DEFORMATION MONITORING SURVEYS – OLD PROBLEMS AND NEW SOLUTIONS

Adam Chrzanowski, Anna Szostak-Chrzanowski

Canadian Centre for Geodetic Engineering, University of New Brunswick, Canada

ABSTRACT

Growing need for fully automated and continuous monitoring of structural and ground deformations creates new challenges for the design and analysis of monitoring schemes in which multi-sensor systems start playing a dominating role. At the same time, old problems of effects of atmospheric refraction and identification of unstable reference points still remain valid. On the other hand, rapid progress in deterministic modeling of deformation makes the design and integrated analysis of the multi-sensor monitoring surveys easier and more efficient than in the past. Through the combination of deterministic modeling with the results of monitoring surveys, a better understanding of the behaviour of deformable objects is achieved. Examples are given from monitoring large dams and open pit mines.

Key words: deformation monitoring, integrated deformation analysis, deterministic modelling, robotic total stations, GPS, design of monitoring schemes

1. INTRODUCTION

Rapid progress in the development of new technologies for monitoring structural and ground deformations has significantly increased the assortment of geodetic and geotechnical instruments being available for the automated monitoring schemes. This puts new demands on the design and analysis of the multi-sensor systems. Full automation, multi-sensor integration, continuous data collection, integrated analysis and physical interpretation, enhanced accuracy and reliability are key issues in the development of such systems. In order to make intelligent decisions on the selection of the optimal combination of the sensors, their optimal location and density, the design must be based not only on the geometrical strength and sensitivity of the monitoring network, but also on a good understanding of the physical process which leads to deformation. For example, the location of the sensors or the observed targets must include points where maximum or critical deformations are expected (Chrzanowski, 1993) while the location of reference stable points must be based on the knowledge of the boundaries of the deformation zone. Thus, the investigated deformable object must 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 physical characteristics of the object under investigation to be included in both the design and analysis of the deformation. This is achieved by using deterministic modelling of the load-deformation relationship using e.g., the finite element method (FEM).
A brief review of new solutions and developments are given in this presentation focusing on recent advances in automation, use of deterministic modeling in the design, and integrated analysis of multi-sensor monitoring schemes.

2. DESIGN OF MONITORING SCHEMES

2.1 Design Criteria

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 deformable objects (e.g. bridges, dams, nuclear power stations, open pit mines) require sub-centimetre or even millimetre level accuracy.

The design 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. Examples of the use of deterministic modeling in the design of monitoring schemes are given in Section 4.

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 TM30). If needed, GPS can be augmented with pseudolites and/or other satellite positioning systems. Other, comparatively new, geodetic techniques include laser scanners and interferometric synthetic aperture radar (InSAR). They have, however, many limitations and restrictions, which still require further research and enhancements. For example, the satellite borne InSAR provides repeated radar images only every several days, even with the newest generation of SAR satellites (Xiaobing et

al.2009). The recently developed ground based InSAR technology (e.g., Pieraccini et al., 2006) promises significant improvement in continuous monitoring of steep slopes and embankments.

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. All geodetic techniques are affected by the old problem of atmospheric refraction and tropospheric delay, as discussed later on.

There is a multitude of geotechnical instruments equipped with electro-mechanical transducers (Dunnicliff, 1988) that may be easily 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). New developments in fiber optics distributed strainmeters and new types of tiltmeters and acceletometers (Danish et al. 2008) based on the micro electro-mechanical systems (MEMS) provide new tools for deformation monitoring at a much lower cost.

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).

2.3 Challenges of Geodetic Monitoring Systems

2.3.1 Effects of Atmospheric Refraction

All 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;**
> **in the case of electromagnetic distance measurements and InSAR, 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).**

