Structural Integrity Monitoring (SIMS) of Pipelines at Geohazardous Locations

A.H. Mohamud, I. Weir-Jones
Weir-Jones Engineering Consultants Ltd., Vancouver, B.C., Canada

GeoCalgary 2022 October 2-5
Reflection on Resources

ABSTRACT
Structural Integrity Monitoring Systems, SIMS, utilizing both conventional and fibre-optic based sensors, are an effective, robust, and accurate way of quantitatively monitoring a variety of parameters associated with the structural integrity of pipelines in the vicinity of geohazards. These may consist of unstable slopes, areas of settlement, environmentally sensitive locations, or areas of seismic risk. In their various configurations, the monitoring systems enable the pipeline operator to manage integrity risks, and provide advance warning of developing hazardous conditions so that pre-emptive remedial actions can be taken prior to a loss of containment. This paper presents a technical background of the various monitoring technologies currently or potentially being used. For strain and temperature-based measurements, these utilize discrete resistance, discrete fibre-optical, and distributed fibre optical cable sensors. Settlement can be measured autonomously using various angular and displacement sensors to define the extent and magnitude of the deformations. To monitor vibration and fatigue, sensors can be used to provide real-time analysis of potentially hazardous situations. A number of case histories will be used to illustrate the use of a range of sensor and system architectures.

RÉSUMÉ
Les systèmes de surveillance de l'intégrité structurelle, SSIS, utilisant à la fois des capteurs conventionnels et à fibre optique, constituent un moyen efficace, robuste et précis de surveiller quantitativement une variété de paramètres associés à l'intégrité structurelle des pipelines à proximité des géorisques. Il peut s'agir de pentes instables, de zones de peuplement, d'emplacements écologiquement sensibles ou de zones à risque sismique. Dans leurs diverses configurations, les systèmes de surveillance permettent à l'exploitant du pipeline de gérer les risques d'intégrité et de fournir un avertissement préalable de l'apparition de conditions dangereuses afin que des mesures correctives préventives puissent être prises avant une perte de confinement. Cet article présente un contexte technique des diverses technologies de surveillance actuellement ou potentiellement utilisées. Pour les mesures basées sur la contrainte et la température, ils utilisent des capteurs discrets de résistance, de fibres optiques discrètes et de câbles à fibres optiques distribués. Le tassement peut être mesuré de manière autonome à l'aide de divers capteurs angulaires et de déplacement pour définir l'étendue et l'amplitude des déformations. Pour surveiller les vibrations et la fatigue, des capteurs peuvent être utilisés pour fournir une analyse en temps réel des situations potentiellement dangereuses. Un certain nombre d'études de cas seront utilisées pour illustrer l'utilisation d'une gamme d'architectures de capteurs et de systèmes.

1 INTRODUCTION

Pipelines are a critical and important method of transporting liquids and gases in the resources sector. They are often transporting resource products such as oil, gas, condensate, diluent, tailings slurry, or treated water from the extraction location to a location of processing and distribution such as a refinery complex or waste storage such as a tailings dam. The lengths of pipelines can range from a few meters to thousands of kilometres. This means that pipelines will generally traverse varying surface and subsurface conditions and geohazards throughout their route. Geohazards are defined as natural geological processes and features with the potential to cause death or injury to persons and damage or loss to property and infrastructure (Komac et al., 2013).

Buried pipelines, in particular, are susceptible to many geohazards, which can vary and change in their development over time. These geohazards are typically located in areas with hostile environments such as water crossings, swamps and permafrost, unstable slopes, landfill zones, locations with heavy rainfall, and areas of seismic risk. In these areas, adverse conditions induce forces on the pipeline resulting in deformations which can cause settlement, bending, buckling, displacement and ultimately loss of containment.

The vast majority of geohazards, and their impact on pipeline integrity, develop in a time-dependent manner. For this reason, monitoring, and the development of a progressive database, should be commenced as early as possible on pipelines located in potentially hazardous locations. It is always more cost-effective to mitigate a potential issue than to repair a leak and the consequences of a loss of containment.

