Geotechnical Instrumentation NEWS

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Introduction

This is the sixty-seventh episode of GIN. Two articles this time.

Interchangeability of Inclinometer Probes

The first article, by Brian Tigani and Rolando Rongo of Monir Precision Monitoring Inc., Ontario, Canada, provides useful practical guidance on monitoring with MEMS digital inclinometer probes. I welcome such nuts-and-boltsy help from experienced users. Any more out there?

Monitoring of Surface Deformation with Robotic Total Stations Using Reflectorless Measurements

The second article, by Damien Tamagnan and Martin Beth of SolData Group in Spain and France tells us about a recent development whereby measurements of vertical deformation can be made by robotic total stations without the need for prisms. This allows us to monitor ground surfaces such as road pavements without obstacles on the surface and consequent interruption to traffic.

Yes, I know that I don't normally publish articles that are written by authors with a commercial interest in the subject, in an effort to keep GIN as a totally professional source of information. But I decided that this article added enough to our toolbox so that I'd make an exception.

Confusion about Initial Readings and Baseline Readings

Some years ago I participated in writing a guide instrumentation specification for a major construction project. Funding regulations mandated that various tasks, including reading the instruments, had to be included in the general contractor's scope of work. In the specification for reading instruments I adopted the term "formal initial readings" (FIRs). These were intended as readings to which all subsequent readings would be referred, hence indicating changes. The FIRs needed to be taken after all installation effects had disappeared, such as 'settling down' after drilling, grouting, welding etc., (remember that swelling of bentonite can cause either reduction of pore water pressure by drawing water out of the pores or increase of pore water pressure by pressing on the soil, and that equilibrium may not be reached for a while), and therefore wording was included to specify timing with respect to installation. FIRs also needed to take into account any non-repeatability from reading to reading, and therefore wording was included to specify how many individual readings were required and how to use these to create an FIR.

This wording has been copied for other construction projects. I've recently learned that others may not fully appreciate the logic behind FIRs, and are confusing them with baseline readings. So I'll try to define what baseline readings are and why they are entirely different from FIRs.

Baseline readings are readings taken over a period of time, before any construction starts, to help in the definition of changes that occur from causes other than construction. For example, seasonal changes in groundwater levels often cause deformation of structures. Tidal and moisture content changes can do the same thing. Climatic changes such as temperature and incidence of sunlight can cause substantial deformation of structures. If these naturally occurring changes are not documented, the task of evaluating measured changes is severely hampered, and it requires significant engineering judgment to adjust day-to-day measured changes to discount those that have nothing to do with construction.

In summary, formal initial readings and baseline readings are entirely different things, and formal initial readings come first.

On a Related Subject

I'm working with a colleague to put together answers to the question, "How should we determine response values (RVs, a.k.a. trigger levels and hazard warning levels)?", and hope to include this in a later GIN. A few thoughts now:

- Don't ignore changes during the green RV period by simply waiting for the green flag to change to amber. Trends during the green period can give useful forewarning.
- Early RVs can be based on calculated changes, whereas later RVs can be based on (unrelated) tolerable changes.

- RVs must recognize the changes that occur from causes other than construction.
- RVs *s*hould be several times larger than the accuracy of measured changes (those last four words are very carefully chosen).

Closure

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

Alla salute! (Italy)

P.S. For those of you who are not long term readers of GIN, here's the background to the line just above. Soon after GIN was born in 1994 a colleague gave me a beer mat inscribed with about a dozen drinking toasts, in different languages. We agreed that they would make appropriate endings to GIN 'columns'. "Alla salute!" is the sixty-seventh different toast to end a column.

Alla salute!

Interchangeability of MEMS Digital Inclinometer Probes

Brian Tigani and Rolando Rongo

This article examines the data collected with Micro-Electro-Mechanical Systems (MEMS) inclinometer probes, using inclinometer probes manufactured by RST Instruments Ltd.

History

Inclinometer systems consist of casings with alignment grooves, inclination sensing probes, communication cables and readout devices. The casing is placed into the ground or attached to a structure which is anticipated to move and the equipment is used to monitor any deformation perpendicular to the alignment of the casing.

