Pipeline deformation and ground movement monitoring with optical fiber sensing in Blue Lake Landslide section of Williams Northwest Pipeline

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Williams   grade sens   EOSS

07 de Noviembre de 2025

Outline

Blue Lake Landslide and Columbia River Gorge Upstream Cascade Locks

- Introduction
  - Blue Lake landslide project background
- Pipeline deformation and ground movement monitoring with optical fiber sensors
  - Concept and technology
- Project implementation
  - Cable installation
  - Challenges
  - Monitoring architecture
- Preliminary results
- Conclusions

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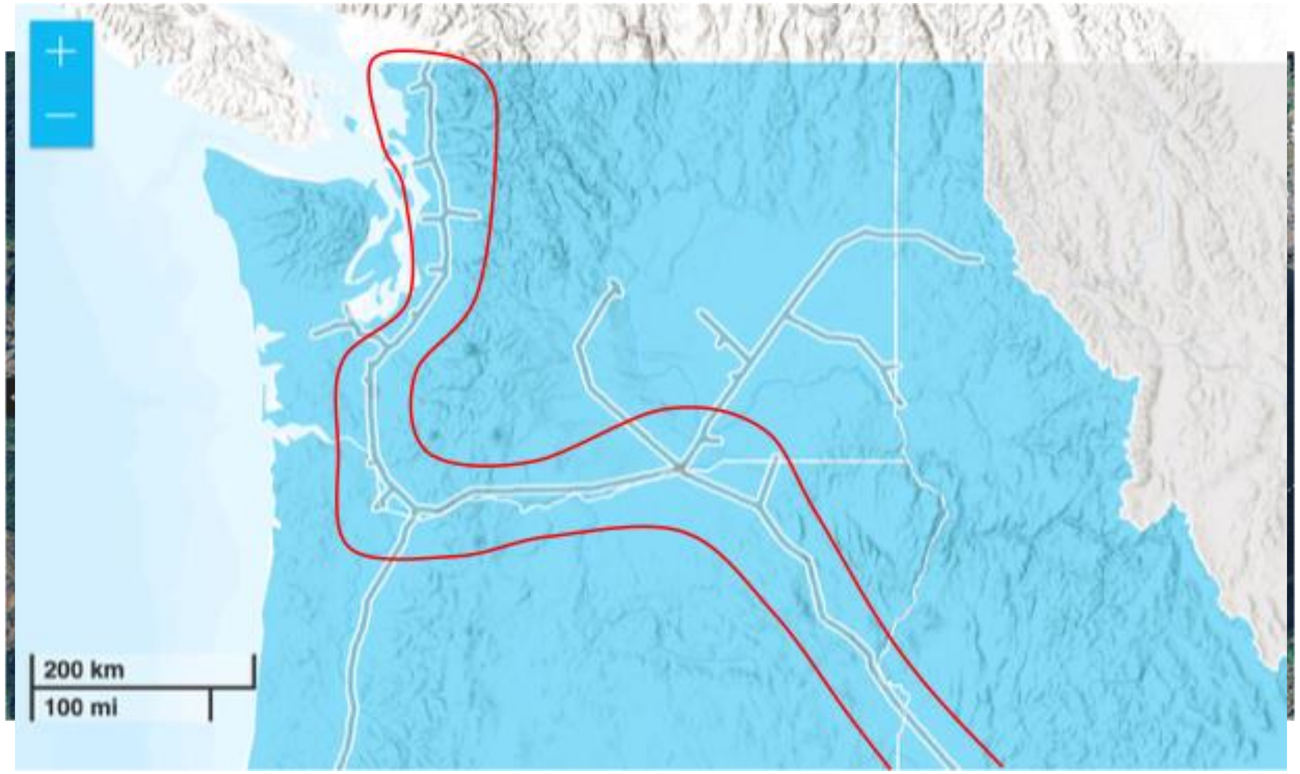
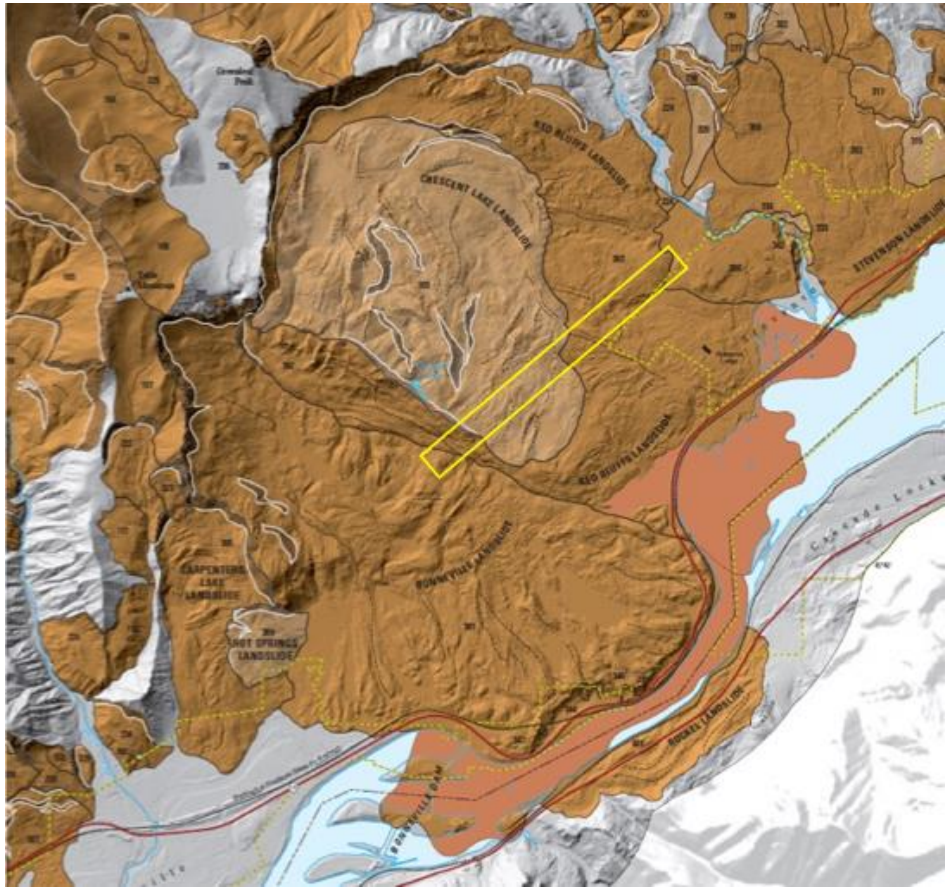
Old and New Pipeline



North West Pipeline System

- Northwest Pipeline System
  - Spanning from Ignacio (CO) to Sumas (WA)
  - Construction in 1950s
  - Primary supplier of natural gas in Northwest region
- Blue Lake Landslide Section
  - Exposed to land movement causing high strain accumulation
  - Old pipe replacement in Blue Lake landslide section

Blue Lake Landslide Background



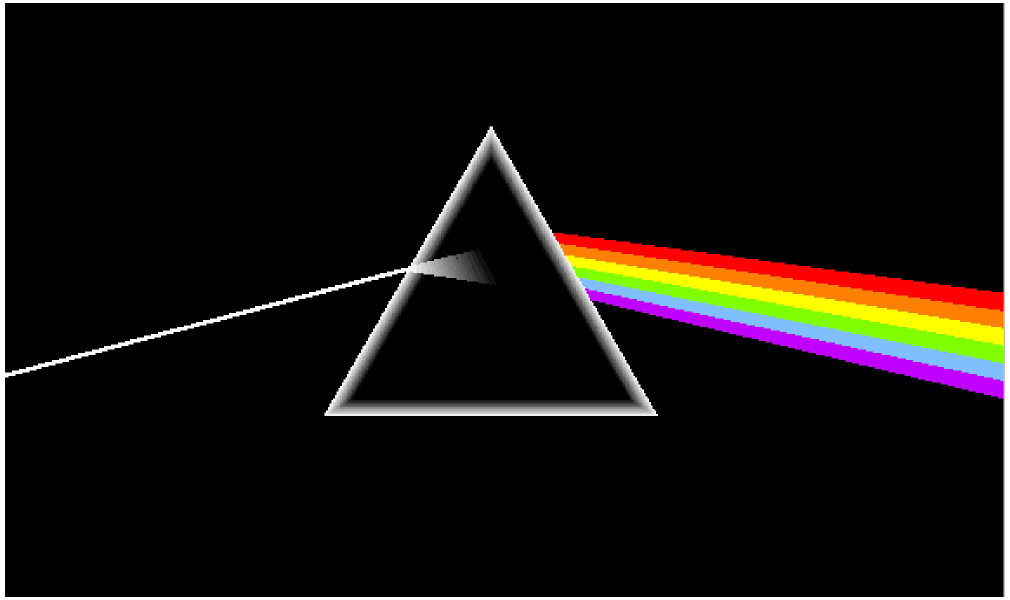
Pierson et al., "Landslides in the Western Columbia River Gorge, Skamania County, Washington", USGS Scientific Investigations Map 3358, Scale 1:12,000, 22p, 2016

- Environmental and geological characteristics
  - Substrate
    - Volcanic activity and fluvial deposits occurring from Oligocene to late Pliocene contributed to a stratigraphic structure composed of hard and soft layers
    - ➢ Natural failure planes for landsliding
  - Ongoing
    - Steep slopes shaped by ongoing scour of Columbia Gorge and continuous tectonic as well as volcanic activity
      - ❑ "Bridge of the God" Legend
    - Heavy rain falls
    - Extensive logging activity causing seepage

What about monitoring?

- Dedicated Monitoring of old pipeline in Blue Lake Landslide section
  - Local Strain Gauges from early 1980's to present
  - Recently, surveys conducted with LiDAR, InSAR, IMU
  - All are periodic captures
  - ➢ no permanent, real-time monitoring nor reference baseline dating back to the 1950's
- Taking advantage of whole section replacement
  - Implement a permanent and real-time monitoring
  - Pipe strain profiling over the whole
  - Monitoring RoW stability
  - ➢ Monitoring technology based on optical fiber distributed sensing

Outline



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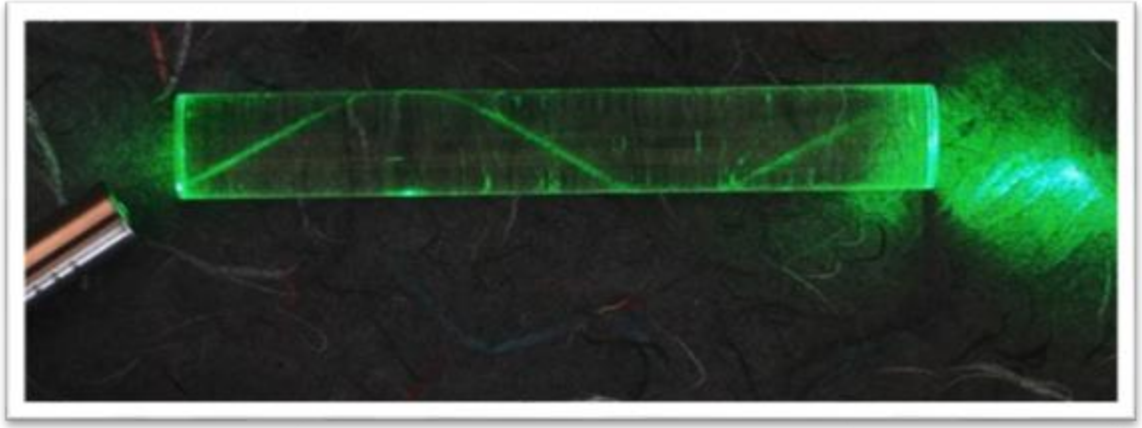
Distributed Sensing – The Concept

- Turning optical fibers into a fully distributed sensor using light scattering

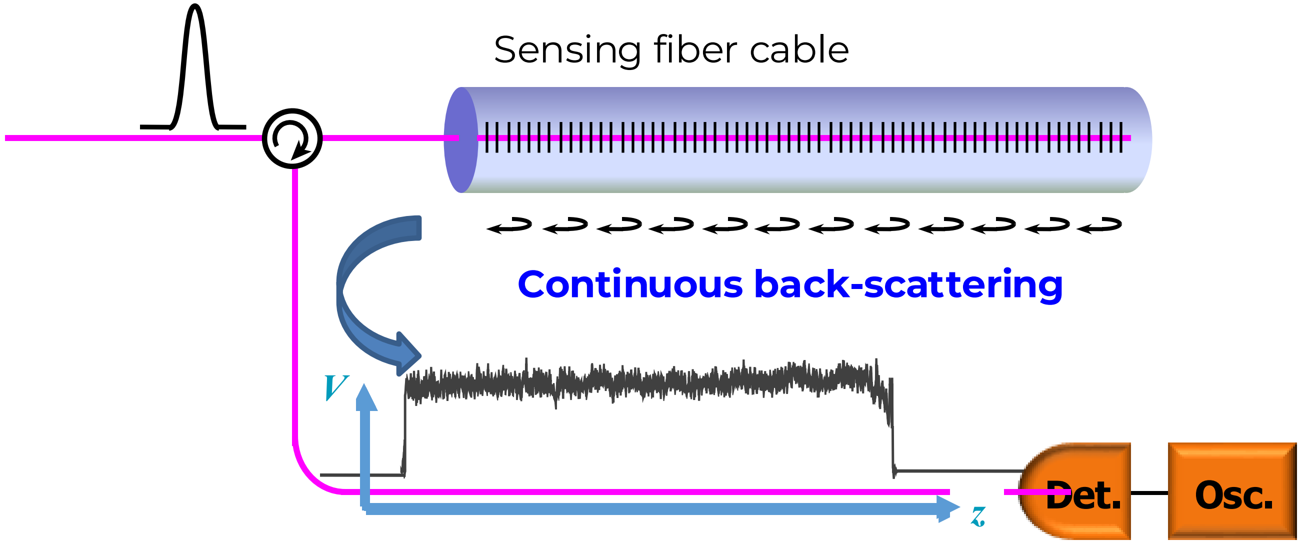
Optical Fiber Distributed Sensing

- Distributed sensing uses light scattering
- Scattering originates from inhomogeneities in silica



Distributed Sensing System Principle: Optical Time Domain Reflectometry - OTDR

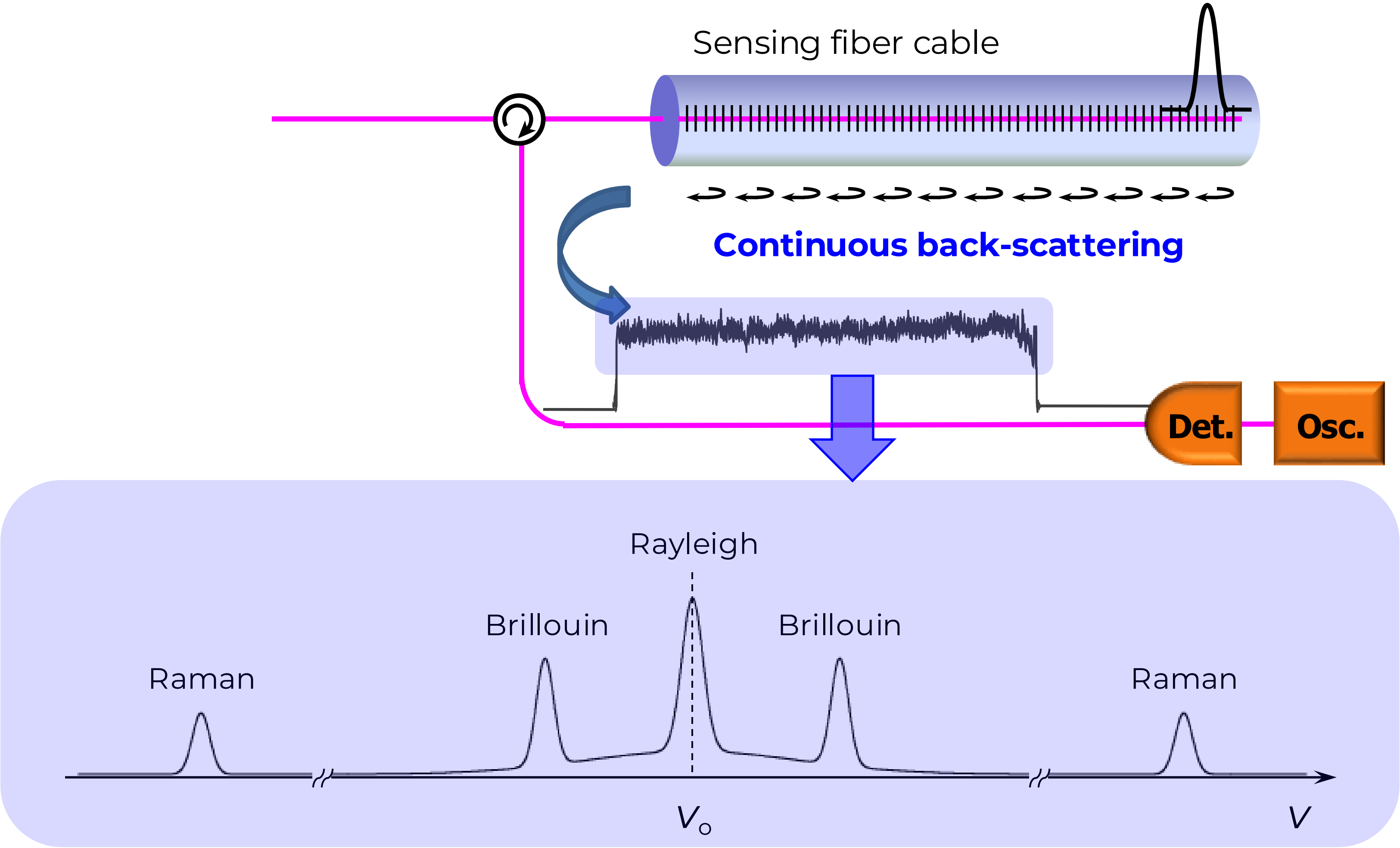
OTDR Principle: combination of the analysis the backscattered pulse and the determination of its time of flight



- The instrument measures a trace which is a function of the time of flight in the fiber.
- The instrument converts the time of flight into a distance.

