Chrzanowski, A., A. Szostak-Chrzanowski, J. Bond (2007) "Increasing public and environmental safety through integrated monitoring and analysis of structural and ground deformations" published in Geomatics Solutions for Disaster Management (eds: J. Li, S. Zlatanova, A. Fabbri) Springer, pp. 407- 426

Increasing Public and Environmental Safety through Integrated Monitoring and Analysis of Structural and Ground Deformations

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ABSTRACT

Recent catastrophies occurring worldwide, including collapses of large civil structures, bridges, and highway overpasses, as well as land slides, rock failures and mining disasters, have all dramatically increased the demand for fully automated, continuous, and reliable deformation monitoring. The Canadian Centre for Geodetic Engineering (CCGE) at the University of New Brunswick is involved in the development of new methods and techniques for integrated monitoring, integrated analysis, and prediction (deterministic modeling) of structural and ground deformations. Recent developments include the ALERT software suite for fully automated and continuous monitoring of deformations with multi-sensor (both geodetic and geotechnical) systems, enhancement of GPS technology augmented with terrestrial pseudo-satellites, and the design and physical interpretation of monitoring surveys based on deterministic modeling of deformations using the finite element method. Further research is needed to increase the reliability of monitoring systems to avoid triggering false alarms.

Key Words: deformation monitoring, deterministic modeling, GPS, pseudolites, ALERT

1. Introduction

Any engineered or natural structure, when subjected to loading, undergoes deformation and/or rigid body movements. Once the deformation, its velocity and/or acceleration, exceed critical values, the structure fails. The critical values are determined using failure criteria that are based upon either empirical formulae or principles of continuum mechanics. By providing continuous and properly designed deformation monitoring schemes, one may provide information about the new state of the deformation. This information can then be used to provide advance warning of imminent structural failure.

Unfortunately, it is not uncommon for large civil structures, dams, bridges, open pit mines, slopes, and underground excavations to be monitored using outdated and inefficient systems and/or inadequately trained operators. Worse, some operations do not use any deformation monitoring system at all. Large dams are a notable example. There are over 45,000 large dams (taller than 15 m) in the world that should be monitored. A study performed during 1990-92 (Chrzanowski et al., 1993) revealed that most owners of dams, even in the most advanced and industrialized countries do not have any monitoring standards and specifications.

Recent catastrophic disasters such as the collapse of highway overpasses in Canada; failures of levees and bridges in New Orleans; collapses of roofs of large civil structures in Germany, Poland, and Russia; land slides in California, Pakistan, and the Philippines; and rock failures and losses of lives in deep coal mines in China have dramatically increased the demand for the development of new monitoring systems and their broader applications. Automation, multi-sensor integration, continuous data collection, integrated analysis and physical interpretation, and enhanced accuracy and reliability are key issues in the development of such systems.

The Canadian Centre for Geodetic Engineering (CCGE) at the University of New Brunswick is dedicated to the development of new monitoring systems and new methods for integrated analysis, modeling, and prediction of structural and ground deformations using an interdisciplinary approach. Some of the significant recent developments at CCGE include: the development of the ALERT software suite for fully automated and continuous monitoring of deformations with multi-sensor systems; enhancement and full automation of GPS monitoring techniques; augmentation of monitoring schemes with terrestrial emitters of GPS-like signals (i.e., 'pseudolites'); the use of monitoring results in the verification of the deterministic models of deformation; and a new approach to the design of multi-sensor monitoring surveys based on deterministic modeling of deformations using the finite element method. This paper gives a review of these recent developments.

2. Design of Monitoring Schemes

2.1 Design Criteria

The design of a monitoring scheme should be based on a good understanding of the physical process which leads to deformation. The investigated deformable object should be treated as a mechanical system, which undergoes deformation according to the laws of continuum mechanics (Szostak-Chrzanowski et al., 2006). This requires the causative factors (loads) of the process and the characteristics of the object under investigation to be included in the analysis leading to the design. This is achieved by using deterministic modeling of the load-deformation relationship. Thus the design process requires an interdisciplinary cooperation between specialists in various fields of geoscience and engineering, including structural, rock mechanics, and geodetic engineering, depending on the type of the investigated object.