Stanley D. Wilson, creator of the "slope inclinometer" in 1954 and co-founder of Slope Indicator Company produced the first production model inclinometer in 1957. Wilson originally attached his inclinometer casing to sheet piling. There has been a tendency to use inclinometers more for dam and soil shear measurements. The majority of inclinometers at Monir Precision Monitoring Inc. are used for monitoring support of excavation walls.

The Survey Process

Analogue vs. Digital (MEMS)

Analogue inclinometer probes have been in use since 1957; however they are not interchangeable. Each probe has its own characteristics and is sensitive to shock and temperature (range: -20 to +50 deg. C) which amplify these characteristics. As a result, the probe used to make an initial reading was thereafter the only probe which could be used reliably to survey that installation. Unlike analogue systems, the MEMS are less sensitive to shock and temperature (range: -40 to 70 deg. C), minimizing such probe characteristics. Also the MEMS system which was tested aids in technician repeatability. For example, the cable grip ensures all technicians read at the same top reference mark, unlike the pulley/cleat assembly typically used with analogue systems.

Data Gathering and Analysis

If different probes survey installations differently, data gathering with only one probe may be a liability in the event of later unavailability for reasons such as; damage, loss, calibration or scheduling conflicts. To address this concern, Monir chooses to take initial readings of every installation with two probes; in the past with analogue and presently with digital. This ensures accurate surveys could always be collected. If a probe is away for its yearly calibration or simply not available, a survey can then be taken without delay.

When first introduced at Monir, we employed the same protocols with the MEMS system, as it was understood that these probes were also not interchangeable. The manufacturer states data gathered from *one* probe are repeatable over 25m of depth to within 2mm, (RST manual, October 12, 2010).

When we make initial surveys of an installation, multiple sets of surveys are taken using two probes to confirm the casing initial position within 1mm over 25m of depth (as compared with 2mm for the manufacturer's specifications). This practice was adopted when attached (not borehole) installation depths in the Toronto area were short, typically 15m. Installation depths for this study ranged from 6.7m to 32.3m.

As we gathered data using different MEMS equipment we began to see a clear trend of interchangeability based on our above criterion. With this trend we questioned the duplicated survey approach and decided in September of 2008 to further analyze our data. It was one thing to get repeatable initial surveys but another to ensure such repeatability for moving installations.

The only way to show that probes were interchangeable was to take consecutive surveys with *multiple* systems and use our above criterion for repeatability. So in addition to two sets of initial readings with different probes, we

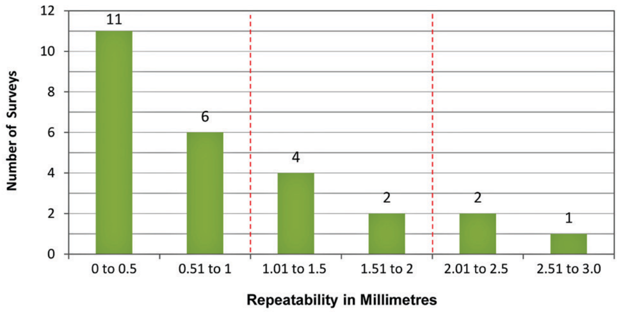

Figure 1. Survey repeatabilities with multiple probes for borehole installations.

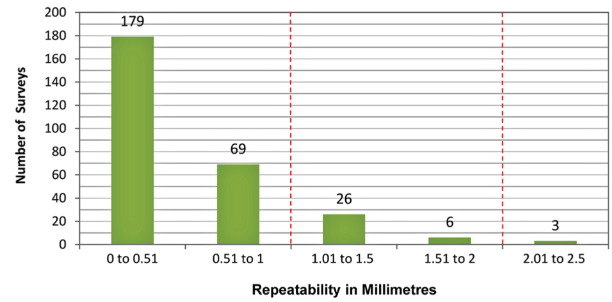

Figure 2. Survey repeatabilities with multiple probes for attached installations.

surveyed using a second probe throughout construction projects. These data were used to build our database.

Study Specifics and Results

Consecutive surveys (A0/A180 data only) were taken with only one probe at two types of installation:

- Borehole installations use ABS casing backfilled with grout into a hole in a suspected zone of ground movement.
- Attached installations use ABS casing attached to piles or rigid structures and backfilled with grout into a caisson wall.

The readings collected were compared and all found to be repeatable to both our criteria and the manufacturer's specifications.