Pipelines need to be monitored on an ongoing basis to ensure that they operate safely throughout their design lifespan. Once the geohazards in a given location are identified, a comprehensive pipeline monitoring programme should be designed and implemented by experienced instrumentation engineers. These monitoring programmes often utilize monitoring methods that are qualitative, semi-quantitative or quantitative, and they should be selected carefully to ensure that the geohazards identified do not adversely affect the pipeline's structural integrity. The ultimate objective of any pipeline monitoring

programme should be to detect adverse conditions developing around the pipeline before a loss of containment occurs.
A solution to monitoring and managing a pipeline's susceptibility to geohazards is to obtain direct strain, displacement, and temperature measurements from the pipeline and surrounding ground using conventional discrete sensors and distributed sensing technologies. This allows for the proactive mitigation of integrity risks before there is a loss of containment, the result is a reduction in maintenance costs and the validation and refinement of numerical models.

2 STRUCTURAL INTEGRITY MONITORING SYSTEMS, SIMS, FOR PIPELINES

2.1 Overview of SIMS for Pipelines

SIMS for pipelines are monitoring systems which collect quantitative information about the pipeline's structural integrity which can be incorporated into an operator's pipeline integrity management system, PIMS. Quantitative information which can be obtained using SIMS includes:

- Strain (axial, hoop, and shear)
- Residual Stress (principal and minor stresses)
- Temperature (surface of the pipeline and surrounding ground)
- Vibration, Pressure, Tilt, etc.

SIMS typically utilize either discrete sensing or distributed sensing technologies. Discrete sensing can comprise of point sensors such as strain gauges, thermistors, pressure transducers, tilt sensors, geophones, and accelerometers.

Once a suitable sensor technology is selected for the application, this critical data should be collected and/or transmitted on an ongoing basis and on a time interval that is based upon the level of geohazard risk. For example, if a pipeline is traversing an unstable slope that is susceptible to landslides and is near a water crossing, then a SIMS utilizing a real-time data collection method should be employed. This ensures that data is continually being collected and processed so that any adverse conditions that may develop are detected in advance.

As noted above, it is widely accepted that very few natural or mechanical processes occur instantaneously, there are almost always precursor events which occur over a finite period of time. These characteristically increase in frequency, rate, and magnitude as the potential failure of the component, in this case a pipeline, approaches. As a result, a SIMS should be carefully selected to monitor the pipeline's structural integrity at geohazardous locations, detecting the adverse conditions before a loss of containment.

2.2 Discrete Sensing Technologies

A conventional method for monitoring the structural integrity of a pipeline consists of installing discrete sensors at locations of interest on the pipe. These include over-bends, under-bends, side-bends, expansion loops, and areas where buckling may occur. Discrete sensors can measure a pipeline's strain, temperature, pressure, vibration, and/or tilt at a discrete location.

Discrete sensors used in pipeline monitoring generate either electrical signals (analog or digital), or fibre optical ones (such as Fibre Bragg Gratings, FBG), the selection depends on the application. The benefit of using fibre optic-based technology is that there are no transmission cable length restrictions (can transmit data kilometres away to a valve house), and they are impervious to electrical noise and moisture.

Typically, discrete strain and temperature sensors are installed on a prepared surface of the pipeline by removing the existing pipe coating, the sensors are then tack-welded onto the exposed steel. This is the preferred method as it ensures that the sensors measure the actual strains and temperatures on the pipe surface. Another method of installing discrete sensors includes bonding or gluing the sensors overtop the existing pipe coating.

Discrete sensors are usually installed at the crown, invert and spring-line around the pipe circumference. This assembly forms a single monitoring station. Figure 1 shows various discrete strain and temperature sensor installations carried out by Weir-Jones Engineering field crews in Canada on buried pipelines traversing geohazardous locations. Once the sensors are installed on the pipe surface, they are protected by applying pipeline wrappings such as visco-elastic or petrolatum-based tapes and rock guard material. This ensures that the sensors are not damaged during backfill. The location is then backfilled and compacted with sand, pea gravel or other appropriate material. The signal cables are routed to the surface and terminated in a readout enclosure.

Figure 1: Various discrete sensor installations on buried pipelines traversing geohazardous locations in Canada.

