Geotechnical Instrumentation NEWS

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John Dunnicliff

Introduction

This is the **fiftieth** episode of GIN. After this 'column', the episode has one topic only—deformation monitoring with robotic total stations.

GIN's 50th Birthday

How can we celebrate together? Some logistical difficulties there! But I have a few suggestions—see the box. Feedback welcome!

Suggestion	How To
Learn the delights of an English gin (not GIN!). *Plymouth Gin.* "The world's smoothest gin". Distilled in Plymouth, 30 miles from here and a few hundred yards from the departure point of the Mayflower.	Learn about it on *www.plymouthgin.com.* The "seven hand selected botanicals" are: juniper berries, angelica root, cardamom pods, coriander seeds, lemon peel, orange peel and orris root. Find via *www.wine-searcher.com.*
Revel in a new musical experience. *The Armed Man: A Mass for Peace, by Karl Jenkins.* Written in 2000. Having enjoyed almost no modern classical music, I discovered this recently – my find of the decade!	Amazon has the CD. Read the text first, to learn the background. Then play tracks 1, 12 and 13. Sing the cello solo to yourself, or "Ring, ring, ring ring". Then play it all.
Read a fascinating book. *Travels on My Elephant by Mark Shand.* Non-fictional tale by an Englishman who bought a 30-year old female elephant in India in the late 1980s and rode her 800 miles. The travels make good reading, but the endearing aspect of the book is the character of the elephant, temper tantrums and all!	Amazon has the book.
Experience a spectacular red wine. *Chilean carmenere.* We're drinking Casa Silva Los Lingues, but I can't find that on North American websites.	*www.wine-searcher.com.* This leads you to suppliers, and several have Casa Silva Carmenere Reserve.

Deformation Monitoring with Robotic Total Stations (RTS)

The first contribution is an article, by colleagues in Greece, about a series of tests to determine the accuracy and performance of various types of reflectors that are used for RTS monitoring. Low-cost non-prismatic reflectors are widely used in the industry, and are shown to result in significantly lower accuracy than the more expensive prismatic reflectors.

That article is followed by six discussions of David Cook's article, "Robotic Total Stations and Remote Data Capture: Challenges in Construction", published in December 2006 GIN. Because this is a 'hot' topic, I solicited these discussions in the hope that we can all learn from the experiences of others.

A Question about Real-time Remote Monitoring of Dams

Jay Stateler at the Structural Behavior and Instrumentation Group at the US Bureau of Reclamation in Denver has asked me the following question:

> *What options are available for performing remote real-time monitoring of dams for evidence of new anomalous or apparently changed site conditions? Camera, satellite, thermal, infrared, other? Monitoring for changed conditions at already recognized locations of interest (such as monitoring existing seepage/drain flow locations, cracks, etc.) is not what we are seeking. Of interest are methods where large areas can be scanned for new, potentially troublesome developments.*

If you have any ideas about this, would you please *e-mail Jay at jstateler@do.usbr.gov,* with a cc to me?

His telephone number is *(303) 445-3064*.

Next Instrumentation Course in Florida, March 2007

The next instrumentation course in Florida will be on March 18-20, 2007 at St. Petersburg Hilton (*www.stpetehilton.com*). Details of the course are on *www.doce-conferences.ufl.edu/geotech*. Come and join us!

International Symposium on Field Measurements in Geomechanics (FMGM), September 2007

The 7th International Symposium on Field Measurements in Geomechanics (FMGM) will be held in Boston, MA during September 24-27, 2007. Details are on www.fmgm.org.

Living in Rural England

We live in Devon, a county near the bottom left hand corner. Largely a farming community, with a strong regional accent and a 'different' way of saying things. Females can be greeted, even at first contact, with "Hello mi luvly", "mi booty" or "mi little flower". Males with "mi ansome". I'm still waiting to experience the last of these personally!

Closure

Please send contributions to this column, or an article for GIN, to me as an e-mail attachment in MSWord, to *john@dunnicliff.eclipse.co.uk, or by fax or mail: Little Leat, Whisselwell, Bovey Tracey, Devon TQ13 9LA, England. Tel. and fax +44-1626-832919*.

Okole maluna (Hawaii), "*oh co lay ma luna*". A version of "Bottoms up". Thanks to Bobbi Daugherty for this.

Monitoring with Electronic Total Stations: Performance and Accuracy of Prismatic and Non-Prismatic Reflectors

Villy Kontogianni, Stefi Kornarou and Stathis Stiros

Abstract

The accuracy and performance of low-cost, non-prismatic reflectors widely used in geodetic monitoring projects in geotechnical engineering was investigated on the basis of experimental measurements. It was found that such measurements are characterised by significant systematic errors, which are minimized by repeated measurements, but they may responsible for apparent fluctuations of monitoring stations or even concealing real displacements.

