Integration of SAA technology for coastal rock slope movement monitoring at Gascons, Gaspé Peninsula, Québec, Canada.

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ABSTRACT
This paper describes deployment and automated data delivery for a diverse range of sensors, including arrays of MEMS (micro electromechanical system) sensors, at a rocky site in Québec. Sensed quantities include weather, crack movement, tilt, and pore water pressure. Articulated MEMS arrays called ShapeAccelArrays (SAAs), have also been installed and are being evaluated for measuring deformations in rocky terrain.

RÉSUMÉ
Cet article décrit le deploiement et la surveillance automatisée d'une série de capteurs, incluant des chaînes des capteurs MEMS, à un site rocheux, au Québec. L'acquisition comprend l'ouverture des fissures, la météo, l'inclinaison, et les pressions d'eau. Des chaînes de capteurs articulés à base de MEMS, appelés ShapeAccelArrays (SAAs), ont aussi été installées pour valider leur application pour mésurer les deformations du terrain rocheux.

1 INTRODUCTION

Miniaturized electronics and digital processors embedded within arrays of sensors have greatly increased the number of measurement points that can be deployed within a geographical area of interest. Communication bandwidth has also increased, making it possible to move large amounts of data in near-real-time from remote sites with or without wires.

This paper describes the deployment of geotechnical sensors on the Gaspé Peninsula in Quebec, Canada, near the municipality of Port-Daniel-Gascons. The sensors monitor a railway line hugging the southern coastline of the peninsula. The rails are underlain, and overshadowed from up-slope, by sedimentary rocks, fractured in many places. The most active part of the site is shown in Figure 1. The geology and geotechnology of the site are described in papers presented in the proceedings of this conference (Cloutier et al. 2010 and Locat et al. 2010).

In October, 2009, instrumentation was installed to monitor various atmospheric, surface and sub-surface points to track deformation over long time periods. The installation has the potential to improve safety at this site, and provides a testbed for technologies that could be of importance at other locations. This paper describes the type of data being measured, and its delivery.

Figure 1. Railway near the municipality of Port-Daniel-Gascons.

2 SENSORS

Figure 2 shows the major features and sensor locations at the "Gascons" site. A single pair of rails hugs the coast, with the Baie des Chaleurs of the Atlantic Ocean approximately 63 m below at the bottom of a cliff. A hill rises above the tracks to an elevation of more than 100 m.

The full complement of sensors is shown in Table 1.

