Introduction by John Dunnicliff, Editor

This is the 90th episode of GIN. Two articles this time.

In red book Chapter 15, I put forward a "recipe for reliability of performance monitoring", and suggested that the ingredients in the recipe can be divided into two categories: *instrument ingredients* and *people ingredients*. Others have used the term *human factors* to mean the same as the second category. In my experience the two categories are of equal importance, but very often insufficient attention is given to the human factors, resulting in failure of the monitoring program. The first article in this episode of GIN is about human factors; the second is about instruments.

Human factors will be one of the symposium themes during the 10th International Symposium on Geomechanics (FMGM) in Rio de Janeiro, Brazil in July 2018: http://fmgm2018.com/2018. Because "very often insufficient attention is given to the human factors", please consider very carefully contributing a paper about these to the 10th FMGM: open the above website and click on the "Call for Papers" tab. Abstracts are due by November 4, 2017.

System checks

The first article, by Isabella Ramaccia and David Cook, describes "System Checks" to test whether installed instruments for displacement monitoring provide correct data. In my view this is a very important subject, and one that is too often overlooked.

More on remote monitoring of displacement

In March 2017 GIN I summarized earlier GIN articles on this subject, and included an article about manual reflectorless total station monitoring (MRTS). Here's another one, this time about global navigation satellite system (GNSS) for landslide monitoring, by Zhangwei Ning and Marc Fish. The authors conclude that a GNSS system specially designed for geotechnical instrumentation and monitoring purposes is capable of achieving millimeter-scale precision at acceptable cost and low power needs.

"Deformation" or "displacement"?

If you're a regular reader of GIN (or of other scribblings by the editor), you may have noticed that I've now replaced the word "deformation" by "displacement". Since moving from USA to England nearly 20 years ago, my European colleagues have been encouraging me to make this change — they're right — it's a better word!

Fourth International Course on Geotechnical and Structural Monitoring

The fourth course was held in Rome, Italy in June this year. We had a record attendance: 140 from 31 different countries. The total attendance for the four courses to date (2013-2017) has been 440 from 49 different countries. We haven't yet decided on the venue and date for the 2108 course — watch this space!

One of the regular speakers at the courses wrote to me after Rome, as part of our discussion about what to do next time: "The course and FMGM [held once every four years] are the only two opportunities that monitoring people have to meet and discuss. We can have different opinions about the structure of the course or the location or the selected speakers, but *we have the course!* This is more important than the structure, the location, and the speakers". I like that!

Names of villages in England

There are many delightful ones: I've just returned from a visit to Upper Slaughter and Lower Slaughter in the Cotswolds, in the county of Gloucestershire (pronounced *Glostersheer*). The word 'Slaughter' stems from the Old English name for a wet land 'slough' or 'slothre' (Old English for muddy place).

Fascinating are the names of some villages in the county of Dorset, all within about five miles of each other: The most well-known one of the villages is Tolpuddle, famous for the "Tolpudle Martyrs", who were a group of 19th-century agricultural labourers who were arrested for and convicted of swearing a secret oath as members of the 'Friendly Society of Agricultural Labourers'. At that time 'Friendly Societies' had strong elements of what are now considered to be the predominant role of trade unions. In 1834 the Tolpuddle Martyrs were sentenced to 'penal transportation' (expatriation) to Australia. Names of nearby villages include:

- Puddletown (alternatively called Piddletown — I kid you not — it's on the river Piddle). The name Puddletown means 'farmstead on the River Piddle'. It derives from the Old English *pidele*, a river-name meaning fen or marsh, and *tūn*, meaning farmstead
- Briantspuddle
- Affpuddle
- Piddletrenthide
- Piddlehinton
- Turners Puddle

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

Yeghes da! (Cornish — Cornwall is most south-westerly county in England, neighboring Devon, where I live).

System Checks/Validations
A practical approach for displacement monitoring

Isabella Ramaccia and David K Cook

What?

