Paper presented at: CIM 2002, Vancouver, B.C
April 28 – May 1, 2002

A Precise, Reliable, and Fully Automatic Real Time Monitoring System for Steep Embankments

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Abstract

The stability of steep embankments is a major safety issue in open pit mining, highway passes, and earth filled dams. A failure in any one of these situations could mean a loss of very expensive equipment, a long term inconvenience, and more importantly, a loss of life. These possible catastrophes could be avoided by installing a reliable real time monitoring system. Robotic total stations (RTSs) give one possible cost effective solution to creating a near real time monitoring system. Repeated surveys at predetermined time intervals can automatically generate warnings if slope movements exceed a preset tolerance level. The variation in atmospheric refraction, combined with possible instabilities in reference targets, can make a monitoring system based on RTSs produce false alarms. A methodology has been developed at the Canadian Centre for Geodetic Engineering (CCGE) for reducing these systematic error effects. The methodology has been realized in the creation of a software package that has been successfully implemented at large earthen dams in California and at an open pit mine operation in British Columbia.

1. Introduction

A major concern involving any steep embankment is its stability. This is the case whether it is the side wall of an open pit mine, a steep slope next to a highway, or a man made structure like a dam or dike used to contain tailings or generate hydroelectric power. In general, for each case there is a slow movement of the formation before a failure actually occurs. With the advanced monitoring of a phenomenon's creep, particularly its acceleration, critical displacements can be detected before the object reaches its failure point.

The detection of possible failure areas allows remedial measures to be undertaken to mitigate the failure or at least allow the opportunity to evacuate equipment and personnel. The result is a much safer and more economical working environment, which in turn creates additional savings in liability premiums. However, an unreliable monitoring system can cause many false alarms, which in turn cause unwarranted and costly stoppages in production.

The goal of the Canadian Centre for Geodetic Engineering (CCGE) was to create a software package that would minimize the effect of these types of systematic errors, hence, reduce the number of false alarms. The recent advances in automated geodetic instrumentation, such as robotic total stations (RTSs), make it feasible to create a fully automatic monitoring system [Duffy et al., 2001]. Therefor the primary measurement devices for the system are RTSs combined with meteorological sensors, all interfaced to a computer using wireless communication links. The wireless links allow for remote installations, which when combined with the automated scheduler, creates a fully automated system. Neither the data collection nor processing activities require human intervention, with changes to the scheduler, data collection, and processing parameters performed from the administrator's office. The stand-alone RTS system becomes even more reliable with the inclusion of Global Positioning System (GPS) sensors.

The creation of a reliable system involves being able to resolve whether the computed displacements of object points are significant. The determination of a point's significance involves the propagation of both random and systematic errors. The random error contribution is very regular and predictable for geodetic observations and therefore does not pose any problem in determining its contribution to the significance testing of displacements. However, it is a completely different situation when considering the systematic errors.

Again, the systematic errors themselves are well understood, but the magnitudes and directions of these errors are very difficult to determine in practice. As an example, atmospheric refraction can change very dramatically throughout the day, creating a bias in displacement results computed at different times of the day. A false alarm could easily be generated when comparing displacements computed from afternoon observations with another series computed from night measurements.

Another systematic error that can easily bias the resultant displacement field is a movement of reference points between cycles. These reference points are relied on to be stable to provide a consistent datum to refer each cycle of displacements. If one or more reference points move between cycles, particularly the instrument itself, a biased displacement field is obtained that may produce a false alarm. This situation can be even more dramatic as it would manifest itself by showing whole blocks of object points moving when in reality they have been stable.

2. Refraction

Temperature gradients affect optical light rays by bending them, creating a curved line of sight, while the atmospheric conditions themselves retard the speed that light rays travel through the atmosphere. The temperature gradients have the largest impact on the angular measurements of horizontal directions and zenith angles, while the varying velocity of light affects only the distance measurements.

If the atmospheric temperature, barometric pressure, and relative humidity are measured, a velocity correction can be computed and applied to each distance. There are many models for computing the actual index of refraction, which defines the velocity correction, and the interested reader is referred to Rueger [1990] for more details. It is sufficient here to say that using this methodology measured distances can be corrected to their "true" values to within 1-2 parts per million (ppm) of scale. This corresponds to 1-2 mm for every kilometre of distance.