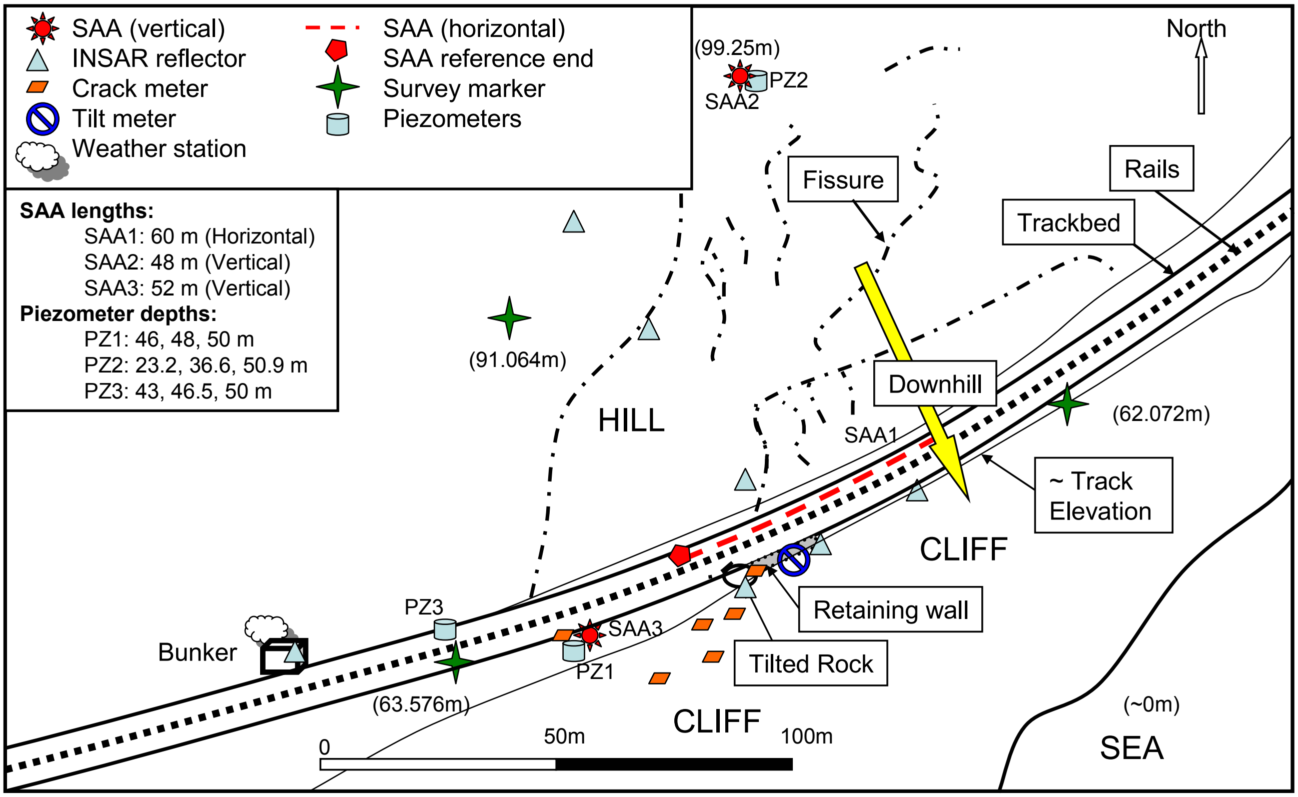

Figure 2. Placement of sensors.

Table 1. Sensor details (Qty = Quantity).

Category of Sensor	Qty	Interface	Length m	Total Number of Sensors (including Temperature)	Measure	Auto-Logging
SAA (vertical)	1	RS485	52	325	3D Deformation	Yes
SAA (vertical)	1	RS485	48	300	3D Deformation	Yes
SAA (horizontal)	1	RS485	60	375	2D Deformation	Yes
Crack meter	6	Vibrating Wire		20	1D Deformation	Yes
Piezometer	9	Vibrating Wire		18	Pore Press.	Yes
Tilt meter	1	Vibrating Wire		1	Inclination	Yes
Precipitation	1	DIO		1	Rainfall	Yes
Atm. Temperature	1	A/D		1	Temperature	Yes
Atm. Pressure	1	A/D		1	Air Pressure	Yes
Anemometer	1	DIO		1	Wind Speed	Yes
Inclinometer casing	1	manual	60		3D Deformation	No
Extensometer anchor	30	manual			1D Deformation	No
INSAR reflector	8				Deformation	No
LIDAR survey					Elevation	No
GPS	1	manual			Reflector Pos.	No
Total	63		220	1043		

The sensors marked “Auto-Logging” are connected to a data logger in a bunker (“Bungalow” in Figure 2). The bunker has 120VAC power and a phone line. An uninterruptible power supply (UPS) protects against power outages.

One of the six vibrating-wire crack meters is shown in Figure 3.

Figure 3. Crack meter (shown before installation was completed).

3 MEMS ARRAYS

Many of the sensors are conventional geotechnical instruments. The three SAAs (Danisch et al., 2005, Bond et al., 2009) are arrays of MEMS (Micromachined ElectroMechanical System) sensors. An SAA is shown in Figure 4. SAAs are used to measure deformation in a manner similar to in-place inclinometers, but at many more points and with greater ability to withstand large deformations. The large number of sensors in each array is indicated in column 5 of Table 1.

SAA technology grew out of earlier work on high-sensor-density arrays using fiber optic bend and twist sensors (Danisch et al., 1998). In the prior-art “ShapeTape” technology, bend and twist along a ribbon-shaped path were measured to determine 3D shape of the path. For SAA technology, two-degree-of-freedom (2DOF) inclinations are measured along a path constrained not to twist.

MEMS accelerometers in each segment of an SAA are used to measure the inclinations of the segments. This gravity-referenced measurement is much more stable and accurate than would be possible using fiber optic bend and twist sensors to measure local angles without an overall reference field. In contrast to conventional arrays of inclinometers, the SAAs use mechanical constraint of torsion within the array rather than from an external grooved casing, and provide hundreds of measurement points in a self-contained array that rolls up on a reel for storage or transport.