When a monitoring system is installed a System Check should be undertaken on instruments to confirm that the data collected are correct, correctly identified and correctly transmitted to and received by those needing to review that data. Reference can be made to "*Monitoring Underground Construction, A best practice guide*" published by the British Tunnelling Society, where it is described as "a process for ensuring that the value obtained for a measurement is a true reflection of the actual change in the parameter being monitored". The most comprehensive form of System Checking is the whole System Check. This involves artificially inducing a known displacement to an instrument and testing whether the expected result is reported.

This differs from a pre-installation acceptance test undertaken to verify that the instrument is operating correctly and not, for example, damaged in transit.

The purpose of this article is to describe how System Checks have been undertaken for a number of instrument types so that methods can be determined for future implementation with these and other forms of instrumentation. This concept has developed over time, as instrumentation becomes more complex so that confidence can be established before the monitoring data is used for decision making.

Whilst this article uses displacement monitoring examples the general principles can be applied to all forms of instrumentation.

Other terms such as "Validation Check", "Verification Check", "Validation Process" and "Acceptance Tests" have also been used to describe this work element.

Why?

A System Check provides the necessary confidence that instrumentation is measuring parameters to the correct magnitude and direction.

When a monitoring system is specified it should be unnecessary for the specifying organisation to know how each component of the instrument, communications system and visualisation software operates and is interconnected. For example valid data production will be dependent on the following elements being correct:

- Instrument location
- Instrument orientation
- Wiring instrument to data logger
- Transmission to processing location
- Import to data management package
- Identification of instrument within the data management/visualisation package
- Calibration factors input
- Sign convention
- Use of environmental corrections (such as temperature and pressure)
- Instrument operation (at time of installation)

If a calibrated displacement is input at the instrument, the resulting data can be compared with the direction and magnitude of that displacement at the output software. If it doesn't match, within reasonable limits for the parameters being checked, then the system should not be considered as commissioned and therefore not accepted until the faults are clearly identified and all discrepancies satisfactorily resolved. Note this is not an accuracy check, it should be considered a reality check. This will provide an indication that the instrumentation system meets specification in terms of operation.

A common error with certain types of monitoring systems is that the combined response of instrumentation and software is not tested before the actual effect of the works is detected. This can result in erroneous readings and a need for corrective action. For example, more than one settlement monitoring system has initially reported heave, instead of settlement, simply because instruments had been connected the wrong way round or an incorrect sign convention programmed into the processing or visualisation software.

The System Check will ensure validity of the data (at the time of the check) and confirm the system configuration, which will depend on site constraints. As an example for instruments connected in a chain (i.e. electrolevel beams) validation of the system configuration is also based on the continuity of the chain installed along a structure.

If novel or unproven technologies are proposed then provision of a System Check will provide confidence to the parties involved.

When?

A System Check is most easily undertaken at the time of installation, as part of the commissioning process. If undertaken retrospectively the System Check is likely to disrupt the readings being recorded. As many projects require a period of background monitoring it is important to have confidence in data obtained from the beginning of that period or it may not be possible to use it for the project.

How the System Check is to be implemented must be considered prior to installation so that it is undertaken at an appropriate point in the process. The monitoring designer must consider how the behaviour of the system can be verified and any false alarms trapped as part of the specification requirements of the System Check. A system of testing should be considered to verify that the monitoring system (including data processing) correctly reports the nature of changes before critical works commence. The System Check process should be detailed in the Inspection and Test Plans (ITP) – see the Glossary at the end of this article.

If an Instrumentation and Monitoring system is altered it may be necessary to undertake at least a partial System Check to maintain confidence in the data output for those elements that have been replaced or repaired.

How?

System Checks are specific to instrument type and the requirement must be clearly defined in the specification regarding scope and inclusion as part of the commissioning process. The method used to undertake the System Check should be described in the Method Statement (see the Glossary at the end of this article) and agreed between all relevant parties with the system commissioning not considered as completed before satisfactory completion. This differs from a laboratory calibration test and may not achieve the same accuracy, but does provide a practical check.

Examples of System Checks

The following were undertaken when technologies were first being implemented but the need for System Checks may remain for future projects, for these instrumentation types.