Distributed Sensing System Principle: Backscatter Analysis

OTDR Principle: combination of the analysis the backscattered pulse and the determination of its time of flight



Backscatter Analysis Determines Interrogator Type

Scattering processes used for sensing applications:

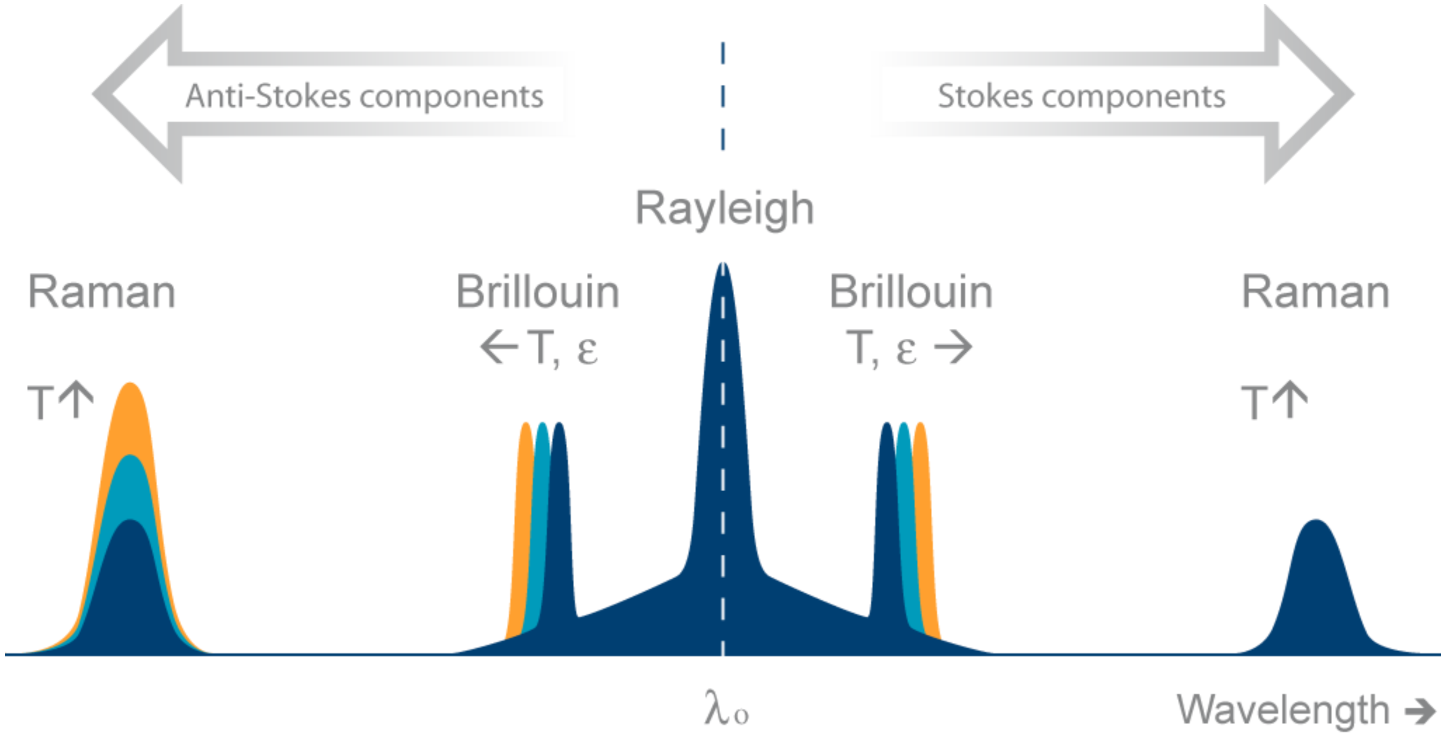
Rayleigh
detection and analysis of fast intensity variations, dynamic strain detection.

DAS – Distributed Acoustic Sensing

Raman
scattered magnitude is temperature dependent

DTS – Distributed Temperature Sensing

Brillouin
lines are temperature and strain sensitive
DTSS – Distributed Temperature and Strain Sensing



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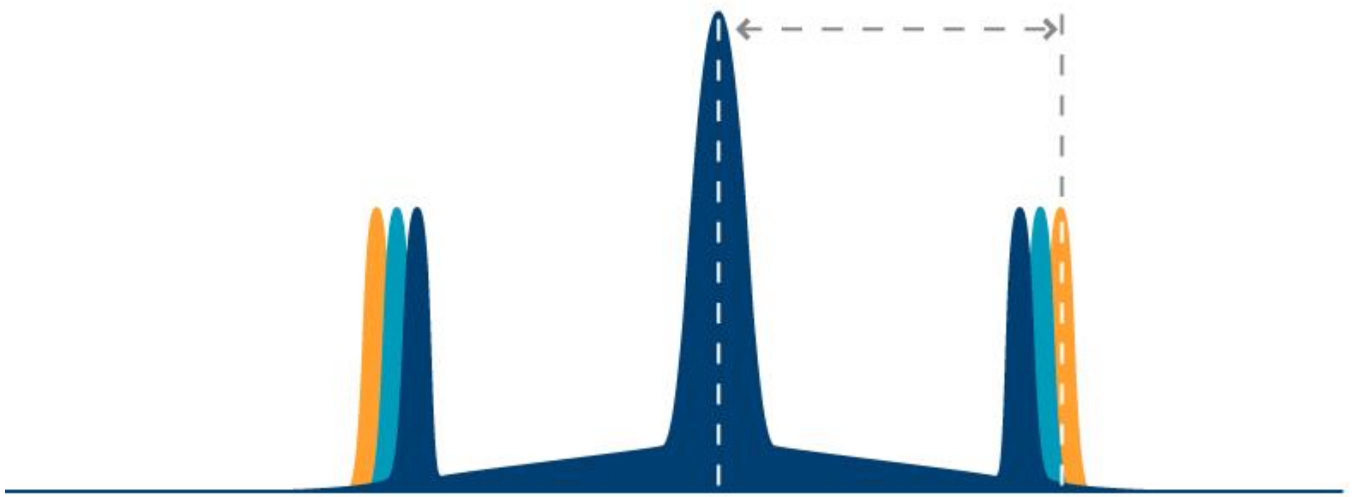
DTSS – Brillouin Optical Time Domain Analyzer (BOTDA)



Brillouin Frequency Shift:

$\nu_B = 2nV_A / \lambda_0$

$\nu_B(T,\varepsilon)$ depends on temperature and strain

$$\nu_B = \nu_{B0} + C_\varepsilon \varepsilon + C_T T$$

- High resolution measurement technique for Strain (<20 $\mu\varepsilon$) and Temperature (<1°C) as well as localization (<1m)
- Fiber ageing and loss increase accomodation for long lifetime operation
- Fully compatible with telecom optical fiber cables

Geohazard Signature and Monitoring

grade sens

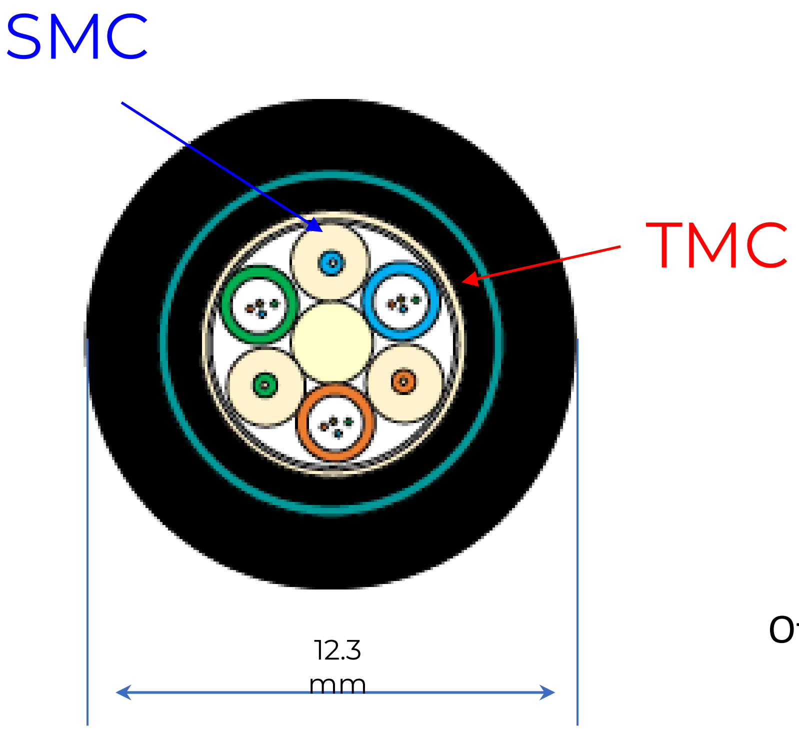
Geohazard	Strain Measurement - DSS/DAS	Temperature Measurement - DTS
Seepage, Erosion and DoC (Depth-of-Cover)		X
Subsidence	X	
Landslide	X	
Pipeline Deformation	X	

Measured with Optical Fiber Communication Cable or dedicated temperature sensing cable (TMC)

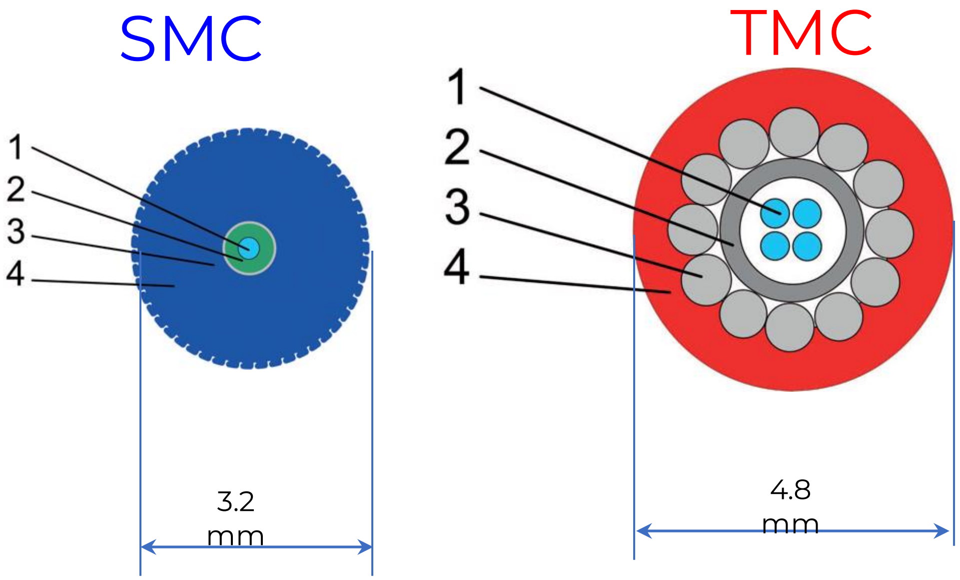
Dynamic (DAS) and static (DSS) strain measured with dedicated (preferably) strain monitoring cable (SMC) but assessment possible with communication cable with lesser sensitivity

Optical Fiber Sensing Cables
(current project)

Hybrid SMC+TMC+Communication Cable
(for soil monitoring)



SMC+TMC
(for soil monitoring and/or structure deformation)



Other designs are possible

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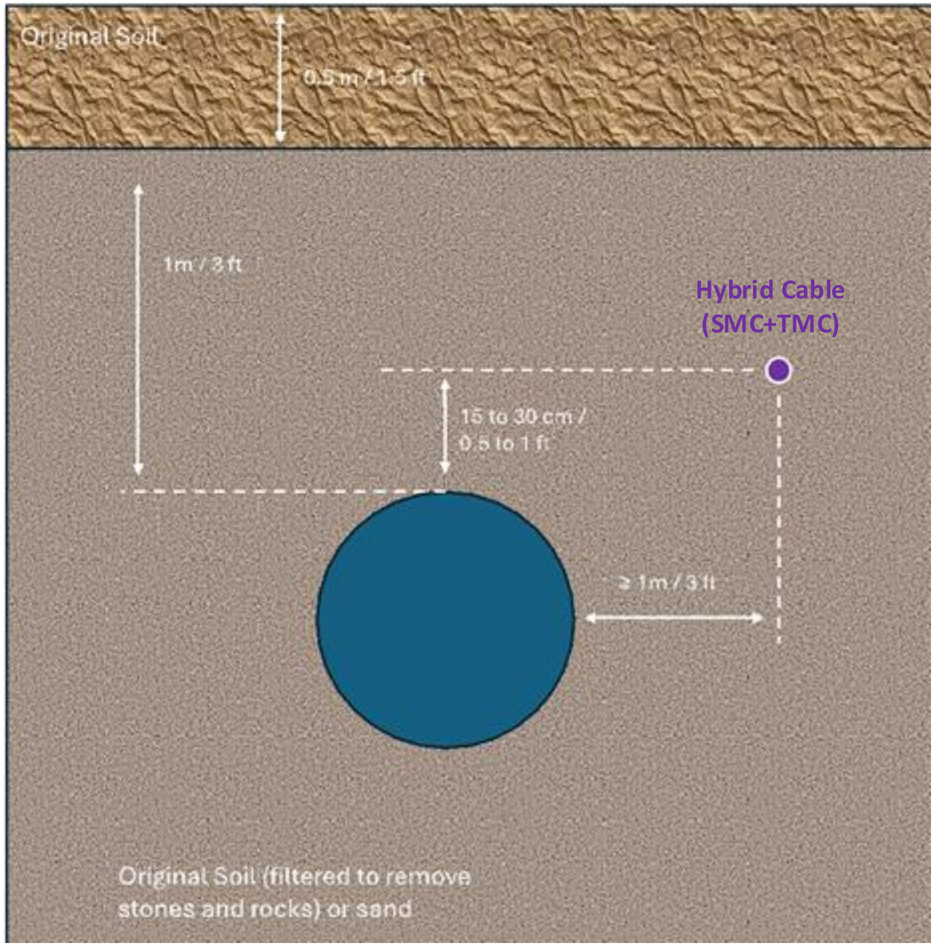
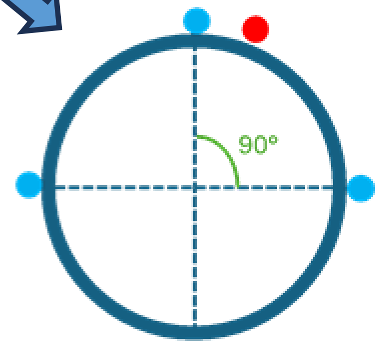
Sensing Cable Implementation