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):

$$e = \frac{3.9Ps^2 10^{-5}}{T^2} \frac{dT}{dL} \qquad (1)$$

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°C, over a 1000 m sight length, a uniform change in the temperature gradient from night-time 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 as much as 2^{0}C/m between night-time and daytime observations. Fig. 1 shows diurnal changes of 'displacements' at a distance of 391m with a line of sight being about one metre above ground along the edge of an open pit mine (a clear day at elevation of 3000 m).
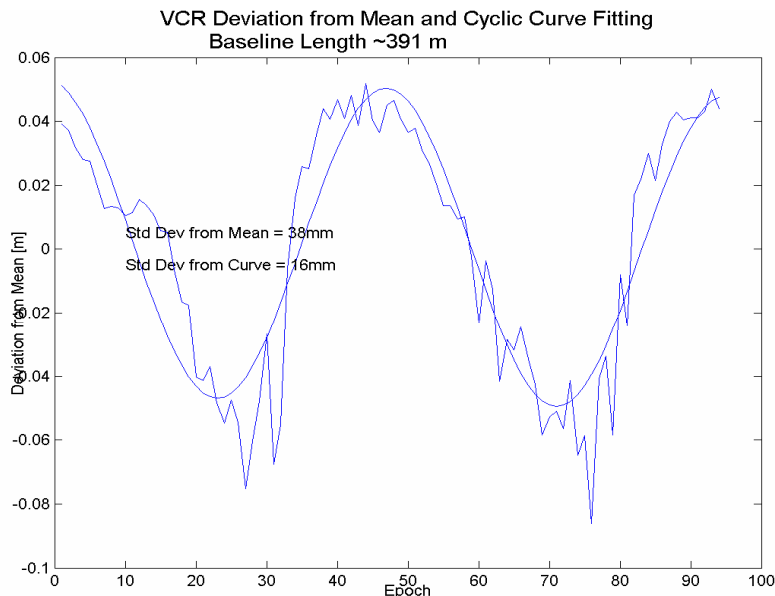

Fig. 1. Diurnal changes of refraction effects (36 hours).

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 diurnal, cyclic effects of refraction can be significantly minimized by daily averaging of the monitoring results if the observation scheme includes continuous or very frequent (several cycles of observations per day) observations distributed evenly over 24 hours. 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°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 Challenges in GPS

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 even 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.

<u>Multipath</u>: 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).

<u>Providing On-time Information</u>: 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.

2.3.3 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 (Chen et al., 1990) at the Canadian Centre for Geodetic Engineering (CCGE) 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. IWST has been incorporated in ALERT-DDS software (see below) software suite for fully automatic monitoring and analysis of displacements.

3. FULLY AUTOMATED MONITORING SYSTEMS

3.1 ALERT Deformation Detection System (ALERT-DDS)

ALERT-DDS, developed at CCGE, is an example of a fully automated monitoring system. Stemming from an earlier developed software package DIMONS (Lutes et al., 2001), the ALERT-DDS system has been commercialized and deployed world-wide in monitoring large earth dams and dikes, large open pit mines, and ground subsidence in mining areas and oil fields.

The current version of ALERT-DDS supports applications of any models of geodetic robotic total stations (RTS) with automatic target recognition (e.g. Leica TM30) as a stand alone system. The system is being continuously expanded by adding various sensors to provide a versatile multi-sensor integrated monitoring system, the concept developed at CCGE. Two very unique features of ALERT-DDS, which are not included in other

commercial software packages for fully automated monitoring with RTSs, require a special attention:

(1) the fully automatic identification of unstable reference stations using the Iterative Weighted Similarity Transformation (IWST) of displacements (Chen et al. 1990), and

