Introduction by John Dunnicliff, Editor

This is the 82nd episode of GIN.

One article this time, a discussion and a closure.

Use of the ShapeAccelArray (SAA) in a rockfill dam

The article by Marc Smith compares settlement data collected from an SAA with data collected from a conventional horizontal inclinometer during the recent construction of a rockfill dam. There is clear preference for the SAA.

Because data collection will be ongoing, the author has agreed to send me a contribution for GIN in about three years' time, to update us on the accuracy and durability of the SAA, by which time it will have been in place for about six years.

Discussion and closure of article in December 2014 GIN about wireless monitoring

The discussion by Adam Dulmage and Matt Trenwith of "The fundaments of wireless monitoring – things to consider" by Simon Maddison is followed by a closure by the author.

Another corporate update

In March 2015 GIN I reported on several corporate changes, notably the acquisition by Nova Metrix LLC, Woburn, MA (www.nova-metrix.com) of various instrument manufacturers with familiar names. Nova Metrix has now acquired Schlumberger Water Services Technology Group, which is comprised of Westbay Instruments and Waterloo Hydrogeologic. Those two companies will be familiar to GIN readers as manufacturers of multipoint piezometers.

What are the characteristics of an engineer?

An astronomer, a physicist, and an engineer were travelling north from London by train. They had just crossed the border into Scotland, when the astronomer looked out of the window and saw a single black sheep in the middle of a field. "All Scottish sheep are black," he remarked. "No, my friend," replied the physicist, "*Some* Scottish sheep are black." At which point the engineer looked up from his paper and glanced out of the window. After a few seconds thought he said blandly: "In Scotland, there exists at least one field, in which there exists at least one sheep, at least one *side* of which is black".

Closure

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

Eis Igian (Greece)

Performance of a ShapeAccelArray (SAA) for settlement monitoring of a large rockfill dam

Marc Smith

Introduction

A ShapeAccelArray (SAA, www.measurandgeotechnical.com) was installed alongside a conventional horizontal inclinometer (INH) during the recent construction of a dam. This setup allowed the comparison of settlement results from both types of instrument and helped gain confidence in the relatively new SAA technology for embankment dam engineering. This article shows Hydro Québec's (Canada) experience with the performance of a SAA used to monitor settlements in a large rockfill dam during its construction. This experience is based on a dam safety context where instrumentation is permanent and expected deformations are relatively small and progress slowly.

Dam cross section and instrumentation

The Romaine-2 dam is a 112 m-high asphalt core rockfill structure part of the Romaine-2 hydroelectric project located in northern Québec, Canada. Dam construction took place mainly in 2012 and 2013 after river diversion by means of two cofferdams. Reservoir impoundment started during spring 2014.

The asphalt core has a width varying from 0.85 m at its base to 0.5 m near the crest. It is flanked on both sides by support and transition zones (3M and 3N) having maximum particle sizes of

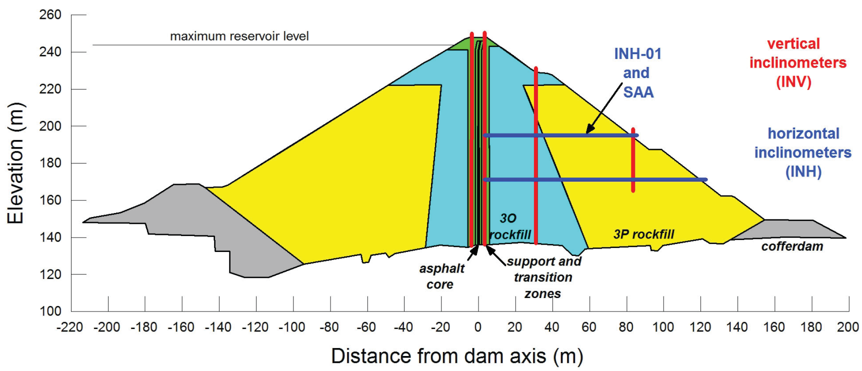

Figure 1. Schematic cross section of the Romaine-2 dam and location of inclinometers and SAA.

