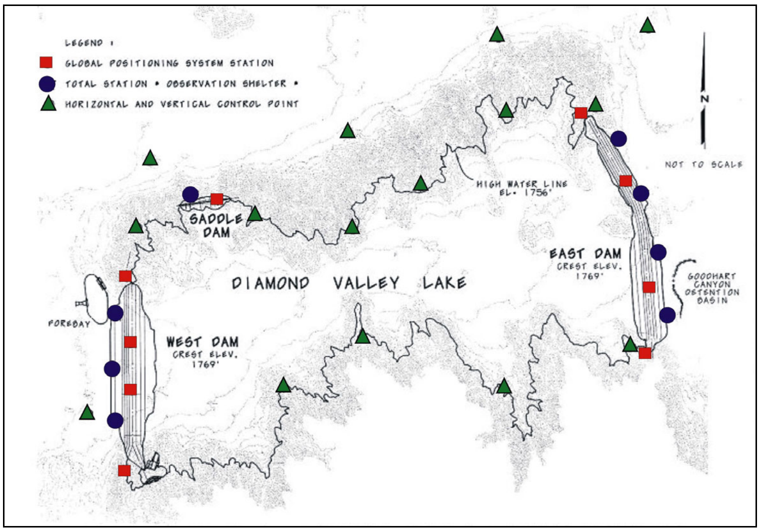

Figure 7. Geodetic Monitoring Scheme at DVL.

The values of Young modulus of the sections of the earth dam were obtained from the analysis during the construction (Szostak-Chrzanowski et al., 2000). In the analysis the material of the dam was modelled as a non linear material using hyperbolic model (Duncan and Chang, 1970).

In the process of the calculation of displacements, one has to determine the change of Young modulus between dry and wet conditions. The results of the geodetic deformation surveys have been used in verifying design geotechnical parameters of the West and East dams using methodology developed as a collaborative project between University of New Brunswick and University of Moncton in Canada (Szostak-Chrzanowski et al., 2000; Szostak-Chrzanowski et methodology developed as a collaborative project between University of New Brunswick and University of Moncton in Canada (Szostak-Chrzanowski et al., 2000; Szostak-Chrzanowski et al., 2002). A preliminary study on the use of geodetic monitoring data in verifying geotechnical parameters of the dam material was performed at the stage of dam construction in dry condition (Szostak-Chrzanowski et al., 2000). In this paper, the authors show only, as an example, a comparison between results of numerical modelling of effects of wetting of the dam material during the filling of the reservoir with the monitoring results in a central cross-section of the East dam (Fig 9). At the end of January of 2003 the calculated vertical displacement was 0.065 m. The calculated maximum vertical displacement of the crest is 0.074m.

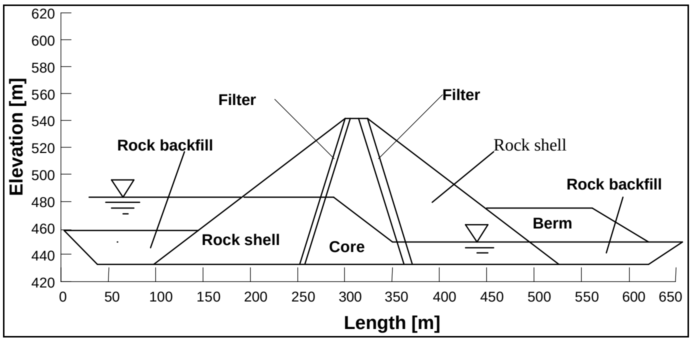

Figure 8. Schematic cross-section of the East Dam with dry and wet zones.

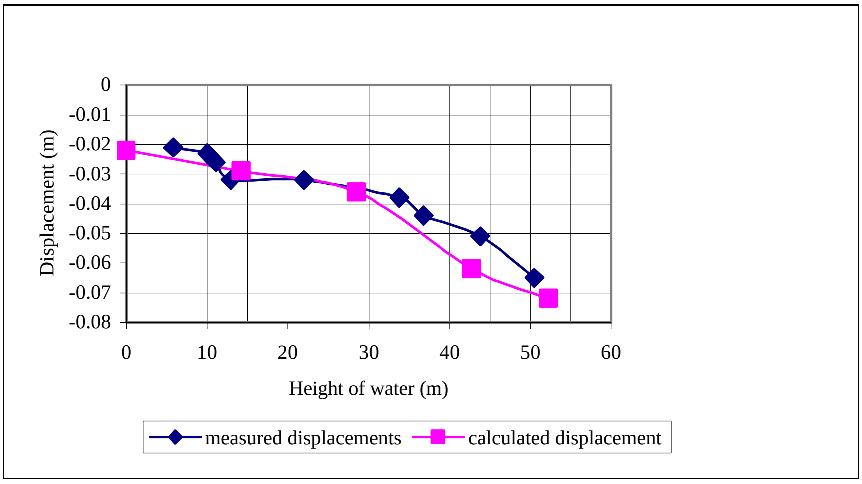

Figure 9. Modelled and measured displacements at the crest of the East Dam.

4. Conclusions

The presented case studies demonstrate the usefulness of the monitoring surveys in solving geomechanical problems. Thus the monitoring surveys serve not only the purpose of giving information on geometrical changes at the surface of the investigated object but become a tool for physical interpretation of the deformation. The role of the monitoring surveys expands into the explanation of causes of unexpected deformation and consequently has impact on the safety and economy as well as environmental effects.

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