If the monitoring system is to be used as a failure warning system, it must be fully automated to handle continuous or very frequent data collection (depending on the expected rate of deformations). It must be able to perform data processing, and visualization in near-real time, and must have sufficient accuracy and capability to trigger the alarm. In order to minimize triggering false alarms, the system must be capable of distinguishing between the actual deformation signal and noise caused by errors of observations. False alarms are expensive and lead to a wrong evaluation of the physical state of the object which may have large economic and sociological impacts.

Design of the monitoring scheme requires decisions to be made regarding the type, location, density, and accuracy of monitoring sensors. The location of the sensors or the observed targets must include points where maximum or critical deformations are expected (Chrzanowski, 1993). Concerning the required accuracy, most of the deformable objects (e.g. bridges, dams, nuclear power stations, open pit mines) require sub-centimetre or even millimetre level accuracy.

2.2 Choice of Monitoring Sensors

The sensors used in monitoring measurements are generally grouped into geodetic techniques (terrestrial and space) and geotechnical/structural instruments (e.g., tiltmeters, extensometers, strainmeters). Among the available geodetic and geotechnical/structural technologies, there are very few, if any, sensors that can fully satisfy the above monitoring criteria as a stand alone system. Therefore, in most cases, various techniques must be combined into an integrated monitoring system. Among geodetic techniques, the best for fully automated and continuous monitoring are GPS and robotic total stations (RTS) with automatic target recognition (e.g Leica TCA 1800). If needed, GPS can be augmented with pseudolites and/or other satellite positioning systems. Other, comparatively new, geodetic techniques include laser scanners, interferometric synthetic aperture radar (InSAR), and digital photogrammetry. They have, however, many limitations and restrictions, which still require further research and enhancements. For example, the satellite born InSAR, provides repeated radar images only every 24-35 days depending on the satellite system. InSAR also suffers from other limitations (Chen et al., 2000). The recently developed ground based InSAR technology (e.g., Pieraccini et al., 2006) promises significant improvement in continuous monitoring of steep slopes and embankments.

All of the discussed geodetic technologies are vulnerable to the effects of changes of atmospheric conditions (changes in the density of air due to the changes in temperature, humidity, and barometric pressure) causing:

- in the case of optical direction measurements, changeable refraction along the lines of sight (see 2.3.1),
- in the case of electromagnetic distance measurements, errors due to the varying velocity of propagation of electromagnetic waves, and
- in the case of GPS, residual tropospheric delay biases when there are large elevation differences between the receivers (Bond et al., 2005).

Geodetic methods supply information on the absolute and relative displacements (changes in coordinates) from which displacement and strain fields for the monitored object may be derived. Thus, geodetic surveys supply global information on the behavior of the investigated object. In some cases, however, the use of geodetic techniques may be uneconomical and may have inadequate accuracy.

There is a multitude of geotechnical instruments equipped with electro-mechanical transducers (Dunnicliff, 1988) that may easily be adapted for continuous monitoring and telemetric data acquisition. Usually, the geotechnical instruments are embedded in the investigated object for the duration of the monitoring project. These instruments supply only very localized information on a selected component of the deformation (e.g., only local tilt or local extension in one direction when using a tiltmeter or an extensometer, respectively).

Geotechnical instruments require thorough calibration for the effects of environmental temperature, drift of the readout, and conversion constant. Once embedded within the structure, however, the geotechnical/structural instruments cannot be rechecked or recalibrated. Because of this, it is not uncommon that geotechnical instruments provide unreliable data or even fail during the life of the structure. Since geodetic measurements allow for redundancy and the possibility of statistical evaluation of the quality of the data, they generally provide more reliable results. Geodetic and geotechnical measurements compliment each other and, ideally, should be used together creating an *integrated monitoring scheme.* In addition, when the investigated object is located within the influence of seismic activity, the local monitoring system must be integrated with a regional system. A good example illustrating these concepts is given in (Duffy, et al., 2001).

To illustrate the use of deterministic modeling in designing an integrated monitoring scheme, an example of a 75 m high, Concrete Face Rockfill Dam (CFRD) resting on a 60 m thick till is given. Fig. 1 shows expected horizontal and vertical displacements caused by filling the reservoir (Szostak-Chrzanowski and Massiera, 2006).