Further consecutive surveys again (A0/A180 data only) using as few as two probes or as many as four probes, were compared for repeatability, with the flowing results:

- Borehole installations. Figure 1 shows 26 surveys. As can been seen, 17 were repeatable within our criterion and 23 met the manufacturer's specifications, representing 65% and 88% respectively.
- Attached installations. Figure 2 shows 283 surveys. As can be seen, 248 were repeatable within our criterion and 280 met the manufacturer's specifications, representing 88% and 99% respectively.

Conclusions

Borehole installations represent 10% of Monir's inclinometers. Typical borehole installations are more out of plumb, have more undulations and undergo more movement than attached installations, and we believe that this is the reason for the poorer repeatability.

As attached installations on piles for excavation support are the majority of Monir's installations, we plan on continuing to focus our attention on these.

Based on the results of this study, Monir will consider probes to be interchangeable for attached installations to the manufacturer's specifications. We will however strive to implement procedural improvements which will achieve the same repeatability for our criterion.

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Monitoring of Surface Deformation with Robotic Total Stations Using Reflectorless Measurements

Damien Tamagnan and Martin Beth

Introduction

Real time monitoring using Robotic Total Stations (RTS) over tunnel excavations in the proximity of diaphragm walls or other construction generally includes monitoring of buildings and ground movements. The challenge in the case of roads and pavements is to leave the site free of any obstacles and to observe surfaces automatically in order to respond to real time monitoring criteria, without installing sensors. The aim is to avoid problems caused by the interruption of traffic and above all, for safety reasons, the danger of making traditional manual topography measurements on an active road.

New generations of robotic total stations allow Reflectorless Surface Point

(RSP) measurements, thanks to a laser beam aimed directly on the surface.

Nowadays two methods of computing surface settlement exist:

- The standard method (single points directly measured by the total station)
- The mesh method (treatment of a number of points to geographically smooth the results).

We have used both methods extensively in Europe over the past few years. Both have advantages and drawbacks.

This article presents the generalities of the technique, its potential limitations and requirements, and then briefly presents two sites where both standard and mesh methods were used.

How does it Work?

3D monitoring with a RTS consists of a zero measurement of a network of points measured in three fixed directions to be able to follow this network over time. Preferably the baseline measurement is performed previous to any construction work. A record of the weather conditions (temperature, pressure and humidity) and all the factors that could influence the measurements is very important.

An automatic 3D monitoring system able to measure surface deformation 24 hours a day is made up of a total station equipped with a reflectorless distance meter and a personal computer which can be operated remotely with specific software able to drive the total station to predetermined locations of the points that are to be monitored. We will refer to this entire system as Reflectorless Robotic Total Station (RRTS) for the rest of this article[1].

[1] *The commercial name of the whole system as developed and used by Soldata is "CENTAURE". This name now appears regularly in articles and specifications, but for the rest of this article and for future generic use we suggest the use of the term RRTS for Reflectorless Robotic Total Stations. As for RTS, the term RRTS will apply both to the total station being used and to the whole system, including all software and data treatment processes.*

Figure 1. Example of Reflectorless Robotic Total Station (RRTS) installation able to measure RSPs and prisms.

During each monitoring cycle the instrument sights at two or three groups of points (see Figure 1):

- RSPs on a flat, homogeneous and planar surface for which vertical deformation is to be monitored. RSPs are not physically marked and are not physical objects: They are just a location on the ground at which the RTS is sighting.
- The stable reference prisms, which permit computation of the correct position and the orientation of the total station.
- If necessary, the same total station and software can sight monitoring prisms installed on structures to be monitored in 3D, the same as for a standard RTS

On completion of the cycle (typically 20-40 minutes, depending of the number of points), the raw data are sent to the database via Wi-Fi or 3G.

If both the availability and the distribution of the values meet the quality criteria then the height of the RSP is calculated and can be published in real time via a web-based GIS. Treatments include sliding statistical analyses of the data. These methods allow removal of any accidental errors produced by the total station, and greatly improve the precision of the data

This system can also trigger alarms sent by SMS or e-mail if predetermined thresholds are exceeded.