Electrolevels

A System Check was carried out on electrolevel chains installed to structures predicted to be affected by a major tunnelling project. The system was designed so that a calibrated shim could be placed at one end of an installed electrolevel beam and the magnitude and direction of that displacement confirmed in the data visualisation software. This determined whether the entire monitoring system (including instrument, loggers, transmission elements and reporting software) correctly reported both the magnitude and direction of the change. It was used to confirm that electrolevels were correctly wired to the multiplexer/data logger, the data correctly referenced and processed and correct calibration factors used. Discrepancies found were investigated and remedied before commissioning was considered complete.

In-place Inclinometers (IPI)

Sometimes IPIs are installed but when construction influences occur the data indicates displacement in the opposite direction to that expected. At that point, usually at a particularly inconvenient time, it may be necessary to retrieve the IPIs to verify correct installation with consequent project delays.

On one project a calibrated frame was constructed and the fully wired up chain of inclinometers arranged so that each IPI was placed in the frame immediately prior to installation in the casing. Whilst in the frame the IPI was tilted in the plane of interest and displacements recorded (in both magnitude and direction) within the data management/visualisation software.

This provided confidence to the Project Owner regarding output from the IPI system before construction works commenced.

Automatic Total Stations (ATS)

In the early days of ATS, prior to major implementation (72 instruments) on a large infrastructure project, it was necessary to provide confidence to the Project Owner before committing to the major investment required that the instruments would perform as required. A trial was undertaken and an ATS installed (which would be required as part of the full installation) with reference targets and a number of the prisms to be monitored. The location of one prism was capable of adjustment by calibrated distances. This one instrument system was set up, the bugs sorted and a System Check undertaken. The adjustable prism was moved by known distances in x, y and z directions. The data visualisation software was then interrogated to determine the displacements the ATS was measuring relating to that prism displacement. Following successful completion of this trial and operation of this reduced system for a period of months the full ATS system was ordered and installed.

Reflectorless Automatic Total Station (RATS)

The use of RATS was proposed on the ATS project described above, as a replacement for manual levelling in trafficked areas along the centre line of each tunnel, to reduce risk to survey teams. There was a need to demonstrate the system capabilities prior to an investment in the number of RATS to supplement the ATS installation.

An RATS was installed to its proposed location and its reading circle on the ground determined at a number of locations, based on the angle of sight from instrument. At each of these locations discs approximating to the reading circle were applied and the changes in x, y and z for those thicknesses recorded by the RATS. Comparisons were undertaken in dry and wet conditions and on different materials to determine whether the reduced accuracy (compared to manual levelling) was acceptable to the project. Another part of the check was to determine the apparent horizontal displacement of the reflectorless monitored point (and its effect) due to the change in level of that point and mitigation methods implemented.

In addition the total time from reading to data availability including cycle time (the time taken for the instrument to physically take a round of readings from all the reference prisms and monitored reflectorless locations), data transmission, processing through to availability of data for review, was verified before project-wide implementation.

Following this successful trial, installation of the remaining RATS was undertaken, "double decking" with existing ATS locations along the trace, using a moving window approach to minimise the number of RATS to be procured.

Conclusions

Monitoring systems should be System Checked to demonstrably prove they meet design requirements and specifications. Dependent on the instrument type, criteria for testing can be based on the simulation of changes in instrument position/orientation and changes to parameters recorded.

Monitoring related problems can arise from:

- The implicit lack of past experience with proposed instrumentation and/or context in which it is being used
- Shortage of appropriately skilled resource
- Shortages of equipment leading to late supply and rushed installation
- Increased reliance on validation of results and background monitoring
- Erroneous results or unforeseen responses in use
- Potential for non-acceptance of system by third parties (i.e. re-assurance failure and resultant late deployment of conventional systems)

Undertaking a full System Check will assist in the minimisation of adverse effects from these problems. Omission or failure to specify or undertake System Checks on a monitoring system before construction activities commence can lead to inaccurate monitoring results to the detriment of a project.

System Checks provide information which will assist in preventing re-occurrences of issues on future projects.

Whilst a System Check will assist in providing confidence in the instrumentation operation, correct positioning of the instruments must be checked independently as they cannot directly form part of the process described above.