80 mm to 200 mm. The rockfill shell is comprised of two zones: the 3O internal shell has a maximum allowable size of rock particles of 0.6 m compared to 1.2 m for the 3P outer shell. Figure 1 shows a schematic cross section of the dam at valley center.

Material placement procedures were of utmost importance to prevent excessive fill movements during dam construction and operation which could have detrimental effects on the thin asphalt core. The placement of support/transition as well as rockfill zones required optimized material characteristics and increased compaction energy to achieve maximum density and thus minimize settlements during construction, impoundment and operation. Therefore, internal deformations of the dam needed to be closely monitored to assess its behaviour as well as in situ materials rigidity parameters to be used for stress/deformation modelling and also to quantify the effects of the increased compaction energy used for the Romaine-2 dam compared to other Hydro Québec projects.

A series of inclinometers is installed in the dam body to measure deformations (see Figure 1). A total of four vertical inclinometers (INV) anchored in bedrock (far end considered fixed) are used to monitor movements closer to the core as well as in the 3O and 3P rockfills. The INV in the 3P zone represented on Figure 1 is located at a section where bedrock elevation is higher. Two horizontal inclinometers (INH) and one ShapeAccelArray (SAA) are also installed to monitor settlements. The far and near ends of these three instruments are not considered fixed. Figure 2 shows the location of the INV, INH and SAA.

The SAA is installed along INH-01 (see also Figure 1). An access road on the dam crest and downstream face allows instrumentation readings.

INH characteristics

The two INH are composed of 1.5 m-long grooved ABS casings installed horizontally in a trench excavated in the placed rockfill. Settlement readings are made using an accelerometer probe which measures tilt at every 0.5 m in the plane of the probe wheels travelling in the top and bottom grooves of the casings. The probe is inserted in the horizontal inclinometer using a system of return cable and pulley. The return cable is installed within a separate pipe alongside the inclinometer casing. The tilt measurements from two sets of readings (probe reversed end-for-end) are converted to settlements at the office.

INH were installed in other Hydro Québec projects but have been subject to operation problems after two to three years due to ice build-ups inside the casings as well as pulley and return cable malfunctions. These problems had a significant effect on the availability and the reliability of results.

Long-term settlement monitoring along a horizontal plane gives valuable information related to the deformation of the various types of materials constituting an embankment dam. Deformations need to be measured during the construction (load increase due to fill placement), impoundment (load due to reservoir) and operation (creep) phases of the dam life cycle. Another option was thus needed to obtain reliable settlement measurements. A SAA was therefore installed in the Romaine-2 dam to gain confidence in this relatively new technology.

SAA characteristics

A SAA consists in a series of rigid segments separated by special joints which can tolerate the range of settle-

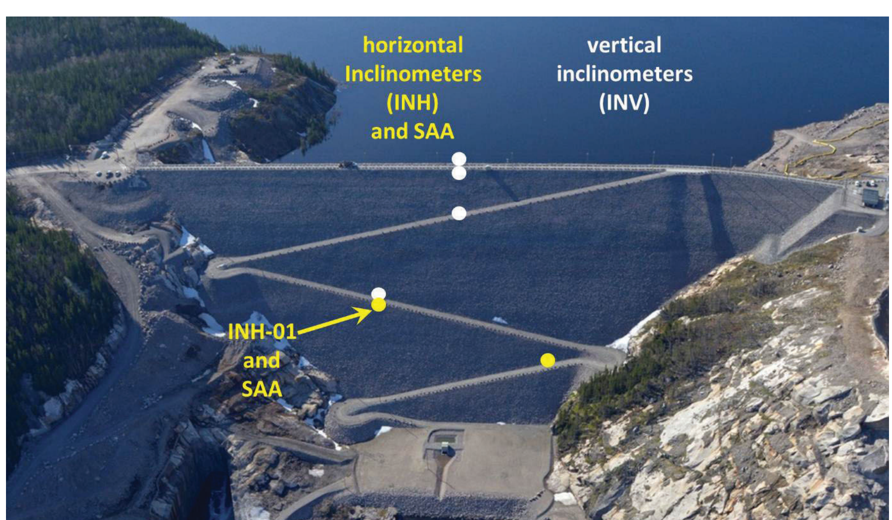

Figure 2. Location of inclinometers and SAA.