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

The underlying structure of ALERT-DDS is a large, specifically designed Microsoft Access database (DB). Each ALERT project has its own DB which holds all the project information including collected data, processed data, cycles, survey settings, and much more (Lutes, 2002). The 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-DDS 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 Windows NT 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. The modular design of ALERT-DDS provides many options in designing the computer networking and communication systems for their monitoring program. The most recommended option is to install computers at each of the RTS sites to provide a fully autonomous data collection system, while an office computer is configured to transfer data from the remote sites via wireless networking. In this scenario, if communication is lost, the system will continue to collect data on schedule and all available cycles are automatically transferred when the network link is restored. Fig. 2 shows a typical configuration of ALERT-DDS.
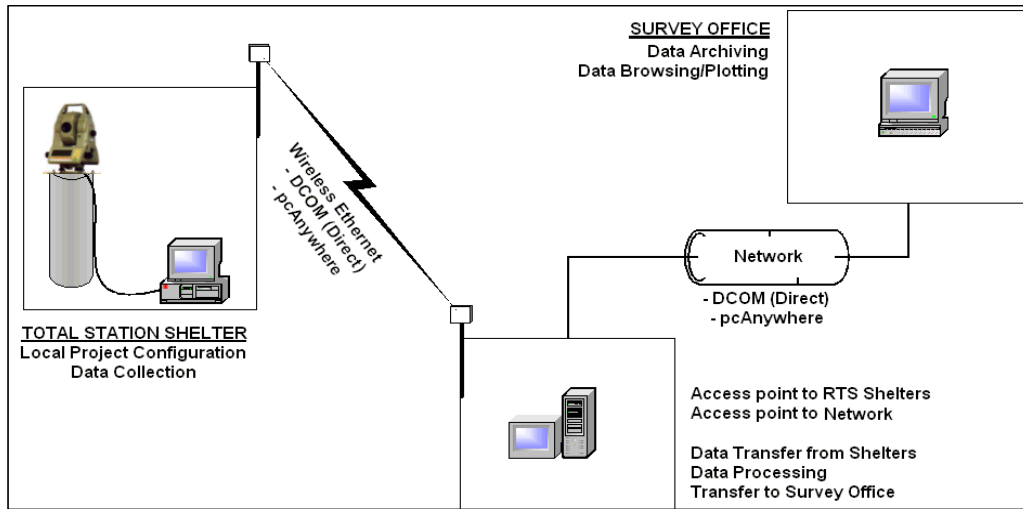
Fig. 2. Typical configuration of ALERT-DDS.

Rigorous geodetic observing and quality control protocols are adhered to. All target points are observed in multiple (pre-selected number) sets. The raw directions, zenith angles, and distances collected by the RTS are corrected for instrument and target offsets. The raw distances are corrected for meteorological conditions. The sets are combined using a rigorous least squares station adjustment, followed by data reduction algorithms employing least squares adjustments to screen blunders from the data set.

An alarm system has been incorporated into the ALERT-DDS 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.

In long term stationary applications, the RTSs are placed in shelters with glass windows. Fig. 3 shows a typical shelter at Diamond Valley Lake project (Duffy et al., 2001) in California where 8 RTSs supported by ALERT-DDS software continuously observe 3 large dams since October 2000. Fig. 4 shows a typical shelter at a copper open pit mine in Western Canada.
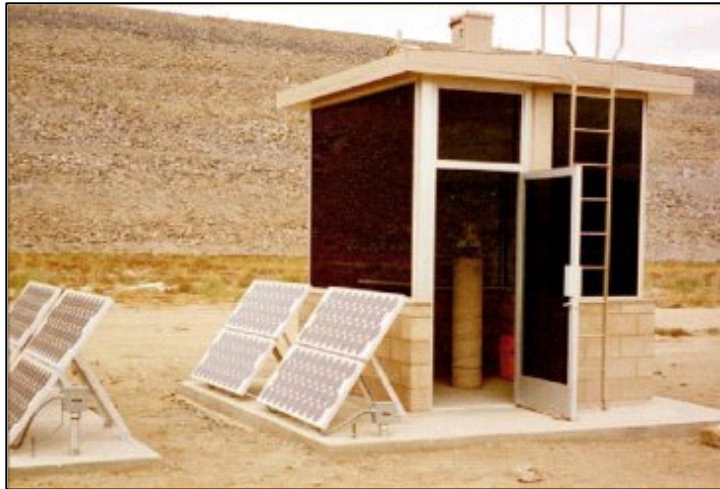
Fig. 3. RTS Shelter of ALERT-DDS system at a large dam.

Fig. 4. Observing shelter at an open pit mine.