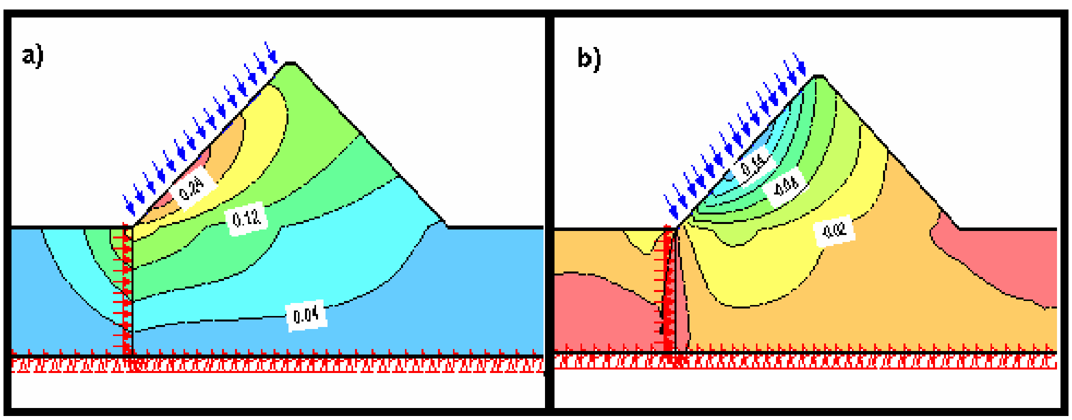

Fig. 1 Predicted displacements [m] after filling the reservoir a) horizontal displacements b) vertical displacements

As one can see from the modelled displacements, the largest displacements are expected to occur at the upstream face of the dam, which is covered by a concrete slab. It is the most crucial area for monitoring the deformation. Since the upstream face is under water, the monitoring scheme should be designed to have geotechnical instruments such as fibre-optic strainmeters and tiltmeters embedded in the concrete slab. The rest of the dam could be monitored by geodetic methods using, for example, robotic total stations and GPS. Besides the deformation sensors, various physical geotechnical sensors must also be used, for example piezometers, seepage gages, and others. Final details of the design including the density of the instrumentation, accuracy requirements and frequency of observations should be discussed between geotechnical and geodetic engineers. For example, by modeling the expected deformation at various water level stages in the reservoir, one can obtain information on the rates (velocity) of deformations. This information will aid in determining the required frequency of repeat surveys.

2.3 Challenges of Geodetic Monitoring Systems

2.3.1 Effects of Atmospheric refraction

Mitigating the effects of atmospheric refraction on direction measurements is the oldest, unresolved problem of geodetic surveys. The pointing error, *e*, caused by refraction is a function of the gradient of temperature dT/dL occurring across the line of sight. It can be derived from the basic theory of refraction that the approximate relationship between *e* and temperature gradient can be expressed as in Eq. (1):

$$e = \frac{3.9 P s^2 10^{-5}}{T^2} \frac{dT}{dL} \tag{1}$$

Where:

s	distance to the target in [m]
P	barometric pressure in [mb]
T	absolute temperature [^{o}K]
$\frac{dT}{dL}$	temperature gradient [^{o}C/m] perpendicular to the line of sight

For example, in atmospheric conditions of 1013 mb and 20^{o}C, over a 1000 m sight length, a uniform change in the temperature gradient from nighttime to daytime of only 0.1^{o}C/m would cause more than a 4 cm change in the determined position of the target. Intensive tests with robotic total stations at two large open pit mines in Chile and in Western Canada (Chrzanowski and Wilkins, 2006) and at a large earth dam in California (Duffy et al., 2001), indicate that the temperature gradients within two metres of sun exposed surfaces may change by 2^{0}C/m or more from nighttime to daytime. Diurnal pointing changes of up to 200 mm were recorded over a distance of 1500 m with the line of sight passing across an open pit mine far away from the pit walls. It must be noted that the effects of refraction are much more severe when large temperature gradients occur near the RTS rather than if they occur closer to the target. This is important criteria to consider when designing the location of the monitoring instruments.

Since the effect of refraction increases proportionally to the square of the distance, it follows that the location of the observing instruments should be as close as possible to the targets being monitored. The dirurnal, cyclic effects of refraction can be significantly minimized by daily averaging of the monitoring results. This approach can only be used if it satisfies the update frequency. Alternatively, one should try to model and predict the cyclic effects of refraction as a function of the time of day based on previous observation data. Otherwise, epoch-to-epoch results will show large erroneous displacements, which could trigger false alarms.