Figure 3. Installation of INH-01 and SAA.

ments expected in the dam. Each segment contains a triaxial gravity sensor measuring tilt at every 0.5 m which is automatically converted in settlements. The readings are made using a portable computer and a specialized program. The Romaine-2 SAA is located next to INH-01 to compare results from these two types of instrument. Figure 3 (looking upstream) shows the installation of INH-01 as well as the SAA which needs to be inserted into a protective PVC conduit.

The installation procedures for both types of instrument are similar. They have to be placed in an excavated trench and protected from large fill particles by using bedding sand, geotextiles and by controlling the grain size distribution of surrounding soils. Moreover, as for a INH, twisting of the SAA must be avoided by carefully aligning cable markers since the software used for data collecting and processing is calibrated according to this alignment.

Measurement and data processing procedures

Measurements along the Romaine-2 SAA (and also INH-01) are taken relative to the near end (the downstream end of the instruments i.e. near the operator) and are corrected considering measured displacements of a nearby survey point.

Readings of the 76 m-long INH-01 requires at least two persons for the handling of bulky equipment and cables. Vehicle accessibility to the instrument is thus essential. Reading time is in the order of hours and can be greatly increased in adverse weather conditions which can also decrease measurement reliability. Only basic checks of the reasonableness of readings can be made in the field. Data processing programs needed to be customized for the Romaine-2 context. Moreover, the INH probe was subject to bias shift errors for which corrections were not trivial since both ends of these instruments are not considered fixed.

The Romaine-2 SAA has a length of 76 m. The specified maximum instrumented length of a typical SAA cable is 100 m but multiple cables can be joined to allow measurements for greater lengths. Readings and data processing are realized in minutes using a portable computer. The actual shape of the series of SAA segments can be immediately viewed on screen. Automated data acquisition and transmission are also possible which can alleviate instrument accessibility problems in Romaine-2 such as in winter when the downstream face of the dam is covered with snow.

Reported accuracy of instruments

The reported random error for INH measurements is approximately ± 1.4 mm per fifty readings. Considering that this type of error tends to accumulate with the square root of the number of readings, the expected random error for INH-01 would be around ± 2.4 mm. However, systematic errors such as those related to probe bias, depth positioning and the effects of adverse weather on the instrument (and the operators) can be much higher and cannot always be entirely corrected.

The reported accuracy deformation value for a SAA is ± 1.5 mm per 32 m. This value tends to increase with the square root of the length which leads to an accuracy of ± 2.3 mm for the SAA installed in the Romaine-2 dam. This value has been confirmed