Introduction

The evolution of electronics in the last decades has led to an enormous advance of surveying and other (e.g. geotechnical) monitoring systems for monitoring deformation of structures and their surroundings. The new generation of surveying instruments, electronic and robotic total stations and electronic levels, permit accurate fast and low-cost results for absolute 3-D displacements referring to a common reference system. The most important achievement is probably continuous or robotic measurements and the real-time acquisition and processing of large volume of data (for instance a few thousands of targets) using GIS and other software (Kaalberg et al. 2003).

Despite this exciting development, accuracy and limitations of modern surveying instruments are not adequately established, while very few detailed monitoring data from recent projects can be found in the literature (for instance see Ruland, 1990; Kontogianni and Stiros, 2002; Beth et al., 2003).

In the following paragraphs the performance and accuracy of common non-prismatic reflectors are discussed on the basis of experimental measurements. This research is part of a broad research on evaluating the overall efficiency of modern geodetic instruments and techniques at Geodesy Lab., Patras University, Greece.

Investigation of the performance of non-prismatic reflectors is important for two main reasons. First, their cost, usually less than 5% of the cost of prismatic reflectors, makes their use widespread. And second, because they represent the dominant source of error for short sighting lines (up to 60m long) - such lengths represent the vast majority of lines in most monitoring applications in geotechnical projects.

Source of Errors in Geodetic Monitoring

Distance and angle measurements, geometrical configuration of instruments and prisms and environmental factors introduce systematic errors in all measurements, and may lead to false conclusions on whether structures are stable.

In most monitoring applications however, all the above factors have trivial impacts on the accuracy of measurements for two reasons. First, because absolute displacements are computed as the difference between two single measurements, and given that they contain the same systematic errors, these errors do not impact on the measurements of displacements. Second, because repeated measurements permit a better control of various errors.

Nevertheless, another source of error that is poorly investigated is related to the performance of the reflectors.

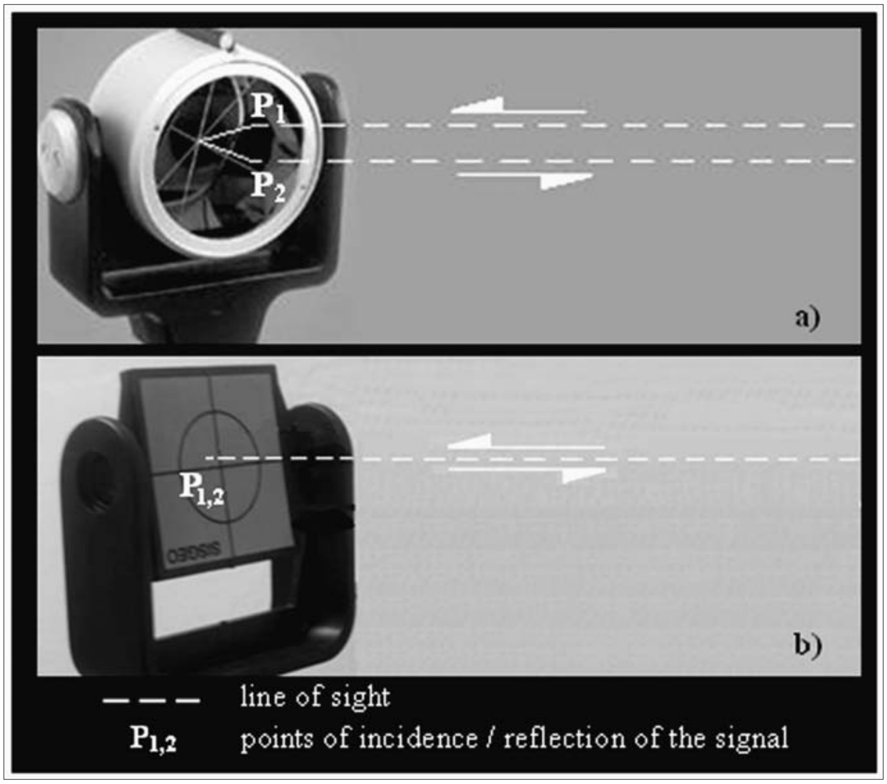

Figure 1. Reflection of the electromagnetic ray of a geodetic instrument (EDM or total station) at (a) a high-accuracy prismatic reflector and (b) a low-cost non-prismatic reflector (simplified).

Low-cost non-prismatic reflectors are widely used for numerous projects, but their performance and accuracy has not been established. The current research includes evaluation of the performance and accuracy of three different types of non-prismatic acrylic reflectors that are widely used in monitoring tunnels, foundation walls, buildings etc.

The Performance of Prismatic and Non-Prismatic Reflectors

For prismatic reflectors the ray transmitted from the total station falls at a certain point on the prism, is reflected into several surfaces inside the prism and reaches its center, and then reflected back through the same path to the geodetic instrument (Fig.1a). On the contrary, for non-prismatic, planar (plastic) reflectors, the signal falls to a point different from the centre of the reflector and is reflected back from this specific point to the total station (Fig.1b).

