# DETERMINISTIC MODELING OF DEFORMATIONS AS A TOOL FOR DESIGNING GEODETIC MONITORING SCHEMES

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**ABSTRACT**

**The design of geodetic deformation monitoring schemes requires decisions to be made regarding the optimal location, density, and accuracy of geodetic sensors and targets. All too often, however, the location of the instruments and accuracy of monitoring are decided upon without regard for the expected location and magnitude of the maximum deformations of the monitored object. This can lead to incorrect interpretations of the behavior of the investigated object. A more rigorous approach is to use deterministic (*a-priori)* modeling of expected displacements derived from the knowledge of the geometry of the object and its environment, causative factors (loads), properties of the material, and physical laws governing the stress-strain relationship. In order to demonstrate how deterministic modeling can be used to design a geodetic scheme for deformation monitoring, an open pit mine scenario was investigated. Finite element analysis was applied to the open pit mine to obtain a prediction model of deformations at various stages of the mine development.**

## 1. INTRODUCTION

**Proper design and interpretation of deformation monitoring measurements requires *a-priori* knowledge of the expected behaviour of the deformable object. This knowledge aids in making decisions regarding the location, density and accuracy of the geodetic technology employed. Without regard for this information, misinterpretation of the actual displacement field can arise which can have serious consequences when safety issues and remedial measures are involved.**

**The *a-prori* knowledge of the expected displacement field may be obtained through deterministic modeling of the deformation (Chrzanowski et al. 2007). In order to determine the displacement field, the following three basic conditions and relations must be defined: (1) conditions of equilibrium of forces, (2) kinematic strain-displacement relations, and (3) stress-strain relations (constitutive law).**

**Deterministic modeling utilizes the knowledge of the geometry of the object and its environment, causative factors (loads), properties of the material, and physical laws governing the stress-strain relationship. Since complex differential equations must be solved in the process of deterministic modeling, numerical methods, (e.g. the finite element method (FEM)) are generally employed.**

**Recent research at the Canadian Centre for Geodetic Engineering (CCGE) has demonstrated how to successfully incorporate deterministic modeling and monitoring design in order to enhance the studies of the behaviour of engineered and natural structures (Chrzanowski et al., 2007). The research has been successfully implemented in ground subsidence studies caused by mining activity (Chrzanowski and Szostak-Chrzanowski, 2004) and by oil withdrawal (Szostak-Chrzanowski et al., 2006), in modeling deformations of large earth and rockfill dams (Szostak-Chrzanowski et al., 2005), and in modeling deformations of concrete structures (Chrzanowski, 1993).**

**Based upon this research, an interdisciplinary approach to designing geodetic deformation monitoring schemes has been developed using deterministic modeling of the expected displacement field. This approach is illustrated by an example of designing a monitoring scheme for an open pit mine.**

## 2. MODELING OF DEFORMATIONS IN AN OPEN PIT MINE

**The stability of steep walls in open pit mines is a major safety issue during operation. In general, during the excavation period, the open pit wall displays a slow (creeping) movement of constant velocity. Any acceleration of the movements may signal an impending failure of the wall. Continuous monitoring of the rock mass movement may detect creep or acceleration of the face and may trigger a warning signal to evacuate equipment and personnel in advance of the failure.**

**One of the crucial conditions of the monitoring scheme is that it is connected to stable reference points. With the information obtained from deterministic modeling it is possible to predict the extent of the deformation zone produced by the planned mining activity. Once the deformation zone is delineated, suitable locations for stable reference points can be chosen. Additionally, deterministic modeling provides general information on the expected magnitude of the deformation and on the location of the expected maximum displacements. The magnitude of the displacement field is a function of the so called deformation characteristics of an open pit. The characteristics include: geometry of the pit and its environment, geology, geomechanical parameters including rock quality parameter, and mining sequence. Additionally, in areas having drastic seasonal climate changes, factors such as the amount of precipitation will have a significant impact on rock face instability.**

**An open pit mine with geometry taken from a real-life example has been used to illustrate the process of determination of displacements caused by mining activity using the FEM. The investigated open pit mine cross-section is shown in Fig. 1. The geology and geomechanical characteristics of the mine used in the FEM analysis have been significantly simplified for the purpose of the example. The rock formation, consisting of only two layers of rock was assumed to be of good quality and isotropic.**