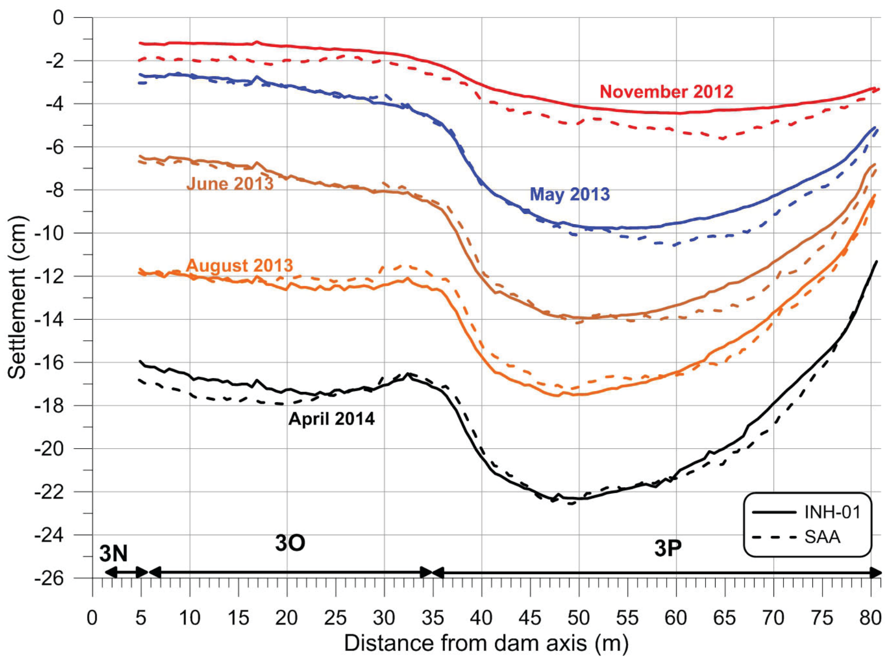

Figure 4. Measured settlements by INH-01 and SAA.

occasionally in the field by repeated measurements for time intervals of less than a few days. Also, the effects of systematic errors, if present, have not been identified.

The random errors/repeatability of both types of instrument are comparable. They are adequate for the purposes of settlement measurements in Romaine-2 namely dam safety assessment and modelling as well as quantification of the effects of increased compaction energy. The uncertainties related to other geotechnical parameters pertaining to the dam have a greater influence on these three aspects. Differences in global accuracy between the SAA and INH-01 are mainly due to systematic errors related to the reading conditions and data processing procedures.

Measured settlements in the Romaine-2 dam

Installation of INH-01 and SAA took place in October 2012 (see also Figure 3). This date corresponds to the initial state of the instruments from which subsequent readings are compared to compute settlements. Figure 4 shows a sample of measured settlements during the construction phase of the Romaine-2 dam.

Both types of instrument clearly show a greater compressibility of the 3P rockfill, as expected. April 2014 corresponds to the last reading during the construction phase. This date now corresponds to the new initial state for the impoundment and operation phases in which the settlement measurements are carried on.

Results on Figure 4 also show that differences between INH-01 and SAA are less than ± 1 cm which is acceptable considering the dam height and thus the internal stresses (up to 2 MPa) and also, as stated before, the uncertainties related to other geotechnical parameters. Figure 5 shows a more detailed representation of these differences. A positive difference indicates that INH-01 measured a greater settlement value than the SAA.

Differences shown on Figure 5 are representative of random errors and uncorrected systematic errors pertaining to INH-01 and SAA.

Conclusions

Settlement monitoring of the Romaine-2 dam is required during the construction, impoundment and operation phases of the dam life cycle. The analysis of the internal deformations allows the assessment of dam behaviour as well as in situ materials rigidity parameters for stress/deformation modelling. The effects of increased compaction energy used during construction can also be quantified. However, the uncertainties related to

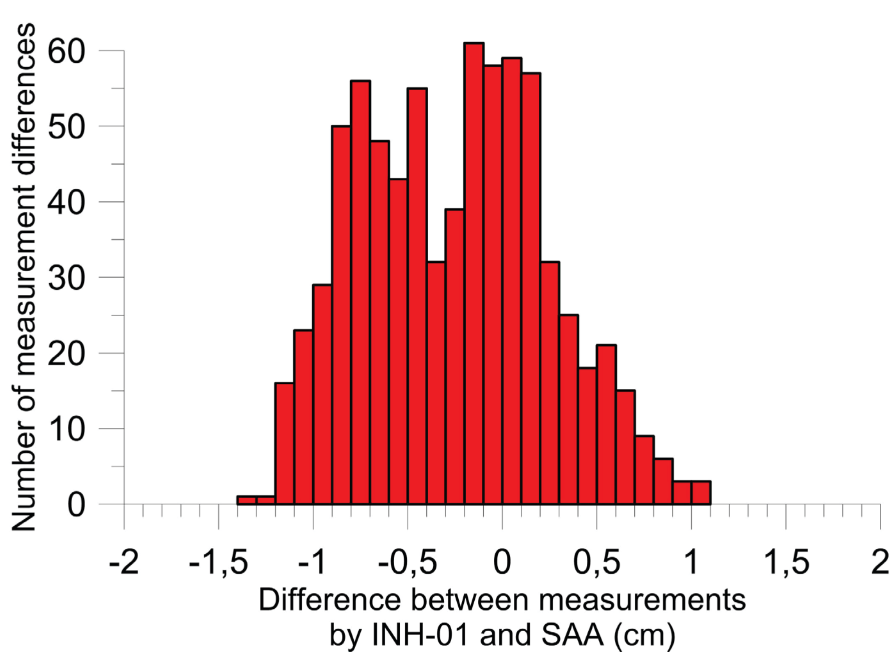

Figure 5. Differences between measured settlements by INH-01 and SAA.

other geotechnical parameters pertaining to the dam have a greater influence on these three aspects than the differences between the SAA and INH-01 measurements.