Consequently, when using prismatic reflectors the measuring path is defined by the transmitting instrument to the centre of the reflector. However, for non-prismatic reflectors this is defined by the transmitting instrument to a random point on the surface of the reflector. This offset between the geometric centre of the reflector and the real, random point of measurement on the reflector introduces an additional error in distance and angle measurements.

In order to investigate the extent of this error, a large number of experimental measurements, (similar to those taken for monitoring of tunnel construction) were made. The experiments and the results of the analysis are briefly presented below.

The Experiment

The aim of the experiments was to measure repeatedly distances to three typical non-prismatic reflectors and to compare these measurements with those to two high quality prismatic reflectors, assumed to represent the real distances. For this reason the five reflectors were fixed on a standard rule, i.e. a plastic base with five metal bolts at equal distances of ~15cm, appropriate to adapt monitoring reflectors on (Fig. 2). Distance measurements were made on all reflectors in a "*tunnel for calibration of geodetic instruments*" at the Geodesy Lab., Patras University, Greece. In this "tunnel", nearly constant environmental conditions (nearly constant temperature ~20^{o}C and pressure ~760mm Hg) permit a reliable comparison of measurements.

The three non-prismatic acrylic targets, an acrylic reflector by SISGEO (Italy), a white acrylic reflector by SINNING (Germany) and a white acrylic reflector by GEODATA (Austria), and

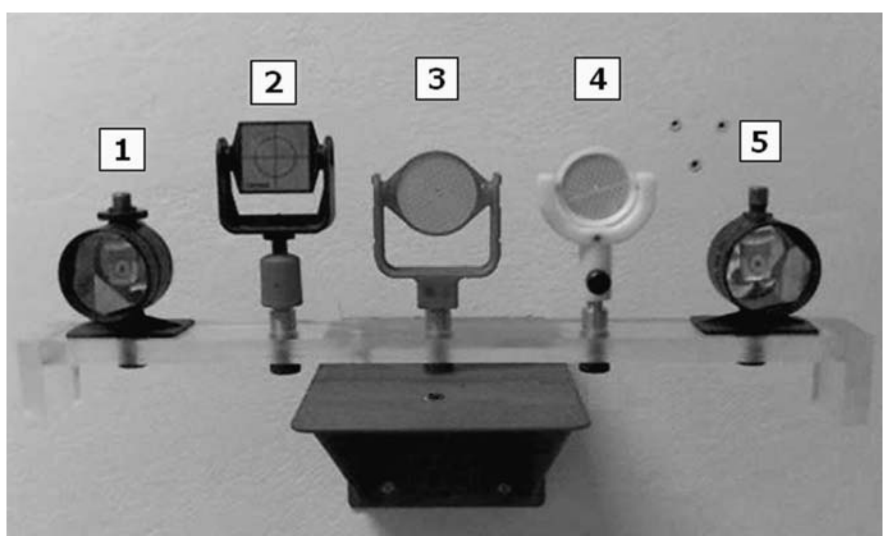

Figure 2. Arrangement of the five reflectors on the rule (plastic base) during the experiment. Reflectors 1 and 5 are prismatic and 2, 3 and 4 are common non-prismatic reflectors (manufactured by SISGEO, SINNING and GEODATA, respectively).

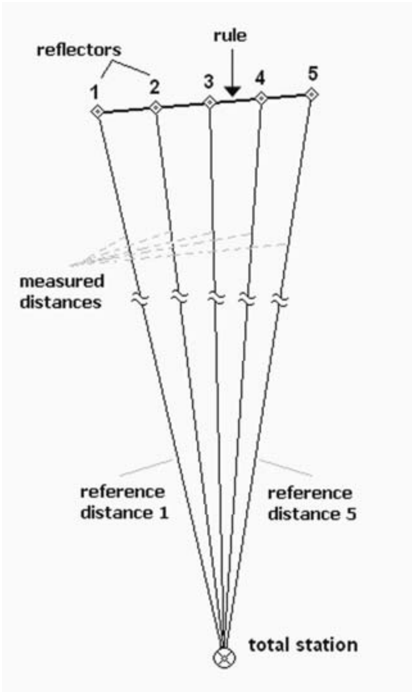

Figure 3. Geometrical arrangement of the transmitting instrument and the reflectors during the experiment.

the two high-quality prismatic reflectors fixed on the rule, as shown in Fig.2, were set at distances between approximately 8 to 55m from the transmitting instrument, and measurements were made to all reflectors (Fig. 3). To control the precision of results, the experiment was repeated five times. Measurement lengths were selected to correspond to the measuring distances at common monitoring applications.

Since the environmental conditions were similar for all experiments, and measurements at the prismatic reflectors are assumed to represent true lengths, the experiments allow a determination of the accuracy of measurements to the non-prismatic reflectors.

