Introduction by John Dunnicliff, Editor

This is the 84th episode of GIN.

Three articles this time.

Specifications for robotic total station field work

I've written several of these, and now realize how flawed they were. I see similar wording being used in new specs, and we need to do all that we can to stop this practice.

The first article by Douglas Roy and Jonathan Stuhl makes this clear, and advises on contract specification language (from a North American perspective) for robotic total station (RTS) field personnel. These field personnel effectively run these systems and manage the data they create. The first author is a geotechnical professional engineer, the second a professional land surveyor, so we must regard their recommendations as from the two disciplines – i.e. don't regard this as a one-sided argument by geotechs.

Although this article should be of interest to professionals involved in RTS technology and usage, **it is particularly intended to guide owners, engineers and specification writers** tasked with the preparation of specifications on projects where RTS technology will be utilized. Those in bold font will generally not be readers of GIN, so the authors and I need your help to pass the recommendations on to the target audience. If you're in professional contact with any of those in bold font, will you please ask the Managing Editor of this magazine, Lynn Pugh, (*gn@geotechnicalnews.com*), cc to me (*john@dunnicliff.eclipse.co.uk)* to send you a pdf of the article, and then share it. We need to break the habit of copying and pasting from the flawed specs.

Please share this article with owners, engineers and specification writers involved with RTS technology – we need to break a habit

Knowns and unknowns

In my June 2012 introduction to GIN I highlighted the concept of known knowns, known unknowns, and unknown unknowns, and attributed the quote to ex-US Secretary of Defense Donald Rumsfeld. Don Shields contacted me to say that he was "ticked off" by this, believing that the concept of different degrees of unknowns is original to Elio D'Appolonia ("D'App").

Don then sent me the following article, entitled "Giving credit where credit is due". For those of you who don't know Don: a graduation thesis on the swelling pressures of Saskatchewan clays led him to a career in geotechnical engineering. His career combined consulting, teaching and research - with a special interest in insitu testing and foundations. He retired in 2000 as Dean of Engineering at the University of Manitoba.

General role of instrumentation, and summaries of instruments that can be considered for helping to provide answers to possible geotechnical questions.

The last of the three articles is an attempt identify:

- The general role of instrumentation for internally and externally braced excavations.
- The possible geotechnical questions that may arise during design or construction, and that lead to the use of instrumentation
- Some instruments that can be considered for helping to provide answers to those questions.

Similar suggestions for other project types will be in subsequent episodes of GIN.

Third International Course on Geotechnical and Structural Monitoring - June 2016 - Italy

The third international course on geotechnical and structural monitoring (www.geotechnicalmonitoring.com) will be held in Tuscany, Italy on June 7-9, 2016, followed by a field trip on June 10 to the Poggio Baldi landslide monitoring site (*www.landslidemonitoring.com)*.

To enhance the content on recent innovations, we're going to have three sessions in which registrants and exhibitors make professional presentations about new trends. In each of these sessions, four invited speakers will make brief presentations on new trends on each of the following:

- Contact monitoring
- Remote monitoring
- Data acquisition and management systems.

We also plan on two sessions in which about ten users will make ten minute presentations on case histories and lessons learned. Speakers will be selected based on an open call. **If you're interested in presenting during these sessions, please send an abstract of your proposed topic to the course organizer, Paolo Mazzanti, *paolo.mazzanti@nhazca.com*.**

Correction methods for inclinometer errors

This subject remains obscure to most users. Manufacturers of inclinometers

Exhibitors' room

Lecture room

Street party

2015 Participants

Field Trip

3rd INTERNATIONAL COURSE ON GEOTECHNICAL AND STRUCTURAL MONITORING

June 7-9, 2016 Poppi, Tuscany (Italy)

Course Director: John Dunnicliff, Consulting Engineer
Organizer: Paolo Mazzanti, NHAZCA S.r.l.

THE COURSE: attendance at the course is a great opportunity to establish a valuable network with colleagues from all over the world, to meet manufacturers and see the most recent and innovative instrumentation, thanks to a large exhibition area.