Unfortunately, the situation is not as simple when dealing with temperature gradients and their effect on angular measurements. The resultant vertical discrepancy (ΔZ) caused by a light ray passing through an area that is influenced by the vertical component of the temperature gradient $\left({dt}/{dz} \right)$ is given by the following equation [Blachut et al., 1979].

$$\Delta Z = \frac{8.0''}{\rho}\left[\frac{pS^2}{\left(273.15+t\right)^2}\right]\left[\frac{dt}{dz}\right] \tag{1}$$

where,

p	barometric pressure in millibars
S	sight distance in metres
t	atmospheric temperature in degrees Celsius
ρ	conversion from radians to arcseconds (i.e. 206264.8 "/radian)

As an example of the influence, in atmospheric conditions of 1013 mb, 20^{o}C, and 1000 m sight length, a temperature gradient of only 0.1^{o}C/m would cause more than a 4 cm discrepancy in the vertical position of the point.

In slope stability monitoring, it is common to encounter lines of sight that graze the side of an embankment, where the temperature gradient increases as one's line of sight approaches the surface. One can appreciate how a temperature gradient can change very rapidly with sun exposure, particularly between day and night. Areas that receive direct sunlight can produce temperature gradients of several degrees per metre that may fluctuate rapidly (i.e. scintillation). In contrast, the same area at night may have a very stable, slowly decreasing temperature gradient as it slowly releases heat into the atmosphere.

This can be seen very clearly in Figure 1, which illustrates the bias in the vertical displacement results for cycles that were observed in the afternoon and at night at a large water reservoir in California. In this case, if only comparisons between single cycles were relied upon for alarms, many false alarms would be generated. Therefore, cycle averaging is used to randomize the effects of systematic errors. The averaging of cycles that have been observed at different times of the day, in different conditions, improves the accuracy and reliability of the displacement determinations.

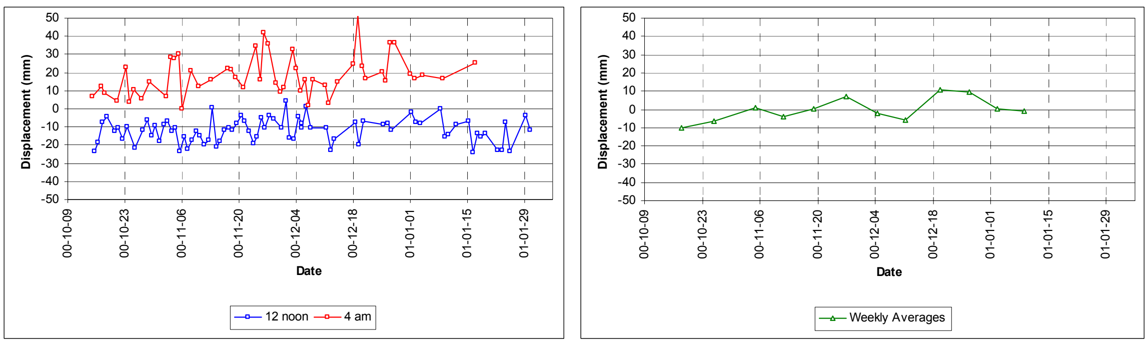

Figure 1. Comparison of time-of-day refraction effects and weekly averages.

3. Stable Point Analysis

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. The identification and removal of unstable reference points has been the focus of a great deal of research at the University of New Brunswick (UNB) since the early 1980s.

At UNB, a methodology utilizing an iterative weighted similarity transformation (IWST) was developed by Chen and Chrzanowski [Chen, 1983; Chen et al., 1990]. The techniques have been successfully applied in all types of engineering projects where reference point stability has been a concern (see Greening et al. [1993] and Chrzanowski et al. [1991]). An example of the UNB methodology used to determine the true displacement field at a concrete dam in the U.S.A. is illustrated here. Figure 2 shows the displacement field obtained when creating the datum using what were thought to be stable reference stations, versus the results utilizing the IWST to obtain the datum independent displacements. Clearly, those obtained from the IWST with the datum biases removed give a more complete picture of what is actually happening to the structure.