A very unique feature of the ALERT-DDS 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 (sighting through glass windows, eccentricities of prisms vs. RTS, etc.) 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 the aforementioned iterative weighted similarity transformation (IWST) to remove the effect of unstable reference stations. The effect of rigid-body translations or rotations of unstable reference stations are automatically removed from the displacements determined on the investigated object, and the resultant datum-free displacements for the reference

points are assessed in terms of their significance. **Figure 5** shows the flow of the data processing.
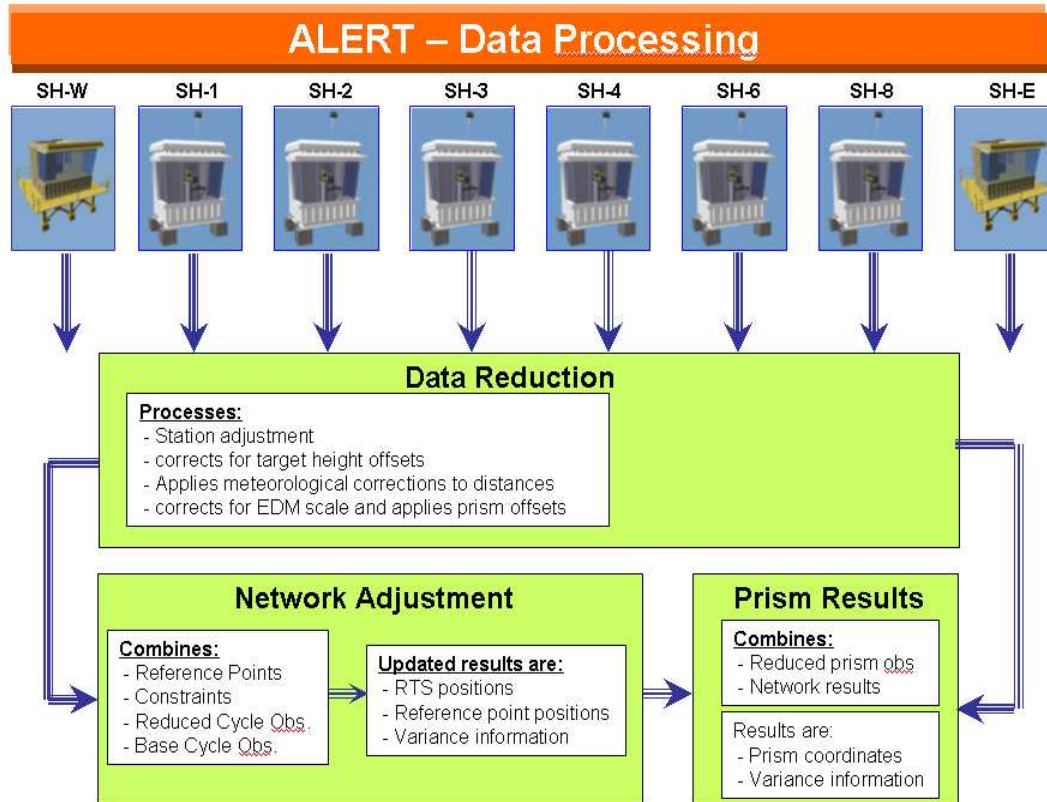

Fig. 5. Data processing flow.

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.

3.2 ALERT-DDS/SCAN Software

Some objects are difficult to access to place prisms for the use of RTSs. In this case, one may use reflector-less total stations to determine changes in shape of the object by profiling (scanning) the walls of the object (Fig. 6) with a dense grid of repeated measurements. Gairns (2005) developed a semi-automatic SCAN software for semi-automatic scanning using laser reflector-less RTSs (e.g. Leica TCRA 1201). Large objects, for example oil tanks, may require several set-ups of RTSs around the object in order to determine the behaviour of the whole object. The set-up points create a network of control points as shown in Fig. 7. To automate the process of scanning, the ALERT-DDS has been interfaced with the SCAN software creating ALERT-DDS/SCAN system. A module of the ALERT-DDS system is used to perform the measurements to the control points (which are targeted)