NEW CONTENT: to enhance the content on recent innovations, there will be three sessions of professional presentations about new trends in contact monitoring, remote monitoring, data acquisition and management systems. There will also be two sessions in which users will make brief presentations on case histories and lessons learned. If you're interested in presenting during these two sessions, please send an abstract of your proposed topic to: info@geotechnicalmonitoring.com.

COURSE EMPHASIS: the course will include planning monitoring programs, hardware and software, web-based and wireless monitoring, remote methods for monitoring deformation, vibration monitoring and offshore monitoring. Case histories will be presented by prominent international experts.

WHO: engineers, geologists and technicians who are involved with performance monitoring of geotechnical features of civil engineering, mining and oil and gas projects. Project managers and other decision makers who are concerned with management of RISK during construction.

LOCATION: the 3-day course will be held in Poppi, Tuscany (Italy). In addition to providing an opportunity to increase your own technical expertise, you will have a cultural and historical experience in one of the most attractive places in the world.

FIELD TRIP: an optional Field Trip will be held, at the end of the Course (10th June), on a large landslide site, where practical demonstrations of monitoring equipment will be performed by international leading Partners.

Course Partners: Measurand, Canary Systems, Geokon, Sylex, 3D Laser Mapping, Vista Data Vision, Soldata, Geosense, GKM Consultants, Marmota Engineering, Campbell Scientific, CSG - Centro Servizi di Geoingegneria, Smartec, Metasensing, Bartec Syscom, IDS Ingegneria Dei Sistemi. (Updated October 2015)

www.geotechnicalmonitoring.com

don't emphasize that there is potential for systematic errors in inclinometer results. Diagnostic plots and correction routines are built into DigiPro 2 – Advanced (*www.slopeindicator.com*) and GTilt (*www.mitresoftware.com*) software, but not others as far as I know, but users can get guidance from Slope Indicator's website *www.slopeindicator.com/index.php*.

Erik Mikkelsen wrote a paper for the 2003 Symposium on Field Measurements in Geomechanics, (FMGM) in Oslo, Norway, titled "*Advances in inclinometer data analysis*", in which he described the major errors and provided guidance in error correction. Together with Elmo DiBiagio, Erik wrote a second paper for the 2015 FMGM in Sydney, Australia, titled "*Depth position errors in inclinometer surveys and false displacement results*", elaborating on part of the 2003 paper.

Because FMGM papers are not as readily accessible as articles in GIN, Erik had agreed to write three articles for GIN:

1. Calibration errors: Bias and sensitivity shifts
2. Rotation errors due to probe azimuth shifts and casing cross-axis inclination
3. Depth positioning errors and influence of casing curvatures

The plan is to publish these articles in the next three episodes of GIN.

Procedings of the ninth FMGM

The proceedings of the ninth International Symposium on Field Measurements in Geomechanics (FMGM), held in Sudney, Australia on September 9-11, 2015 are now available. The bound proceedings (829 pages) contain 65 papers, divided into the following subject areas:

- Case studies
- Civil tunneling
- Water flow and monitoring
- Underground mining
- Transport corridors
- Coal mining and associated excavations
- Carbon sequestration
- Slope stability

The proceedings include a stage-setting presentation by Philip Pells, titled "Monitoring - the good, the bad and the ugly".

The proceedings can be ordered at www.acg.uwa/edu.au/shop - scroll to "FMGM 2015". The cost is Australian $220, US$170, including courier delivery.

Mea culpa

In the previous GIN I wrote, "The rugby world cup will be played here in England during September and October. Yes, USA will be competing, but not Canada". I was wrong! Soon after we went to press I realized that Canada **was** playing, and expected a blast of complaints from readers. But only one! This seems to mean that:

- Only one Canadian reads my stuff, or
- Canadian readers don't care about rugby, or
- Canadians are uncomplaining and forgiving.

Now to the single blast:

> "I strongly resent your assertion that Canada is not good enough to go to the Rugby World Cup however, the USA is good enough. Maybe I should not believe your opinions on instrumentation either! A humble retraction in the next Geotechnical News is warranted."