Changes in atmospheric conditions cause much smaller errors in distance measurements than in the direction observations. For example, a 1^{o}C change in air temperature causes approximately a 1 ppm change in the distance. This can be further reduced by introducing meteorological corrections to the observed distances. Thus, the design of a geodetic monitoring scheme should rely more heavily on distance observations than direction measurements.

2.3.2 Instability of Reference Points

In deformation surveys, the definition of the datum is adversely affected by the use of reference points that are erroneously assumed stable. This in turn gives a biased displacement pattern that can easily lead to a misinterpretation of what is really happening to the deformable object.

A methodology utilizing an iterative weighted similarity transformation (IWST) of displacements for the identification of unstable reference points was developed at CCGE (Chen et al., 1990) in the early 1980s. The methodology is based on using a similarity transformation of displacement components d_i with the condition that $\sum|d_i|$ = min. The weights of individual displacement components are inversely proportional to the absolute value of the component itself. The transformation is an iterative process that is repeated until subsequent iterations reach a preselected convergence criterion.

3. ALERT Software for Fully Automated Multi-Sensor Monitoring Systems

Initially, the ALERT software suite (Wilkins et al. 2003) developed at CCGE was designed for automated monitoring of deformations using only robotic total stations (RTS) and meteorological sensors (for correcting observed distances). Very recently, GPS has been added to ALERT to work either as a stand alone fully automated GPS monitoring system or to work together with RTSs as a hybrid RTS/GPS system. In the latter case, GPS is used to control and give positional corrections to the RTSs, which may be setup within the deformation zone. GPS allows the network of RTSs to be connected to stable reference points since it does not require intervisibility between stations. Figure 2 shows typical observation shelters of the ALERT system. Figure 2a shows one of eight RTS stations installed at the Diamond Valley Lake Project in Southern California (Duffy et al., 2001) to monitor three large earth dams. Figure 2b shows a RTS/GPS shelter in a large open pit mine in Western Canada.

Figure 2: a) RTS shelter with solar power panels, b) Typical RTS/GPS ALERT shelter

The ALERT software suite is composed of a series of modules that automate surveying tasks, handle database management, and provide graphical user interfaces. An initial setup is required to catalog the elements of the monitoring networks (e.g., survey point names, RTS locations, communication parameters, etc.) and create ALERT projects. Once projects are defined, one can create observation, data transfer, and processing schedules for each monitored site to obtain displacement results. Processed data is automatically made available in a near-real time fashion. Using computer network connections, oversight of current data collection activities and modifications to observation schedules can be done remotely.

The system takes advantage of the core functionality of the Microsoft systems (e.g., NT 4.0, Windows 2000, and Windows XP). There is full support for remote operation via LAN and Internet connections and provider-independent database access. In addition, the software's observation and processing tasks are automated according to any desired schedule and the system is able to recover from power outages with no user intervention.

An alarm system has been incorporated into the ALERT software. An alarm definition is created by attaching to it one or more user defined criteria with a list of action items. The criteria can be defined for displacements, velocity, or acceleration. The action items attached to the alarm can be triggered either by individual points or groups of points, when their movement reaches or extends beyond the predefined criteria values associated with the alarm. The action items for each alarm can report to a log file, email a list of recipients, change point status, and/or trigger external alarm hardware (e.g., light, siren, etc.) via a serial port.

Figure **3** gives a more illustrative view of this process in terms of a flow chart.