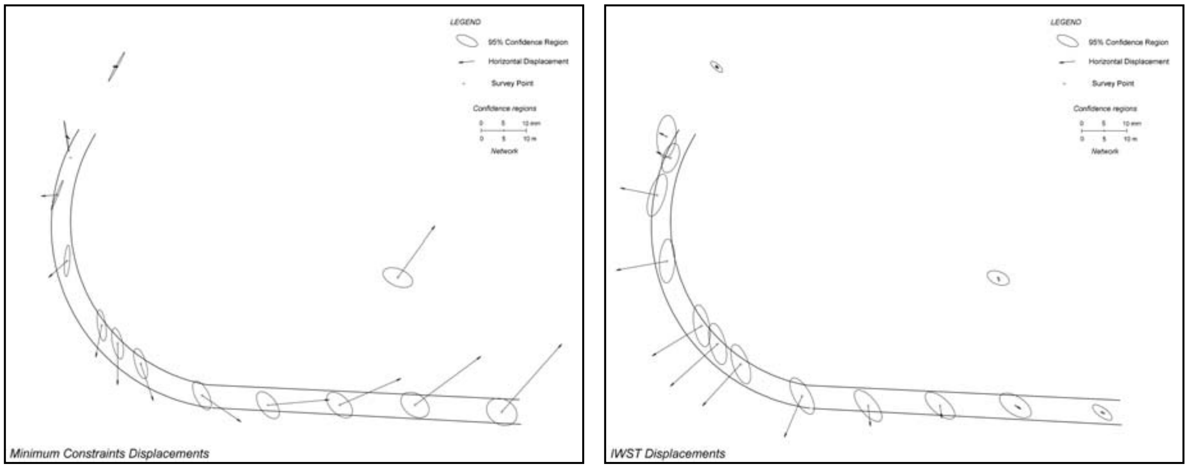

Figure 2. Use of IWST to remove effect of unstable reference points.

The methodology is based on using the stability of each of the reference points as a means of determining its contribution to removing the datum defects. It is an iterative process that computes the current iteration displacements based on the displacements from the previous iteration.

The following equation gives the relationship between the two sets of displacements [Chen et al., 1990].

$$d_{i+1} = (I - H(H^T P_w H)^{-1} H^T P_w) d_i \tag{2}$$

where,

d displacement vector for i and i+1 iterations
I identity matrix
H datum defect matrix
P_w displacement weight matrix

The more unstable a point is, clearly, the less influence it should have on the final datum definition, hence, final displacement results. This is accomplished by utilizing a weight matrix (P_w) that defines the relative weighting of each coordinate that is involved in removing the datum defects. The diagonal of the resultant matrix can be directly populated to reflect this relative weighting.

4. Multi-Sensor Capability

The use of multiple sensors improves the accuracy, and particularly the reliability, of the displacement results. Each RTS observes a distance, horizontal direction, and zenith angle and therefore is only able to uniquely determine the 3D position of each target point that is observed. This does not allow for any statistical analysis or verification of the results for each cycle. In these cases, it is not possible to separate bad pointings or refraction effects that are contained in one cycle from the actual movement of the object point.

When simply treating the observations from multiple RTSs independently the situation improves dramatically. For every object point that has multiple observations, it can be verified whether any computed displacement is similar for both sets of observations and whether they agree with the previous cycle results. Therefore, it creates a mechanism for identifying possible mispointings or refraction effects before a false alarm is activated.

However, the best situation occurs when observations from multiple RTSs are combined. This allows for a complete statistical analysis for the measurements from each cycle. Any blunders in the pointings, as well as an estimate for whether the precision of the observation set was as expected, will be identified. Small mispointing or refraction errors are reduced, as they are smoothed by the least squares process.