**The FEM modeling of the expected response of the open pit slope was performed to analyze the effects of enlarging the mine from the existing depth of 600 m to the designed final depth of 750 m. This was done by an additional excavation at the bottom and at the left wall. The analysis of the expected deformations was performed for five stages of the mining sequence as marked in Fig. 2. The behaviour of the rock mass was assumed to be linear-elastic. Two models of the open pit mine were investigated. In the**

first model it was assumed that the rock strata were homogenous. In the second model, a geological discontinuity (a fault zone) was introduced as shown in Fig. 3. The FEM analysis was performed using GeoStudio SIGMA/W software (GEO-SLOPE, 2007). A trial and error approach was used to determine the horizontal and vertical extents of the model required so that the calculated displacements would not be significantly influenced by the introduced boundary conditions. It was determined that the mesh should extend 9 km from the rim of the pit on both sides to avoid instabilities on the surface greater than 2 mm.

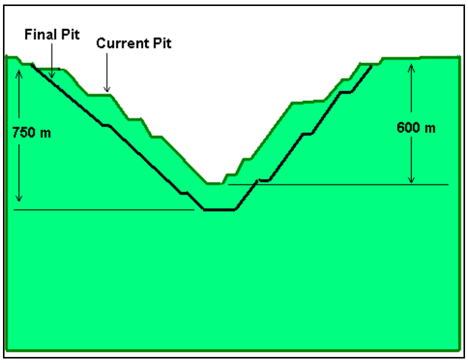


**Fig. 1. Open Pit Mine Scenario.**

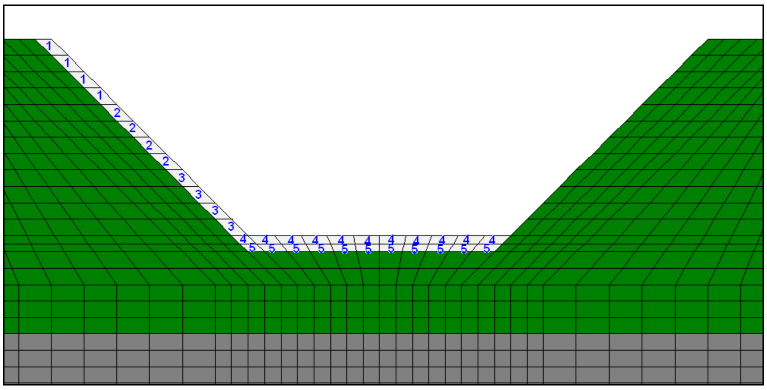

**Fig. 2. Mining Sequence.**

Table 1 summarizes the total expected displacements at selected points (as marked in Fig. 3.) as a result of the mining activity at various stages of the development. Fig. 4 shows the total accumulated displacements and Fig. 5 illustrates contours of horizontal displacements without and with the fault. It can be seen that maximum accumulated displacements (uplifts) of up to 40 cm are expected to occur at the bottom of the pit. At point 2, which is located 4 km to the left of the rim of the pit, the total displacements may still reach 1 mm and 5 mm with and without the fault respectively. As expected, the presence of the fault reduces the transfer of tensional stresses beyond the fault. At point 11, which is 2 km to the right of the rim of the pit, the displacements may still reach 3 mm and 7 mm with and without the fault respectively, even though the right slope is not excavated.