Bibliography

"Monitoring Underground Construction – A best practice guide" published by British Tunnelling Society ISBN 978-0-7277-4118-9. Information about this book is available on-line at www.geotechnicalnews.com/instrumentation_news.php . Scroll to December 2011.

Glossary

Inspection and Test Plan (ITP)

A standard quality assurance requirement, which requires that monitoring systems are supplied with calibration certificates, calibration checking arrangements and specific frequencies and protocols for such checks including any integral processing and reporting software.

Method Statement

A written document that details a safe system of work and identifies the conceivable hazards that may arise during the construction work. Method statements are usually provided to the Project Owner by the main contractor and/or to the main contractor by the sub-contractor(s). The Method Statement should explain in detail the work that is to be undertaken and the necessary measures that need to be in place in order to protect the site workforce and members of the public who may be affected by the work actions.

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A case study of Global Navigation Satellite System (GNSS) in landslide ground movement monitoring

Zhangwei Ning and Marc Fish

Principles of GNSS positioning

GNSS was originally designed for precise navigation and positioning. In recent years GNSS applications have extended to civil and construction industries such as surveying, construction machine control as well as structural/ground movement monitoring. As positioning is the core for most GNSS applications, its underlying principle is similar to a very old surveying technique: trilateration. Both of them rely on the measurement of distances from an unknown point to a certain number of known points (control points). For trilateration these control points are fixed points on the earth surface, while for GNSS the control points are satellites orbiting the earth at a speed of several kilometers per second. As the instantaneous position of each moving satellite on the obit is precisely monitored and known by the GNSS ground control sector, the distance measurement (ranging) is derived from the travel time of the satellite signal transmitted from outer space to the receiver on the earth.

GNSS signals and ranging

GPS (Global Position System) was developed by the USA as the first global operational GNSS. It has been used as a synonym for GNSS until more global or regional GNSS such as

GLONASS (Russia), BeiDou (China) and Galileo (EU) have been developed. A GPS satellite is sending three legacy binary codes known as the Precise code (P (Y) code), the Coarse/Acquisition (C/A) code, and the Navigation (NAV) code. These codes are modulated into electromagnetic waves known as L1 at 1575.42 MHz and L2 at 1227.60 MHz. Both the code and the carrier signal can be used for ranging. The code based ranging is achieved by comparing the time shift between a section of code from the satellite and the same synchronized code generated at the receiver. The carrier-based ranging requires resolving the integer number of wavelengths included in the entire carrier signal from the satellite to the receiver (integer ambiguity), which involves more sophisticated algorithms and yields more accurate results.

GNSS errors and differential positioning

Errors exist in all kinds of measurements including GNSS. The main contributing sources of GNSS errors are: satellite clock error, satellite orbit error, ionospheric delay, tropospheric delay, multipath and receiver noise, causing errors in the orders of magnitude from a few decimeters to several meters. Without removing these errors, the accuracy of GNSS positioning would not satisfy many applications including geotechnical ground movement monitoring, for which sub-centimeter accuracy is expected. The solution to eliminate these errors is differential positioning, on which most, if not all, accurate GNSS positioning techniques rely. In differential positioning, the position of a fixed GNSS receiver (referred to as a base station) is determined to a high degree of accuracy using conventional surveying methods. The position of the base station is also calculated by using either code-base or carried-base ranging, which includes the errors listed above. Because most of the GNSS errors are spatially related, the difference between accurate and calculated position are nearly equal within a limited geographical area. Therefore, a spatially close receiver with its position in question (rover) can integrate the 'difference' received from base station via a wireless data link to 'correct' its calculated positon. The closer the rover is to the base station, the better the correction at base could match to the rover. DGPS (differential GPS) and RTK (Real-Time Kinematic) are the two common differential positioning techniques. The DGPS is code-base ranging with 100-200 km typical baseline (the distance between the base and the rover), providing approximately +/-1meter accuracy whereas RTK is carrier phase-based ranging with 10-20 km baseline, providing cm level accuracy even when positioning fast moving objects.