surrounding the object and the SCAN module is used to perform measurements to the tank surface (no target prisms). Data collected from both sources are combined and processed through existing ALERT-DDS adjustment module to provide adjustment of the network and coordinates for all observed points. These can then be examined and analyzed to derive information about the structural integrity.
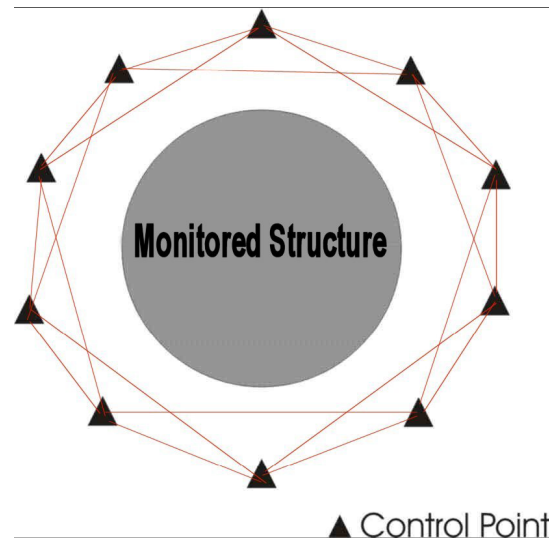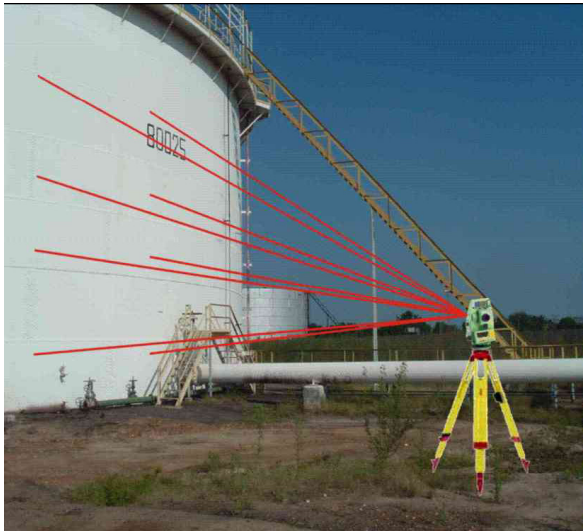

Fig. 6. 'Scanning' of oil tank with reflector-less Total station.

Fig. 7. Control network.

3.3 Precise Position Monitoring (PPM) Software for Automated GPS Monitoring System

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 (PPM) (Bond et al., 2007). PPM 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 PPM 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 in the ALERT-DDS.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 PPM. Fig. 8 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. Fig. 9 presents the east, north and up components of the same baseline processed using PPM. There is a height change of a few mm that is detected after hour 50, which is not so easily identified in Fig. 8. The peak-to-peak spread of the Up component in Fig. 9 is in the order of 1 cm after the change in height.
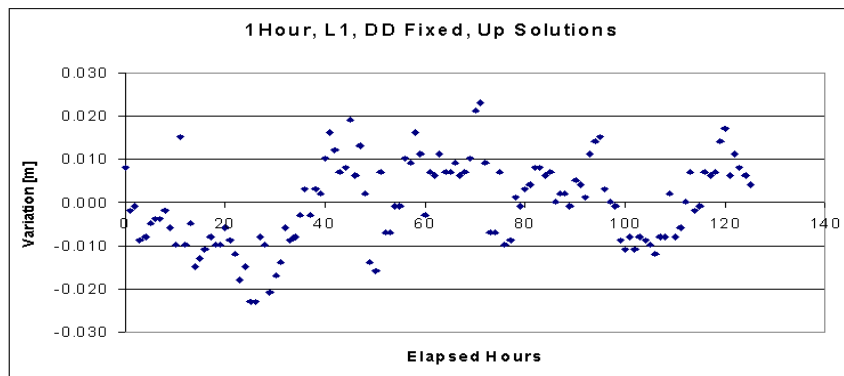