Results

Computed accuracy of distance measurements to the three non-prismatic reflectors are shown in Fig. 4. From this figure it is evident that significant (5-10mm) errors characterize measurements to all non-prismatic reflectors, and that such errors are maximized for short lengths (<15m). It is also evident that accuracy of distance measurements is a non-linear function of the length of the sighting distance. This result obviously indicates that in case of changing the location of the transmitting instrument (quite often a necessity at construction sites), the changes in sighting distances will introduce additional errors in measurements.

Such errors are responsible for fluctuations in recorded displacements at experimental and actual measurements (see e.g. Stiros et al., in press and Kontogianni and Stiros, 2002 respectively). They obviously do not justify the specifications advertised by the industry (usually ±1mm) but they are minimized but not eliminated by repeated measurements.

Conclusions

Plastic (acrylic) non-prismatic reflectors are widely used in geotechnical monitoring projects both because of their small dimensions and their minimal cost. However, they introduce some errors in measurements, which must be taken into serious consideration during the evaluation of geodetic monitoring data. In particular, such errors may be responsible for apparent fluctuations of coordinates of some monitored points (control points on structures or on ground) and may not reflect, and may even conceal real displacements (see for instance Stiros et al., in press and Kontogianni and Stiros, 2002).

Acknowledgements

Mr George Chatzigiannelis and Mr George Papastamos are thanked for providing the non-prismatic reflectors used in our experiments.

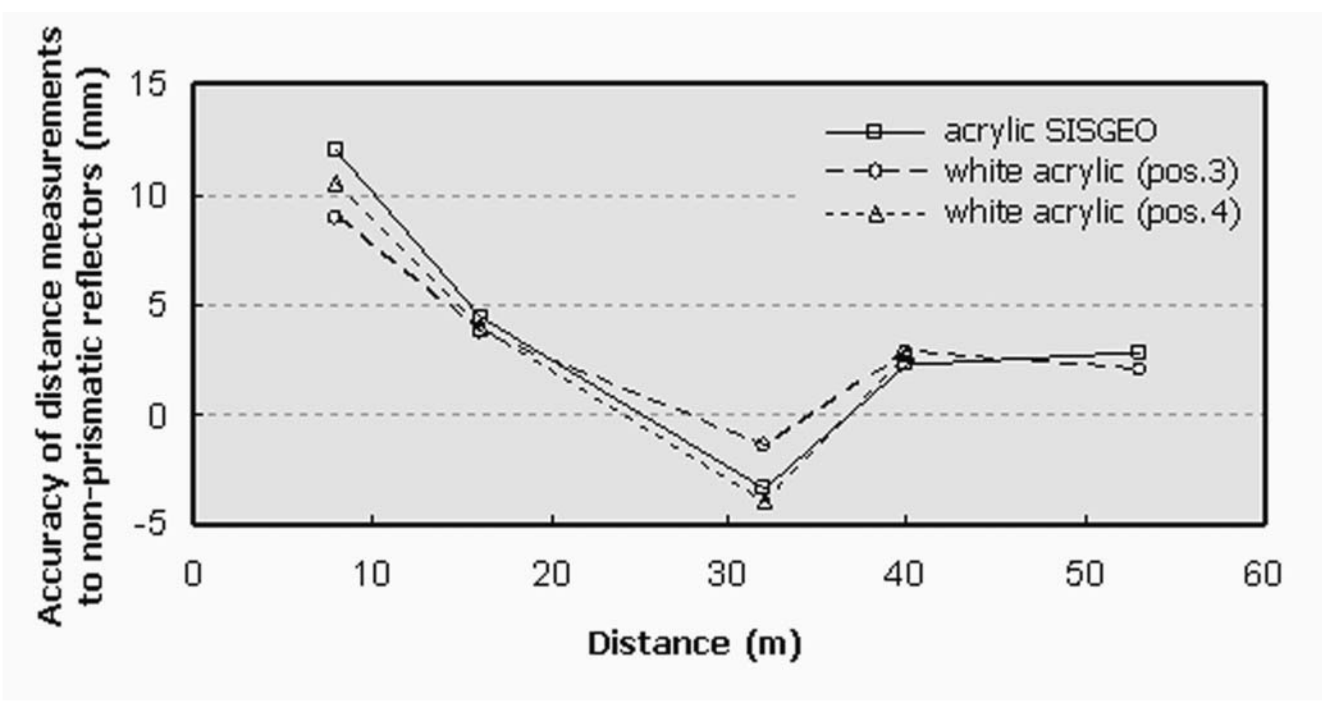

Figure 4. Accuracy of distance measurements to non-prismatic reflectors for different sighting distances.

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Discussions of "Robotic Total Stations and Remote Data Capture: Challenges in Construction"

David Cook

Geotechnical News, Vol. 24 No.4, December 2006, pp 42-45

Martin Beth

As an important starting point, I would like to say that David Cook's article gives a good and complete summary of the situation with motorized theodolites, and that most of the subjects he mentions agree with our experience of more than 500 units installed in the last ten years.