Wow! We made peace, and I learned that it was 'tongue in cheek'!

Finlay Currie as Abel Magwitch in Great Expectations*, 1946.*

A tale to tell

Did you read Charles Dickens' classic novel *Great Expectations*? Or see the original 1946 movie or the 2012 re-make? A primary character is Abel Magwitch, an escaped convict. I recently spent some ouchy days in a hospital with a fractured hip, and on the second day 1946 Magwitch (same frightening face and same heavy physique) was wheeled to the adjacent bed space. Handcuffed to the bed, with two policemen, one of whom was also handcuffed to the bed, presumably to prevent rescue by his buddies by taking patient and bed! He'd broken a knee and arm while playing soccer in the nearby high-security prison in the Dartmoor National Park (I live in the Park). He and his guards were very noisy, even after the lights went out, and I was relieved to be moved to a different room the next day. But the following day he reappeared alongside me, again with the noise! And can you believe this? – the two moves were repeated two days later! Not what I needed, but the UK National Health Service was superb.

Closure

Please send an abstract of an article for GIN to *john@dunnicliff.eclipse.co.uk* —see the guidelines on www.geotechnicalnews.com/instrumentation_news.php

Stin ijiasas (Greece). Make a toast to their future – they need you to do that.

Qualifications of the robotic total station construction monitoring professional

Douglas Roy and Jonathan Stuhl

Introduction

The use of robotic total stations (RTS), also referred to as automated motorized total stations (AMTS), has become more and more prevalent in modern construction related monitoring programs. This increase comes from realization by practitioners to the cost and efficiency benefits over manually survey monitoring as well as through contract specifications from owners and engineers to provide tighter tolerances and quicker response times. With the gap closing (or widening) between North American Professional Land Surveyors and Professional Engineers regarding the use of RTS units, questions arise as the necessary background and experience required for practitioners to effectively design, as well as run these systems and manage the data they create. Although this article should be of interest to all professionals involved in RTS technology and usage, it is particularly intended to guide owners, engineers and specification writers tasked with the preparation of specifications on projects where RTS technology will be utilized.

RTS for construction monitoring

In the early twenty-first century the improvements in telecommunications along with integration of robotics into the total station brought about the possibility of using these RTS units for remote monitoring. A total station that normally required a survey technician or transit man to run could now be controlled remotely and data sent to a remote location for plotting and analysis. With hardline communication and power connections an RTS unit could be installed in a location possibly inaccessible to a survey crew and no longer require untimely access in order to provide 3D survey monitoring information, see Figure 1. In addition to the access issues this system overcame, it introduced a level of high accuracy/high volume measurements not previously available. Measurement cycles were completed and data returned for review within short minutes and the process completed electronically heavily limiting the human error side of survey monitoring. Continuous changes in technology have led to the wireless alternative of the RTS where a wireless cellular modem is used to maintain communications and solar panels are used to power the system.

As the technology of RTS has become more accessible the use of the instruments in monitoring for construction large and small has increased. When initially introduced the cost of these systems was prohibitive to the point that only large scale "mega" projects could find the improvement outweighing the cost. Today the RTS monitoring solution is prolific in many construction venues from tunnels and bridges to high rise sky scrapers and dams to even residential construction in urban environments.

Recent contract specification requirements

As the value of RTS monitoring was evident and the desire for increased monitoring data found appeal with owners and engineers, some modifications to contract specifications were expected. Specifications regarding frequency of measurements and expectations of data delivery timelines were updated. No longer was there a one day turn around for a survey crew to complete field measurements, return

Figure 1. Typical RTS installation.

to an office environment and complete calculations and produce deformation results. Now the process was specified to be more streamlined and provide same day turn around and include forms of automated notification to stakeholders of deformations above limits.