GNSS in geotechnical instrumentation and monitoring

Ground/earth structural surface deformation is one of the most crucial subjects in geotechnical instrumentation and monitoring (I&M), for which GNSS appears to be a perfect tool, as its direct output is the position of the object to which the receiver is attached. Also, there are some unique advantages of GNSS compared with other common monitoring methods, for example: the distance measurement range of GNSS is almost unlimited in 3D. The base station can be placed very far away on a stable zone from the active monitoring zone. However, GNSS it is still not commonly considered in geotechnical I&M, mainly due to the follow reasons:

- It is a less familiar technology to most geotechnical engineers;
- Its high hardware cost per monitored point (e.g. using high-end geodetic GNSS receiver);
- Many of the GNSS products are not capable of delivering millimeter scale precision;
- Relatively high power needs of the system to provide near-real time data (meaning bulky power supply equipment).

Although there are certain demanding requirements by geotechnical I&M, we shouldn't neglect there are also some very 'favorable' conditions compared with other GNSS applications when designing a GNSS-based monitoring system:

- Although a moving rate of centimeters per day is quite significant to geotechnical engineers, it is still considered 'static' positioning for GNSS which was originally designed to track fast moving objects;
- The area of the monitoring zone is usually not large, so the base station can be located closely to the rover (< 5km), which will help to improve the accuracy of differential positioning;
- The monitoring data is usually only required to be updated every few hours or even less frequently, while the sampling rate of GNSS is usually in 'Hz'.

Implementation of GNSS to monitor landslide movement

A recent pilot project performed by Sixense and Washington State Department of Transportation (WSDOT) geotechnical office has implemented a GNSS system in a small landslide site in Washington State. The project site is located along a short section of a notoriously unstable 40 km long stretch of US Highway 101, between the cities of Aberdeen and Raymond, which is about 170 km to the south east of Seattle (Site photos are shown in Fig. 1 and Fig. 2). This site suffers from frequent small-scale landslide movement, especially during the Pacific Northwest rainy season (November – April). The active landslide head scarp is estimated to be about 100 meters in length and the presumed landslide toe is around 175 meters downslope (~2H:1V slope), near an un-named creek. Over the last decade, WSDOT maintenance crews have had to resurface the highway on an annual basis

Figure 1. Site photo 1.

Figure 2. Site photo 2.

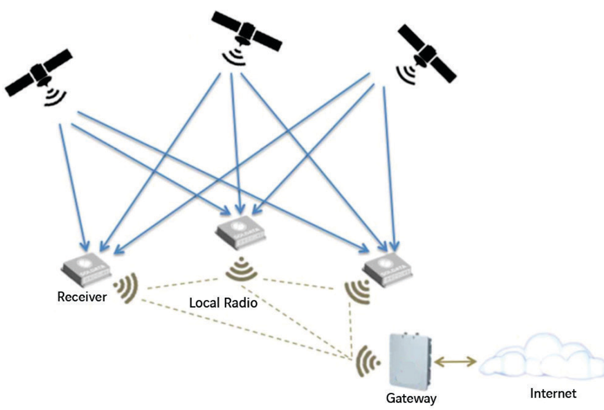

Figure 3. Schematic of GNSS monitoring system.

and have placed nearly 2-3 meters of asphalt over the down sliden block in order to keep the highway level. Since January 2016, recently installed inclinometers and piezometers have been actively monitoring ground movement and groundwater elevations to help develop a landslide response rate to precipitation. This instrumentation has measured ground movement at depths as deep as 34 meters below ground surface, with movement rates approaching 2.5 cm/month during the rainy season. The groundwater elevation appears to rise by as much as 4 to 5 meters between the dry (summer) and wet (winter) seasons, with ground movement accelerating when the groundwater elevation stays elevated over extended time periods.

Figure 4. Layout of GNSS receivers on site (red line shows the outline of the landslide).