Each SAA has rigid segments 50 cm long (See Figure 4), each containing three orthogonal MEMS accelerometers. 30 cm segments are also available. In-array microprocessors at 8-segment intervals, with associated analog-to-digital converters, digital temperature sensors, and multiplexing circuitry provide for digital transmission of 24, 16-bit tilts and one 12-bit temperature from each group of 8 segments.

Figure 4. Left: SAA on reel. Right: SAA rigid segments connected by joints that resist twist. Segments hold MEMS accelerometers, microprocessors, and electronics.

Special joints between the segments minimize torsion and allow for up to 90 degrees of bend from segment to segment. The non-torsion joints make possible a calculation of 3D rotation at each joint, using just two Tilts. The rotations are used to calculate a 3D polyline representing the shape of the array (if none of the segments is closer than 30 degrees to horizontal). In the near-horizontal case, different mathematics are used in the calculation algorithm, yielding a 2D polyline. All calculations, including compensation for temperature, sensor offsets, and sensor gains, are done automatically in software, using factory calibration files.

MEMS arrays are installed in PVC electrical conduit with an inner diameter of 27 mm. In vertical installations, SAA joints swell slightly under in axial compression, which results from the weight of the array after installation. This snugs the array into the conduit. In vertical installations, the conduit is grouted into a borehole, cased or not. In horizontal installations, the conduit may be buried in a trench.

In this installation, 3 m sections of conduit were glued and taped over the arrays and then the conduit with array inside was either fed into a borehole and grouted in (Figure 5), or buried in a trench (Figure 6).

The principle is the same for SAAs or for conventional in-place inclinometers: the conduit or casing is grouted in so that it will bend in response to soil movement. The rigid segments tilt in response to bends. The conduit is approximately 20 times less stiff than 80 mm inclinometer casing. The SAA requires no grooves to maintain torsional alignment.

Figure 5. Vertical installation of SAA already inside PVC conduit.

Figure 6. Horizontal installation of MEMS array inside PVC conduit in a trench in the rail bed.

4 LOGGING

The automated sensors are all connected to a single Campbell Scientific CR1000 data logger (Campbell Scientific, 2010). The logger and associated equipment are shown in Figure 7.

Some of the cable runs exceed 200 m, but in all those cases the communication is either by vibrating wire (VW) interface or RS485 serial communication (see Table 1). Precipitation, atmospheric temperature, atmospheric pressure, and wind speed sensors, which are located near the logger, use pulse counting and analog voltage interfaces.

Multiplexers (MUX's) direct pulse excitation to each of the VW sensors. A VW interface performs Fast Fourier Transform analysis of the vibration frequency of each transducer to infer the sensor value (displacement or pressure).

Each MEMS array is connected to a serial port of the logger through an "SAA232" converter. Each converter enables a port on the logger to communicate with a MEMS array using RS485 protocol. The SAA232 also provides control of power to the SAA, and surge protection. An SAA is only powered if the serial port is active. Each in-array microprocessor in the SAA has a unique address, and is interrogated by the logger for its 25 sensor values. This is done up to 1000 times for each microprocessor, to obtain average raw data values with minimal noise (less than 10μG). In this installation, the logger saves only the averaged data, not all the samples, to conserve memory.

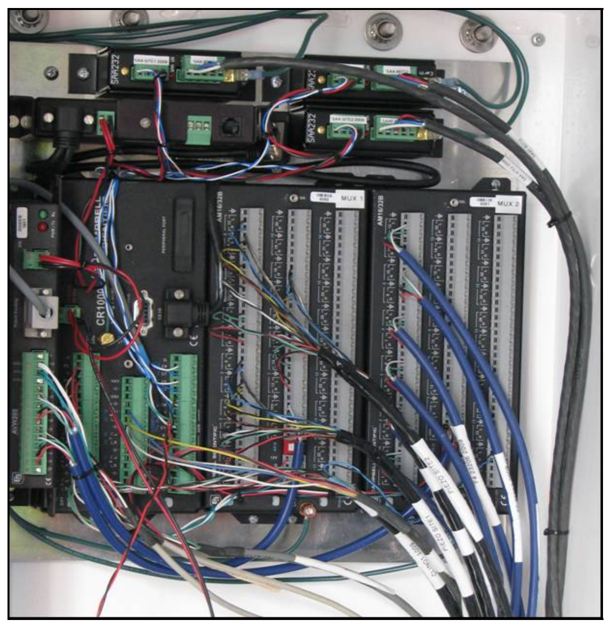

Figure 7. Logger with MUX's, VW interface, modem, and SAA232 converters.