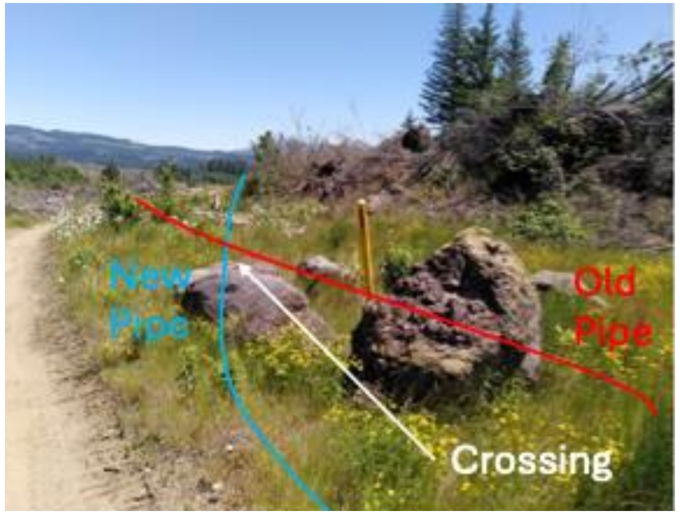


Hybrid cable is laid in the trench in the vicinity of pipeline

SMC and TMC attached to the pipeline

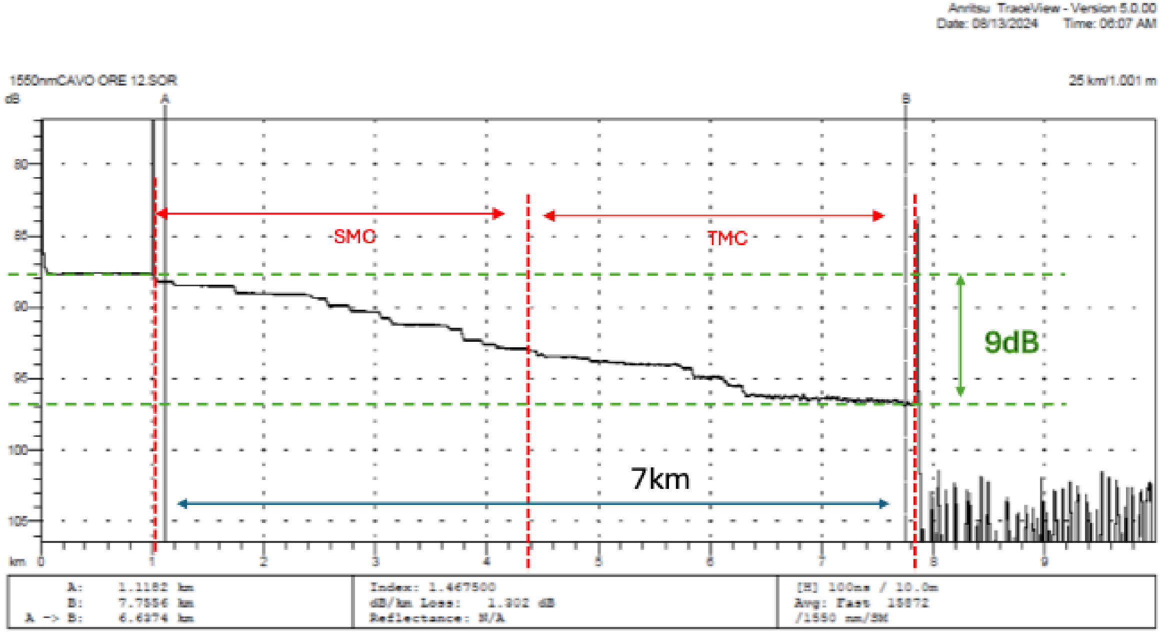


Project Challenges



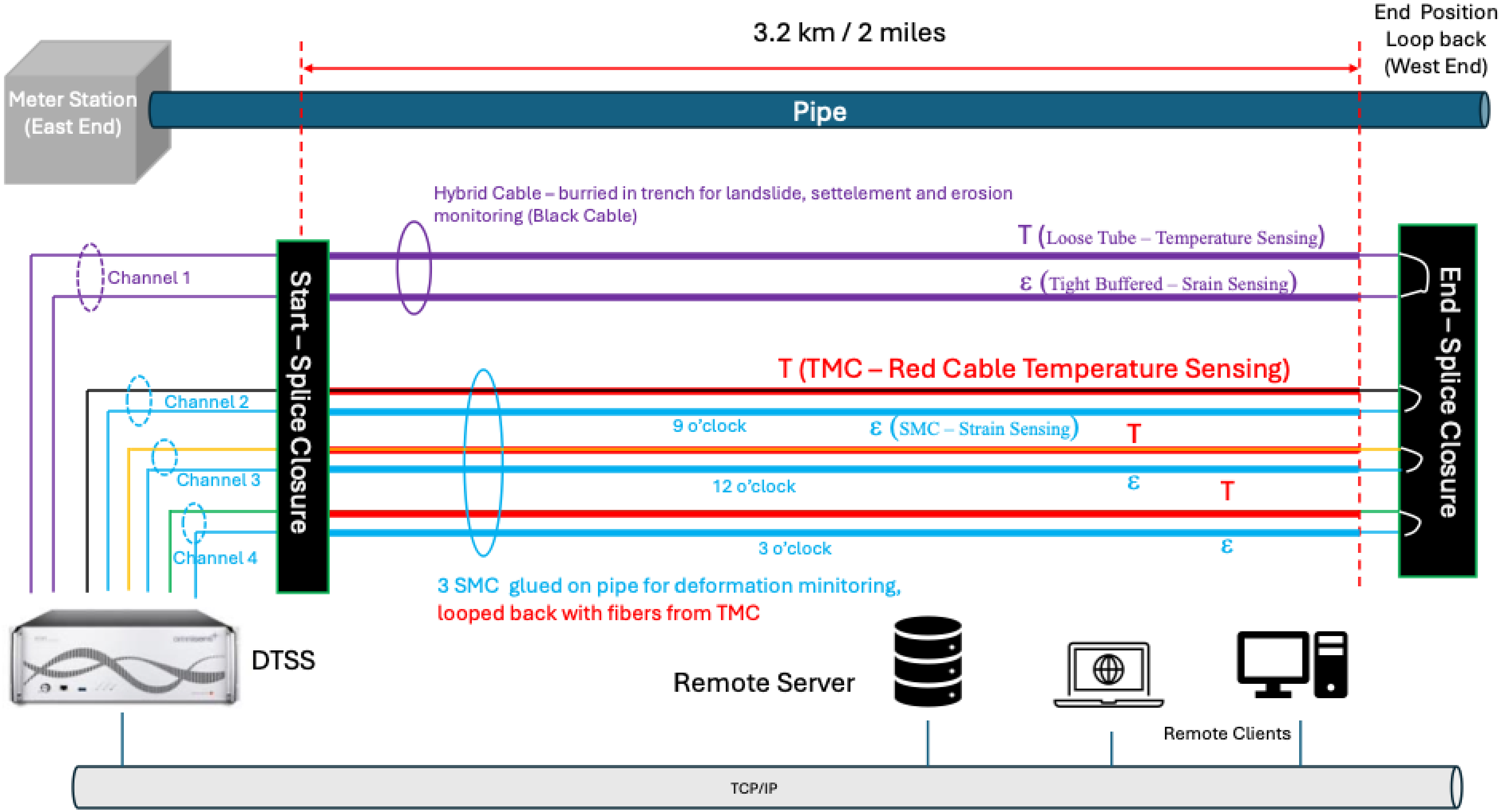
- Procurement
  - System components (interrogator, cables, adhesives…) lead time vs construction schedule
  - 14 weeks from order to installation completion
  - ➢ Experienced project management and engineering team, close cooperation between suppliers (equipment, cable, adhesive, etc.)
- Construction
  - Old (active) pipe crossings, access road crossings, accidental cable cuts
  - ➢ 13 optical fiber splices
- Optical fiber cable constrains
  - Specialty cable for sensing required experienced personal, special tools and dedicated methodology
  - Dusty and windy environment
  - ➢ Splice loss larger than 0.5 dB
- Data Communications
  - No communication optical fiber cable, only cellular or satellite network

Project Challenges – Optical Fiber Cables and Splices



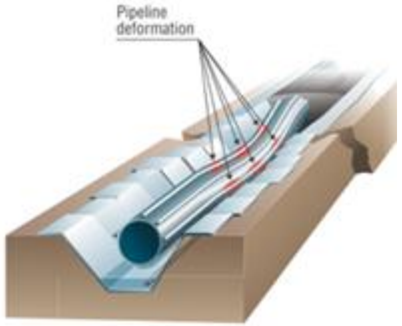
- Construction and optical fiber cable constrains influence monitoring performance
  - From 1.1 dB/km to 1.4 dB/km per sensor
- DTSS has a dynamic range over 24 dB guarantying a measurement repeatability better than 20 me and 1°C with 1m spatial resolution and 5 minutes averaging time

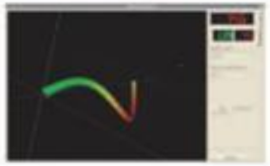
Monitoring Architecture

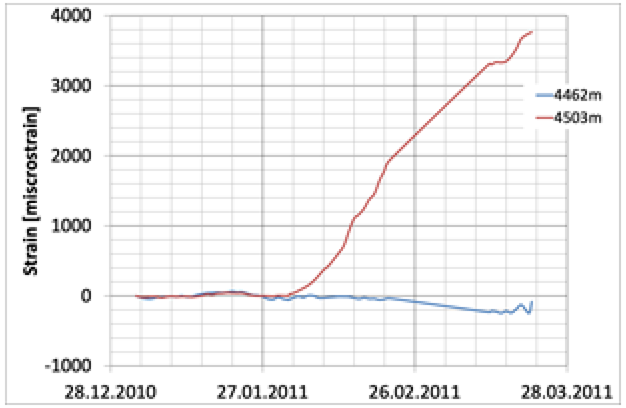


Parameter	Value
Spatial Resolution	1 m
Sampling Interval	0.25 m
Averaging Time	≤ 5 minutes

Outline







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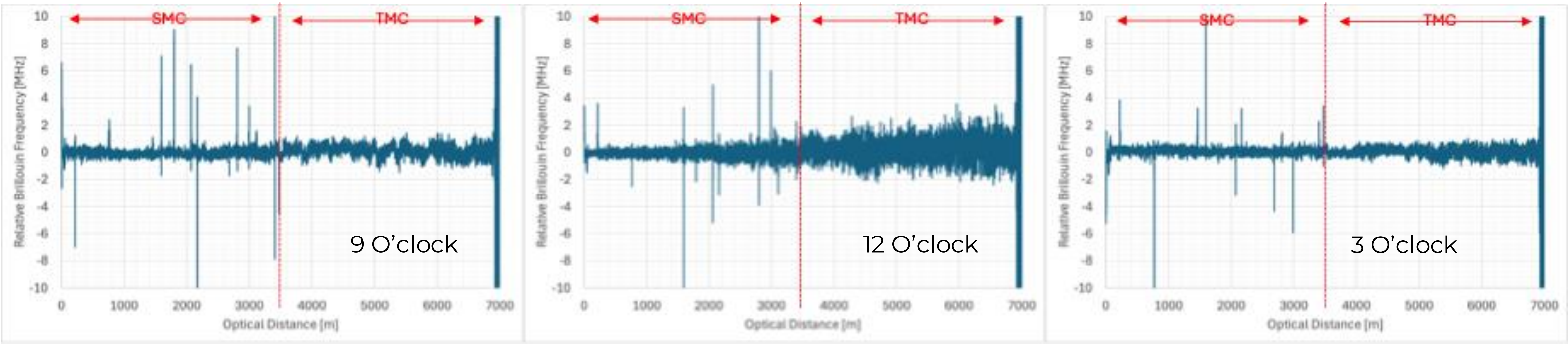
Brillouin Frequency Profiles

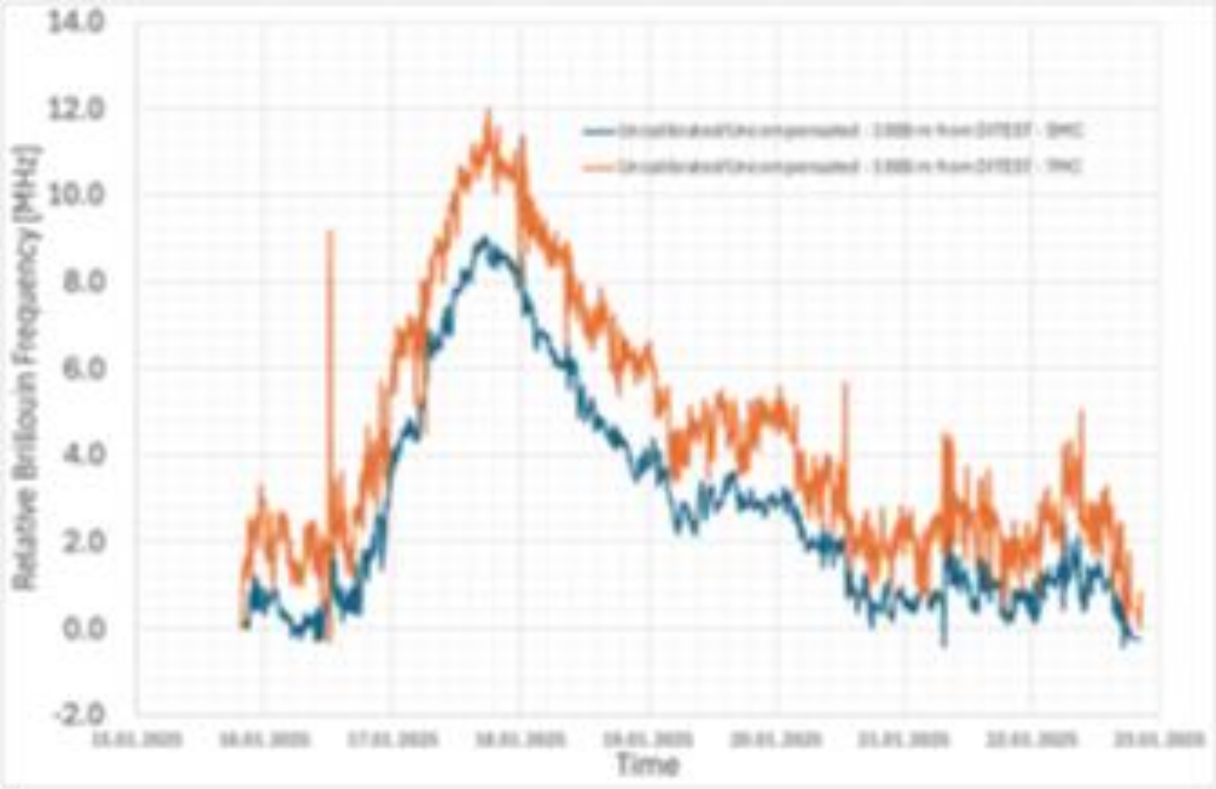
Profiles snapshot at the time of the full-length article submission