2.3 Wireless Sensor Monitoring Systems, WSMS™

Once the discrete sensors are installed on the pipeline, the ditch is backfilled, and the signal cables are routed to the surface. They are then terminated in a readout enclosure. Although the traditional method has been to manually read the analog sensor data using a hand-held reader, advances in low-power, wireless Internet of Things, IoT, technology, allow the processing and transmission of data to occur right at the sensor installation location. These units are powered by lithium-ion batteries, eliminating the need for line power and an instrumentation bungalow. Figure 2 shows the installation and commissioning of WSMS™ enclosures at a discrete sensor installation on a buried pipeline in Canada. The sensor data is transmitted wirelessly from each location to a base station (such as Weir-Jones' ***OmniMonitor®***, acquisition unit) in quasi-real-time and subsequently to the desired data display location (valve house/SCADA, server/cloud, or data portal, etc.).

Figure 2: WSMS™ enclosures and antennae installed at the surface and transmitting data wirelessly.

The WSMS™ allows critical data to be transmitted wirelessly to a local base station from each sensor installation. This may be located several kilometres away, and at this point, the data is autonomously sent to a server/cloud and displayed on an online data visualization portal. Figure 3 shows the typical WSMS™ data collection and transmission layout and flow. Hundreds of discrete sensors can be connected to a WSMS™, and data can be available to engineers and operators.

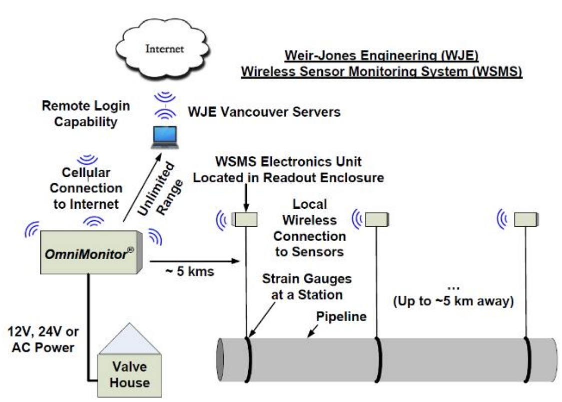

Figure 3: Typical Wireless Sensor Monitoring System, WSMS™, data collection and transmission layout.

2.4 Discrete Sensing – Case Studies

Lateral pipeline movement detection:

A pipeline section traversing a river valley in Eastern Canada was undergoing visible deformation due to side-slope movement. The solution was to dig bell-holes at 5m intervals and install discrete strain gauges on the pipeline. The sensors were installed at the crown and spring-line positions of the pipe for this application. We were able to confirm that the slope movement continued to adversely affect the pipeline over the following year and that the spring-line strains were reaching the tensile alarm threshold. To mitigate the pipe movement, the operator daylighted the entire affected area, performed a strain relief, and moved the pipe back up the slope to its original position. The result was that the pipeline tensile and compressive strains recovered and stabilized, as shown in condition 3 in Figure 4.

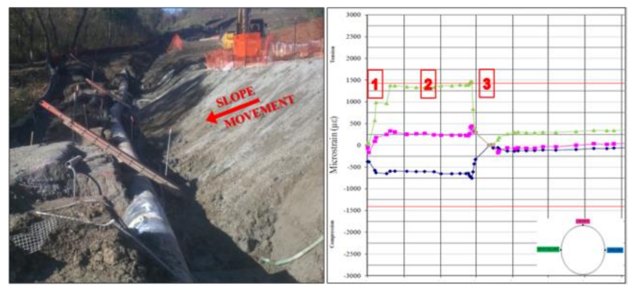

Figure 4: Side-slope movement affecting a pipeline, detected using discrete electrical resistance-based sensors.

Downslope pipeline movement detection:

A pipeline section in Northern Canada instrumented with discrete strain sensors (electrical resistance-based) experienced increasing tensile strains at the crown and compressive strains at the invert, indicating the development of an over-bend, as shown in Figure 5. The operator conducted a strain relief and re-buried the section. Strain stabilized for a year before continuing to increase gradually, prompting the operator to conduct another strain relief operation two years later.