Considering this context, a SAA represent an interesting alternative to a conventional INH. The installation procedures for both types of instrument are similar as well as global accuracy although the SAA appears less prone to systematic errors. However, the SAA provided significant advantages over INH-01 due to easier and faster measurement, in situ checking and data processing procedures. Simple automatic data acquisition and transmission options are also available for the SAA which can alleviate accessibility problems and give more flexibility in determining instrument reading frequency.

Both INH in the Romaine-2 dam began to show signs of malfunctioning after less than two years of operation. Operation of the pulley and return cable became more difficult with time, and ultimately impracticable due to excessive probe and cable friction inside the inclinometer casing and/or the return pipe. Readings had to be postponed until summer 2015 to assess if these friction problems are caused by ice build-ups. The SAA is still performing well after nearly three years but its long-term durability and accuracy remain to be proven.

SAA offers more possibilities than conventional inclinometers for measuring internal deformations in dams, since there are no series of casings to install and to access later for readings. A series of six horizontal SAA cables will be installed in a 92 m-high embankment dam to be constructed in 2015 and 2016 to monitor settlement in the upstream and downstream rockfill shoulders

The Romaine-2 experience has shown that a SAA installation can have higher initial hardware costs than a conventional inclinometer. However, these costs can be recouped in a longer term considering reading and data processing time, instrument accessibility as well as durability.

Both types of instrument, SAA and INH, provided useful results for Romaine-2 but the SAA did so more conveniently, with more flexibility and, apparently, for a longer period of time.

Marc Smith
Hydro Québec
Dam Safety Division
75 René-Lévesque west, third floor
Montréal, Québec, Canada
H2Z 1A4
Tel. 514-289-2211 ext. 5162
E-mail: smith.marc@hydro.qc.ca

Discussion of "The fundaments of wireless monitoring – things to consider" by Simon Maddison. Geotechnical News, Vol. 32, Number 4, December 2014

Adam Dulmage and Matt Trenwith

This is a very useful article when considering data acquisition options for geotechnical monitoring (or any application for that matter). We have direct experience with mesh networks in mining environments, primarily underground, but also many surface applications, and we will touch on some of the lessons learned in these harsh environments.

The term 'wireless'

In many cases, the term 'wireless' is used interchangeably with 'Wi-Fi' - so let's clarify this point first (as this tends to be a hot topic with mining companies right now). 'Wireless' can be any type of technology that does not use wires for communication. It can use any range of frequencies, bandwidth, protocol, antenna type, etc. It is a very generic term. 'Wi-Fi' is much more specific and is defined as any wireless local area networking product based on the IEEE 802.11 standard. This is what most home wireless networks are built upon - your computer and your cell phone typically have a Wi-Fi radio built into them. 'Wireless' as it relates to geotechnical monitoring is almost always NOT Wi-Fi, but often a purpose built sensor network designed just for data acquisition and monitoring of (typically) low power sensors.

Frequency selection

So, onto the good stuff. Talking about frequencies — 2.4GHz is generally license-free worldwide, and 900MHz is license-free primarily in North America and Australia, so this needs to be considered at the beginning of the project. However, additional restrictions may be imposed by the mining firm, especially in blasting zones. There is also a significant difference in signal propagation between 900MHz and 2.4GHz. 900MHz is more forgiving, allowing non-line-of-sight

(NLOS) transmission which is often the case for an underground or tunneling environment where line of sight can be challenging. Another consideration is power consumption and range. All other things equal, a 900MHz radio will provide up to 2.7 times the range than the otherwise equivalent 2.4GHz product for the same given transmit power. This means that for a same given installation the transmit power of the 900 MHz radio can be reduced, further improving battery life. A typical underground range for our 900MHz mesh network (battery-powered) is between 50-150m at +14dBm transmit power and using a +3dBi omnidirectional antenna , but can sometimes throw as far as 350m when tunnel size and conditions are ideal. Surface range with a standard omni-directional antenna is typically 300-1000m.