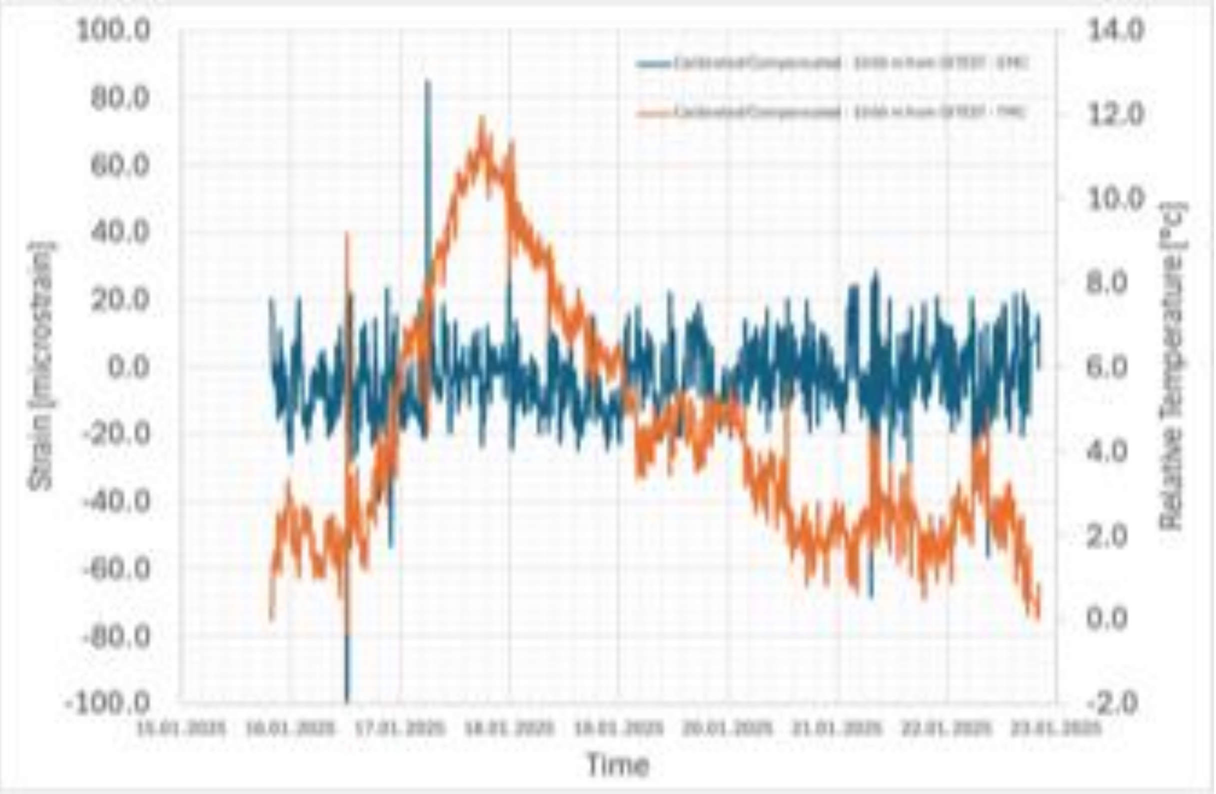


Profile appears noiser on 12 O'Clock sensor due to attenuation increase which ended as a fiber break

Pipeline Strain and Temperature Profiles

Profiles snapshot at the time of the full-length article submission





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Conclusions

- System implemented for continuous and automated monitoring
  - Pipeline deformation
  - Ground movement in Right-of-Way (erosion, landslide)
  - Capability of localizing event in monitored section with metric resolution
  - Final commissioning phase
- Strengthen operator capability to detect events and take measures at an early stage
- DTSS technology implemented, based on BOTDA, benefits from a large dynamic range allowing for loss increase accommodation
  - Fiber ageing caused by axial and hoop stresses on the cable
  - Additional splices

Acknowledgements

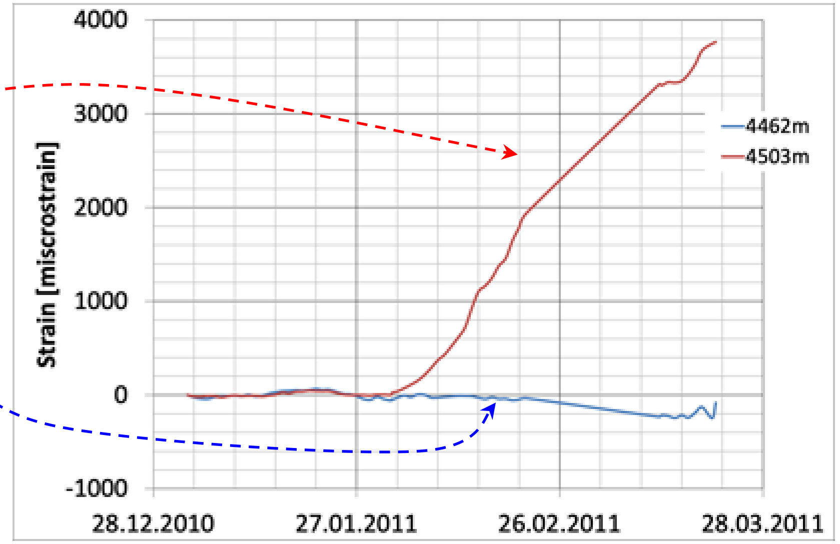
The authors are grateful to

- Williams for authorizing and supporting the work
- Their colleagues for the stimulating and encouraging discussions
- ACIEM for organizing the event
- The audience for his kind attention

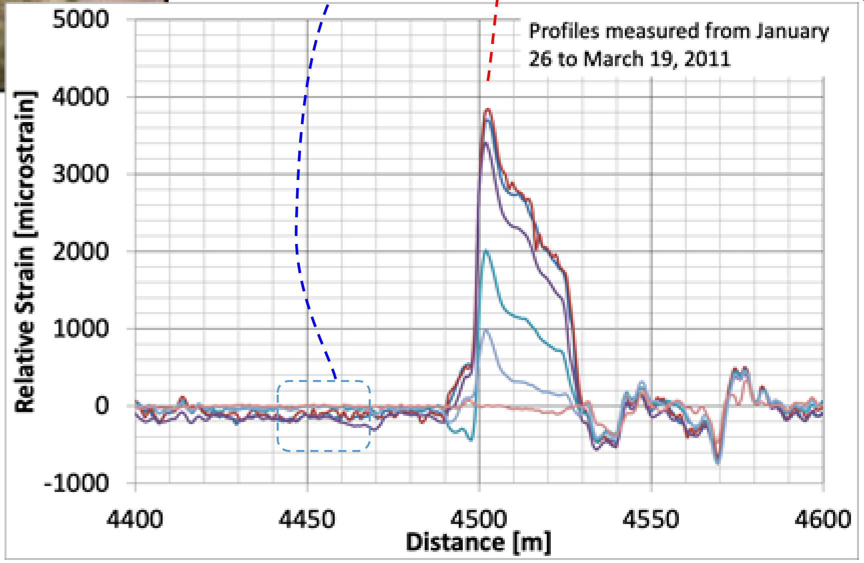
Landslide Detection and Monitoring (Static Strain)

PLNG Transport System, Sierra Section, Peru

Temporal pattern



Spatial pattern

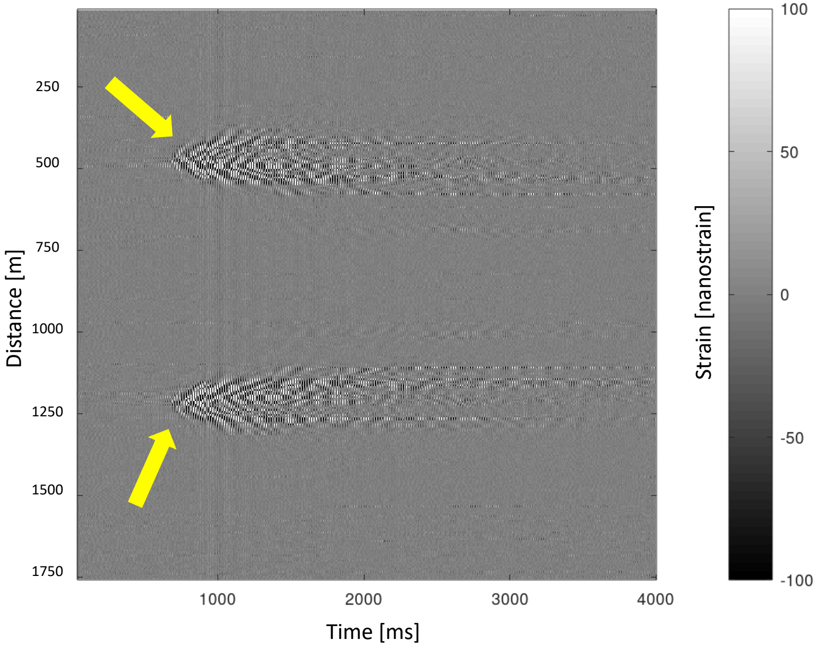


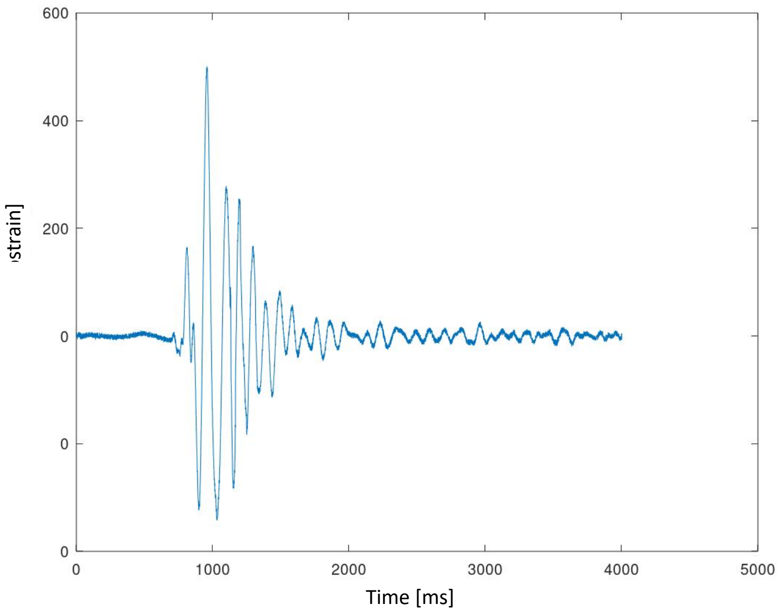
Extracted Information:

- Severity
- Position
- Spatial extension
- Velocity

Rockfall detection

La Sionne Trial, November 2020

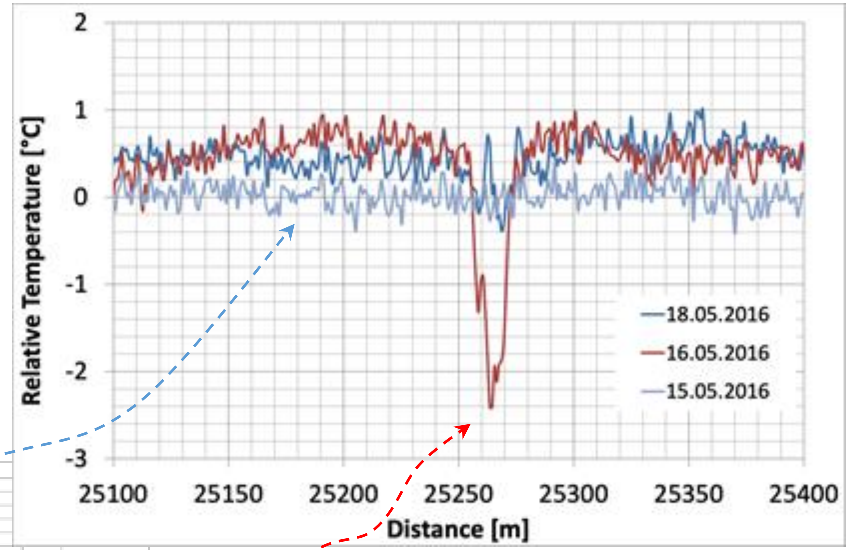




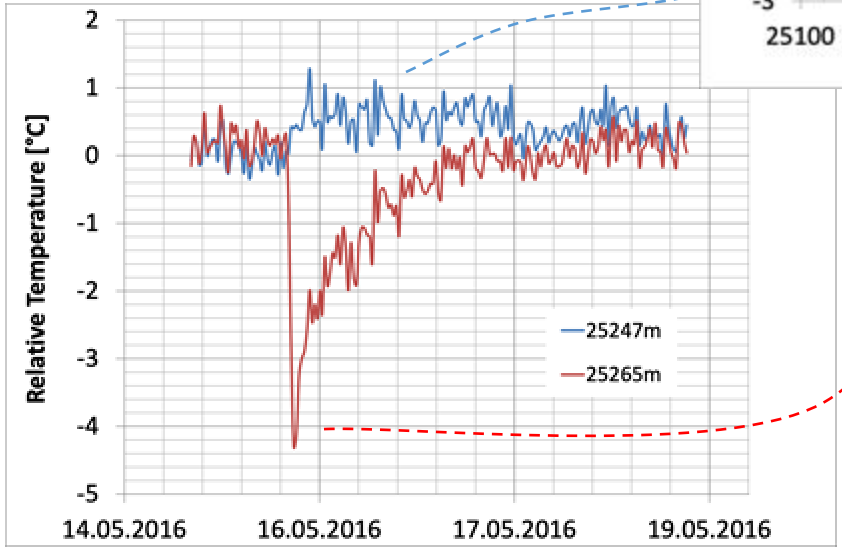
Erosion Detection and Monitoring - Infiltration

Ramones Transport System, Mexico

Spatial pattern

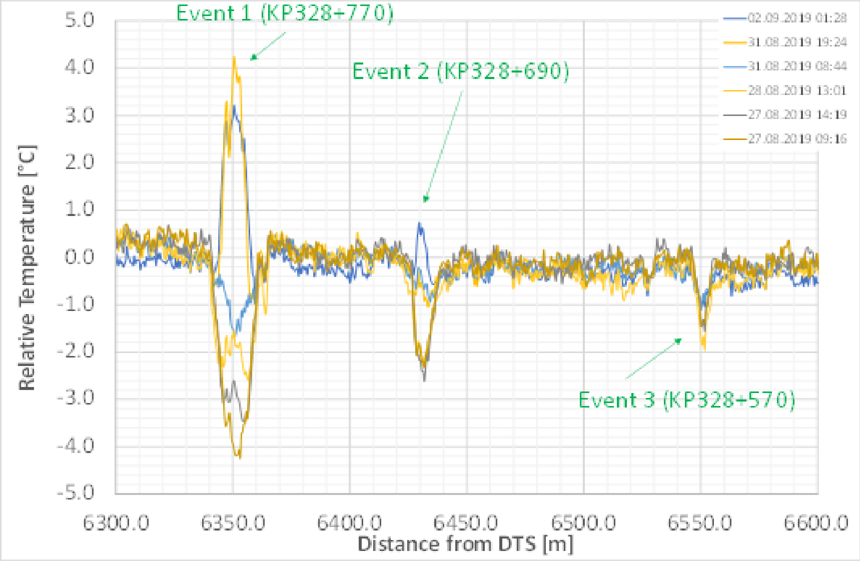


Temporal pattern

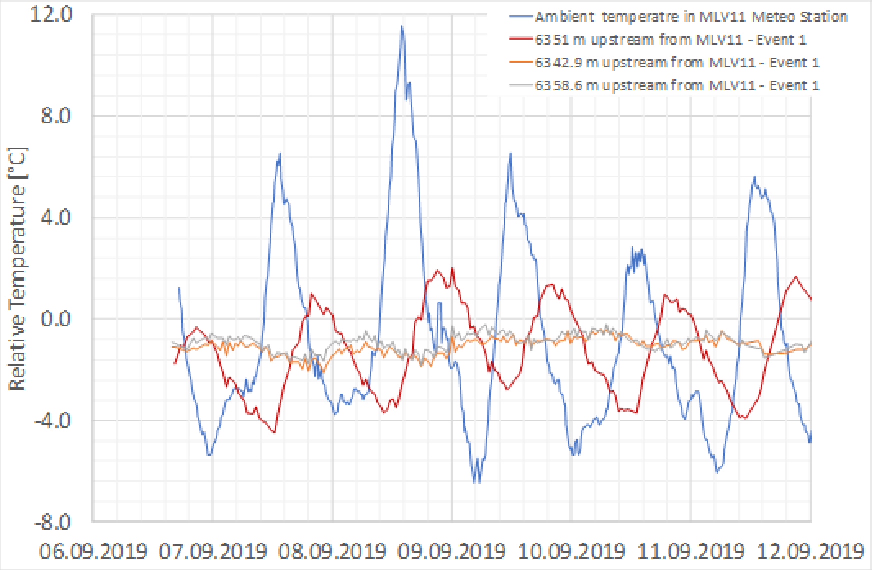


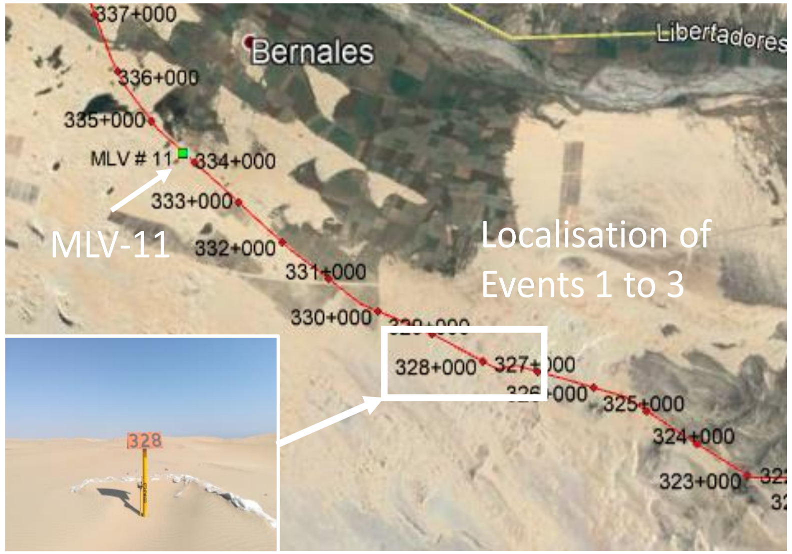
Events near KP328

Spatial pattern



Visual pattern





Event detection and localization but also cable DoC

- Period is always 24 h and depth independant
- Delay and amplitude change depending on cable depth
  - Delay mesurement more robust as Insolation and other effect may affect the amplitude