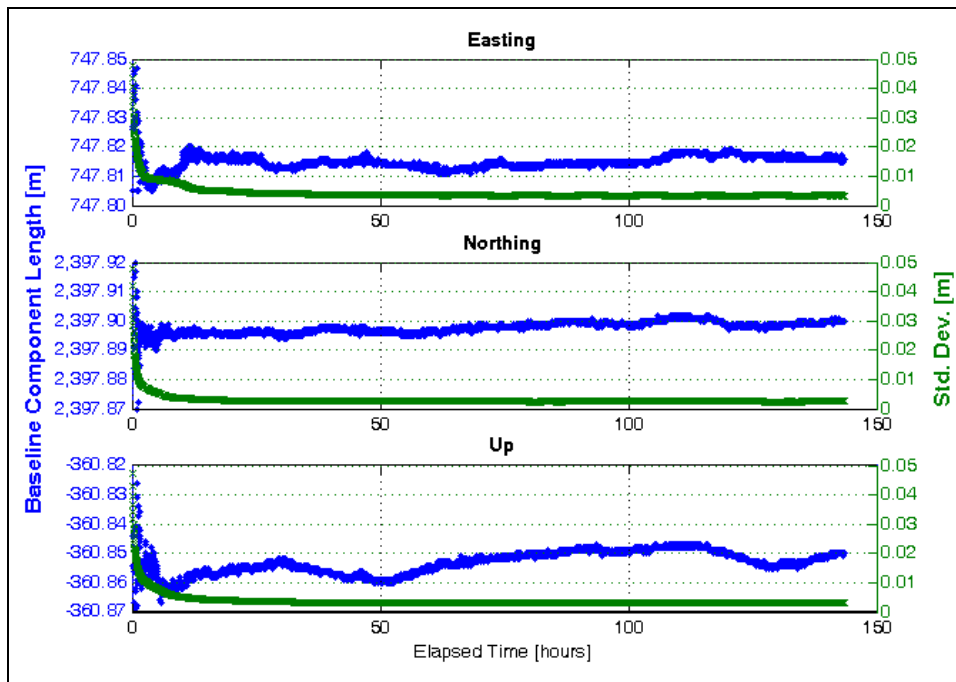Fig. 8. Commercial, 1 Hour, DD Fixed, 'Up' Component Solutions.

Fig. 9. Continuous, TD, east, north, up solutions using PPMS.

4. USE OF DETERMINISTIC MODELING IN THE DESIGN OF MONITORING SCHEMES

4.1 Open Pit Mine

Finite element method (FEM) was applied to the analysis of an open pit mine to predict the displacement fields at various stages of mining sequence. The predicted displacement field delineates the deformation zone so that suitable locations for stable reference points can be chosen; supplies information about sensor placement to capture displacements of interest; and provides information for predicting global deformation. The actual values of the displacements may significantly vary from one open pit mine to another.

Determinstic modeling of an open pit mine (Fig.10) of a 2 km diametre at the surface was performed to calculate effects of enlarging the mine from the existing depth of 600 m to the depth of 650 m by extracting the left wall and the bottom. The main purpose of the analysis was to estimate the magnitude of the expected deformations and localize stable area for placing the reference points for geodetic monitoring surveys. FEM analysis of the expected deformations was performed for various stages of the mining sequence and various homogeneity of the rock mass (with and without faults). Figure 10 shows expected accumulated displacements for the simplest model of the homogenous rock strata. The maximum displacements (uplifts) of up to 40 cm are expected to occur at the bottom of the pit. The effects of mining reach several kilometres beyond the rim of the mine with 5 mm displacements still possible at a distance of 4 km to the left of the extracted wall and 2 km beyond the rim at the right hand side of the mine.
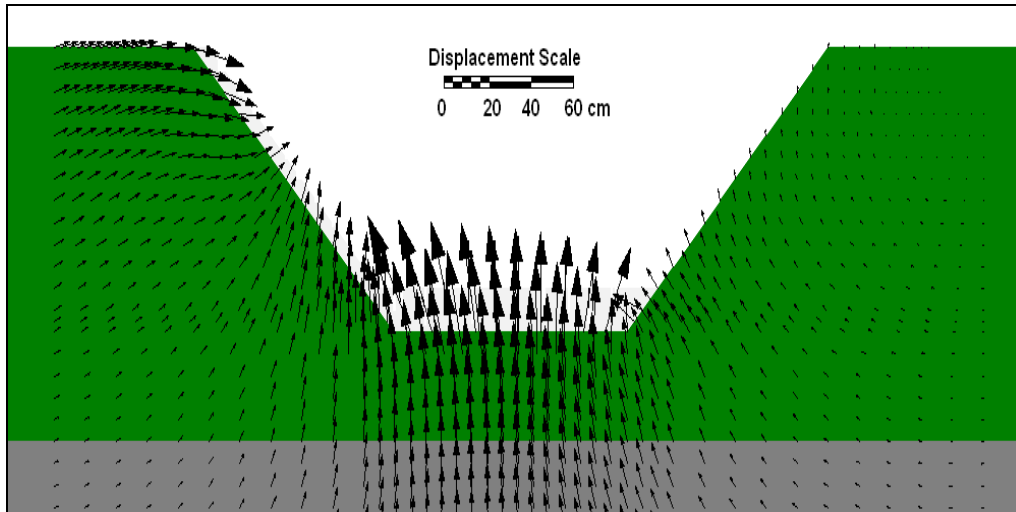
Fig. 10. Cumulative Displacement Field after all Excavations.