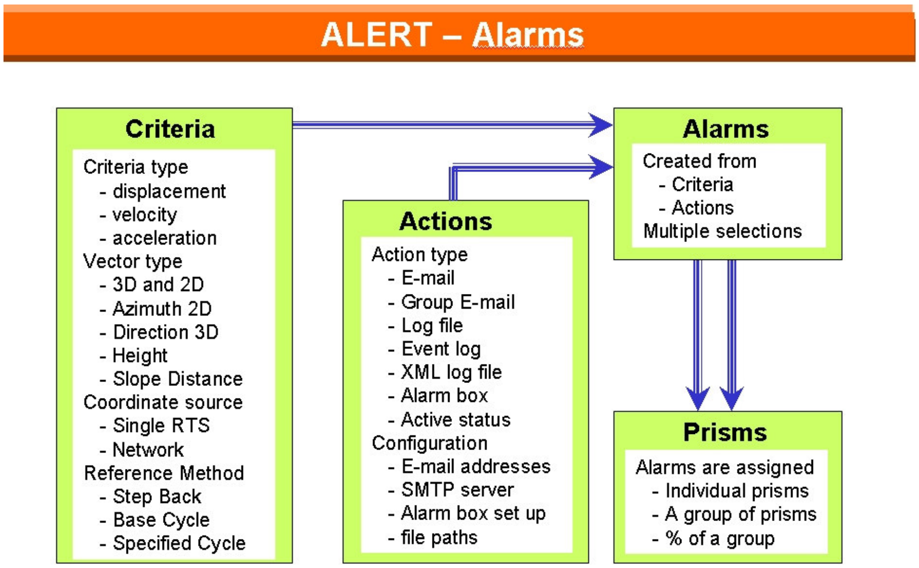

Figure 3: Flow for creating an alarm

ALERT is completely autonomous with several self-recovery features that are critical for the automated monitoring projects. The computers that run ALERT are configured to automatically reboot if power is lost, allowing a backup service to complete any interrupted data collection tasks

A very unique feature of the ALERT software is its automated handling of multiple-RTS networking. Observations between RTSs, common control points, and multiple shots to object prisms can all be combined automatically to obtain one overall network solution. This takes advantage of the redundant information and gives a more accurate and reliable result. Due to the configuration defects in this type of RTS network, the processing of this data requires a special least squares algorithm that adjusts observation differences with respect to a user defined reference epoch. The results of the network adjustment are further processed using iterative weighted similarity transformation of displacements to identify unstable reference points (Chen et al. 1990) and remove their effect.

The result of data processing is a series of time-tagged coordinate values that are stored in the project database. Plotting utilities allow rapid visualization of displacement and velocity trends as well as vector plots of displacements and velocities with their confidence regions. To increase the accuracy of the results, observation cycles may be grouped into mean values over a selected period of time to minimize, for example, the cyclic effects of atmospheric refraction. The database is in a readily accessible format, therefore, the end user can easily extract coordinate values using standard Structured Query Language (SQL) queries and build plotting and analysis tools to meet specialized needs. The storage of coordinate solutions in a relational database makes it very easy to selectively examine subsets of the data

4. Enhancement of GPS Applications

Implementing GPS for deformation monitoring poses difficult 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. Some of the challenges faced in designing a system that meets deformation monitoring needs include (Bond et al. 2007a):

– Satellite Visibility: In deformation monitoring environments where there are obstructions hindering satellite visibility (e.g., dams, open pit mines, buildings), dilution of precision values rise due to the degradation in satellite geometry. The system must be able to cope with periods of the day during which there are too few satellites visible to provide a high enough quality solution to meet project requirements.

- Residual Tropospheric Delay: In deformation monitoring environments where there are significant changes in elevation (e.g., open pit mines, volcanoes), residual tropospheric delay can cause significant positioning biases, especially in height. The differential troposphere causes a 3 to 5 mm relative height error for every millimeter difference in zenith delay between stations (Beutler et al. 1988). Residual tropospheric delay must be accounted for if the desired precision is to be achieved.
- Multipath: In deformation monitoring environments where multipath sources are abundant (e.g., building structures, vehicles) multipath can contaminate the position solutions. Practically every observation site is affected to some degree by multipath. Multipath biases can reach up to $\lambda/4 \approx 4.8$ cm for the original L1 carrier-phase measurement (Leick 1994).
- Providing On-time Information: Deformation monitoring poses a unique GPS scenario; the points of interest are neither quite static nor kinematic because there is motion but it is usually very small. In providing GPS position updates, it cannot be assumed that the antenna's position at an epoch agrees with that of a prior epoch. One way to handle this is to model the motion as static and to add process noise.

4.1 PPMS Software

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 (TD: differencing consecutive double-differenced observations) carrier phases. Test results have indicated that the software is capable of detecting millimeter 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 (DD: differencing between receivers followed by differencing between satellites or vice versa) processing methods. The trade-off in using the TD approach is a longer convergence time than for DD methods. This is generally not a concern, however, for deformation monitoring applications where long term structural behaviour is of interest.