Subsidence Detection and Monitoring

Subsidence Modelling

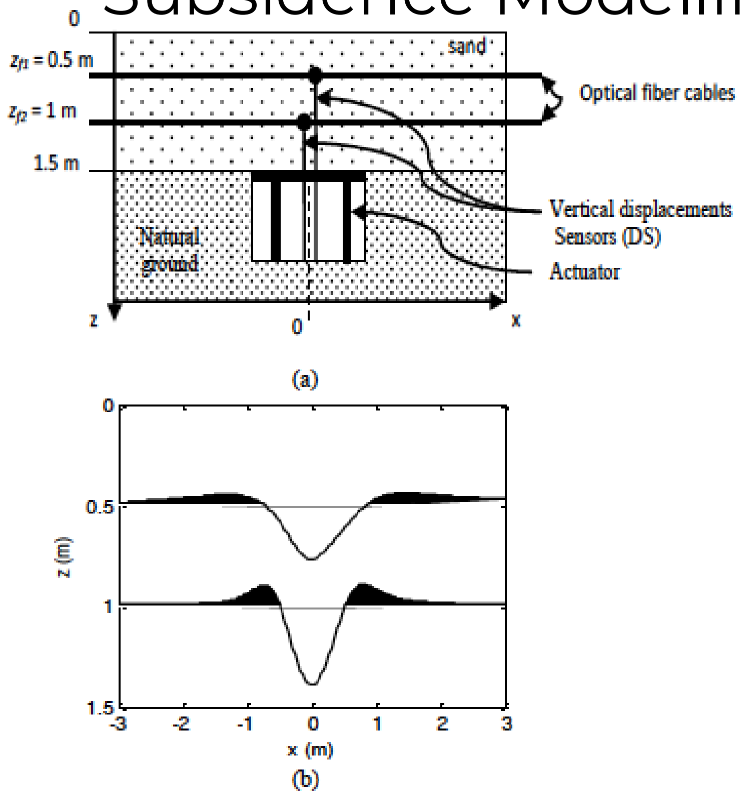


Fig. 3. (a) Illustration of the trap-door experiment: two cables and vertical displacements sensors are installed at two observation depths z_1 = 0.5 m and z_2 = 1.0 m from the surface of the sand. (b) Strain measurements at z_1 = 0.5 m and z_2 = 1.0 m provided by the OBR 1600 Rayleigh scattering device for ground settlement generated by a plate with E_1 = 2 mm. The signatures are rescaled and their positive areas are in black.

Subsidence Measurement

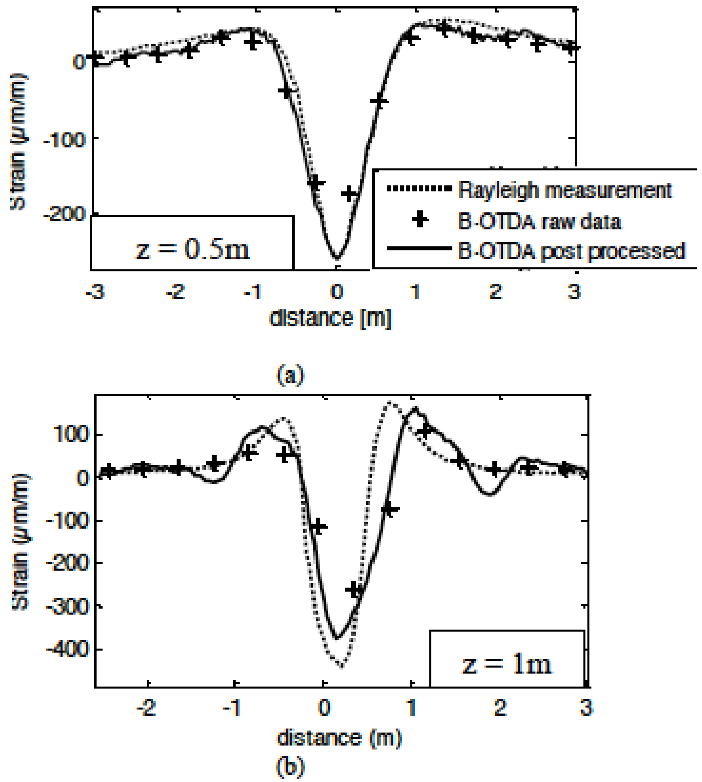
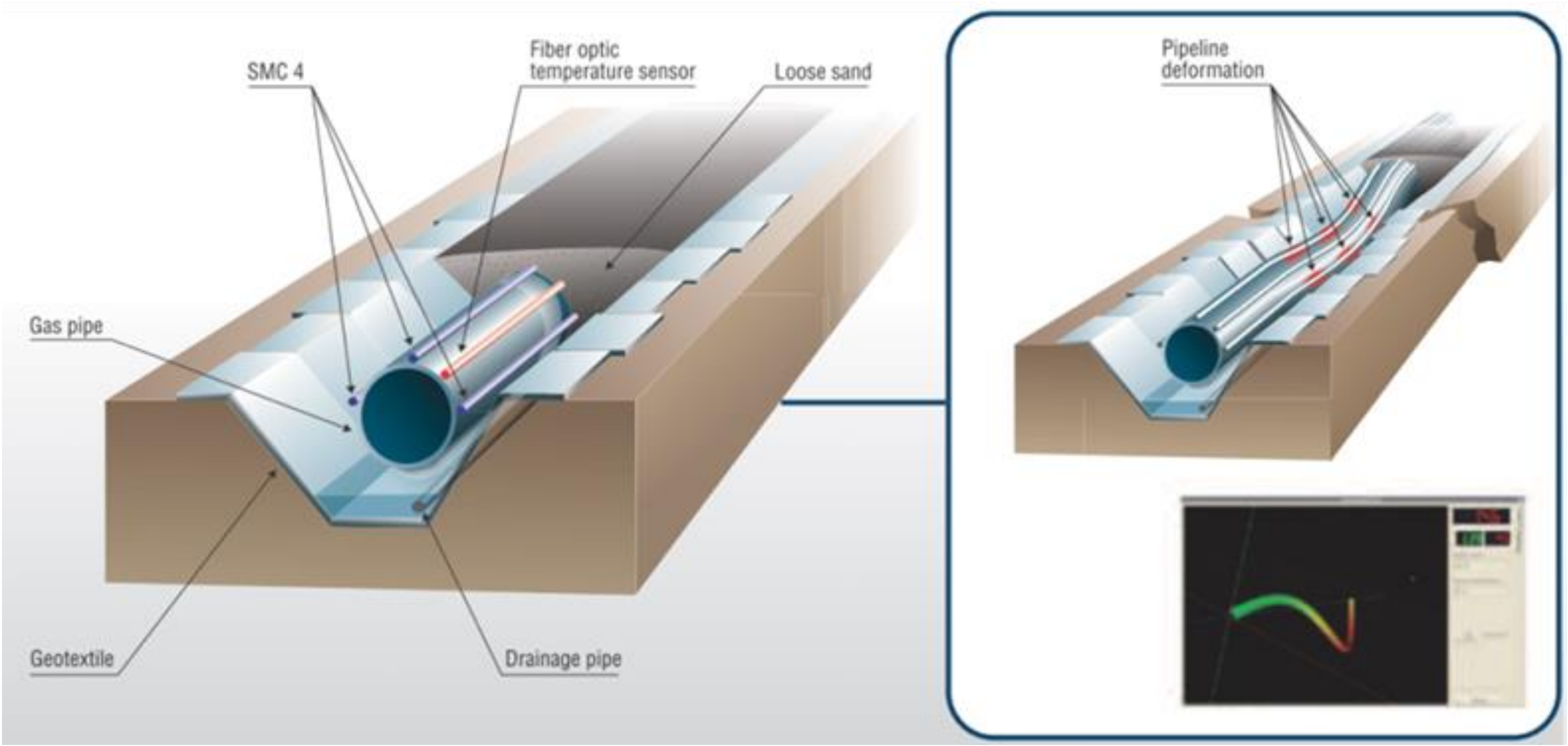


Fig. 6. Post-processed strain profile from raw B-OTDA spectral data with a spatial resolution of 5 cm (solid line). Comparison with the raw data provided by the industrial B-OTDA device (+) and the Rayleigh strain measurements (dotted line), with spatial resolutions of 40 cm and 3 cm, respectively, for both of the depth observations of z_1 = 0.5 m (a) and z_2 = 1.0 m (b), for E_3 = 0.6 mm.

Buchoud et al, 2015

Example of Pipe Deformation Monitoring (Static Strain)



IPG2025-0004

PIPELINE DEFORMATION AND GROUND MOVEMENT MONITORING WITH OPTICAL FIBER SENSING IN BLUE LAKE LANDSLIDE SECTION OF WILLIAMS NORTHWEST PIPELINE

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ABSTRACT

Geohazards such as landslides, earthquakes, and soil erosion can pose significant risks to transportation infrastructures. It is particularly the case for gas pipelines. The main purpose of this work is to share information about a recent implementation of a solution combining pipeline deformation and ground movement monitoring.

The natural gas transportation system of interest faces several challenges. The pipeline route runs through the Columbia River Gorges, known to be a seismically active and exposed to heavy rainfalls. The gorge is also characterized by unstable slopes. The Blue Lake Landslide is of particular concern as the pipeline crosses the slope over a width of 3.2km. Due to the extension and complexity of the landslide, the use of strain gauges would have been very challenging and would have implicated many compromises in the selection of their position along the pipeline and delays in the construction schedule. An efficient alternative is the use of optical fiber distributed sensing. The deployed solution is composed of Strain and Temperature Sensing Cables (SMC, TMC), attached to the pipe external surface over the 3.2km of length, as well as of a Distributed Temperature and Strain Sensing (DTSS) interrogator. Additionally, a hybrid strain and temperature sensing cable was laid in the trench parallel to the pipeline.

The current work describes the challenges associated with the project implementation such as proper material selection, lead-times and practical installation. Preliminary results are presented and discussed.

Keywords: Pipeline deformation monitoring, DTSS, BOTDA, Optical Fiber Sensors, geotechnical monitoring, Geohazards, Landslides, Geotechnical Monitoring

NOMENCLATURE

A.D.	Ano Domini
BOTDA	Brillouin Optical Time Domaine Analyser
BOTDR	Brillouin Optical Time Domain Reflectometer
BS	(Spontaneous) Brillouin Scattering
DSS	Distributed Strain Sensing
DTS	Distributed Temperature Sensing
DTSS	Distributed Temperature and Strain Sensing
FFT	Fast Fourier Transform
GTMS	Geotechnical Monitoring System
GIS	Geographical Information System
HDPE	High Density Polyethylene
IEC	International Electrotechnicaal Commission
ILI	In Line Inspection
IMU	Inertial Measurement Unit
InSAR	Interferometric Synthetic Aperture Radar
ITU	International Telecommunication Union
LiDAR	Ligth Detection and Ranging
NA	Not Applicable
NOAA	National Oceanic and Atmospheric Administration
OD	Outer Diameter
OFC	Optical Fiber Cable
OFDR	Optical Frequency Domaine Reflectometer
OTDR	Optical Time Domain Reflectomer
PA	Poly Amide
RAP	Road Access Point
ROW	Right-of-Way
SBS	Stimulated Brillouin Scattering
SMC	Strain Measuring Cable
SSL	Stainless Steel
TMC	Temperature Measuring Cable
USGS	United States Geological Survey

1 INTRODUCTION

Geohazards are natural threats that can cause severe damages to transportation infrastructures such as pipelines ([1], [2], [3], [5], [6]). Geohazards can result in ruptures with dramatic social and environmental consequences. Depending on the pipeline route, local climate and landscape, different types of geohazards can impact ROW ranging from landslide and rock fall in mountain areas to soil subsidence, erosion and water flooding or other environmental condition changes like permafrost thaw settlement along northern pipeline route or dune migration in arid regions. Climate change also enhances the risk in these regions [7].

To mitigate natural hazard risks, operators have developed asset integrity programs which include conventional and innovative geotechnical instrumentation to secure their pipeline's operation. The implementation of such programs in the Peruvian jungle and Andes is discussed in references [8], [9], [10] and [11]. In difficult environments, remote sensing solutions for pipelines offer significant advantages over conventional inspection techniques. Optical fiber sensor technologies are one of the most suitable approaches being implemented for environmental and natural hazard risk mitigation along transportation infrastructures ([12], [13]). Such solution was implemented in the form of the GTMS.

The present work discusses the implementation of a pipeline deformation and ground movement monitoring solution for the 26 inches mainline owned and operated by Williams Northwest Pipeline. The line is a bi-directional natural gas transmission system, built in the mid-1950s, and traversing the Columbia River Gorge, which is an area exposed to heavy rainfall, geologically unstable terrains and active seismicity. A particular region along the route is characterized by an active landslide known as the Blue Lake Landslide. Due to the age of the pipeline and its history of land movement related integrity incidents, it was decided to replace this specific section. The total length of the replacement was 3.2 km and took place during the Summer of 2024. To improve the safety of its operation and the reliability of the monitoring and mitigation measures, the decision was made to pursue a monitoring technology that could provide continuous and real time data on pipeline deformation and movement of the land mass over the whole section. Implementing this technology during the replacement work was essential to allow for monitoring of the actual strain value from an initial baseline

Optical fiber sensing was considered as an efficient alternative to conventional strain gauges due to the large area to be monitored. In fact, DTSS technology allows continuous, in line and automated measurement of the pipe deformation over long distances [12]. SMC's need to be attached to the pipe as one would have done for strain gauges ([14], [15], [16], [17]). In addition, a TMC is required to compensate for thermal effects that can affect the strain readings. In complement, an OFC with hybrid strain and temperature sensing capabilities was laid in the trench in parallel to the pipeline for ground movement monitoring [18]. The comparison of the pipe strain readings with the soil deformation monitoring would bring invaluable information concerning pipe-soil interaction.

The deployment of the fiber during pipeline construction and the lessons learnt during the installation and commissioning of the system are presented. The rationale for selecting the fiber optic-based system is discussed. Preliminary results obtained from the monitoring are reviewed.

2 BACKGROUND

2.1 Pipeline Details

Williams Northwest Pipeline owns and operates 3,900 miles of bi-directional natural gas transmission pipeline in the western United States. The pipeline system consists of a mainline extending from Ignacio, Colorado up to the Canadian border at Sumas, Washington as well as several laterals. The mainline pipe is a 26-inch (66-cm) diameter pipeline that was originally installed in the mid-1950s. Table 1 summarizes the pipeline characteristics.

Table 1: PIPELINE CHARACTERISTICS AND ENVIRONMENTAL CONDITIONS

Characteristic	Description
Pipe OD	26" (66 cm).
Nominal Operation Pressure	55 bars
Typical DoC	1 m (3 ft)
Pipe material	OD X-70 Grade Steel
Coating	15-17 mils Fusion Epoxy
Length	2 miles (3.2 km)
Shelter Position	Metering station close to landslide (<100 m East, of landslide)
Communication Optical Fiber	Not available
Local Temperature	Min -6°C / Max: 26°C
Rain	150 - 250 cm Yearly average [19]

2.2 Geohazards Risks

Northwest's Ignacio to Sumas mainline traverses the Columbia River Gorge in southern Washington state. This region of the United States is prone to significant mass movement events due to a number of geomorphic and climatological factors. The region is characterized by heavy rainfall, with the western Columbia River Gorge averaging between 150 and 250 centimeters (60 and 100 inches) of precipitation annually [19]. Additionally, the underlying geology of the Columbia River Gorge consists of weak volcanic and pyroclastic deposits from the Oligocene through the early Miocene topped with later Miocene lava flows (Columbia River Basalt Group), Pliocene era fluvial deposits, and capped with more competent lava flows (Pleistocene) [20]. Simplified, this stratigraphic geology of more competent material resting on weaker deposits creates a natural failure plane for landsliding. Further, the Missoula Floods in the late Pleistocene epoch swept catastrophic amounts of water across eastern Washington state and scoured the Columbia River Gorge. Ongoing scour from the Columbia River continues to shape the area today. The region has also been shaped by ongoing tectonic uplift and volcanic activity associated with the Cascadia Subduction Zone and Yakima Fold Belt contributing to sharp relief and steep slopes.