5 COMMUNICATION

At this site a telephone line was available, so a wired modem was used. The logger will also work with a wireless connection to the cell telephone data network through a "cellnet" modem. In both cases, the logger is available for interrogation through an IP address on the internet.

The logger is interrogated using Loggernet software (Campbell Scientific, 2010). The interrogation results in a download of all data held in the logger, or any desired portion. It is also possible to change the data collection program in the logger over the internet connection.

6 SOFTWARE

The logger is programmed for data collection using CR Basic (Campbell Scientific, 2010), which has functions for all the conventional sensors. The CR Basic program is compiled, resulting in a data collection program held in non-volatile memory in the logger, for acquiring data from the sensors. Subroutines for interrogating SAAs through the CR1000 have been developed by the manufacturer of SAA (Measurand, 2010).

Data collection from an SAA requires an "include file" during compilation. This file contains background subroutines and parameters (such as serial numbers of the in-array microprocessors, serial port assignments, and number of samples to average) that simplify programming. When compilation is complete, the logger contains a data collection program for acquiring data from all the attached sensors at programmed intervals.

Data from the conventional sensors such as piezometers and crack meters can be converted to engineering units either in the logger or in Loggernet software operating on raw data.

The large amount of data from the MEMS arrays requires post-processing of the raw data. This is done using SAACR_raw2data software (Measurand, 2010). The post-processing can be carried out automatically by using Loggernet to make a command-line call to the post-processing software.

The three arrays produce X, Y, and Z values from 320 locations, 365 times a year. SAA3D viewer software (Measurand, 2010) is used to show the data as colored surfaces (colors are keyed to deformations) or more-familiar "SI" style curves. Data may be exported to other applications in ASCII or Matlab format.

7 DATA

Continuous data acquisition from SAA sensors started in January 2010, with an acquisition rate of one reading per day. The two vertical SAA strings were put in place to help determine the positions of failure planes at two locations. The horizontal SAA was set next to the railroad track to monitor deformation of the railroad ballast. Long-term repeatability of SAA is approximately ±1.5mm per 30m (Dukuze, 2010, Rollins, 2009). Conclusions based on deformations below that level should be avoided.

In the analysis of the following data, one has to remember that the overall failure mechanism involves planar, and/or toppling, failure mechanisms in well-stratified sedimentary rocks. Any vertical path is likely to intercept multiple failure planes.

7.1 Vertical SAAs

Two vertical SAA strings were installed at locations "SAA2" and "SAA3" in Figure 2, and the results are shown in Figures 8 and 9. Near SAA3, a biaxial inclinometer was installed down to a depth of 60m to enable comparison of both methodologies. For both sites, when drilling was done, core data were acquired, including core recovery (%) and RQD (Rock quality Designation).

At SAA3 (Figure 8) the absolute cumulative displacement, near the top, was about 5mm while nearby extensometer data indicate a displacement less than 2 mm. By inspection of Figure 8, there seems to be significant shift in the displacement data (although close to the accuracy limit of the instrument) at the depth of about 20m. Below that depth there are other steps but since they are less than 3 mm in magnitude, they are not considered yet as potential failure surfaces. Toward the surface, the RQD profile in Figure 8 shows some significantly low RQD values above the depth of 20m.

At SAA2 (Figure 9), the absolute displacement near the top is about 8 mm, and displacements are significant down to a depth of 23 m. Another significant shift in the displacement data is also seen here at a depth of 14 m. The nearby extensometer data indicate a cumulative displacement of about 5 mm. The RQD data from this borehole show a possible transition near that depth. The estimated depth of failure here is close to the estimated one at SAA3.