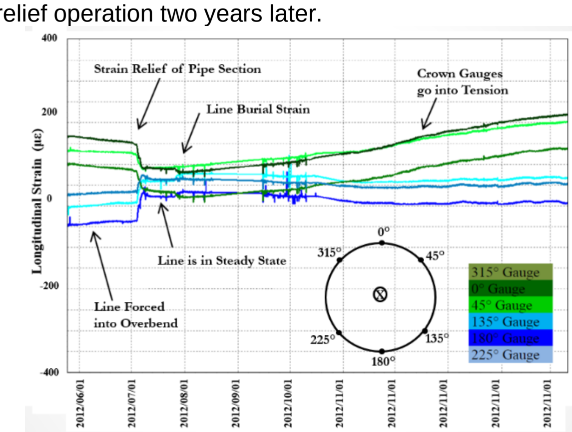

Figure 5: Tracking pipeline deformation utilizing discrete strain gauges installed at the crown and invert.

Detection of localized strain concentrations at expansion loop bends:

A pipeline section in Northern Canada was instrumented with discrete strain and temperature sensors using Fibre Bragg Gratings (FBG) optical sensing technology. The sensors were installed on the expansion loop side-bends at a section known for downslope movement and landslides. Over the course of a decade, the strains remained relatively stable, until localized compressive strain concentrations started to develop rapidly at the intrados of the side-bends due to downslope movement, as shown in Figure 6. This indicated that buckling was likely occurring at these locations. These anomalous strain trends were used to refine the existing numerical models for the pipeline. The operator was informed and was able to commence remediation activities before a loss of containment occurred.

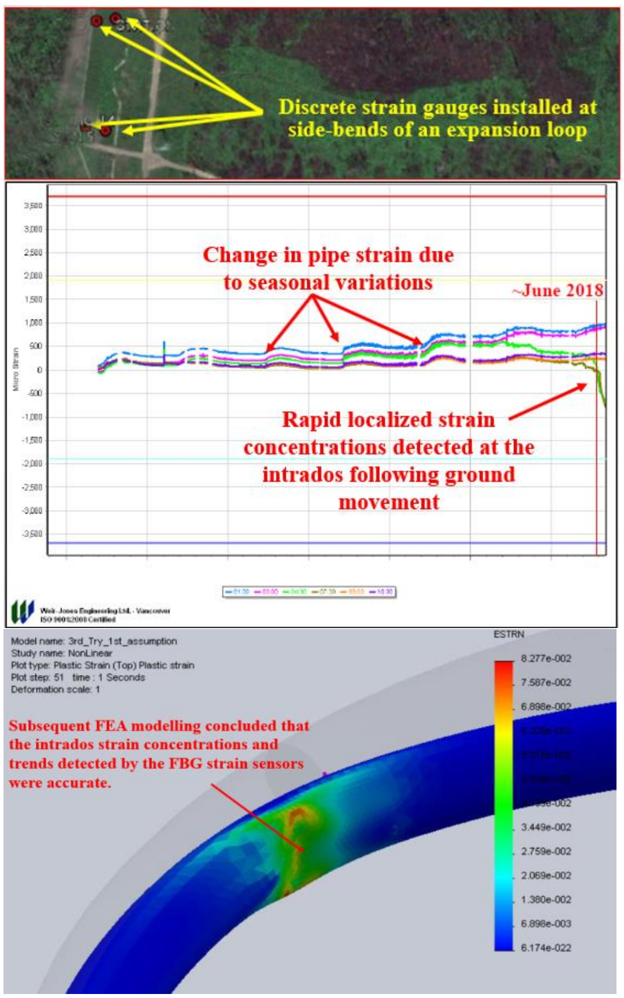

Figure 6: Development of rapid, localized strain concentrations at the intrados of an expansion loop side-bend due to downslope ground movement.

Pipeline settlement detection using discrete sensors at critical locations:

A tailings slurry pipeline was constructed near an open-pit mine in an area known for subsidence. To effectively monitor the structural integrity risk to the pipeline due to large settlements, autonomous tilt sensors were installed at critical locations along the pipeline route from the tailings process facility to the tailings dam. These discrete sensors use the Wireless Sensor Monitoring System, WSMS™, technology to wirelessly transmit data to a control room and data visualization portal in quasi-real-time. This allows the operator to remediate the affected sections of the pipeline in a proactive manner before a loss of containment occurs.