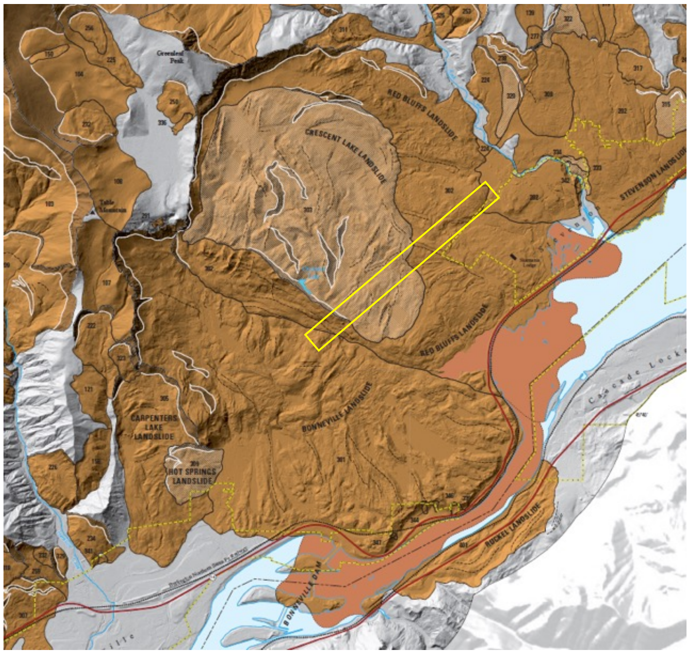

FIGURE 1: MAPPED LANDSLIDES WITHIN THE CASCADIA LANDSLIDE COMPLEX [20]; THE PIPELINE ROUTE IN THE LANDSLIDE IS HIGHLIGHTED BY THE YELLOW RECTANGLE.

Of primary concern through this region is the Cascade Landslide complex, which contains the largest area of recent and currently active landslides within the Columbia River Gorge [20]. The most recent mass movement of the area is thought to have occurred around A.D. 1421-47 based on radiocarbon dating of trees entrained within the landslide deposits. Deposits from this landslide briefly dammed the Columbia River and permanently altered its course [21]. The area of interest is mapped in Figure 1.

FIGURE 2: VIEW LOOKING DOWNSLOPE ACROSS A CLEARCUT PORTION OF THE RED BLUFFS LANDSLIDE.

2.3 Blue Lake Landslide

Within the Cascade Landslide complex, of especial interest to Northwest Pipeline is the Red Bluffs Landslide (see Figure 1), and a more recently activated portion of Red Bluffs referred to internally as the Blue Lake Landslide. The Blue Lake landslide is also commonly known and mapped as the Crescent Lake Landslide (see Figure 1). Northwest's 26-inch (66 cm) mainline extends across the toe of the Crescent Lake (Blue Lake) Landslide and body of the Red Bluffs Landslide for approximately 3.2 kilometers (2 miles).

The Blue Lake landslide has been mapped by the USGS as a currently active landslide. It encompasses an area of approximately 7.5 square kilometers and sees movements averaging 11 to 18 centimeters per year (four to seven inches per year) and possibly reaching 25 centimeters per year (10 inches per year) [20]. Northwest's internal geodetic monitoring has seen movements ranging between 5 and 15 centimeters per year since 2014. Movement of the Blue Lake landslide primarily occurs during the winter and spring, coinciding with heavy precipitation in the Pacific Northwest. The topography is consistent with hummocky terrain, ponding, and seeps throughout the slide body. While vegetation in the area consists primarily of coniferous forest, much of the area is owned by local logging companies. Periodic clear cutting of timber in the area can affect the hydrology and amount of groundwater seepage, directly impacting the amount of movement experienced by the landslide mass over time (Figure 2, Figure 3).

FIGURE 3: VIEW LOOKING UPSLOPE AT THE HEAD SCARP OF THE BLUE LAKE (CRESCENT LAKE) LANDSLIDE

Northwest Pipeline has experienced serious integrity concerns regarding high strain accumulation from land movement within the Cascade Landslide complex. Movement of the Cascade Landslide complex is considered to be the primary cause of ruptures in 1972 and 1979 [22]. This led to Northwest's early adoption of geodetic monitoring beginning in the mid 1980's. The use of vibrating wire strain gauges for local strain monitoring began in the late 1980's through the 1990's. This monitoring network has since expanded to include the use of expanded strain gauge and geodetic survey locations, LiDAR, InSAR, and IMU bending strain assessments. Mitigation of high strain areas has occurred by excavating areas of high strain build-up to allow for the pipe to rebound back to a lower stress state. Strain and pipe movement monitoring during these stress relief excavations began to show a concerning trend of decreasing pipe rebound. The absence of a competent baseline from pipe construction combined with these concerning strain trends illustrated a need to perform mitigation of the pipeline through this area. To ensure the ongoing integrity of the asset, Northwest Pipeline made the decision to replace the 3.2 kilometers (two miles) of pipeline through the Crescent Lake landslide. Construction of the pipe replacement was completed during the summer and fall of 2024 (Figure 4, Figure 5).

FIGURE 4: PIPELINE LOWERED INTO THE EXCAVATED TRENCH.

FIGURE 5: PIPELINE ROUTE (ORANGE LINE) THROUGH THE BLUE LAKE (CRESCENT LAKE) AND RED BLUFFS LANDSLIDES.

2.4 Monitoring Challenges

The magnitude and complexity of the Blue Lake and Red Bluffs Landslides create logistic and economic challenges associated with accurately monitoring movement across the landslide and the associated accumulation of strain in the pipeline. Historically, Northwest Pipeline has relied on a combination of geodetic survey monuments and manual read strain gauges across the site.

Geodetic monitoring, consisting of repeated ground-based survey of discrete monuments, provides for an accurate, low-cost method of tracking movement of the ground surface through the landslide area. While this gives a good general depiction of movement across the landslide, these monuments are discrete and typically spaced 60 to 150 meters (200 to 500 feet) apart through the slide mass, failing to give a continuous profile of movement across the landslide. Additionally, geodetic monitoring requires manual reading by a ground-based crew and does not offer automated, real-time monitoring of ground movement.

Northwest Pipeline has heavily relied on the use of manual read, vibrating wire strain gauges for measuring the accumulation of strain on the pipeline. While these have provided a cost-effective way of measuring strain on the pipeline, efficient use of these as a monitoring technique has been hampered by the following factors: 1) measurement of strain is limited to discrete locations along the pipeline, 2) difficulty in automating strain reads across the larger landslide area, and 3) lack of a consistent baseline to measure accumulated strain.

Manual read strain gauges have historically been spaced at intervals ranging from 30 to 150 meters (100 to 500 feet) apart across the body of the landslide. While accuracy is high at the exact strain gauge location, inferences must be made to estimate strain accumulation within the pipeline between gauge sets. This can prove challenging since the nature of a large deep seated landslide complex can result in differential movement and differential accumulation of strain across the broader slide area. Further, while strain gauges easily identify bending strain, signatures related to accumulation of axial strain are more subtle and difficult to identify.

Northwest pipeline has traditionally relied on manual read strain gauges at the site. This requires a local technician to physically read each individual gauge. This can be problematic since peak movements are typically associated with adverse weather and access conditions. As part of the Blue Lake replacement project, automation of strain gauges was considered as part of the scope. This would require pulling signal cable attached to each individual gauge through pvc conduits placed in an excavated side trench, a minimum of three feet deep. The signal cable would ultimately terminate at a datalogger and communications panel. Power would be required at the datalogger panel to read the gauges. Northwest Pipeline worked with a licensed electrical engineer on potentially automating strain gauges at this location. It was determined that approximately 80 kilometers (50-miles) of conduit would need to be laid inside trenches through the project area to accommodate automation of strain gauges. An alternative solution would be to install a localized solar powered datalogger at each individual strain gauge site. However, this alternative came with significant risk of vandalism and damage to the power and automation infrastructure. Ultimately, the vast amount of additional excavation and materials to accommodate power and communication needs for automating strain gauges would have added a significant amount of time to the project schedule and was determined to be cost prohibitive.

It is also important to note that while the pipeline was installed in the mid-1950's, strain gauges were not used on the pipeline until the late 1980's. While additional gauges were installed ad hoc from the 1990's through the early 2010s, accumulated strain in the pipeline since original install was not measured and the overall effects and total strain involved were based on inferred estimates associated with the geodetic survey data. Often strain gauges were installed without extensive stress relief excavations meaning the cumulative strain reads were not reading from a 'zero' baseline. This means that strain monitoring across the Blue Lake Landslide was largely arbitrary and based on overall trends and could not reliably be used as an absolute strain number.

More recently Northwest Pipeline began utilizing other technologies at the Blue Lake landslide area. While LiDAR and InSAR are good alternatives for measuring ground-based changes, they do not give data related to the accumulation of strain on the pipeline. IMU bending strain assessments can be a good source for continuous strain measurements, however since the pipeline was originally constructed in the 1950's a 'zero' baseline was not available and bending strain values were arbitrary based on accumulated strain between runs. Additionally, IMU bending strain is dependent on running ILI assessments to collect data and does not provide continuous, real-time monitoring.

3 GENERAL CONSIDERATIONS FOR PIPELINE GEOTECHNICAL MONITORING WITH OPTICAL FIBER SENSING

3.1 Geotechnical Monitoring System

A GTMS is usually composed of a combination of the following building blocks, depending on the project monitoring requirements [12]:

- DSS interrogator, DAS interrogator and DTS interrogator, amplification modules and optical switches; each of these units constitute an optical node located in a pipeline node such as a compressor station.
- SMC and TMC as sensors; TMC can ensure the communication between stations and control centers.
- data communication interface between the monitoring units and the control centers, including the use of the TMC cable or a dedicated OFC.
- Monitoring software including measuring unit control, GIS visualization and configuration, as well as alarming; more advanced processing can be implemented to extract additional information on pipeline integrity status such as deformation, crack development, buckling and bending.

3.2 Distributed Measurement Principle

3.2.1 Light backscattering

Distributed sensing relies on the phenomenon of light scattering [23]. Scattering occurs as soon as a lightwave propagates in a physical medium whose impedance is inhomogeneous. In an optical fiber, the scattered light can be observed in the backward and the forward directions. Distributed sensing technology only analyses the spontaneously backscattered light. A spectral analysis of the backscattered light reveals several independent lines, which are known as Rayleigh, Brillouin and Raman.

In the current work, the backscattered component of interest is the Brillouin whose optical frequency is sensitive to strain and temperature. BS is the physical principle on which the DSS and DTS rely to complete the measurements. It is also found in DTSS (Distributed Temperature and Strain Sensing) interrogator which combine both measurements capabilities ([23], [24], [25], [26]).

Brillouin spontaneous scattering is caused by the interaction between the propagating optical signal and thermally excited acoustic waves in the GHz range existing naturally in the silica fiber, giving rise to frequency shifted components. It can be seen as the diffraction of light on a dynamic grating generated by the acoustic wave (an acoustic wave is a pressure wave which introduces a modulation of the index of refraction through the elasto-optic effect). The diffracted light experiences a Doppler shift since the grating propagates at the acoustic velocity in the fiber. The acoustic velocity is directly related to the medium density which is temperature and strain dependent. As a result the so-called Brillouin frequency shift carries the information about the temperature and strain of the fiber ([23], [24], [25], [26]). The Brillouin frequency shift is an intrinsic parameter of the fiber. Its value is independent from the measuring system, ensuring long term unbiased measurements with no need for periodic recalibration. Furthermore, its perfect linear dependency on temperature and strain allows for the accurate and straightforward determination of fiber conditions unaffected by connectors or splice losses, as well as multiple connections. Brillouin scattering offers an additional advantage. It can be stimulated by a counter-propagating lightwave, whose wavelength is locked on the Brillouin frequency shift ([23], [24], [26]). This mechanism enhances the scattering leading to a resonance phenomenon and is known as SBS. The stimulation significantly improves the measurement range and performances. Sensing distances larger than 80 km can easily be achieved. Alternatively, short sensing distances affected by a high attenuation can also be measured without significant performance degradation. In addition, SBS is compatible with optical amplification schemes, extending the measurement range to hundreds of kilometers [28].

3.2.2 Distributed Measurements

The most common approach to obtain distributed measurements is based on the OTDR technique ([23], [24], [26]). In such technique, a pump pulse is launched into the fiber and a photodetector measures the amount of light that is backscattered as the pulse propagates along the fiber. The pulse time of flight is converted into distance information provided that the refractive index speed of light is known, similar to radar or lidar detection techniques. The pulse length determines the spatial resolution, which is the ability of the measuring unit to discriminate two adjacent locations submitted to different temperature/ strain conditions whilst fully quantifying the local temperature / strain.

The alternative to the time domain approach consists in using a continuous wave signal that is frequency modulated. The technique is known as OFDR ([23], [27]). The pump lightwave frequency is tuned over a frequency range that fixes the spatial resolution. A FFT (Fast Fourier Transform) is applied to the result of scanned backscattered light to recover the strain/temperature spatial distribution.

3.2.3 Distributed Measurements Performance and Standardization

Performance parameter definitions and testing regarding optical fiber sensors in general and distributed sensing specifically are now formalized by generic requirements form the IEC [29]. These requirements concern among other parameters the spatial resolution, the strain and temperature resolution as well as the distance and attenuation measurement range.

When the DTSS is designed with time resolved technique, it is known as Brillouin Optical Domain Reflectometer (BOTDR) when it uses BS. The frequency domain would name the interrogator as a Brillouin Optical Domain Reflectomer (BOFDR). When the interrogator relies on SBS, the naming is Brillouin Optical Time Domain Analyzer (BOTDA) and Brillouin Optical Frequency Domain (BOFDA) depending on the method using to achieve distributed sensing.

3.3 Sensing fibers and cables

Most of the situations of infrastructure monitoring require long distance sensing capabilities. In such cases, SMF are preferred. In addition, it is common practice for communication backbones to deploy single mode fiber-based cables along assets. Finally, DTSS operates best with SMF. These fibers and the test methods have gone through a standardization process and are currently the object of recommendations by the ITU and the IEC ([30], [31]). Whilst the single-mode fiber flavor is not critical for sensing, the cable structure plays a much more important role depending on the target application. The next three sections review some generic fiber sensing cable requirements.

3.3.1 Strain Measurement Cables

SMC are robust fiber optic cables specifically designed for distributed strain monitoring applications. Unlike telecommunication fiber optic cables, the SMC design allows the cable strain to be transferred to the optical fiber and subsequently detected and monitored by the interrogators. The basic cable design implies a tight buffered where the fiber is mechanically bonded to all the layers. Mechanical and optical characteristics of SMC cables must comply with the IEC Optical Fiber Cables requirements [32]. To address a broad variety of conditions, various models of strain measurement cables were developed and qualified as discussed in reference [17]. Schematic stress-strain response of a SMC is presented in Figure 6.

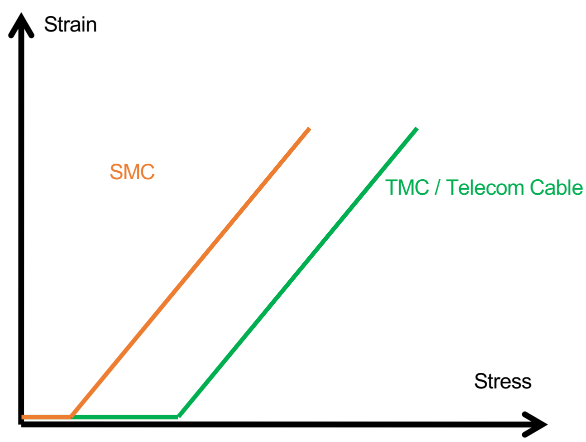

FIGURE 6: RESPONSE OF SMC, TMC AND COMMUNICATION OFC TO LOADING

3.3.2 Temperature Measurement and Communication Cables

TMC are higher grade versions of standard armored telecommunication fiber optics cable usually used for direct burial applications. The preferred design uses loose tube structure, which reduces the mechanical bonding between cable layer. The design also considers an excess fiber length of 1% or more to delay the strain transfer when the cable is subjected to loading. The cable includes the optical fibers used for temperature monitoring as well as fibers for data communication between the instruments and the control room. Mechanical and optical characteristics of the cable are following IEC 60794 Optical Fiber Cables requirements [32]. Schematic stress-strain response of a TMC is presented in Figure 6.