In order to assure that quality data were to be provided per specification the language was changed to incorporate RTS measurements with other geotechnical monitoring data under what is often referred to as the Geotechnical Instrumentation Engineer (GIE). This engineer, typically required to be a Professional Engineer in the state/province that the work is undertaken is specified to have many years of experience with the installation, use and interpretation of data from all of the monitoring instruments to be installed per the contract including the RTS. Beyond this general qualification for the GIE there is little requirement for the experience of technicians or the GIE for reduction of RTS data for use in deformation monitoring as it relates to the statistical or realistic reliability of the monitoring data. There have been a small number of specifications that include a requirement for an AMTS (RTS) Specialist. These specifications generally require that this position be filled by a person with two to three years of experience with and having successfully completed some number of similar projects involving RTS monitoring.

Relevant experience for practitioners

The practice of land surveying is often defined by 50 United State and one district boards and similarly in the remainder of North America as that practice which includes special knowledge and application of mathematics to measuring, plotting and layout of dimensions, areas and volumes on and above the earth or of/on man-made structures. It also includes the location, layout, measurement of the lengths and directions of boundary lines (property lines), monumentation thereof and the application of legal rules and regulations for legal descriptions and conveyance of real property. The Professional Land Surveyor (PLS) is entrusted with taking measurements of the earth and structures and applying mathematical and regulatory principals to determine positions and elevations.

Figure 2. Prisms monitoring large crack in a building.

Professional Engineering is often defined by 50 United State boards and similarly in the remainder of North America as that practice which includes the planning, designing, composing, evaluating, advising, reporting, directing or supervising that requires the application of engineering principles which concerns the safeguarding of life, health, property, economic interests, the public welfare or the environment, see Figure 2.

Professional Engineers (PEs) work to guarantee the public's safety and promote its interest where engineering matters are concerned. They must also ensure that provincial laws adequately and properly serve and protect the public, and participate in the establishment and maintenance of engineering standards while adhering to a code of ethics.

Now every state and province regulates the practice of engineering to ensure public safety by granting only PEs the authority to sign and seal engineering plans and offer their services to the public.

PEs are defined by various disciplines, (Civil, Structural, Mechanical, Electrical, Nuclear, etc.) by various state and provincial boards, typically with different testing and experience requirements. Often the state and provincial boards for both PEs and PLSs are under the same administrative arm. Important to this discussion is that PE and PLS standards of care require that they shall only undertake assignments when qualified by education or experience in the specific technical fields involved.

This goes to the heart of this discussion. Is a Professional Engineer, licensed in the state/province where work is being performed, or any other state/providence for that matter, qualified to administer a RTS program? To answer that lets first discuss the process of the design and implementa-

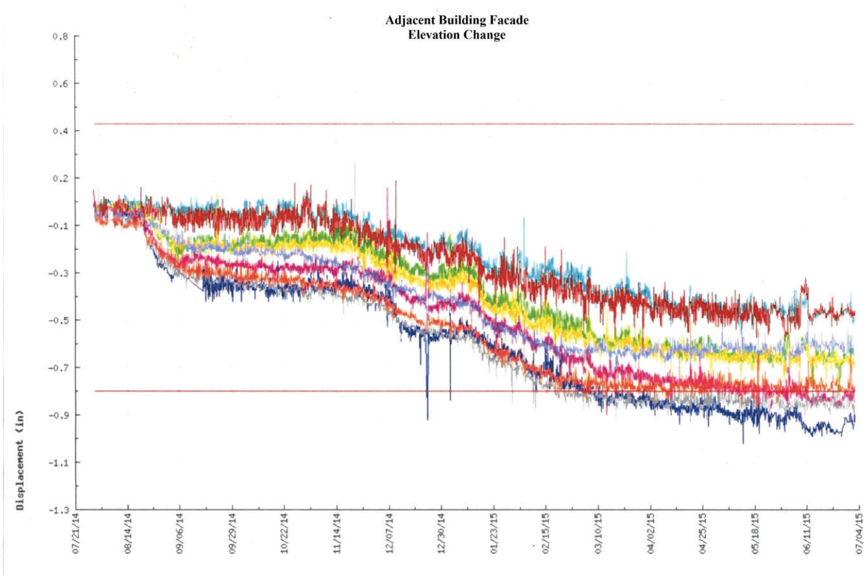

Figure 3. Long term monitoring data from a RTS system showing settlement of a building façade.

tion of a RTS program based on five distinct steps.