Having said that, I am now obliged to list all points with which I partially disagree! Here they are below:

Introduction to the Article

We do not believe that we can make measurements on holographic prisms with most of the theodolites currently on the market. We have found only one manufacturer (out of four that we use) that can support it, and the precision of the system is still to be checked.

Co-ordinates

Automatic re-section of the RTS coordinates should be implemented even if the theodolite position is outside the zone of influence. For example, there is always some degree of rotation of the theodolite on its own axis.

Environmental Factors and Vandalism

Fully closed glass protective enclosures for the theodolites can be manufactured, provided that the right glass characteristics and the right geometrical design are used. They are particularly useful for protection against vandalism and for protection in very inclement weather. We have also installed heated glass helmets.

Power

Power drain of the RTS in itself is not so large, on the order of a few amps at 12 V, so an uninterrupted power supply can be used. However, it is the rest of the acquisition chain that might require a large power supply: radio and PC for example.

Intermittent Line of Sight Issues

We have not experienced the problem about the first prism in a cycle requiring a clear line of sight. Maybe the mention arises from an automatic data quality improvement tool that we developed and installed on the North-South Line Project in Amsterdam, with which David Cook was heavily involved. It uses the principle of circle closing, well-known to surveyors. The system uses what is called an "open" target, that is sighted both first and last in the cycle. This is used to detect and correct any variation of the measurement conditions during the cycle. Of course, the sighting to this prism should be of good quality.

RTS Use within Tunnels

Our experience is that despite the difficult geometry, the precision is better than outside tunnels, because of more stable air conditions. The typical precision outside tunnels is generally about

+/- 0.5 or 0.6 mm for prisms within 80 m of an RTS, and +/- 0.3 mm in tunnels.

Again, this was a very good article, and by the way we were very honored to see one of our CYCLOPS shown in figure 1!

Bibliography

Here are some further papers to add to the ones included in the article:

"Excavation and instrumentation within the Grand Palais in Paris: A case study", 4th International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground, Toulouse, 2002, Beth, M, Lavisse, J, and Amicel, Y.

"Ground movement and structural monitoring for King's Cross Station redevelopment", ICE proceedings 2005, Beth, M, and Obre, X.

"Automated Monitoring of the Existing Airport Express Line at Nam Cheong Station", Underground Conference Singapore 2001, Thurlow, P, and Carayol, S.

"King's Cross Station Redevelopment, London: Design of the Monitoring System", FMGM 2003, Olso, Beth, M, Macklin, S, and Nichols, Z.

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Brian Dorwart

This article is well thought out and presented. For many years, and with mixed success, the mining industry has used these instruments to provide an early indication of pit slope and high wall movement that may indicate instability. Robotic total station (RTS) failures have generally been tied to misunderstanding of issues and instrument capabilities that have been well described in the article. This discussion provides an example of several issues unique to a specific mining application that merit further emphasis.

Mining Issue

The mining issue is stability of an 800-foot high wall with limited structural ability to construct stable benches as required for safety. The haul road traverses the toe of the high wall. Regulations require positive rock fall protection systems for workers entering the area below the high wall. It is not financially practicable to construct slope reinforcement to secure the slope, therefore an observational approach along with an active annual rock scaling and testing program has been designed for providing protection. A portion of this observational system is an RTS system that monitors targets strategically placed on the rock face.

System Design

Hardware selection was done with the assistance of a pre-qualified expert surveyor who also would be the overall chief of survey for the project. This decision probably was the single most cost effective decision for achieving our project goals. The system consist of a removable robotic theodolite, 17 monitoring locations, 3 permanent instrument platforms, and 3 back sight benchmarks. Design requirements were: horizontal and vertical accuracy +/-1 cm; shot length maximum 460 m; reading interval quarterly after baseline data established; prisms capable of surviving harsh mine and weather environment including blasting, ice, dust, rock fall; targets that can be added or subtracted from the monitoring program as mining changes the areas of concern.

Short and Long Term Instrument Platform Locations

For system accuracy, we required three stable benches within sight of the instrument hubs, three instrument hubs situated to provide a minimum of two independent target readings for each target with no more than a 30 degree sweep of the instrument; +/-15 degrees horizontal and vertical plane perpendicular to the high wall at the instrument hub location. A pit mine has few areas around the perimeter that are sufficiently stable for both an instrument platform and still provide a back sight to a stable bench. This pit is no exception. A ridge located opposite the pit high wall was selected for the hubs and benches. The hubs consisted of 3 cubic yards of concrete cast on undisturbed rock. Permanent mounting brackets were mounted at each hub location to permit accurate replacement of the instrument. The location of the hubs was mined out within four years of placement, requiring new hubs. The new hubs will be set this year on a lowered bench and consist also of concrete on rock. The benches have not been disturbed thus allowing reestablishment of readings after new baseline data base is established.