The GNSS system deployed at the site includes one base station receiver, four rover receivers and a post-processing gateway. The raw GNSS data is first logged at all rover and base receivers and then transmitted to the gateway via local radio network. The data are then post-processed using carrier-phase ranging algorithms with network adjustment at the gateway to produce high accuracy geographical positions of each rover receiver. From the gateway, which is connected to the Internet via a cellular network, the calculated results are sent to the remote server and accessible to end users via a web-portal. Because the calculating module is removed from the receiver and the antenna is integrated into the receiver, both the hardware cost (per monitor point) and power consumption (0.5 w in this case) are effectively reduced. In addition, by combining public Internet connection and local radio network with mesh topology, it allows for a highly flexible deployment of GNSS node and the gateway (as shown in the schematic of Fig.3).

In April 2016 two rover receivers were installed in the sliding zone (#2 and

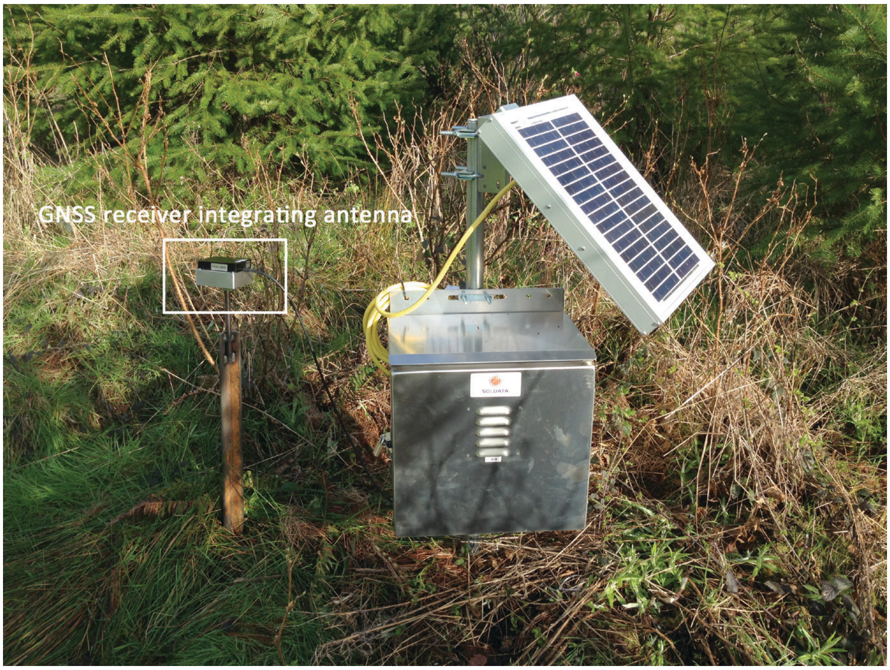

Figure 5. GNSS receiver and its power supply.

#3) while one rover receiver (#4) was installed outside the sliding zone. The base station receiver (#1) was installed at about 80 m away from the head scarp which was assumed to be relatively stable (as shown in Fig. 4). The gateway was installed near the base receiver. The entire system was powered by solar panels. Fig. 5 shows one of GNSS receivers installed on site.

Learned from the monitoring data

During the pilot project, this GNSS monitoring system had continuously been collecting data for nearly a month, delivering the post-processed results every minute. Although the test duration is not very long and the active landslide season had passed, the results show very promising repeatability (precision) as well as capture small anticipated ground movement.

Fig. 6 shows the time-series graphs of the relative ground movements of receiver #2 and #4 in horizontal E/W (East is positive in Y-axis) and vertical directions (upwards is positive in Y-axis). The following observations can be drawn from Fig. 6:

- The precision in both horizontal and vertical directions of the two receivers are in millimeter-scale while the horizontal precision is better than vertical precision.
- Receiver # 2 which is inside the slide zone shows almost zero movement in E/W direction and 3 mm vertical movement downwards while receiver # 4 which is outside the slide zone shows about 5mm movement towards the west (upslope direction) and about 10 mm movement upwards (all relative to the base station). From the relative moving direction shown in receiver #4, it seems plausible that the base station is still located within the influence zone of the landslide, and it moves in the opposite direction as to what receiver #4 shows. If this is the case and we assume receiver #4 to be the stable point instead, the actual movements of receiver # 2 would become approximately 12 mm downwards and 5 mm towards the downslope direction (west).