- Design the layout of RTS locations to maintain stability, reduce environmental errors and incorporate sufficient stable control to evaluate movement of the RTS and may also include the design of the specific locations to be monitored
- Proceed with the installation and testing of the system to verify functionality and adherence to designed criteria for accuracy and precision
- Data processing is setup to compile and reduce the measurements using appropriate methods of calculation
- Review of the data for quality assurance and identification of movements and trends as well as properly identifying possible data spikes due to transient factors, see Figure 3.
- Use information from the data review to refine and adjust the processing model as needed for changed conditions in the control reference frame or environmental factors.

The direct measurement, taken with a RTS would be the same whether programed by a PLS or PE. Much different then in previous generations where each measurement was made in the field by a two man survey crew, one of which was often the PLS.

Where the Professional (Professional Engineer or Professional Land Surveyor) is needed involves how this resulting measurement is processed, refined and used within an instrumentation data base. Given the advancements in data processing and database manipulations that are undertaken using the least square programs (see Figure 4), the initial phases of data base processing of the direct survey data are more akin to that a professional mathematician or computer software engineer. But key to the Professionals input is the installed RTS location(s) and layout to the reflective monitoring points, confirming that the measurements between these two points will give the best quality data, how corrections to data is undertaken to correct for various error types, and of most important how to address trends or direct movement of points. In this evaluation the Professional must also consider the structure being monitored, its ambient movement as a result of thermal expansion, the impact of the movement to the structure and some of the reasons that movement may be occurring, such as the excavation or tunnel construction.

RTS construction monitoring does not include the definition and layout of boundary lines (property lines), nor the legal description and conveyance of real property. Whereas it does include the use of highly precise instruments for the measurements of

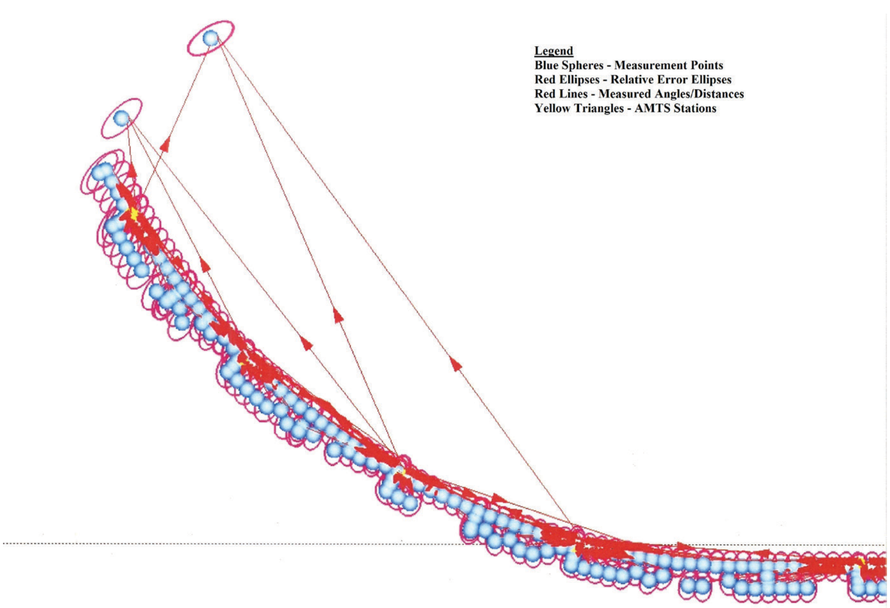

Figure 4. Least squares adjustment plot showing relative error ellipses.

the earth and structures and applying mathematical and regulatory principals to determine positions and elevations of points on structures or the ground surface where the change in position of such points are a concern for safeguarding of life, health, property, economic interests, the public welfare or the environment.

Clearly both the PE and PLS standard of conduct requires that the Professional only undertake assignments when qualified by education or experience in the specific technical fields. The difficulty in the RTS implementation is that neither a PLS nor PE is formally trained on all these issues. On projects without formal specification, the Professional typically decides if he or she has the qualifications required to perform the work.