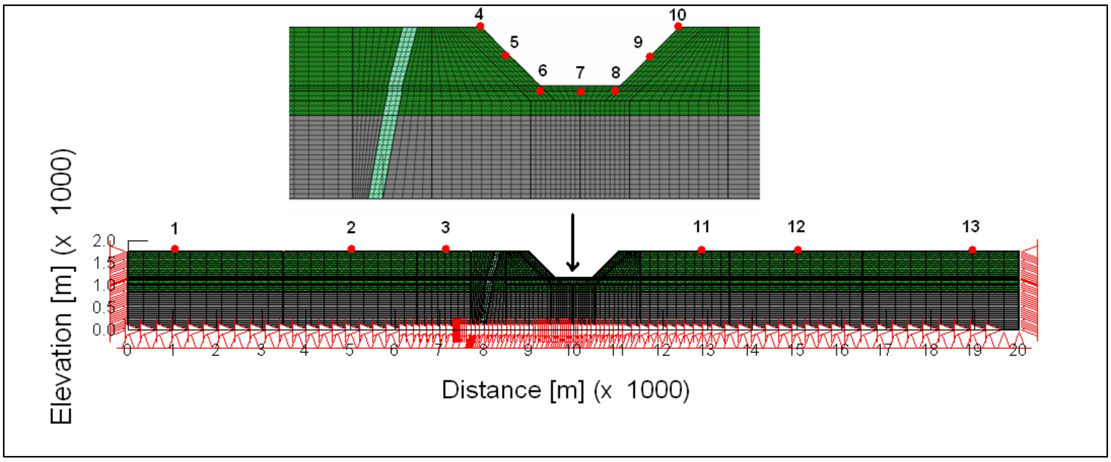


**Fig. 3. Finite Element Mesh of the Open Pit Mine.**

**Table 1: Displacement Summary for Selected Points.**

| | Without Fault | | | | | | With Fault | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Excavation Stage | | | | | | Excavation Stage | | | | | |
| **Pt #** | **1** | **2** | **3** | **4** | **5** | **Total** | **1** | **2** | **3** | **4** | **5** | **Total** |
| **1** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **2** | 0.000 | 0.001 | 0.003 | 0.000 | 0.001 | 0.005 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 |
| **3** | 0.001 | 0.006 | 0.013 | 0.001 | 0.002 | 0.024 | 0.000 | 0.001 | 0.001 | 0.002 | 0.001 | 0.005 |
| **4** | 0.175 | 0.065 | 0.061 | 0.019 | 0.006 | 0.326 | 0.133 | 0.050 | 0.016 | 0.049 | 0.031 | 0.279 |
| **5** | 0.110 | 0.029 | 0.107 | 0.028 | 0.014 | 0.289 | 0.092 | 0.025 | 0.031 | 0.050 | 0.031 | 0.229 |
| **6** | 0.019 | 0.055 | 0.120 | 0.119 | 0.047 | 0.360 | 0.016 | 0.040 | 0.084 | 0.139 | 0.087 | 0.366 |
| **7** | 0.004 | 0.008 | 0.024 | 0.224 | 0.141 | 0.401 | 0.003 | 0.006 | 0.011 | 0.223 | 0.144 | 0.387 |
| **8** | 0.001 | 0.003 | 0.009 | 0.107 | 0.040 | 0.161 | 0.001 | 0.002 | 0.004 | 0.119 | 0.045 | 0.169 |
| **9** | 0.001 | 0.001 | 0.002 | 0.024 | 0.014 | 0.042 | 0.000 | 0.000 | 0.001 | 0.029 | 0.013 | 0.043 |
| **10** | 0.000 | 0.001 | 0.001 | 0.014 | 0.006 | 0.022 | 0.000 | 0.000 | 0.000 | 0.022 | 0.009 | 0.032 |
| **11** | 0.000 | 0.000 | 0.001 | 0.002 | 0.003 | 0.007 | 0.000 | 0.000 | 0.000 | 0.002 | 0.000 | 0.003 |
| **12** | 0.000 | 0.000 | 0.000 | 0.001 | 0.001 | 0.002 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **13** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

It can be seen that: (1) excavation of the slopes causes the surrounding rock mass to move in the direction of the previously occupied material, (2) the pit floor experiences uplift as a result of excavation of the slope, and (3) excavation of the pit floor is mainly responsible for the displacements occurring along the right (non-excavated) slope. The most significant displacements manifested are uplift vectors occurring along the pit floor. These displacements occur as a result of a relaxation of stresses as the pit floor is excavated. Even though excavation occurs only along the left slope and pit floor, the stability of the right slope is also affected. The rim on both sides of the pit experiences displacements. This has important implications for choosing suitable locations for geodetic instrumentation. As indicated, the fault limits the extent of the region of deformation (Fig. 5).