Selection of Target Type and Mounting Details

Target selection was critical to the system accuracy for the required shot lengths and angles. Prisms were 62mm diameter and were made of glass. Mounts were universal adjustment with a 5/8 inch diameter mounting thread. This thread mounted on a standard threaded rock anchor. The mounting required portable hand tools as all target locations required repelling several hundred feet down the high wall then installation and adjustment while hanging from the rope. After all targets were mounted, the surveyor with the RTS and the target mounting team, using radio communication, adjusted each of the prisms to an optimal alignment.

Environmental Damage to Targets

The target installation was considered permanent, more than 10 years life. Therefore targets were required to survive rockfall, snow and ice loads, and dust and flyrock from mining activities. These requirements could not be fully guaranteed in a mine environment. Therefore, selectivity for target stations and redundancy were used to reduce the risk of losing a target station. Each target station had a two prisms mounted not closer than 0.5 m and not further than 2 m apart. Sensitive rock masses had two to three separate target stations on the rock mass. Target stations were selected on overhangs and in dry rock sections to protect against falls and ice. Long-term annual maintenance is required for all targets. Prism alignment is checked and adjusted if necessary and broken prisms replaced if necessary. Additionally, all prissm lenses nses are cleaned annually.

Mining Environment Reading Stability

The mining environment includes blasting flyrock and a hole in the ground. The flyrock can hit anywhere in the mine area. No protection other than the overhang for rock fall protection was provided as it was considered to impede the reading ability of the prisms. The shots crossed the quarry pit. During the day, the pit developed thermal gradients along the shot lines. These gradients impacted the accuracy of the readings. Reading intervals were limited to the early morning time or on a cloudy day, to reduce the thermal influence.

Monitoring Results

System performance has been within design requirements.

1. Twelve prisms have required realignment since installation, though only one full target station has been lost when both prisms were hit by an icefall.
2. One prism has been destroyed by rockfall and required replacement. Spare prisms on site have proven very cost effective during remediation periods as replacement prisms in quantity are not locally available.
3. One target has been relocated to a new rock mass of concern and added to the survey monitoring program.
4. Benchmark verification surveys have indicated that one bench is not sufficiently stable and requires replacement. This bench is being replaced.
5. Readings in elevation and position are reproducible to +/-3 mm.
6. Servicing the prisms for replacement, cleaning, and realignment require survey assistance along with skilled rock climbers. This can only be done in good weather with all critical personnel on site at the same time. This has been difficult to schedule because of the limited rock experienced people and the limited qualified survey staff for assessing the service adequacy.
7. One round of instrument hub relocation is being done presently and is not anticipated to be a problem as the bench surveys have indicated stability. However, the readings have been interrupted for approximately one year as the hub locations were all in the same mining zone. Better coordination with the mine plan could have prevented this data gap.

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Richard F. Flanagan

It was gratifying to see David Cook's recent article in GIN (*Geotechnical News, December 2006*) on remote data collection using Robotic Total Stations (RTS). A benefit to the geotechnical engineering industry would be case history articles on this system, especially those using wireless data transmission approaching near real time monitoring.

Optical prism monitoring, from basic applications to fully automatic RTS, played an important role in the newly completed Singapore Deep Tunnel Sewerage System Project (DTSS). The DTSS tunnel system includes 48 km of large diameter tunnels excavated primarily by 8 TBMs through an urban area. Singapore is known for its highly variable ground, ranging from soft clays in low lying coastal areas to fresh granite to residual soils in the interior. Major infrastructure such as expressways, flyovers, and a number of underground, at-grade and elevated Mass Rapid Transit (MRT) railways were within the DTSS tunnel construction influence areas, sometimes only a few meters distant.

One such RTS application was an installation in a twin 12 meter deep MRT cut & cover tunnel, constructed by diaphragm wall methodology. The DTSS tunnel passed at right angles underneath the MRT. The crossing was at a busy surface roadway intersection that was undergoing major construction with a new overpass bridge. The MRT requirements included the following:

- Frequent displacement monitoring inside both MRT tunnels for all sidewalls, crowns and rail ties.
- For safety and security reasons, access to the MRT tunnels was strictly limited and controlled.

Optical prisms were set up on uniform longitudinal intervals on the tunnel crowns, sidewalls and rail ties. For example, there were 20 prism locations on each tunnel crown with matching points on the walls and rail ties. Readings were logged several times a day while the TBM approached and passed the crossing. The duration of the monitoring was two weeks.

Production readings commenced well before the TBM entered into its expected excavation influence zone in relation to the MRT structures. During the latter time, total 3-dimensional displacements in the range of 5 mm were observed. This displacement magnitude were observed at nearly all prism locations on the walls, crown and rail system, and in both tunnels at the same time. The same total displacements and pattern continued to be observed as the TBM passed and left the MRT area. There was never a plausible explanation as to why these displacement magnitude and pattern occurred regardless of the TBM excavation location. Nonetheless, the monitoring mission was accomplished and no appreciable displacements appeared to have occurred other than the initial 5 mm previously noted. Other monitoring instruments did indicate that there were shallow ground movements, but these may have been influenced by a nearby DTSS shaft and the new overpass bridge construction.