Until such time that the relatively new field of RTS monitoring advances to influence the state or provincial registration boards, this "mix" of Professionals involved in RTS construction monitoring will likely continue.

It is these writers' opinion that both a PE and PLS can be qualified to undertake a RTS program, and that other degrees and experience may also qualify. The argument of who should be qualified as the GIE, will not be debated here.

Recommendations for contract specification language

The frustration with RTS program specifications has been prevalent in the North American industry for more than a decade, and discussed well in the September 2009 GIN article by Dail and Volterra.

It is these authors' recommendation, as representatives for both PEs and PLSs that the need for a separate AMTS (RTS) specialist is well suited and generally the best for the project, especially in the cases where there is a large amount of "in ground" instrumentation being addressed by the GIE.

We would anticipate that such a specification would generally outline as follows:

Robotic Total Station (RTS) Specialist who shall have previous experience in installation, monitoring, and data interpretation of at least two RTS systems in applications similar to those specified herein. The RTS Specialist shall perform the following tasks:

- Design and detail the overall configuration and appurtenant hardware and installation procedures for the entire RTS system, including final locations of the components.
- Perform pre-installation and post-installation acceptance tests and supervise installation of the system in its entirety.
- Collect, reduce, process and plot RTS data.
- Review RTS system data for quality assurance, identification of erroneous data and identification of movement trends.
- Incorporate information from data review, changed site conditions and/or unanticipated changes to system design into the RTS system processing model.
- Be a PE or PLS in the state or province where the project is located

We hope to see additional attention paid to the details and qualifications of this specialty as the use of RTS monitoring continues to grow.

References

Emily B. Dail, and Joel L. Volterra, "Instrumentation and Monitoring Trends in New York City and Beyond", Geotechnical News, September 2009. www.geotechnicalnews.com/pdf/GeoTechNews/2009/GIN%202703.pdf

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Giving credit where credit is due

Donald Shields

I am at the age when finding myself in the kitchen I have to stop and ask myself "Why did I come here? What am I looking for?" Also at the age that things 'tick me off' probably more frequently than they used to.

I was ticked off three years ago when I read Geotechnical Instrumentation News [GIN] give credit to ex-US Secretary of Defense Donald Rumsfeld. The mention of Rumsfeld's name, usually in association with Dick Cheney, ex-US Vice President, makes me grit my teeth, I admit.

The introduction to June 2012 GIN highlighted the concept of Known knowns, Known unknowns, and Unknown unknowns. These are risk management terms that apply, for example, in resource development when the long term environmental hazards of development are being considered. It is not possible to imagine today all of the issues that might manifest themselves say 10 or 100 years from now. Hence the concept of Unknown unknowns.

The GIN introduction seemed to imply that the concept originated with Rumsfeld at the U.S. Department of Defense news briefing he gave on February 12, 2002. The subject at hand was the lack of evidence linking the government of Iraq with the supply of weapons of mass destruction to terrorist groups.

In spite of my inability to remember why I am in the kitchen, the synapsis of longer term memory fired on reading the introduction. I remembered the moment in 1979 when Elio D'Appolonia used the words Unknown knowns and Unknown unknowns. The reason I remember was I said to myself "Why didn't I think of that?" That is now 36 years ago.

The occasion was the presentation by Dr. Elio D'Appolonia at the Province of British Columbia Royal Commission of Inquiry into Uranium Mining (1). With respect to the design and construction of uranium tailings impoundments, Dr. D'Appolonia testified:

Site conditions always pose unknowns, or uncertainties, which may become known during construction or operation to the detriment of the facility and possibly lead to damage of the environment or endanger public health and safety. The risk posed by unknowns is somewhat dependent on the nature of the unknown relative to past experience. This has led me to classify unknowns into one of the following two types: 1. known unknowns (expected or foreseeable conditions), which can be reasonably anticipated but not quantified based on past experience as exemplified by case histories in Appendix A, and 2. Unknown unknowns (unexpected or unforeseeable conditions), which pose a potentially greater risk simply because they cannot be anticipated based on past experience or investigation.