Figure 7: Monitoring pipeline settlement in an area known for subsidence using autonomous tilt sensors.

Pipeline leak detection using discrete sensors at critical locations:

Pipeline operators often run different products with different properties through their pipeline networks. A method for monitoring temperature variation effects on pipelines is the installation of discrete temperature sensors directly on the pipeline surface at critical locations.

This allows for the compensation of strain sensors to eliminate temperature effects. In addition, thermal anomalies can be monitored to detect small variations related to seepage or minor leaks at these locations.

Figure 8 shows pipeline surface temperature data collected autonomously using discrete temperature sensors installed at the toe of a slope that was experiencing higher ground movement rates than expected.

Larger temperature anomalies are rapidly and precisely detected, and the operator is immediately notified. In many instances, these are due to flow variations, or the pipeline being shut down briefly for operational reasons.

At this particular site, over the course of two years, the slope movement rates continued to increase, after which the operator decided to shut down the affected pipeline section and remediate the pipeline and slope. With the pipeline not flowing elevated temperature product, the discrete temperature sensor data showed a return to the ambient soil temperature of the slope.

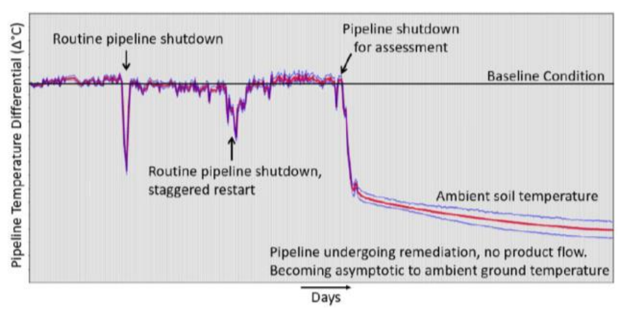

Figure 8: Pipeline temperature variations being monitored for leaks using discrete sensors at critical locations on a moving slope.

2.5 Distributed Sensing Technologies

For decades, conventional discrete sensing technologies have been used to monitor pipeline structural integrity risks due to geohazardous conditions. However, the use of distributed fibre optical sensing technologies to monitor pipelines has increased. The main benefit of distributed sensing is that fibre optic sensing cable can be directly installed on a pipeline or in the surrounding ground and yield thousands of more data points along the entire length of the pipeline, with spatial resolution of ~0.5m, compared with discrete sensors which can only monitor a single location. Another benefit of optical technology is that, since the entire area of interest is being monitored by the fibre optical sensing cable, there is no requirement for pipeline engineers to pre-determine the exact location in which the discrete sensors should be installed.

Distributed fibre optical sensing can utilize different optical sensing methods for pipeline monitoring at geohazardous locations such as:

- Brillouin Optical Frequency Domain Analysis (BOFDA) to quantitatively monitor pipeline strain.
- Raman Effect to quantitatively monitor pipeline temperature.
- Rayleigh Effect to qualitatively monitor intrusion, noise, leaks, or nearby construction activities that may affect a buried pipeline.

The technologies usually involve two light waves, injected into an optical fibre from both ends, which interact and cause the fibre to shiver. This creates an acoustic wave inside the fibre. Influenced by this acoustic wave, the backscattered light that arrives at the interrogator carries information on the fiber's speed of sound, which is directly proportional to the strain and temperature of the fibre.

The fibre optical sensing cables are typically mounted overtop the existing pipeline coating at the crown, invert, and spring-line positions around the circumference of the pipe. They can be bonded directly to the pipe surface using industrial adhesives and visco-elastic tapes as shown in Figure 9, and are impervious to moisture.

The fibre optical sensing cables are then interrogated using autonomous equipment which can yield information about the pipeline deformation and settlement with a spatial resolution of ~0.5m, a strain precision of ±5με (0.0005%), and a temperature precision of <0.1°C along the entire length of the pipeline. This allows the operator to detect global, progressive pipeline strain accumulation and deformation trends due to ground movement over time before a loss of containment occurs.