Figure 11 shows schematically the proposed monitoring scheme for the above case. The scheme would include RTSs placed on the right wall that would be connected to stable reference points by GPS. Since the RTSs are located within the deformation zone, their positions (coordinates) would be automaticly updated by GPS using the discussed earlier ALERT-DDS and PPM software suites.
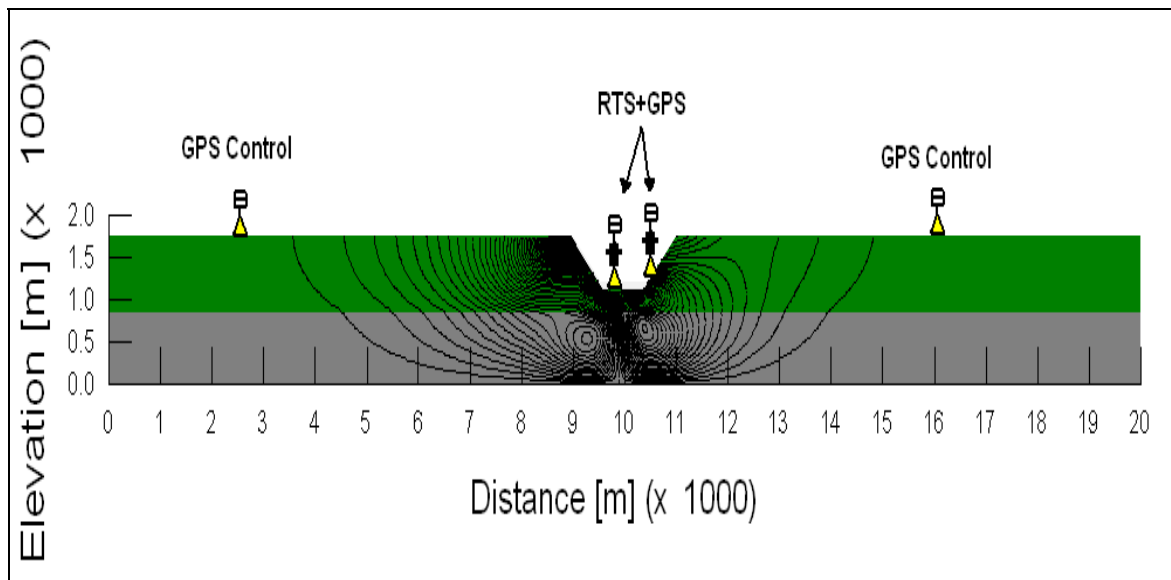

Fig. 11. A Geodetic Deformation Monitoring Scheme based upon deterministic modelling.

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

geodetic monitoring results can be used to locate fault zones. For example, if a monitored point shows stable behaviour in a region thought to be active, this may suggest that a fault exists somewhere between the monitored target and the area of mining activity. Both the FEM results and actual measurement values should therefore be used to complement each other in the overall physical interpretation process.