However, the largest improvement is in the determination of the horizontal displacements. The horizontal coordinates for a single RTS are a function of both the distance and the horizontal direction from that RTS. When multiple RTSs are combined, the horizontal coordinates become a function of the observed distances only, with the horizontal directions serving simply as a blunder detection tool. The advantage of this becomes quite apparent when looking at the small residual effect refraction has on distances compared to the large impact that it can have on directions (see Section 2 above). The result is horizontal coordinates that remain consistent to a few millimetres cycle to cycle and only change if the point actually moves beyond these amounts. Of course, this is based on the assumption that meteorological sensors are being used, allowing the distances to be corrected for atmospheric variations.

Unfortunately, unless the lines of sight are very steep the distances contribute very little to the elevation of the point. The elevations are therefore still primarily determined by the zenith angle measurement, which can be adversely influenced by refraction. The refraction effects on the zenith angles cannot be eliminated, but can be reduced by using multiple RTSs and reducing the sight lengths. However, the closer the RTSs are to the monitoring area, the greater the chance of having an unstable instrument location. In addition, the lines of sight distances to most reference targets would increase. This in turn would force the bulk of the inaccuracies to the reference target observations, which would reduce the confidence in being able to detect an unstable instrument, particularly in height.

A solution to this problem is to add additional sensor types to the analysis that are less dependent on sight lengths and atmospheric conditions. A GPS antenna could be mounted with each instrument that would allow the position of the instrument to be determined independently for each cycle. Each instrument position can be updated for each cycle, eliminating the need to observe multiple reference targets. The update would be with respect to a master station outside the zone of influence. For complete reliability, multiple master stations could be utilized. This would make it possible to verify the stability of the master stations by using the IWST methodology.

Another feasible approach for verifying stability, that uses fewer GPS receivers, would be to install some geotechnical or rock mechanics instrumentation to monitor the change in antenna position. The additional instrumentation could be used anywhere within the area of concern to help improve the reliability of the monitoring system.

5. Software Design Philosophy

CCGE has developed a comprehensive automated monitoring system [Lutes et al., 2001]. The ALERT software implements the methodology for deformation monitoring and analysis that is described in this paper. The system has continued to evolve, with features being added to improve accuracy, increase reliability, and address user needs as they are identified.

The software allows for a remote control and pre-programming of observations with RTSs and other sensors. It allows fully automatic reduction and processing of positioning surveys, automatic identification of unstable reference stations using the IWST, and automatic determination and graphical presentation of displacements of monitored points with their variance-covariance information.

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 (Figure 3 illustrates a typical configuration). 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.

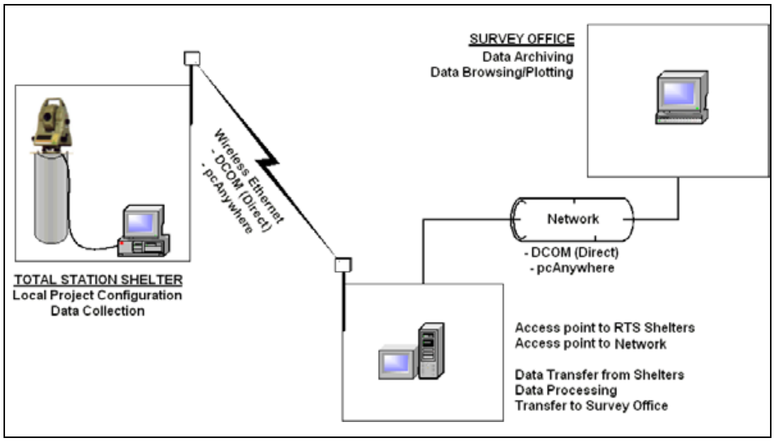

Figure 3. A typical computer network configuration for remote access.

Rigorous geodetic observing and quality control protocols are adhered to. All target points are observed in multiple sets of face left and face right RTS pointings. The raw directions, zenith angles, and distances collected by the RTS are corrected for atmospheric conditions and instrument and target offsets. 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.

Several network configuration options are supported. A single RTS may observe any number of reference and object points, with observations to subsets of points and multiple schedules possible. Several single-RTS networks may be controlled by a single computer, or by multiple computers with all data being automatically transmitted to a central facility for processing. To improve accuracy and enhance reliability, ALERT supports multiple-RTS configurations where targets are observed simultaneously by more than one instrument. In this type of configuration, many points may need more than a single target (see Figure 4) due to the angular pointing limitation of retro-reflectors ($\pm 20^{o}$). This of course creates some obvious configuration defects by defining one point with more than one physical location (i.e. each target can't occupy the same 3D space). The processing of this data requires a special least squares algorithm that adjusts observation differences with respect to a chosen reference epoch.