This discusser has been queried by colleagues who were in the process of designing RTSs. Some of the queries have been:

- What is the maximum theodolite-to-prism operating range? The manufacturer should be consulted for accuracy and precision with respect to distance.
- What happens when a train blocks the line of sight during a monitoring cycle? The system can simply skip the set of readings. This may not be acceptable if the frequency of blockage is great—then one would need to re-design the line of sight layout and perhaps add more stations.
- How often does one need to clean the targets when located in an operating rail tunnel? Cleaning the prism surface obviously depends on the particular rail system characteristics but generally every several weeks should suffice.

This discusser's additional suggestions for those considering RTS are:

- Provide sufficient time for good baseline readings well in advance of construction.
- Involve experienced geotechnical engineers with the data interpretation throughout the entire monitoring program

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email: flanaganr@pbworld.com

Trevor Greening

David Cook's article provides a thorough point-by-point summation of the practical considerations and issues associated with deploying Robotic Total Stations (RTS) in support of deformation monitoring programmes. However, several key factors are worthy of additional discussion and emphasis.

Design of Monitoring Networks

Figure 2 of Mr. Cook's article illustrates a typical RTS monitoring network configuration combining multiple instruments and prisms. The use of reference prisms located well beyond the zone of expected deformation highlights one of the major strengths of a RTS solution, namely the ability to extend to stable ground, thereby providing a fixed datum for displacement computations and trend analysis. However, the stability of the reference points – and hence of the datum – must be confirmed either during the observation-computation cycle, or periodically via independent measurements and analysis. Analytical methods are available specifically for this purpose. The undetected movement of a reference point can lead to spurious monitoring point trends, with undesirable consequences in terms of improper interpretation, and inappropriate remedial actions and associated costs.

Accuracy and Monitoring Sensitivity – System Design

The spatial accuracy of a RTS network is primarily a function of the equipment performance and network geometry. Mr. Cook has highlighted many of the secondary effects which can lead to accuracy degradation. Nonetheless, during the design phase, it is advisable to perform a pre-analysis using least squares techniques to predict the spatial accuracy of the computed co-ordinates of the monitoring prisms. This will ensure that the system has sufficient sensitivity to detect trends at the requisite level of confidence (e.g., 95% probability). As real measurements become available, a network may require minor modifications (e.g., the addition of common prisms) to improve its sensitivity at any identified locations. Off-the-shelf software is available for these analytical tasks.

Meteorology and RTS Calibration

Each RTS setup should be equipped with sensors for ambient atmospheric temperature and pressure measurements, and meteorological corrections must be applied automatically to the raw distance observations. As a rule of thumb, for this class of instrument, a temperature error of 1 degree Celsius will result in a distance error of 1 part per million (ppm); while a pressure error of 3.5 mbar will also cause a 1 ppm error. Since RTS distance meters are usually standardised at around 15°C it is clear that large temperature variations can induce significant errors unless the corrections are applied.

Every RTS-prism combination should be calibrated to determine the actual 'prism constant', especially if the RTS systems and prisms derive from different manufacturers.

Hybrid Monitoring and Control Systems

Modern RTS control and analysis software may include interfaces for ancillary geotechnical equipment such as multiple position borehole extensometers and digital inclinometers. Such data may prove invaluable in interpreting trends, filling in gaps in the RTS observation cycle, and in validating vertical datum issues in situations where the reference prisms are located in areas characterized by expansive soils. Global Positioning System (GPS) data may also be incorporated into some systems, thereby extending the 'reach' of a RTS system to relatively distant reference points.

RTS systems are commonly used in tunnels as the primary TBM guidance device, while additional sensors such as inclinometers augment the information and improve reliability. RTS systems are now being used for road-header guidance, with auxiliary inputs from digital encoders and inclinometers.

Other Considerations and Future Prospects

As Mr. Cook has pointed out, physical and environmental factors such as weather, dirt accumulation and vandalism can be intractable problems, but are not insurmountable. Other factors to consider include refraction (lateral displacement) of the optical line-of-sight through glass enclosures, and the rigging and maintenance of the control and data communication sub-system.

The basic RTS hardware has appeared to have reached something of a limit in terms of accuracy and functionality. There is, nonetheless, room for further development of the control and analysis software to include additional monitoring devices, enhanced analytical rigour, Internet integration, threshold detection and alarm distribution.

This discussion has focussed on extending the debate of a few key points. However, Mr. Cook's article is complete to the point where it could be used as a guideline for the design and implementation of a RTS monitoring programme.

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Douglas Roy Niels Jensen

The article by David Cook provides a nice summary of the capabilities and limitations of Robotic Total Stations (RTS) as experienced in Europe. Our technical experiences in the United States are similar, as noted below, although some commercial issues are specific to the use in urban (Chicago, New York) locations in the United States.