Dr. Elio D'Appolonia in 2008.

Known unknowns result from phenomena which are recognized, but poorly understood. On the other hand, unknown unknowns are phenomena which cannot be expected because there has been no prior experience or theoretical basis for expecting the phenomena.[1]

The concept of different degrees of unknowns is original to D'Appolonia I believe. As the above testifies, the concept certainly did not originate with Rumsfeld. Rumsfeld's presentation was 23 years after Elio D'Appolonia made his remarks.

The Royal Commission of Inquiry into Uranium Mining was set up in response to development work that was being carried out for the proposed Blizzard uranium mine near Kelowna, BC. British Columbia has nearly two hundred known mineral occurrences of uranium. In spite of these mineral riches, there had never been an operating uranium mine in the province.

I was one of a team of consulting engineers working on the Blizzard site. My particular responsibility was waste disposal. Hence, I had an invested interest in the workings of the Commission, and in its eventual findings and recommendations. I attended the presentations to the Commission on the disposal of uranium-laden waste rock and tailings.

One of a small number of principal presenters to the Commission was Elio D'Appolonia who had considerable experience in mine development in the United States and other countries. D'Appolonia was a consultant to regulatory bodies in the US, and he sat on mine design and development review boards. His presentation to the Commission was on the long term storage of uranium mine tailings.

The findings and recommendations of the Commission were disheartening. On February 27, 1980, the Government of British Columbia ordered a seven-year moratorium on uranium exploration and mining. As recently as March 12, 2009, the BC Government issued a Cabinet order that stopped any review of proposed uranium and thorium exploration and development in the province, thereby extending the 1980 moratorium to the present day.

Donald Shields, Retired

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[1] Statement of Evidence of E. D'Appolonia, D'Appolonia Consulting Engineers, Pittsburgh, Pennsylvania. Proceedings of the British Columbia Royal Commission of Inquiry into Uranium Mining, Phase V: Waste Disposal, ISBN 0-7718-8198-3, Page 9.

General role of instrumentation, and summaries of instruments that can be considered for helping to provide answers to possible geotechnical questions. Part 1.

John Dunnicliff

Introduction

This is the first of a series of articles that attempt to identify:

- The general role of instrumentation for various project types.
- The possible geotechnical questions that may arise during design or construction, and that lead to the use of instrumentation
- Some instruments that can be considered for helping to provide answers to those questions.

Of course it is recognized that there may be additional geotechnical questions and also additional instruments that are not described in this article.

The sequence of geotechnical questions is intended to match the time sequence in which the question may be addressed during the design, construction, and performance process, and does not indicate any rating of importance.

The suggestions for types of instruments are not intended to be dogmatic, because the selection always depends on issues specific to each project, and is influenced by the personal experience of the person making the selection. In the tables some of the most likely instruments that can be considered are listed, with other possible types in parentheses. The tables include the term "remote methods" for monitoring displacement. An overview of these remote methods is given in a December 2012 GIN article by Paolo Mazzanti (www.geotechnicalnews.com/instrumentation_news.php). Readers who want to learn more about these methods may want to consider participating in the annual International Course on Geotechnical and Structural Monitoring held in Italy (www.geotechnicalmonitoring.com), where they are discussed in detail.

Part 1 of this series focusses on internally and externally braced excavations. Later parts will include:

- Embankments on soft ground
- Embankment dams
- Cut slopes and landslides in soil
- Cut slopes and landslides in rock
- Tunnels
- Driven piles
- Bored piles (drilled shafts)

Internally braced excavations

General role of instrumentation

The design of internally braced (strutted) excavations is based for the most part on empirical procedures and past experience. The consequences of poor performance can be severe and may on occasion be catastrophic. A monitoring programme may not be required if the design is very conservative, if there is previous experience with design and construction of similar facilities under similar conditions, or if the consequences of poor performance will not be severe. However, under other circumstances a monitoring programme will normally be required to demonstrate that the excavation is stable and that nearby structures are not affected adversely. Depending on the specific needs of each case, the monitoring programme may apply to the wall and struts, to the ground beneath or surrounding the excavation and/or to adjacent structures or utilities.