System Limitations

References

RRTSs are nearly always installed inside the area of influence of the work site where settlements are expected. The position of the total station and the associated prisms are computed based on reference prisms located outside the area

The adequacy of the whole system is based on the quality of the reference prisms. They need to be:

- Well distributed to guarantee the robustness of the system
- Located in a stable zone outside the area of influence
- Located at a distance which depends on the precision required

Range

Depending on the type of total station used, the range of the distance meter is limited (typically 60-70m). To guarantee a good reflection quality of the laser beam the angle of incidence on the measured surface is also a criterion that influences the range of the measured RSP. Finally the surface

Figure 2. Total stations in Amsterdam sighting prisms and RSP. In this case two total stations are installed to allow a larger number of points to be measured more often. Both total stations can measure both RSPs and prisms.

characteristics (colour, smoothness, material) also affect the range and the precision. All these elements shall be taken into account when designing a site setup.

Obstructions

Due to their location in roads and pavements the RSPs are likely to be randomly hidden by obstacles such as pedestrians or cars, in which case the total station will take the measurements but the data will be filtered during the acquisition chain.

Weather Conditions

Rain, snow and fog clearly downgrade the emitted distance meter signal and can prevent some of the measurements from being made. Snow, leaves or mud on the ground will also change the height of the apparent RSP.

Results of Field Studies, Standard and Mesh Methods

In this section we will present both methods, their advantages and their drawbacks and an assessment of the precision.

The Standard Method

For the standard method the RRTS is simply programmed to sight the road surface in predefined horizontal and vertical angles. The RRTS measures the inclined distance, and the software calculates the variations in vertical position (only) of the point.

It is possible to automatically estimate an adjustment of the horizontal and vertical angles depending on calculated movements of the point and of the stations. This is to try to reduce potential errors linked to the sighted point moving on the ground (there is no search of a prism centre as with the usual use of a RTS, so a movement of the ground or of the RRTS would lead to a different point being sighted for unchanged horizontal and vertical movements).

In Amsterdam (Netherlands) over 82 total stations (See Figure 2) are used to measure surface movements above the tunnel boring machine during the construction of the metro line, both with conventional RTS and with RRTS. Due to the quantity of points measured: 5320 RSP for RRTS and 5820 prisms for RTS, and the delivery period of one hour, the standard method is used to comply with the client's requirements.

In addition to RRTS and RTS a network of manual levelling benchmarks on buildings, quays and on the ground was set up. The 3590 levelling benchmarks confirmed the consistency between the precise levelling and the RSP movements. The precision obtained was better than ±1 mm on the RSPs.

The Mesh Method

The mesh method uses a number of RSPs around the point of interest to smooth and eliminate automatically any surface irregularities, through a geographical statistical treatment of the measurements. This method is therefore more complex, but is has been well proven in practice since 2005.

In Toulon (France) during the construction of the south road tunnel a network of 1830 RSPs have been measured over roads and pavements along the tunnel excavation from 36 total stations fixed positions (see Figure 3). They allowed the measurement of cross sections every 9 meters, larger or smaller depending on the urban environment and to deliver data every 2 hours.

An external control using traditional precise levelling on benchmarks was performed to validate the results with a precision about ±0.5mm.

Figure 3. Reflectorless Robotic Total Station in Toulon.

Table 1. Comparison between the standard and the mesh method

Method	Pros	Cons
Standard Method	• Fast: Time depends on model of total station used: approximately 5 to 10 seconds per reflectorless measurement point. • Simple.	• Slightly lower precision, approximately ±1mm. • Risk of false reading and even false trends depending on the state of the surface.
Mesh Method	• Very high precision in the order of ±0.5mm. • Numerous security quality checks.	• Rather slow process, each point of interest requiring between 30 seconds and 1 minute of sightings.

Pros and Cons

The advantages and drawbacks of each method can be summarised as shown in Table 1.

Conclusion

Real time monitoring with RTS has demonstrated the value of this method for many years. Thanks to the improvement of the range and the repeatability of the laser beam, monitoring of surface deformation with RTS using reflectorless measurements (RRTS) has become reliable, precise and very helpful as an early warning system, detecting movements and trends 24 hours a day.

Generally RRTS is slightly less precise and the range is shorter than the RTS method but for safety purposes it is an ideal solution for dangerous sites and an alternative to levelling measurements with a high frequency of readings.

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