4.2 Concrete Face Rockfill Dam

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. 12 shows expected horizontal and vertical displacements caused by filling the reservoir (Szostak-Chrzanowski and Massiera, 2006).
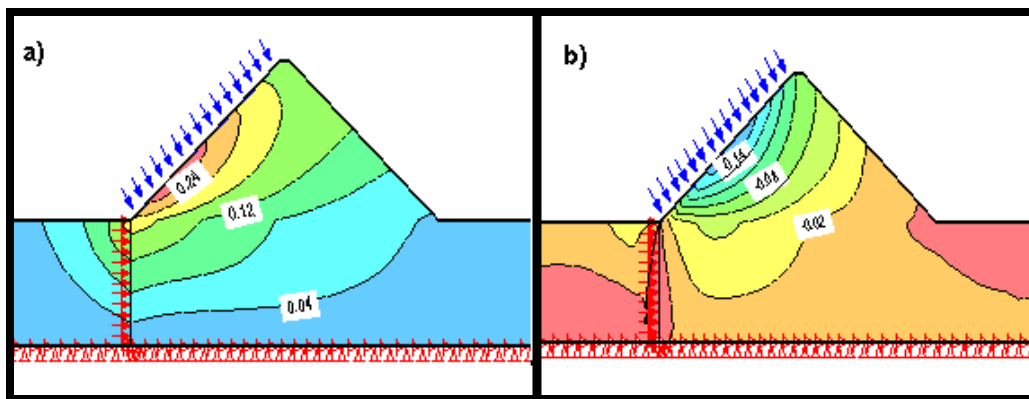

Fig. 12. Predicted displacements [m] after filling the reservoir a) horizontal b) vertical.

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, RTSs 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 (velocities) of deformations. This information will aid in determining the required frequency of repeat surveys.

**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).

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.

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 modeling 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 investigated 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 AND RECOMMENDATIONS FOR FURTHER RESEARCH

Significant progress has been made 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 various types of geodetic and geotechnical 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.

The research at CCGE continues in the development of new methods and techniques for integrated monitoring and integrated analysis of structural and ground deformations. The long term objective of the research is to consolidate and integrate previous and new research results to develop a generalized Integrated System (IS) for the detection and physical interpretation of deformations of any type of deformable objects subjected to any type of causative factors (loads). The diagram (Fig. 13) below shows major components of IS and their interaction.
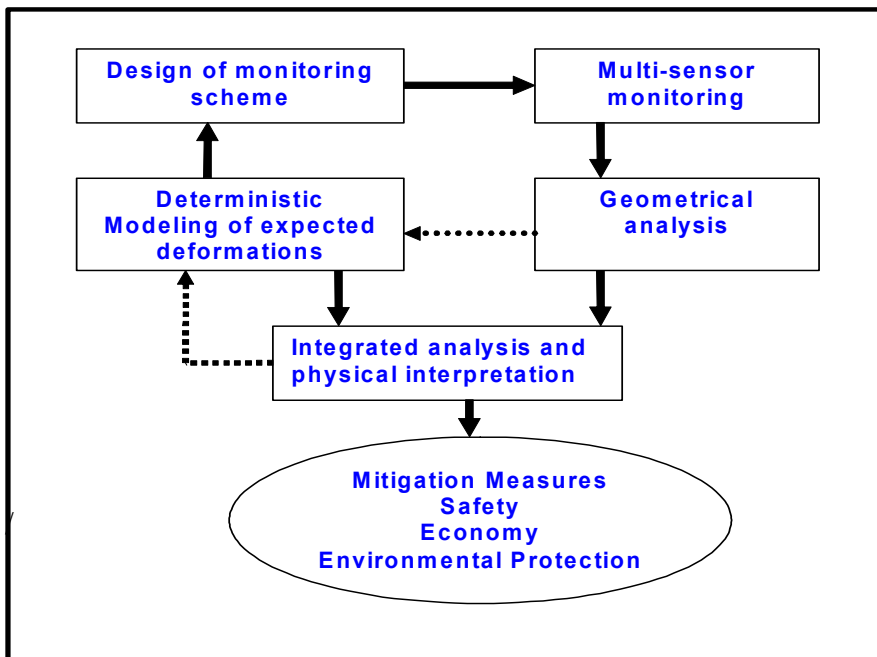

Fig. 13. Concept of generalized Integrated System.

Each major component contains several processes. For example, Geometrical Analysis includes: determination of displacement and strain fields from integrated monitoring results; identification of unstable reference points; and evaluation of accuracy and reliability of monitoring results. Each process poses various problems to be solved.

Due to the continuous advancements in the development of new monitoring technologies and development of new applications, the Integrated System will require continuous enhancements and modifications over many years to come.

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