As was shown in Table 1, the fault zone allows stable reference points to be located closer to the open pit. This information has further important implications: knowing that a fault limits the extent of the region of instability, geodetic instruments can be used to locate fault zones. For example, if a target point shows stable behaviour in a region thought to be active, this may suggest that a fault exists somewhere between the target and the area of mining activity. Both the finite element model results and actual measurement values should therefore be used to complement each other in the overall physical interpretation process.

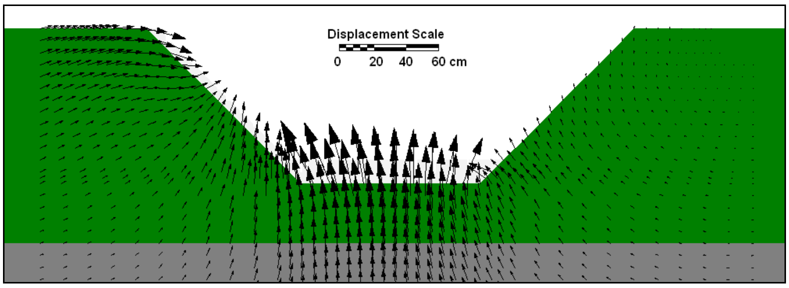


**Fig. 4. Cumulative Displacement Field after all Excavations.**

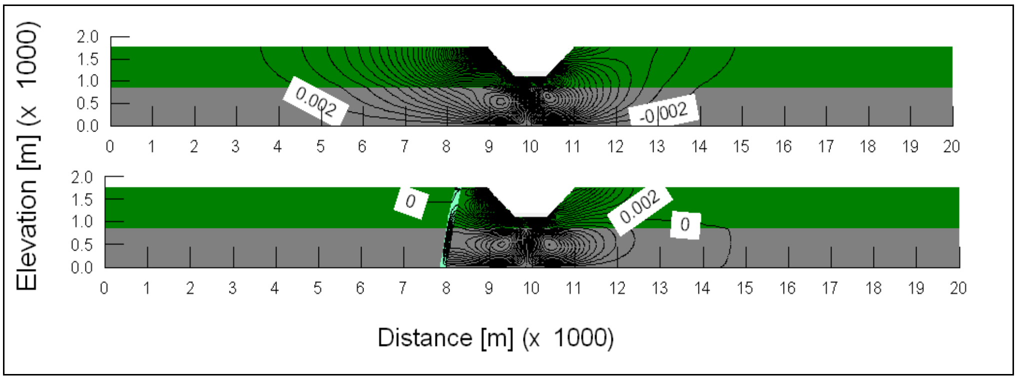


**Fig. 5. Comparison of Horizontal Stability (top without fault, bottom with fault).**

## 3. DESIGN OF THE MONITORING SCHEME

**Monitoring of deformations serves dual purposes: (1) it can verify the designed or expected behaviour of the investigated object and (2) it can provide a warning system by signalling when observed deformations show acceleration or other irregularities.**

**In most large open pit mines, the geodetic monitoring system requires hundreds of targets to be continuously monitored with sub-centimetre accuracy at the 95% confidence level. The large number of targets required is due to the complexity of the deformation characteristics of the mine. The deterministic model provides useful information on the global expected response of the rock strata to the mining activity. This is sufficient for a general design of the monitoring technology and methodology. Very detailed monitoring is required, preferably continuous in both space and time domains.**

**The instability of bench walls is defined empirically by the velocities of observed points located in the deformation area. Newcomen et al. (2003) define the status of point instability using four categories: (1) the "Background" category represents velocities showing the expected response to mining and/or stress relaxation; (2) the "Watch"**

**category represents increased velocities mostly caused by mining sequence or weather conditions (e.g., rain season); (3) the "Caution" category is used for points having increased velocities associated with accelerations; and (4) the "Alert" category describes points having velocities which exceed the previously measured values in the same area.**

**The actual values of the displacements for each category may significantly vary from one 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.**

**Based upon the expected displacement rates and on the global predicted displacement field generated through FEM modeling, the design of the monitoring scheme may be performed with regard for the technology to be used and locations of the instrumentation. Some of the most commonly used geodetic sensors in deformation monitoring are robotic total stations (RTSs) equipped with automatic target recognition (e.g Leica TCA 1800), Global Positioning System (GPS) augmented, if needed, with pseudolites (Bond et al. 2007), interferometric synthetic aperture radar (InSAR) (Chen et al., 2000; Liu et al., 2002), and laser scanners (Roberts and Hirst, 2005).**