The TD approach can be considered an extension of the observation difference, least squares approach used for processing deformation monitoring data (Wilkins et al., 2003). The attractiveness of the TD observation is that it is a time difference of DD observations and consequently any biases common to both observations will be highly correlated and therefore significantly reduced. This strategy has some important benefits:

- the user no longer needs to solve for the ambiguity term, which allows the system to be more robust;
- for observation intervals less than a few seconds, the correlation between atmospheric parameters between consecutive epochs will be large and therefore, biases originating from them will be significantly reduced. This is useful for mitigating residual tropospheric delay biases over large height differences; and
- for observation intervals less than a few seconds, the correlation in the low frequency component of multipath terms between consecutive epochs will be large and therefore biases originating from them will be significantly reduced. The high frequency component still remains.

The effectiveness of the software is illustrated by comparing solutions obtained using traditional, DD processing techniques employed by commercial software with those obtained using PPMS. Figure 4 presents the up component solutions (generally the poorest precision) of a GPS baseline observed in an open pit environment. The height difference between master and rover stations is 361 meters. It can be seen that a peak-to-peak spread of just over 4 cm exists. Figure 5 presents the east, north and up components of the same baseline processed using PPMS. There is a height change of a few mm that is detected after hour 50, which is not so easily identified in Figure 4. The peak-to-peak spread of the up component in Figure 5 is in the order of 1 cm after the change in height.

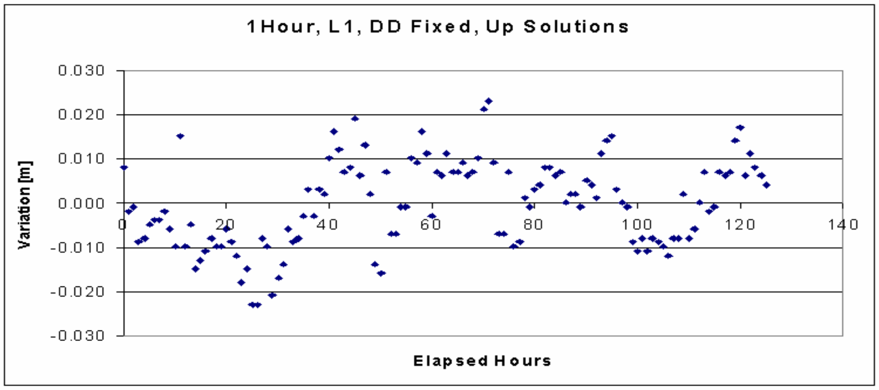

Figure 4: Commercial, 1 Hour, DD Fixed, 'Up' Component Solutions

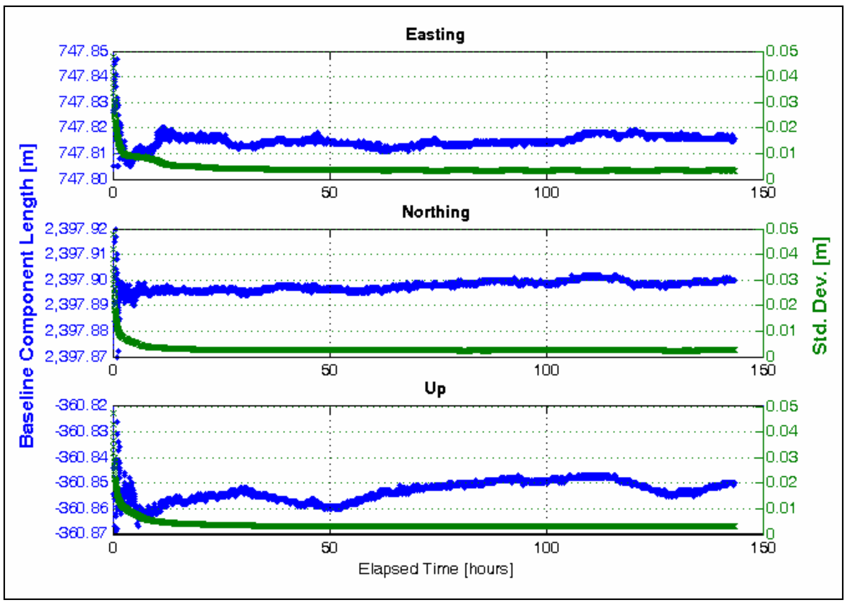

Figure 5: Continuous, TD, east, north, up solutions using PPMS

4.2 Augmentation of GPS with Pseudolites

GPS data obtained from a large open pit mine indicated that there were several periods during the day for which fewer than 4 satellites were visible. This leads to degradation in the precision of the solutions as well as a reduction in the frequency of updates. Consequently, the potential of augmenting GPS with pseudolites (PLs) has been investigated to improve the frequency and precision of solutions (Bond et al. 2007b).