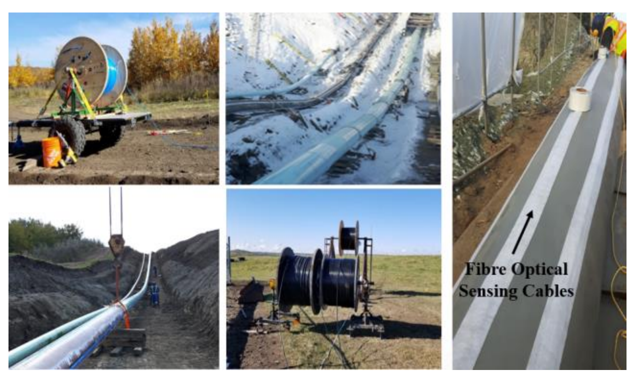

Figure 9: Distributed fibre optical sensing cables being installed on pipelines in Canada.

2.6 Distributed Sensing – Case Studies

Pipeline settlement detection using fibre optical sensing:

A pipeline section near a critical water crossing in Canada was undergoing progressive settlement resulting in mechanical damage. The section of pipeline was excavated for repairs and distributed fibre optical sensing cables were installed at the quarter points along the length of the exposed pipeline. After a year and a half, compressive strains started to develop at the crown of the pipe at the mid-section due to settlement of the surrounding ground. The operator was notified and commenced an engineering assessment to further characterize the trends.

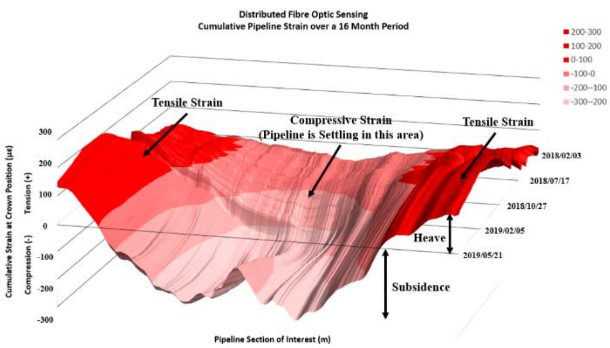

Figure 10: Pipeline settlement detection using fibre optical sensing.

Landslide detection at an unstable slope using fibre optical sensing:

A pipeline section traversing an unstable slope known for landslides was monitored for tensile strain development in surrounding ground to alert the operator prior to a slope failure which could adversely affect the pipeline's structural integrity. Distributed fibre optical sensing cables were installed in near-surface trenches along the entire length of the slope directly above the pipeline.

Tensile strain build-up in the ground was detected by the sensing cables at the mid-section of the slope over a period of two years until they exceed a critical alarm threshold as shown in Figure 11. Compressive strain build-up was also detected at the toe of the slope due to downslope movement. The operator was notified, and a site visit was conducted where tensile ground cracks were discovered in the area of concern. The operator commenced a slope remediation programme consisting of improved drainage, bentonite plugs, and improved compacted backfill.

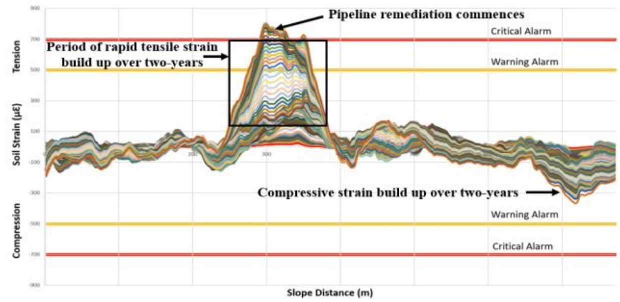

Figure 11: Landslide detection at an unstable slope using fibre optical sensing technology.

2.7 Data Management, Integration and Flow

The data collected from Structural Integrity Monitoring Systems, SIMS, installed on pipelines are often collected and transmitted in real-time and result in very large volumes of data. The proper onsite collection, transmission, processing, and interpretation of this data is a critical step in ensuring a pipeline is operating safely in a geohazardous location. This requires several stakeholders to work together to derive the most value out of this data as shown in Figure 12.