Data backhaul

Data backhaul options in mining are unique in comparison to surface. Often there are no backhaul options at all, and in these cases a store-and-forward type of system where the data are collected and relayed to a central gateway which can then be polled at a later time is quite beneficial. However, this is not the ideal option as real time data is sacrificed. In most North American mines there is usually a radio network for voice communication (called Leaky-Feeder), and also fibre-optic cables for backhaul. Fibre is always the preferred option, allowing for much higher bandwidth than leaky feeder, and in most cases this is what is used in the top-tier mines worldwide. In this way, the mesh is deployed to the point where the sensors are installed (sometimes upwards of 50 nodes in a linear fashion) and relayed back to the gateway for backhaul over fibre to surface.

Network topology

The network topology should always be designed with robustness in mind, so ensuring that there are redundant links is important. In the case of mining, wireless node placement is critical to ensure not only that the signal propagation is the best available, but the risk of damage to the node is minimal from effects from blasting and damage caused by vehicles. The considerations for surface deployments are often very different in nature. Things like snow, rain, wind, extreme hot or cold then become potential issues and cause for concern. Snow and rain may affect signal propagation, whereas with extreme hot or cold one also has to consider the effects on battery life over time. If you deploy in the middle of winter in a forested area, what will be the effect of leaves growing on the trees in the spring - will this affect your signal (let me answer that for you: yes). If careful consideration is taken during the planning phase, there is a very high probability of success during deployment.

The future of wireless monitoring is promising, and should never be discounted just because someone has 'tried wireless before' without success. Both businesses and consumers alike are driving the research and development of new wireless technologies and applications every day, so what may have been problematic before can now be resolved. It's always worth picking up a copy of GIN to see what's new and improved!

Adam Dulmage and Matt Trenwith
Mine Design Technologies Inc.
6-1045 John Counter Blvd.
Kingston, ON Canada K7K 6C7
Tel: +1-613-549-5223,
email: adulmage@mdt.ca,
mtrenwith@mdt.ca

Response/ Closure

Simon Maddison

It is very positive to hear of Adam and Matt's practical experiences with using wireless mesh for monitoring in the extremely demanding and specialised domain of mining. This is precisely the sort of circumstance where mesh shows its strengths in terms of ease of deployment, robustness and flexibility – but properties that are also indispensible in many if not most geotechnical monitoring applications.

They make some very valuable points relating to wireless frequency and power. There are limitations on certain frequencies in many countries, as well as specific radiated power limits, both factors which are generally treated much more liberally in North America in comparison to Europe for example! This is a challenge for suppliers operating in international markets in terms of what equipment operating frequency and power is supplied to reach the largest possible range of customers. For this reason 2.4GHz is probably the most favoured frequency.

For data backhaul, it is correct in our experience that it is necessary to work with whatever options are available when underground. However with a flexible gateway solution, it should be possible to hook up to whatever transmission media is available, using industrial grade communications interface equipment. We have provided a multiplicity of such solutions for a range of installations in metro railway tunnels, including the use of solid state industrial PC's for storage and even rendering of data for local access.

My final point is that there are a number of emerging wireless monitoring companies, often with claims that cannot be backed up or where performance is not as stated. I fully endorse the conclusion regarding wireless geotechnical monitoring solutions, but go further. Wireless should be a prime choice but only one that has been shown to really work; then and only then can one say there are now available leading-edge solutions supporting 100+ node networks and running for up to 15 years on a single battery reporting every 20 minutes and with stable precise data in a tough and busy mining or geotechnical environment.

Simon Maddison, Senceive Ltd.
Hurlingham Studios, Ranelagh Gardens, London SW6 3PA, England
Tel: +44 7679 5720 email: smaddison@senceive.com