Being a ground-based transmitter, PL error sources must be handled differently than GPS signal error sources. PPMS was modified to address nuances in PL data processing which include cycle slip detection, PL location determination and PL observation modelling. Figure 6 illustrates the results of a baseline that was observed in a harsh environment (having a 40 degree elevation cut-off) while using a PL.

A slow, 15 mm displacement occurs in the horizontal plane beginning at hour 14 and ending at hour 20. It takes approximately 10 hours for the solution to converge. It can be seen that the combined GPS+PL system allows at least some of the displacement to be detected whereas the results from standalone GPS are inconclusive.

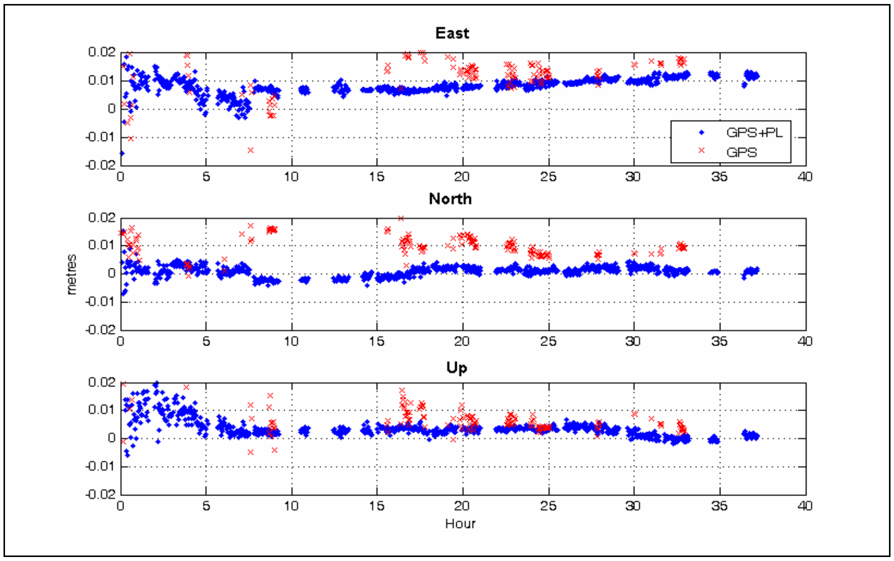

Figure 6: GPS+PL results in a harsh environment

5. Integrated Analysis and Physical Interpretation of Deformations

Analysis of deformations of any type of deformable body includes geometrical analysis and physical interpretation. Geometrical analysis describes the change in shape and dimensions of the monitored object, as well as its rigid body movements (translations and rotations). The ultimate goal of a geometrical analysis is to determine the displacement and strain fields in the space and time domains for the whole deformable object. The *Generalized Method of Geometrical Deformation Analysis* (Chen 1983; Chrzanowski et al., 1983) allows for a simultaneous analysis of any type of observations (geodetic and geotechnical) even if scattered in space and time. The displacement field is obtained by iterative least squares fitting of an appropriate displacement function to the measured deformation quantities. Examples are given in (Chrzanowski, 1993).

Physical interpretation is based on establishing the relationship between causative factors (loads) and deformations. This can be determined either by:

- A statistical method, which analyses the correlation between the observed deformations and loads; or by
- A deterministic method, which utilises the loads, properties of the material, and physical laws governing the stress-strain relationship.

By comparing the geometrical model of deformations with the deformations obtained from the deterministic model, one can determine the actual deformation mechanism (Chrzanowski et al., 1994) and/or verify the designed geomechanical parameters (e.g., Chrzanowski et al, 2002). Integrated analysis may also explain the causes of deformation in the case of abnormal behaviour of the investigated object. Thus, the role of monitoring surveys is much broader than serving only as a warning system.

The ultimate goal of deterministic modeling of deformations is to develop a prediction model. The model is developed for the given geometry, loading conditions, boundary conditions, and specific behaviour and properties of the material. Once a prediction model is developed, it may be used for the design of a monitoring scheme.