Figure 4. Dual-targetted points for multi-RTS observations create more than one physical location.

The displacements, derived with respect to a user-defined base cycle, are analyzed using the IWST. The effect of rigid-body translations or rotations are removed from the displacements, and the resultant datum-free displacements for the reference points are assessed in terms of their significance. If any reference points are found to have moved significantly, they are not used in the final calculation of coordinates.

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 trends and advanced trend analysis, such as grouping observation cycles into mean values to smooth the effects of daily refraction. Because the database is in a readily accessible format, 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.

A typical displacement visualization is a plot of the two-dimensional displacement vectors compared to the statistical confidence region (Figure 5). The confidence region describes the uncertainty of the point position, based on the acuracy of the RTS or other sensor observations. If a displacement vector does not exceed the bounds of the point's confidence region, it is considered insignificant, as it cannot be determined whether it is the result of an actual displacement or just observation error.

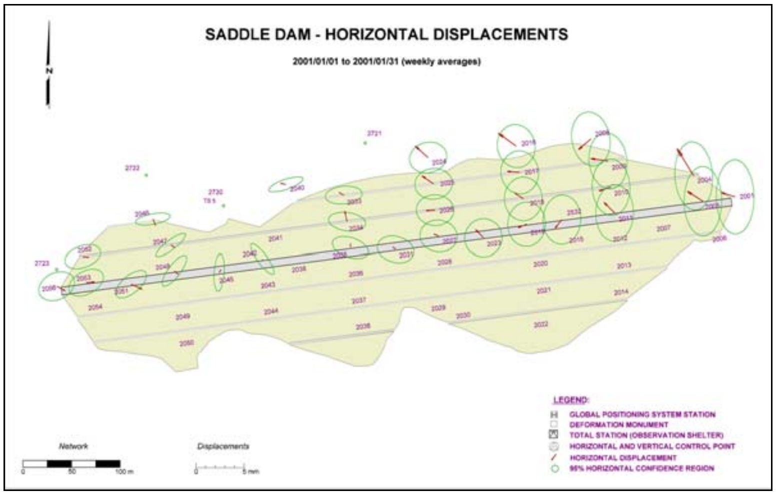

Figure 5. Displacement vector and confidence region plot.

The horizontal displacement plot is useful when the user wishes to examine displacement trends among groups of points. However, it can be helpful to examine the time series for a given point, to see the day-to-day repeatability of coordinate solutions and to determine if there is a systematic trend in the position differences. The storage of coordinate solutions in a relational database makes it very easy to selectively examine subsets of the data (e.g., Figure 1). SQL allows the user to specify virtually any criterion in order to choose the particular solution set desired.

6. Conclusions

The real time monitoring system developed by CCGE offers the possibility of fully automated reliable monitoring in remote areas. Once the system has been implemented, no human intervention is required to obtain displacement results. The observation gathering and processing can be scheduled to take place at preset intervals. Even if power failures occur, the system will automatically resume exactly where it left off without the loss of any data cycles.

The use of multiple sensors increases the accuracy, and more importantly the reliability of the system. Horizontal displacements are better determined, and redundant vertical observations, although not fool proof, increase the reliability of height determinations. The inclusion of GPS sensors allows the instruments to be located closer to the monitored area (shorter lines of sight), which creates a significant increase in the system's vertical reliability.

The inclusion of a variety of sensor types creates an extremely flexible monitoring system. GPS augmented with geotechnical sensors creates a very reliable method of maintaining instrument stabilities. If deemed beneficial, the geotechnical sensors could also be implemented as stand alone instruments. This would provide another means of increasing the monitoring scheme's reliability.

With these increases in reliability the number of false alarms will be dramatically reduced. Of course, one needs to err on the side of caution, but many unwarranted work stoppages can be eliminated.

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