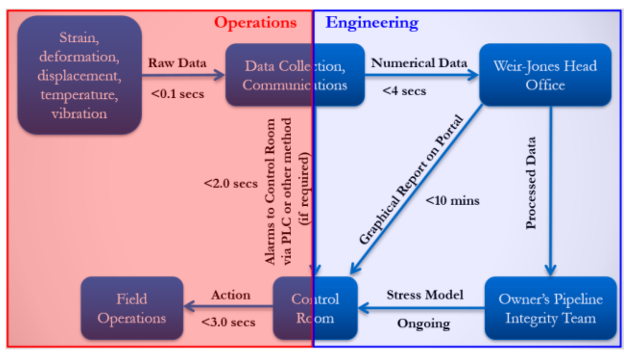

Figure 12: Typical pipeline SIMS data handling flow.

Data is first collected in the field from the discrete or distributed sensors, followed by the transmission of the data to a server/cloud or control room for interpretation and/or immediate action. A well-defined data handling flow allows for the timely management of integrity risks to pipelines due to geohazardous conditions. Data can also be displayed on a data visualization portal as shown in Figure 13. This allows for engineers and operations personnel to view the integrity data in near real-time and proactively manage any developing integrity concerns.

For example, pipeline engineers typically use the strain data collected from SIMS to refine their numerical models and adjust their "time to potential mechanical failure" estimates, or schedule routine maintenance such as integrity digs. Geotechnical engineers may use the strain rates collected from the pipeline and compare them to ground movement rates derived from geotechnical instrumentation such as inclinometers, which allows for the refinement of their soil-pipe interaction, SPI, numerical models.

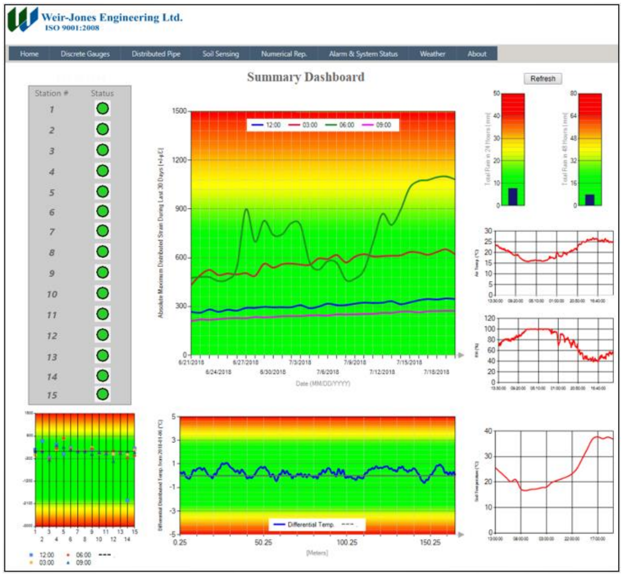

Figure 13: A sample custom data visualization portal displaying discrete and distributed sensing data from several pipelines traversing a geohazardous location.

3 SUMMARY AND CONCLUSIONS

Pipelines often traverse geohazardous locations which can adversely affect their structural integrity over time. The implementation of a Structural Integrity Monitoring System, SIMS, in these critical areas allows for asset owners to proactively monitor and mitigate these geotechnical risks prior to a loss of containment.

Discrete and distributed sensing technologies can be used to obtain quantitative information about the pipeline strain, temperature, deformation, displacement (vertical, horizontal, differential), settlement, and movement due to geohazards. The type of monitoring technology and the installation method deployed is dependent upon the application, location, environmental conditions, surrounding infrastructure available, and the anticipated level of risk to the pipeline and surrounding environment.

A transparent and effective SIMS will assist in defusing adverse public reactions to pipeline projects and potentially eliminate the negative affect that product leaks have on an asset owner’s corporate reputation.

4 ACKNOWLEDGEMENTS

The authors wish to acknowledge their colleagues at Weir-Jones Engineering Consultants Ltd. for their valuable input to this paper.

5 REFERENCES

Komac, C., Zorn, M., and Melik, A., 2013, "Geohazards", in Encyclopedia of Natural Hazards, Brobrowsky, P., ed., Springer Science + Business Media Dordrecht, New Yor, NY, 1133p.