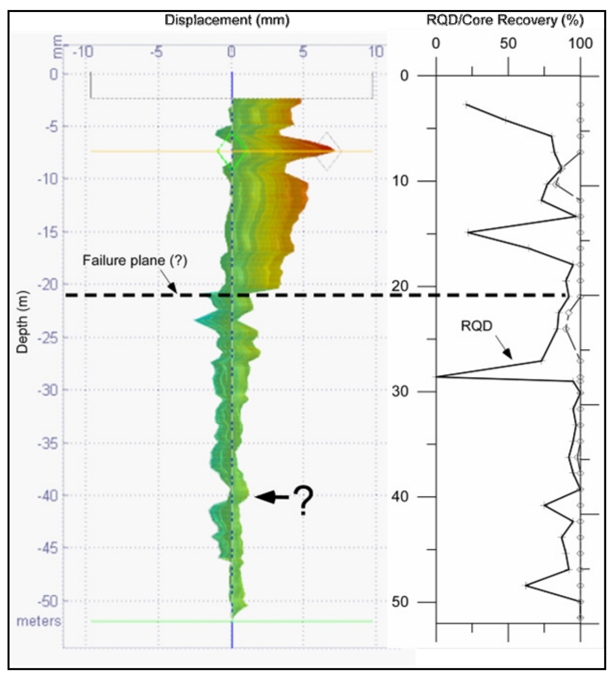

Figure 8. SAA displacements, RQD and Core Recovery profiles at SAA3 (south of tracks). The lower "?" indicates a possible incipient failure surface.

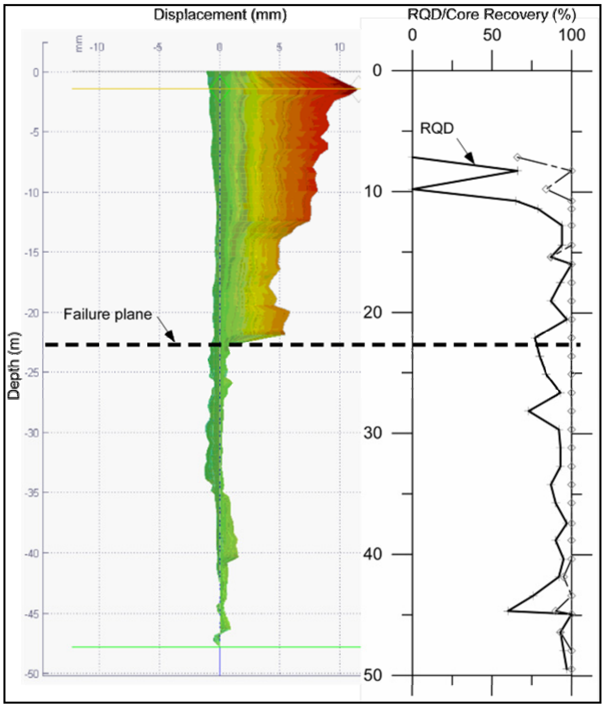

Figure 9. SAA displacements, RQD and Core Recovery profiles at SAA2 (north and above tracks).

In the future, some attention will be devoted to a sinuation which appears to be developing between depths of 6 and 11 m in SAA3 (Visible in Figure 8). Analysis of the sinuation indicates it could possibly reflect a vertical compression of that portion of the SAA and casing, with lateral deformation allowed by the low RQD in that region, and the flexibility of the narrow casing (27 mm inside diameter). The sine shape has an amplitude of approximately ±5 mm laterally, distributed over approximately 5 m. Z data over that range of depths shows a differential vertical compression of about 0.2 mm, shown in Figure 10.

At the time of writing, the slope displacements measured using SAA sensors are just becoming large enough to represent significant measurements. The actual data on movement direction are still unclear at this time and are not commented on here.