Summary of instruments that can be considered for helping to provide answers to possible geotechnical questions

Table 1 lists the possible geotechnical questions that may lead to the use of instrumentation for internally braced excavations, together with possible instruments that can be considered for helping to provide answers to those questions.

Externally braced excavations

General role of instrumentation

The general role of instrumentation for externally braced excavations (using ground anchors or tiebacks) is the same as for internally braced excavations. However, it is possible to make regular visual inspections of internal bracing, but external bracing cannot be seen. Although confidence in the performance of an externally braced excavation is increased by conducting a proof test on every anchor, if an anchor subsequently fails, the failure may be progressive and catastrophic. In general, therefore, instrumentation plays a role in three phases of external bracing that are not applicable to internal bracing:

- Testing of *test anchors* during the design phase or at the start of construction, as input to design of the project anchors.
- *Performance* and *proof testing* of anchors during construction.
- Subsequent *monitoring* of selected representative anchors. This` phase may be omitted if a conservative design has been used.

Table 1. Some instruments that can be considered for monitoring internally braced excavations

Possible geotechnical questions	Measurement	Some instruments that can be considered
What are the initial site conditions?	Groundwater pressure	Open standpipe piezometers Vibrating wire piezometers installed by the fully-grouted method (Pneumatic piezometers)
	Vertical displacement	Conventional surveying methods Remote methods
	Widths of cracks in structures	Crack gauges
Are the struts being installed correctly?	Load in struts	Calibrated hydraulic jack
Is the excavation stable, and are nearby structures being affected adversely by ground movements?	Settlement of ground surface, structures and top of supporting wall	Conventional surveying methods Remote methods
	Horizontal displacement of ground surface, structures, and exposed part of supporting wall	Conventional surveying methods Remote methods (Convergence gauges)
	Change in width of cracks in structures and utilities	Crack gauges
	Subsurface horizontal desplacement of ground	Inclinometers In-place inclinometers (Fixed borehole extensometers) (Fibre-optic instruments)
	Subsurface settlement of ground and utilities	Probe extensometers (Fixed borehole extensometers)
	Load in struts	Surface-mounted strain gauges
	Groundwater pressure	Open standpipe piezometers Vibrating wire piezometers installed by the fully-grouted method (Pneumatic piezometers)
	Bottom heave	Probe extensometers
Is an individual strut being overloaded?	Load in strut	Surface-mounted strain gauges
Is the groundwater table being lowered?	Groundwater pressure	Open standpipe piezometers Vibrating wire piezometers installed by the fully-grouted method (Pneumatic piezometers)
Is excessive bottom heave occurring?	Bottom heave	Probe extensometers
	Subsurface horizontal displacement	Inclinometers In-place inclinometers

Summary of instruments that can be considered for helping to provide answers to possible geotechnical questions

Table 2 lists the possible geotechnical questions that may lead to the use of instrumentation for externally braced excavations, together with possible instruments that can be considered for helping to provide answers to those questions.

Table 2. Some instruments that can be considered for monitoring externally braced excavations

Possible geotechnical questions	Measurement	Some instruments that can be considered
What are the initial site conditions?	As in Table 1	As in Table 1
What is a suitable design for tieback anchors (by constructing and testing *test anchors*)?	Load in tieback Displacement at head Load transfer in grouted zone	Load cells Dial indicators Surface-mounted strain gauges
Are the tiebacks being installed correctly (by *performance* and *proof testing*)?	Load in tieback Displacement at head	Calibrated hydraulic jacks (Load cell) Dial indicators
Is the excavation stable, and are nearby structures being affected adversely by ground movement?	As in Table 1, except for load in struts Load in tieback	As in Table 1, except for load in struts Load cells (Calibrated hydraulic jacks and load cells: *lift-off tests*) Surface-mounted strain gauges
Is the groundwater table being lowered?	As in Table 1	As in Table 1
Is excessive bottom heave occurring?	As in Table 1	As in Table 1