3.3.3 Multifunctional Cable

In some cases, a single cable installation is required for cost and practical purposes. These requirements lead to the introduction of a multifunctional cable [18]. Such cables combine strain, temperature and vibration measurement capabilities together with conventional Datacom functionalities. They were designed to offer the appropriate sensitivity and the required mechanical strength as per IEC 60794 Optical Fibre Cables requirements [32].

TABLE 2: MEASUREMENT PARAMETER AND EVENT MONITORING [12]

Event	Ground Strain	Ground Temperature	Pipe Strain and Temperature
Erosion		X	
Landslide	X		
Subsidence	X		
Pipe deformation			X

3.4 Geohazard Monitoring Using DTSS

DTSS is at the core of the monitoring system aiming at detecting and locating at an early stage all the natural events that can be a threat to the pipeline [12]. It is also used as a pipeline deformation monitoring system ([14], [15], [16], [17]). The monitoring system will emphasize the early signs of these threats. Geohazards and associated sensing quantities which are either strain or temperature are listed in TABLE 2, with the corresponding sensing technologies. The temperature sensing capabilities of the DTSS are used for temperature sensing and hence erosion detection. Temperature measurement is also needed for thermal effects compensation on strain measurements. Its strain sensing capabilities are used for strain sensing. It is then the tool for landslide and subsidence monitoring as well as pipeline deformation.

TABLE 3: SENSING CABLES USED IN THE PROJECT

	SMC	TMC	HYBRID
Application	Strain	Temperature	Strain & Temperature
OD	3.2 mm	4.8 mm	12.3 mm
Armouring	Central SSL Tube	Central SSL Tube and SSL strength members	Central strength member and corrugated steel sheath
Outer Sheet	Structured PA	PA	HDPE
Tight buffered	1 SMF	NA	3 SMF
Loose Tube	NA	8 SMF	6 SMF

3.5 Selection of DTSS and sensing cables

The preferred DTSS interrogator for the project is based on the BOTDA technique which maintains best performance in challenging installation and monitoring conditions thanks to the advantages provided by SBS. It can accommodate large loss fibers, several connectors and cable ageing usually causing attenuation increase. It is common is deformation monitoring project to have cable breaks increasing the number of splices. Moreover, deformation usually increases attenuation in optical fibers. The selected interrogator can accommodate 24 dB of total attenuation while measuring with a spatial resolution of 1m, a temperature resolution of 1°C and a strain resolution 20 με. It is worth mentioning that the supplied DTSS can operate in BOTDR mode as well. It implies that in the case of a fiber break the monitoring of the sensor can continue up the break point.

Three sensing cables are installed in the project: SMC and TMC for pipeline deformation monitoring and a hybrid cable for ground movement detection. Cables characteristics and cross-sections are presented in TABLE 3.

4 INSTALLATION METHODOLOGY, CHALLENGES, AND SOLUTIONS

4.1 Installation Process

To determine three-dimensional pipeline deformation, three SMC were glued to the pipeline surface as illustrated in Figure 8. An additional TMC was also attached to the pipe to compensate thermal effects from the strain measurements. The TMC is also used to close the sensing loop as required by BOTDA. On the whole pipeline section to be monitored, the cables were attached in the trench after it was lowered down, to reduce risks related to damages to the cables during the pipeline displacement with heavy machinery.

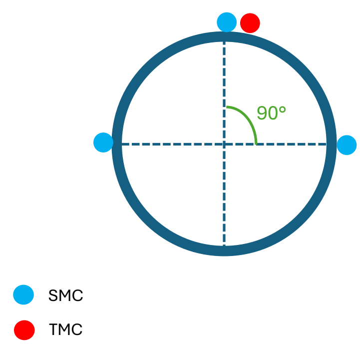

FIGURE 7: PIPE CROSS SECTION WITH OPTICAL FIBER POSITIONS.

Further to the pipeline strain measurements, the landslide detection system included a dedicated hybrid fiber optic cable for measuring ground displacement and its temperature. The hybrid sensing cable is laid in the trench parallel to the pipe (Figure 8). The cable is installed when the trench is partially backfilled.

The process of installing the cables on the pipe can be summarized as follows:

1. Marking of the exact position were the TMC and SMC's will be installed.
2. Pipe surface cleaning and roughening.
3. Continuous fixing of SMC with adhesive on the pipe.
4. Strapping of the TMC.
5. Splicing of the fibers (Figure 9).
6. OTDR measurements for checking fiber continuity.

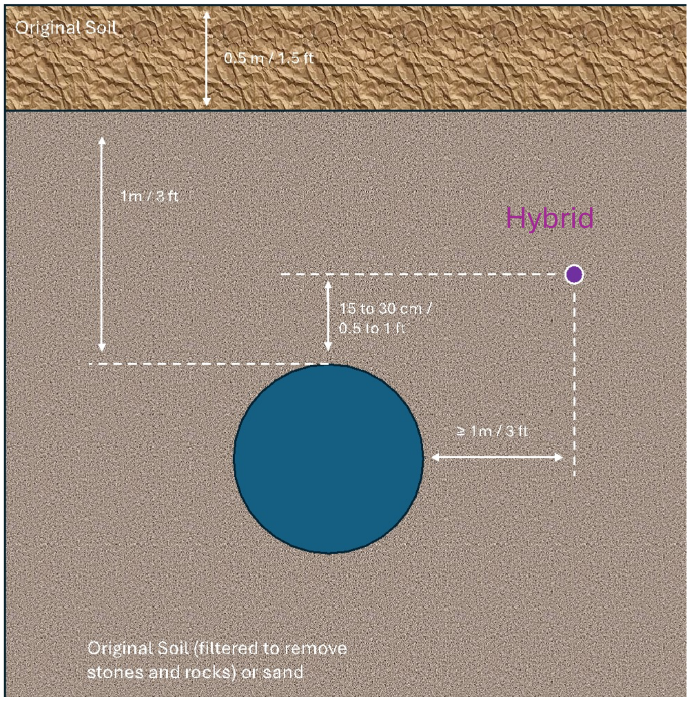

FIGURE 8: TRENCH CROSS SECTION WITH PIPE AND POSITION OF HYBRID SENSING CABLE.

FIGURE 9: OPTICAL FIBER CABLE SPLICING.

4.2 Challenges

4.2.1 Construction Constraints

Three construction constraints affected the SMC-TMC loop installation as the new pipeline could not be built in a continuous and monotonic process.

First, being a pipeline replacement project, the ROW is shared with the old pipeline which was still active during construction. In the landslide area, the new pipeline route is crossing thrice the old pipeline route, splitting the construction into four sections. The crossing could be closed only once the old line was turned off. An example of crossing is shown in Figure 10.

Second, Construction required to keep RAP's (Road Access Point) to the ROW active to allow machinery displacement, people and material access in Figure 11.

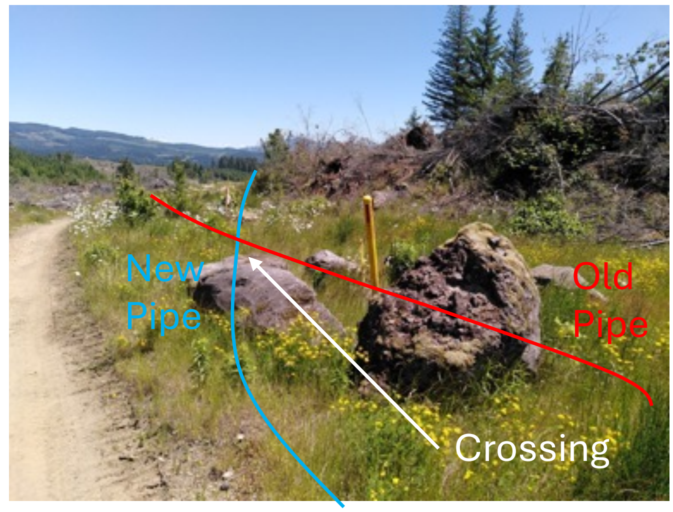

FIGURE 10: CROSSING BETWEEN OLD AND NEW PIPES.

FIGURE 11: EXAMPLE OF ROAD ACCESS POINT.

Third, the pipe replacement construction work was on a constricted schedule. First of all, limited amount of time was available to complete the project prior to adverse weather conditions. Moreover, Northwest Pipeline is also the primary supplier of natural gas to the region and had limited windows available for an extended outage on the existing system. The tight project schedule and safety requirements did not allow the cable installation to occur at the end of the construction process, once the whole length of the pipe was laid in the trench.

Consequently, the installation of the SMC and TMC had to be completed by sub-sections whose limits are defined by the RAP and the pipe crossings. It implied up to 12 sections distributed over the whole length and required 13 optical fiber splices per sensor.

4.2.2 Optical Fiber Cable Constraints

Splicing activity was also facing two significant challenges. First, the construction site was exposed to difficult environmental conditions. Wind and moving machines kept the atmosphere dusty which made tedious the splicing activity affecting both people and equipment. Second, SMC and TMC have FIMT type structure. Their preparation and splicing required special techniques and dedicated training of the cable installation crew.

Achieving loss below 0.5 dB per splice was particularly difficult. Attenuation coefficient measured at 1.55 µm for the complete loop is comprised between 1.1 dB/km and 1.3 dB/km depending on the SMC-TMC. A single ended OTDR measurement trace shown in Figure 12 illustrates how the numerous splices affects the overall attenuation. Despite such high attenuation, DTSS performance for the SMC-TMC loop is better than 1°C or 20 µε for a spatial resolution of 1 m and a measurement averaging time less than 5 minutes.

Attenuation coefficient values range from 0.4 to 0.5 dB/km are for the Hybrid cable. DTSS performance for the SMC-TMC loop is about 0.5°C or 10 µε for a spatial resolution of 1 m and a measurement averaging time less than 5 minutes.

4.2.3 Procurement Constraints

Since the decision to install the monitoring system was shortly before the mobilization of the construction contractor, the project required a fast reaction that was achieved by close collaboration with 2 cable suppliers and the manufacturer of the adhesive that were able to produce and deliver the materials in record time. 14 weeks after the confirmation of the order, the cable was completely installed. The cable installation lasted 5 weeks and time frame was tightly matching the pipe installation project schedule.

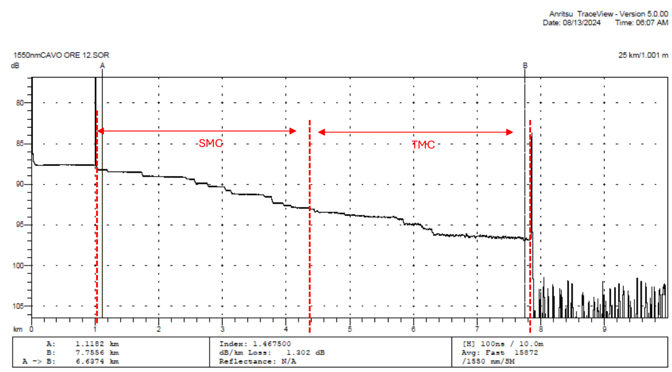

FIGURE 12: OTDR TRACE OF 12 O'CLOCK SMC-TMC LOOP MEASURED AT 1550 NM

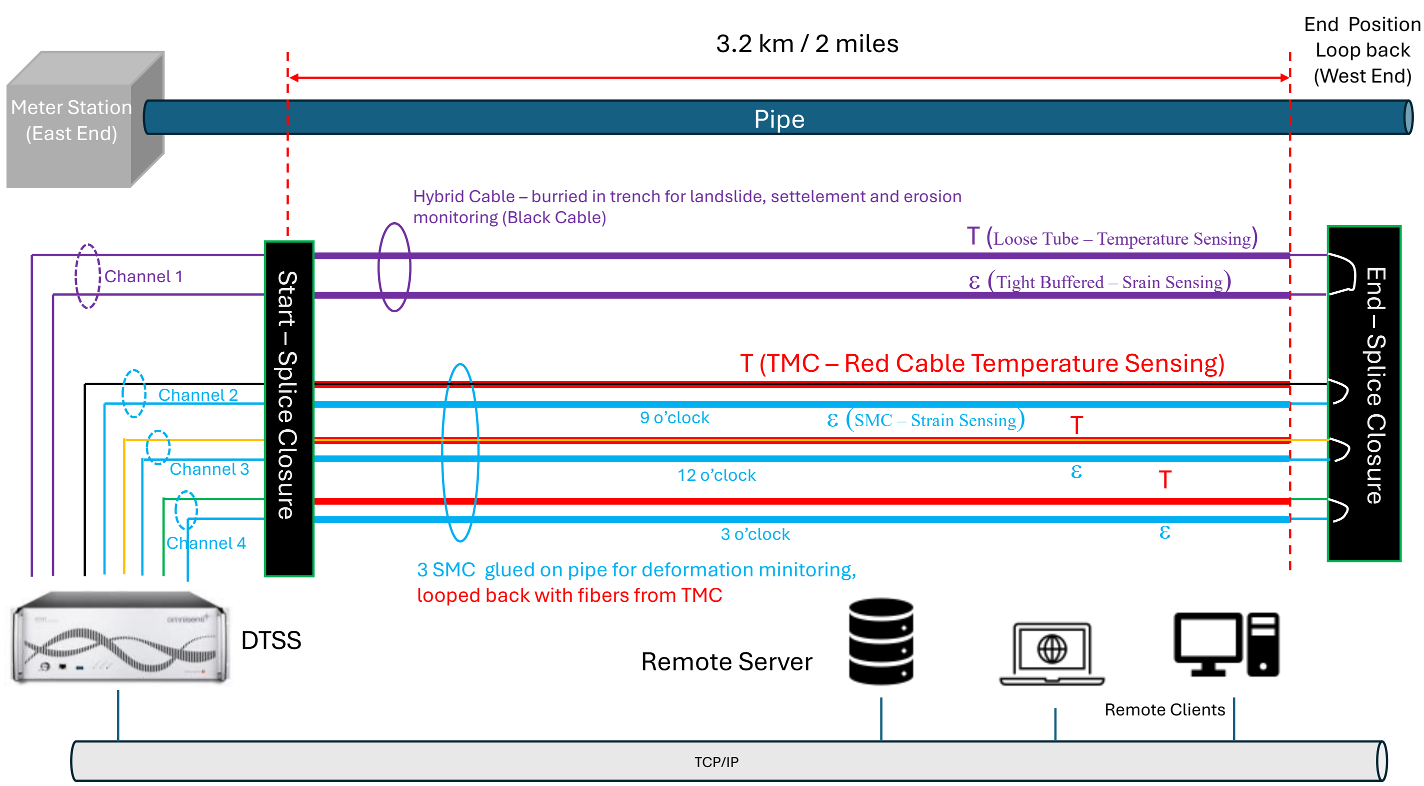

FIGURE 13: MONITORING SYSTEM ARCHITECTURE AND SENSOR ROUTING.

5 MONITORING: BASELINE AND ONGOING STATUS

5.1 Monitoring System Architecture

The DTSS interrogator is hosted in a climatized cabinet near the meter station. A 50m long launching cable connects the interrogator to the sensing cables in the first splice closure. The sensors are looped back at the landslide west-end splice closure. Strain sensing is completed on the way-in and the temperature sensing is achieved on the way back. The interrogator has a four channels optical switch. Each channel measures a single loop. The complete architecture and sensor routing is presented in Figure 13.

The sensing data are stored temporarily in the DTSS database. The data are then transferred to the remote server for processing, storage and display. Data visualization can be done directly on the server and remotely on client computers.