Like Mr. Cook, we have experienced limitations on repeatability of monitoring point readings due to a combination of factors, including temperature, vibration, and atmospheric conditions—as experienced with any survey based measurements. These tend to be especially pronounced when RTS are used in subway tunnel situations, where the temperatures and atmospheric conditions are influenced by the mechanical components of subway cars (e.g. brakes and air conditioning units). Under these conditions we have found that repeatability in the X and Y directions of +/- 2.0 mm is achievable, with slightly better repeatability in the Z direction. We have found that the use of a red pointing laser is helpful in establishing line of sight and prism locations in low visibility tunnels.

Mr. Cook is correct in stating that in tunnels, the use of three or more backsights in an effort to triangulate (lease square method) the RTS location is of little use, as the limited angles reduce the accuracy of the mathematical equations. We have now taken to locating, if at all possible, the RTS outside the anticipated zone on influence within tunnels.

Related to power, a hard line power source is not always available on outside applications, where we have found that a proper sized solar panel and deep cycle batteries will provide adequate power to run the RTS and limited communication.

Commercially, the United States contracting practice and labor conditions have made the use of RTS more cost effective than manual survey and cost competitive in lieu of tiltmeter-based tunnel deformation monitoring systems. These cost savings on the RTS are not only in the form of the limited amount of labor required to install the RTS, but also in avoiding the costs of union labor usually required to install the long data cable runs which are required for tiltmeter-based deformation monitoring systems. It is our experience that a RTS tunnel deformation system can be installed in about a quarter of the time required for a tiltmeter-based deformation system. This time reduction is also a benefit to the subway authority as it reduces the track outages on the subway system—for example New York and Chicago typically run on a 24/7 basis.

United States contracting practice has most recently dictated that that instrumentation be supplied and installed by the General Contractors (much to the distaste of the GIN Editor). Although not ideal in a technical sense, given the possibility of low cost or minimally experienced subcontractors, we see a greater issue with the quality and content of the RTS specifications provided by the design/specifying engineer. Errors and technical mistakes in these specifications often lead to unnecessary cost increases to the project. We would hope that the equipment manufacturers would address this issue, by educating the engineering community.

One item that Mr. Cook does not address on the commercial side that we perceive common in the United is the lack of competition of RTS manufacturers. Our experience is that only one manufacturer has provided a product that can be used with automatic target recognition and has RTS software that can easily interface with remote communication systems.

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One of my colleagues sent me the following suggestion:

I would suggest you contact the manufacturers of the motorized theodolites that are used in robotic total station monitoring to get their perspective on essential maintenance and protection. My impression is that there is a gap be tween what is required for maintenance when using these instruments for 'traditional' surveying (such as checking the face error adjustments, etc) and what is necessary for a 'fixed' location application.

I think it is very important, given that the instruments are very expensive, that if they are not operating properly they (a) give subtle errors that are 'believable' and (b) affect the entire monitoring system, in contrast to one or two sensors going bad on a logger.

I was told by one manufacturer's maintenance group that the theodolites should be re-adjusted once each week, every 3-4 days if the instrument is running almost all the time. That level of attention doesn't make the system very 'remote' (particularly in tunnels where access is all but impossible for long time periods).

A good suggestion, so I asked Leica, Sokkia, Topcon and Trimble for their comments. Despite several requests, I received one response only, from Leica.

JD

David Rutledge

Since 1998 Leica has manufactured instruments for robotic total station monitoring. The units are very robust and there is no need to calibrate them every week. In a typical monitoring project the total station is installed on a stable pillar and is programmed to take measurements automatically. For most projects we recommend that the instruments be serviced by Leica once per year. Following the yearly service, we recommend that the on-board calibration program be used when the instrument is re-installed on the pillar.

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Author's Reply

I would like to thank all the contributors for their inputs, sharing examples of lessons learned and challenges overcome. To follow up on a few points:

I concur with Martin Beth's comments regarding the use of holographic prisms with RTS. This particular combination is caveated within the introduction to the article, but possibly not strongly enough.

I will expand further regarding his comment on intermittent line of sight issues. This problem was experienced within a rail tunnel in the UK and was the "open" target as Martin describes. Making this a target for which the line of sight could not be interrupted reduced the number of unsuccessful cycles. This was not a reference prism, but Martin´s comment regarding closure is important. This minor change proved a useful, relatively non-technical, solution for the problem experienced.

Richard Flanagan raises the issue of frequency of prism cleaning, which can vary considerably from project to project. We have experience of prisms in tunnels located at a high level on electric traction railways, requiring cleaning at approximately nine month intervals, but lower prisms could be monthly (due to brake lining dust) and even more frequently where detritus discharged directly onto the track.

Whilst not restricted to RTS, I agree with the need to provide sufficient time for good baseline readings to be taken prior to the start of construction operations. So very often previously unknown background movements are measured, for which the project would otherwise be deemed liable.

Douglas Roy and Niels Jensen bring up the lack of competition of RTS manufacturers in the US. Given a similar situation in the UK, this is presumably a global issue.

Thank you once again. I would be pleased to address any further queries/points directly. Contact details below.

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