7.2 Horizontal SAA

Data from the horizontal SAA ("SAA1" in Figure 2) show an overall decrease (or settlement) relative to the western end of the string. The profile is given in Figure 11 and its detailed location in Figure 12. The SAA string has been put in place over a sand layer and partly disturbed ballast so that the absolute

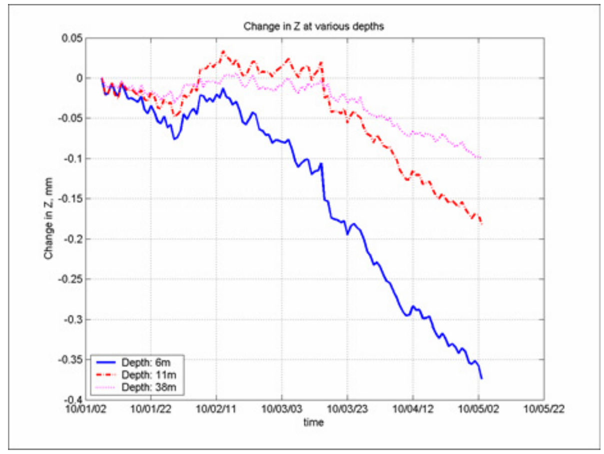

Figure 10. Possible vertical compression measured by SAA between 6 and 11m depth.

displacement seen in Figure 11 could be largely due to the settlement of this material.

Still, it is interesting to note that there is a sharp change in the settling of the SAA string starting 20 m east from the reference end of the SAA. This is at a point corresponding more or less to the beginning of a large block inclined toward the east, i.e. in the direction where the maximum settlement (about 18 mm) is observed. The closest crack meter which is aligned to the large block ("F1" in Figure 12, and also shown in Figure 3) experienced a significant decrease in displacement at the same time as the settlement captured by the SAA horizontal string 40 m east along its length (Figure 13). This would suggest that the movement of the ballast may be partly influenced by movements of the underlying bedrock.

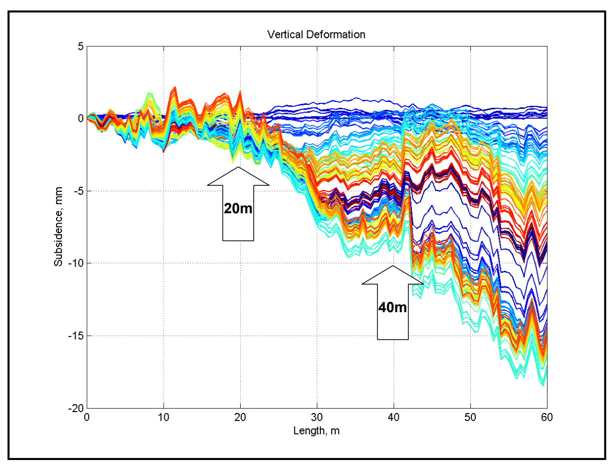

Figure 11. Settlement profile from horizontal SAA1. "20m" and "40m" are distances along the SAA, referred to in the text.

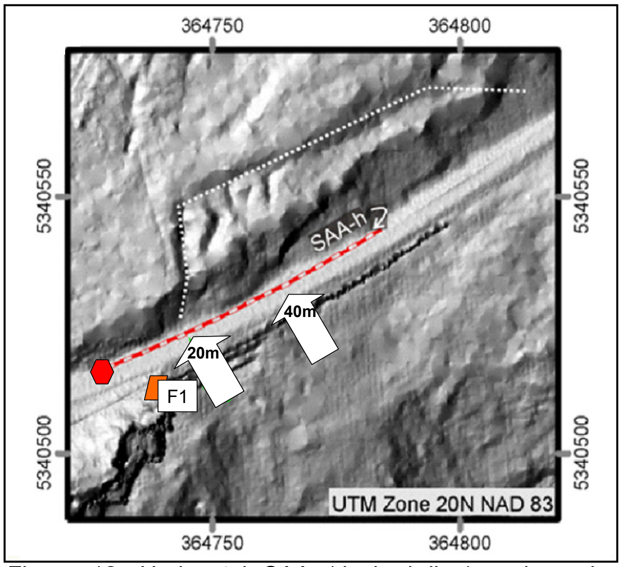

Figure 12. Horizontal SAA (dashed line) and crack meter F1, showing distances also indicated in Figure 11. The west reference end of the SAA is marked. The dotted line emphasizes a large block.