**The scale of the presented example and the sub-centimetre accuracy requirements eliminate the possibility of using a laser scanner for deformation monitoring. The requirements of the continuous monitoring eliminate InSAR (repeatability of surveys once every 24 days or more) as an option. The large number of targets required in open pit mines eliminates the use of GPS as a stand-alone system. Consequently, use of robotic total stations is left as the most viable option for geodetic sensors. However, as indicated by (Chrzanowski and Wilkins, 2006), RTSs must be located within a few hundred metres from the wall in order to statisfy the sub-centimetre accuracy. This means that in the case of the presented example, RTSs will have to be located within the pit in the unstable zone while the stable control points will have to be located several kilometres away from the mine. Therefore, the best solution for the given scenario will be to combine RTSs with GPS. The latter will control and correct positions of the RTSs and will provide connection to the stable reference points. One possible arrangement of a combined RTS+GPS deformation monitoring system is illustrated in Fig. 6. In this arrangement, two GPS control stations are located in such positions as to have instabilities less than 2 mm, while still maintaining short baseline status (< 10 km). These control stations are used to redundantly monitor the stability of two RTS stations located within the pit. The RTS stations are then used to monitor target points strategically placed on the pit walls. Since the visibility to the satellites from within the mine may be significantly limited (Bond et al., 2005), one could augment GPS with 2-3 pseudolites located around the rim of the pit.**

## 4. CONCLUSIONS AND RECOMMENDATIONS

**In order for the monitoring scheme to be effective, it must be connected to stable reference points. Deterministic modeling aids in fulfilling this requirement by allowing the extent of the deformation zone to be assessed based upon the designed mining**

activity. Once the deformation zone has been delineated, suitable locations for stable reference points can be chosen. Additionally, deterministic modeling provides a method for predicting global displacement behaviour and determination of the areas of maximum expected deformation.

The presented example of a large open pit mine illustrated the usefulness of deterministic modeling in designing the monitoring scheme. Robotic total stations combined with GPS and, if needed, pseudolites, should satisfy the monitoring requirements.

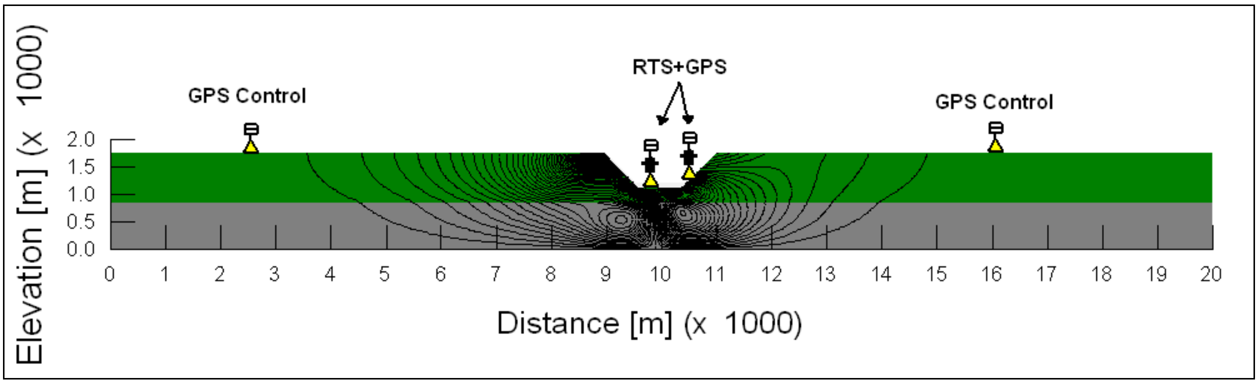


**Fig. 6. Geodetic Deformation Monitoring Scheme based upon Deterministic Modeling.**

## ACKNOWLEDGEMENTS

**This research has been sponsored by the Public Safety and Emergency Preparedness Canada Research Fellowship in honour of Stuart Nesbitt White, the Natural Sciences and Engineering Research Council of Canada (NSERC), and Atlantic Canada Opportunities Agency (ACOA).**

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