Deterministic analysis of deformation is based upon continuum mechanics, in which solving differential equations of equilibrium of forces is the main problem. In many cases closed form solutions of the equations may be difficult or impossible to obtain. Consequently, numerical methods, such as the finite element method (FEM) are used. The basic concept of the finite element method (displacement approach) is that the continuum of the deformable body is replaced by an assembly of individual small elements of finite dimensions, which are connected together only at the nodal points of the elements (Zienkiewicz and Taylor, 1989). The elements may be of any shape, but usually three or four nodal elements are chosen for two-dimensional analysis. For each element, one can establish the relationship between the nodal loads and displacement or strain field variables. The displacements are calculated using the equilibrium equation:

$$Kd = r - f^{b} + f^{\sigma_0} + f^{\varepsilon_0} \quad (2)$$

Where:

d	is the vector of nodal displacements
K	is the total stiffness matrix
r	is the vector of external forces concentrated at nodal points
f^{b}	is the loading vector of body forces
f^{σ_0}	is the vector from initial stresses
f^{ε_0}	is the loading vector from initial strains

The global matrices and vectors are calculated through a superimposition of local (at each element or at each node of the FEM mesh) matrices K_e and vectors r_e, f_e^{b}, $f_e^{\sigma_0}$, $f_e^{\varepsilon_0}$

The stiffness matrix for an element in two dimensions is given as:

$$K_e = \iint B_e^T D B_e t dx dy \quad (3)$$

Where:

B_e	is the matrix relating strains in the element to its nodal displacements
D	is the constitutive matrix of the material which in the case of linear-elastic material contains Young modulus and Poisson ratio
t	is the unit thickness of the elements

Since the total stiffness matrix K is singular, boundary conditions must be applied in order to solve equation (2) for the displacements.

The most critical problem in modeling and predicting deformations, particularly in rock or soil material, is to obtain in-situ characteristics of the materials. The difficulty in determining material characteristics is the main cause of uncertainty in deterministic modeling of deformations. The process of collecting samples to determine in-situ characteristics is very difficult and very costly. Often the data is incomplete. Additionally, this process has the following limitations:

- it is impossible that the selected samples will represent the true characteristics in all locations;
- the samples may be disturbed during the collection process; and
- laboratory loading conditions may differ from natural conditions.

Results of properly designed monitoring schemes may be used to enhance the deterministic model (e.g. by correcting the material parameters of the observed object). This can be achieved using forward or back analysis (Chrzanowski et al. 1994). In turn, the enhanced deterministic model may be used in improving the monitoring scheme.

Recent research at CCGE has demonstrated how to successfully incorporate deterministic modelling and monitoring in the analysis of engineered and natural structures. In particular, research was implemented in ground subsidence studies caused by mining activity (Chrzanowski and Szostak-Chrzanowski, 2004) and in modeling deformations of large earth and rock filled dams (Szostak-Chrzanowski et al., 2005). In these projects, a "large-scale" approach has been used. This approach is characterized by an introduction of a concept of equivalent (averaged) material properties. The investigared object is treated as a homogeneous or is treated as being built of blocks in case of discontinuities of the material. The approach to modeling rock deformations is supported by a method known as the S-C method (Szostak-Chrzanowski et al., 2005). The method was developed to model the behaviour of brittle and evaporate rock material. In the case of brittle rock, it is modeled as a non-tensional material. Evaporates (e.g. salt rock), which have characteristics of viscous material, are modeled as a non-Newtonian liquid. The behaviour of the soil material, for instance in modeling behaviour of earth-filled dams, may be determined by using a non-linear hyperbolic model of the stress-strain relation developed by Kondner (1963).

6. Conclusions

Significant progress has been made at the CCGE in the development of fully automated monitoring systems and in the deterministic design and analysis of deformation surveys. The effects of changeable atmospheric conditions on geodetic measurements and the effects of improper calibration and poor reliability of in-situ geotechnical/structural instrumentation still remain as the main problems of current monitoring systems. Further research must be devoted to the development of integrated monitoring systems in which the two types of measurements complement each other to increase the reliability. Geodetic engineers should become acquainted with principles of continuum mechanics. They should utilize deterministic modeling of deformations in order to make sound decisions regarding the design and analysis of monitoring surveys.

Acknowledgements

The research reviewed in this paper has been supported by the Natural Sciences Research Council of Canada, Atlantic Canada Opportunities Agency, and the Canadian Wireless Telecommunications Association.

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