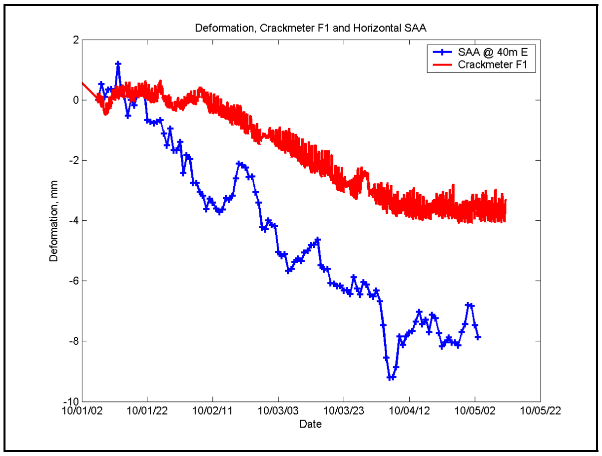

Figure 13. Deformations from crack meter F1 and horizontal SAA.

8 EXAMPLE FROM ANOTHER SITE

Data from a site in Minnesota with more dramatic movement are shown in Figure 14 (A and B views) and Figure 15 (A vs. time at -6 m). The collapse of a roadway at the site, which involved deformations exceeding 2 m vertical and 2 m lateral, is shown in Figure 16.

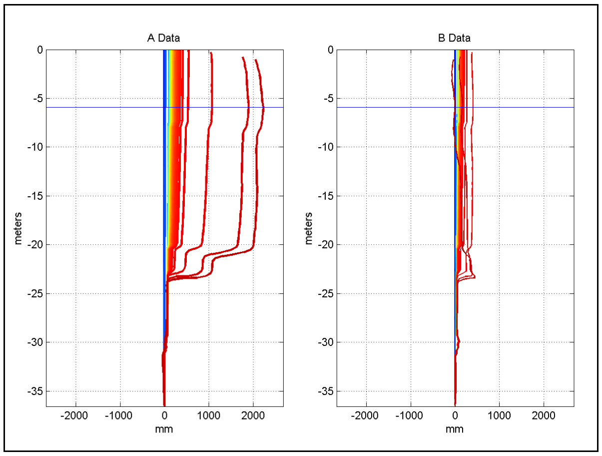

Figure 14. A and B data from Minnesota landslide site.

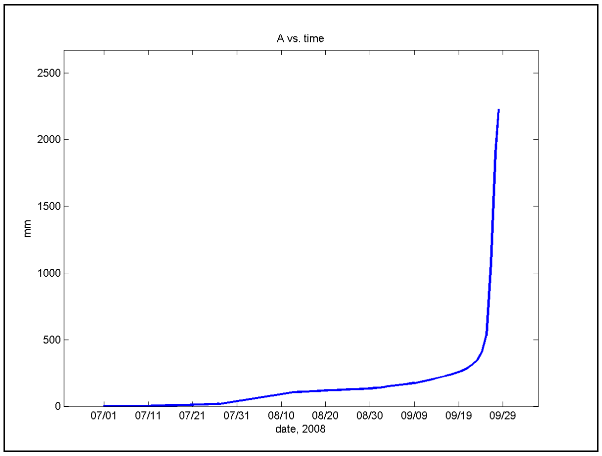

Figure 15. A data vs. time for Minnesota landslide site.

Figure 16. Minnesota site after a major slide.

In this case the sharply increasing shear rate was picked up by two nearby SAAs down-slope from the roadway at least 10 days before the event. Highway traffic was diverted before the collapse, based largely on the data from the SAAs. It is noteworthy that almost two years after the event, the two SAAs are still functioning.

The Minnesota site is supported by clay rather than rock, but the Minnesota example demonstrates that monitoring can be successful in avoiding the disastrous effects of landslides.

The instrumentation for the Minnesota site and a detailed description of the slide are reported by Dasenbrock (2010).

9 CONCLUSIONS

Extensive instrumentation has been installed to monitor an active rock slide in Québec. Over 1000 active sensors are deployed on and below the surface, including MEMS deformation arrays, piezometers, crack meters, a tilt meter, and a weather station. Data from all active sensors are acquired autonomously by a logger at the remote site, and can be collected using the internet. The site also has passive INSAR corner reflectors with attachments for GPS measurements, extensometer anchors, inclinometer casing, and survey markers which provide additional deformation data.

The site will be monitored for at least several years to gain a better idea of magnitude and location of geotechnical movement, with objectives of improved safety at the specific site, and to act as a test bed for new geotechnical instruments and methods of analysis.

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