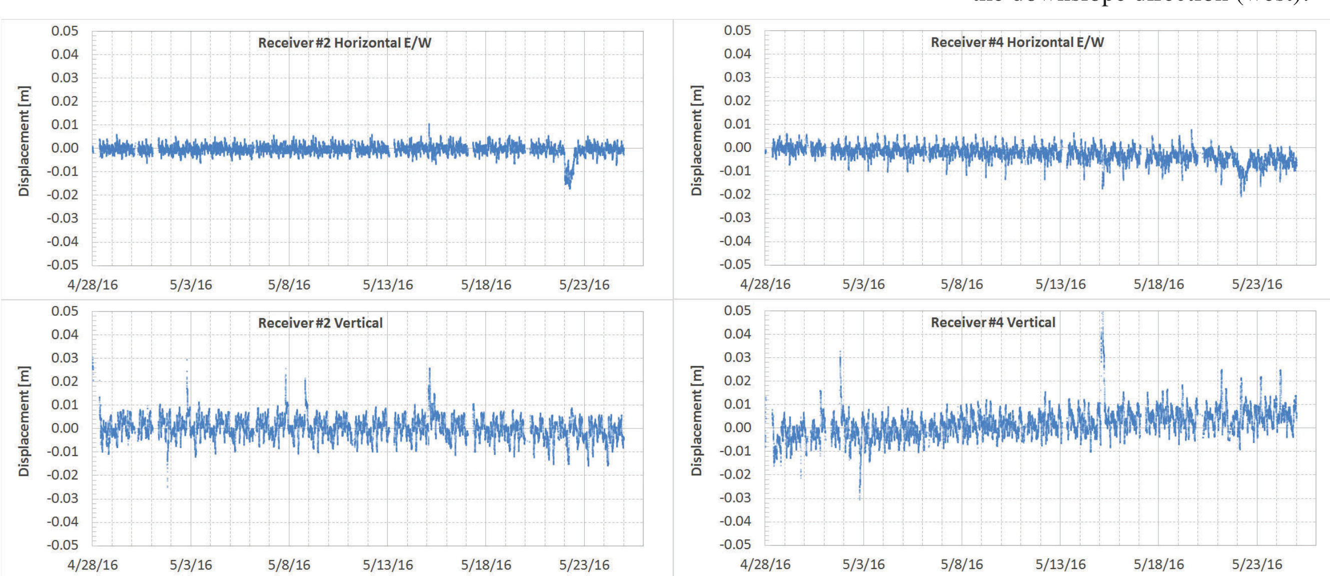

Figure 6. GNSS monitoring data.

This coincides with the horizontal movement measured by a nearby inclinometer during the same period.

- There is a clear daily cyclical pattern shown in the monitoring data. This is related to the residual of atmospheric errors after the majority of them have been removed by differential positioning. Thus applying a 24-hour averaging on the detailed one-minute interval data would further improve the precision of the results.
- There are a few major spikes shown in the data, which is due to the rainy weather as recorded by a local weather station.

Final words

The pilot project demonstrates that with today's developments in GNSS hardware and post-processing techniques, a GNSS system specially designed for geotechnical I&M purposes is capable of achieving millimeter-scale precision at acceptable cost and low power needs.

As more GNSS systems become globally operational by the end of this decade, the availability of GNSS satellites will be largely increased while the hardware cost will decrease. Using GNSS for high precision, near-real time monitoring is anticipated to become common in supplementing the existing conventional geotechnical I&M methods.

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The CFEM (2006) was prepared by a team of 17 contributors to keep abreast of current state-of-practice and to provide a consistent and up-to-date cross-reference to the National Building Code of Canada (NBCC2005) and the Canadian Highway Bridge Design Code (CHBDC 2000 and 2005), enabling the user to interpret the intent and performance requirements of these codes.

Le MCIF est désormais disponible en français. Pour rester au fait de l'état actuel de la pratique et fournir des renvois cohérents et à jour au Code national du bâtiment du Canada (CNBC 2005) et au Code canadien sur le calcul des ponts routiers (à CCCPR 2000 et 2005), une équipe de 17 experts a préparé le MCIF 2013.

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