5.2 Preliminary Measurement

Data are collected by the DTSS since December 11, 2024. Measurement profiles for the pipeline deformation application are displayed in Figure 14 to Figure 16. Relative measurement profiles are presented to emphasize the numerous splices marked by the spikes in the graphs, particularly visible in the SMC sections. The system being still in commissioning phase, the presented measurements are raw data, or in other words, uncalibrated and uncompensated in temperature. Thirteen spikes are observed in the SMC part of the profile and are the signature of the SMC-to-SMC splicing. By the completion of the commissioning, which includes the distance calibration, the conversion from frequency to strain or temperature and temperature compensation, the influence of the splices will be removed from the monitoring display.

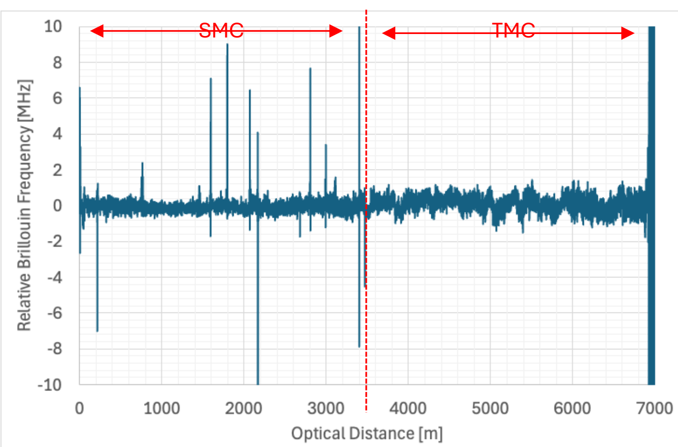

FIGURE 14: RELATIVE BRILLOUIN FREQUENCY PROFILES COLLECTED POSITIONS 3 O'CLOCK SMC.

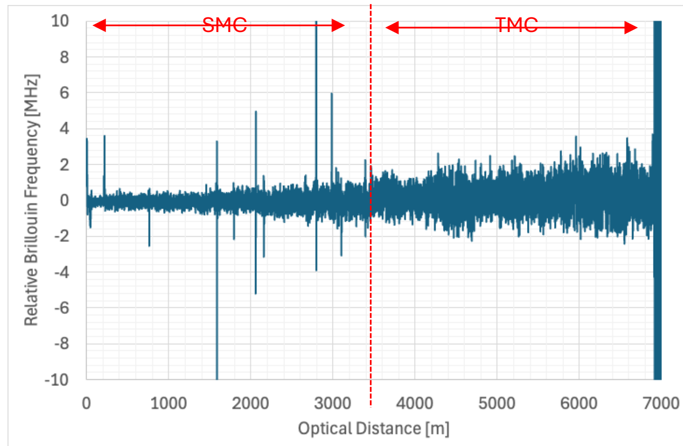

FIGURE 15: RELATIVE BRILLOUIN FREQUENCY PROFILES FOR 9 O'CLOCK SMC.

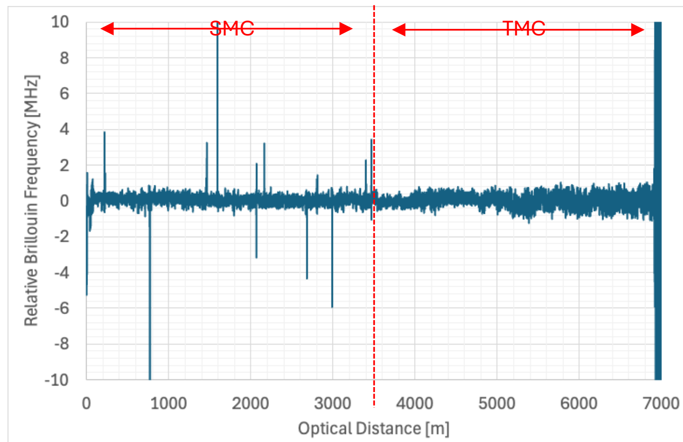

FIGURE 16: RELATIVE BRILLOUIN FREQUENCY PROFILES FOR 12 O'CLOCK SMC.

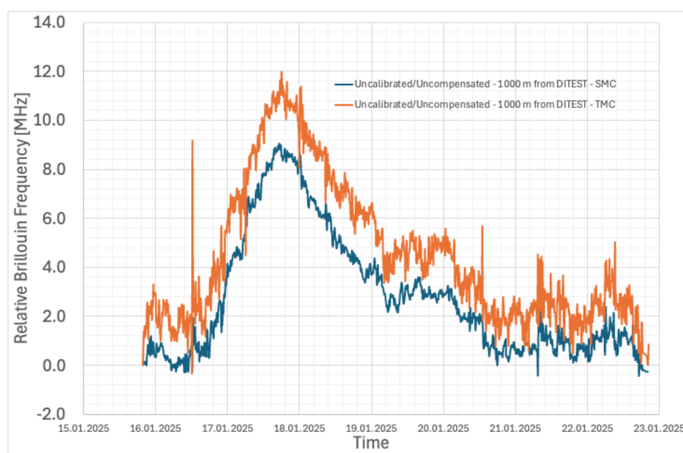

FIGURE 17: UNCALIBRATED AND UNCOMPENSATED MEASUREMENTS (STRAIN IN BLUE AND TEMPERATURE IN ORANGE) FOR SENSOR 3 O'CLOCK AT 1000M FROM THE INTERROGATOR.

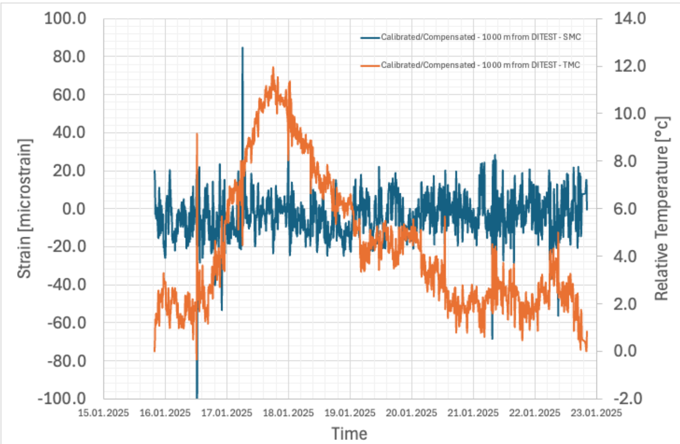

FIGURE 18: CALIBRATED AND THERMALLY COMPENSATED MEASUREMENTS (STRAIN IN BLUE AND TEMPERATURE IN ORANGE) FOR SENSOR 3 O'CLOCK AT 1000M FROM THE INTERROGATOR.

The effect of temperature influence on the strain measurement is presented in Figure 17 at position 1000 m for 3 O'clock sensor. SMC and TMC experience a similar temporal evolution. Figure 18 illustrates the effect of calibration and the importance of thermal compensation. Response is similar for 9 and 12 O'clock sensors.

6 CONCLUSION AND NEXT STEPS

In large complex landslide terrain such as the Cascade Landslide system, early detection of ground movement and adverse strain conditions is essential to maintaining the integrity of the pipeline. The ability to monitor and identify threats continuously in real time allows pipeline operators to make real-time efficient decisions. Implementation of the DTSS based GTMS at Blue Lake will give Northwest Pipeline greater transparency into the movement of the slide mass itself through the hybrid sensing cable while also allowing for long term monitoring of pipe strain through the affixed TMC and SMC. With this system, Northwest can more efficiently and effectively target exact movement zones and track strain accumulation trends, allowing for proactive mitigation.

On the short term, the main objective is to fully complete the commissioning. On the long term, monitoring data collected from the DTSS will be compared with strain gauge readings. As one collects data as well from the ground deformation, comparison between soil displacement and pipeline deformation will be conducted. This analysis will provide the community with information to improve the understanding of soil-pipe interaction from a real-world installation.

The implemented DTSS unit based on the BOTDA technique is the appropriate interrogator model. Such unit is capable of handling large optical losses and accommodate severe cable ageing. The choice was key due to the installation challenges which induced sensing loop attenuation equivalent to a 50km long link, which is expected to increase during the system operations lifetime.

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The DTSS is a DITEST interrogator, with BOTDA and BOTDR capabilities, from EOSS, a Prysmian Group company. SMC and TMC are supplied by Solifos AG while the hybrid cable is the AIMCOM from Prysmian Cables and Systems USA, LLC.

REFERENCES

[1] Lee, E.M. "Landslide risk assessment: the challenge of estimating the probability of landsliding", Quarterly Journal of Engineering Geology and Hydrogeology, Vol. 42, pp. 445–458, 2009. https://doi.org/10.1144/1470-9236/08-007

[2] Bruce, I. "Estimating the influence of natural hazards on pipeline risk and system reliability.", Proceedings of the 2004 International Pipeline Conference, Calgary, Alberta, Canada, October 4 – 8, paper IPC04-0238, 2004. https://doi.org/10.1115/IPC2004-0238

[3] Lee, E.M., Audibert, J.M.E., Hengesh, J.V., Nyman, D.J. "Landslide-related ruptures of the Camisea pipeline system, Peru" Quarterly Journal of Engineering Geology and Hydrogeology, Vol. 42, pp. 251–259, 2009. https://doi.org/10.1144/1470-9236/08-061

[4] Hearn, G., Wise, D., Hart, A., Morgan, C., O'Donnell, N. "Assessing the potential for future first-time slope failures to impact the oil and gas pipeline corridor through the Makarov Mountains, Sakhalin Island, Russia", Quarterly Journal of Engineering Geology and Hydrogeology, Vol. 45, pp. 79–88, 2012. https://doi.org/10.1144/1470-9236/10-033

[5] Dzyuba, S., Chepkasov, A., Savchenkov, S. "Experience of Designing Natural Gas Transmission Pipelines in Super Challenging Geological and Environmental Conditions of Eastern Siberia and the Far East." 25th World Gas Conference, Kuala Lumpur, June 2012.

[6] Palmer, A. C., and Williams, P. J. "Frost heave and pipeline upheaval buckling", Can. Geotech. J., Vol. 40, pp. 1033–1038, 2003. https://doi.org/10.1139/t03-044

[7] Winter, M.G., Dixon, N., Wasowski, J., Dijkstra, T.A. "Introduction to land-use and climate change impacts on landslides". Quarterly Journal of Engineering Geology and Hydrogeology, Vol. 43, pp. 367–370, 2010. https://doi.org/10.1144/1470-9236/10-035

[8] Gasca, A., Gutierrez, E., "The Challenge of Crossing the Andes: A Data Base Analysis and Peru LNG Project Description", 1st International Pipeline Geotechnical Conference, Bogotá, Colombia, Paper IPG2013-1951, 2013. https://doi.org/10.1115/IPG2013-1951

[9] Malpartida, J., Oliveros, F, Massucco, G. "Integration of monitoring and inspection systems for geohazard assessment on pipelines that cross Amazonian Jungles and the Andes", 9th International Pipeline Conference, Calgary, Alberta, Canada, Paper IPC2012-90501, 2012. https://doi.org/10.1115/IPC2012-90501

[10] Oliveros Montes, EF, & Leynaud, FGL. "Integral Management of Risk: From a Corrective to a Preventive Approach" Proceedings of the ASME 2013 International Pipeline Geotechnical Conference. ASME 2013 International Pipeline Geotechnical Conference. Bogota, Colombia. July 24–26, 2013. V001T04A003. ASME. https://doi.org/10.1115/IPG2013-1921

[11] Malpartida, J., Massucco, G., "Alternative geohazard risk assessment and monitoring for pipelines with limited access: Amazon jungle example", 10th International Pipeline Conference Calgary, Alberta, Canada, paper IPC2014-33628, 2014. https://doi.org/10.1115/IPC2014-33628

[12] Ravet, F., Briffod, F., Goy, A., Rochat, E. "Mitigation of geohazard risk along transportation infrastructures with optical fiber distributed sensing". Journal of Civil Structural Health Monitoring **11**, 967–988, 2021. https://doi.org/10.1007/s13349-021-00492-x.

[13] Ip, E., Ravet, F., Martins, H. et al., "Using Global Existing Fiber Networks for Environmental Sensing", Proceedings of the IEEE, vol. 110, no. 11, pp. 1853 - 1888, 2022. https://doi.org/10.1109/JPROC.2022.3199742

[14] Glisić, B., Inaudi, D., "Fiber Optic Methods for Structural Health Monitoring", pp.235 – 247, John Wiley & Sons, Ltd, 2007. https://doi.org/10.1002/9780470517819

[15] Borda, C, Niklès, M, Rochat, E, Grechanov, A, Naumov, A, & Velikodnev, V. "Continuous Real-Time Pipeline Deformation, 3D Positioning and Ground Movement Monitoring Along the Sakhalin-Khabarovsk-Vladivostok Pipeline", Proceedings of the 2012 9th International Pipeline Conference. Volume 2: Pipeline Integrity Management. Calgary, Alberta, Canada. September 24–28, 2012. pp. 179-187. ASME. https://doi.org/10.1115/IPC2012-90476

[16] Ravet, F., Zou, L., Bao, X., Chen, Rong Feng H., Liang, C., Khoo, H. A., "Detection of buckling in steel pipeline and column by the distributed Brillouin sensor", Optical Fiber Technology, Volume 12, Issue 4, 2006, Pages 305-311, ISSN 1068-5200. https://doi.org/10.1016/j.yofte.2005.12.002.

[17] DuToit, D., Ryan, K., Rice, J., Bay, J., Ravet, F., "Analysis of Strain Sensor Cable Models and Effective Deployments for Distributed Fiber Optical Geotechnical Monitoring System", Proceedings of the ASME 2015 International Pipeline Geotechnical Conference. ASME 2015 International Pipeline Geotechnical Conference. Bogota, Colombia. July 15–17, 2015. V001T03A004. ASME. https://doi.org/10.1115/IPG2015-8520

[18] Risch, B., Lovie, R., Roland, D., Rochat, E., DuToit, D. (2015)., "Optical Fiber Cable Design for Distributed Pipeline Sensing and Data Transmission", Proceedings of the 64th IWCS Conference, 64-70.

[19] National Weather Service, National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce, https://www.weather.gov/.

[20] Pierson, T.C., Evarts, R.C. and Bard, J.A., "Landslides in the Western Columbia River Gorge, Skamania County, Washington", U.S. Geological Survey Scientific Investigations Map 3358, Scale 1:12,000, 22p, 2016. http://dx.doi.org/10.3133/sim3358.

[21] Palmer, L., "Large landslides of the Columbia River Gorge, Oregon and Washington", Geological Society of America, Reviews in Engineering Geology, v. 3, p. 69–83, 1977. https://doi:10.1130/REG3-p69

[22] Braun, J., major, Graeme, W., D.O., and Bukovansky, M., "Geologic hazards evaluation boosts risk-management program for Western U.S. pipeline", Oil and Gas Journal, V. 96 issue 45 (11/9/98), 13p., 1998.

[23] Hartog, A.H., "An Introduction to Distributed Optical Fibre Sensors", (1st ed.). CRC Press, 2017. https://doi.org/10.1201/9781315119014

[24] Niklès, M., Thévenaz, L. and Robert, P., "Simple distributed fiber sensor based on Brillouin gain spectrum analysis", Opt. Lett. 21, 758-760, 1996. https://doi.org/10.1364/OL.21.000758.

[25] Niklès, M., Thevenaz, L, and Robert, P., "Brillouin gain spectrum characterization in single-mode optical fibers", in Journal of Lightwave Technology, vol. 15, no. 10, pp. 1842-1851, 1997. https://doi.org/10.1109/50.633570.

[26] X. Bao, D. Webb, and D. Jackson, "Combined distributed temperature and strain sensor based on Brillouin loss in an optical fiber", Opt. Lett. 19, 141-143, 1994. https://doi.org/10.1364/OL.19.000141

[27] Garus, D., Gogolla, T., Krebber, K., Schliep, F. "Brillouin optical fiber frequency-domain analysis for distributed temperature and strain measurements," Journal of Lightwave. Technology, Vol. 15, pp. 654–662, 1997. https://doi.org/10.1109/50.566687

[28] Gyger, F., Chin, S., Rochat, E., Niklès, M., Ravet, F., "Ultra Long Range DTS (>300km) to Support Deep Offshore and Long Tieback Developments", 33rd International Conference on Ocean, Offshore and Arctic Engineering, OMAE 2014, San Francisco, PAPER OMAE2014-24019, 2014. https://doi.org/10.1115/OMAE2014-24019

[29] IEC 61757-1 Ed. 2.0: Fibre optic sensors - Part 1: Generic specification; IEC 61757-2-2 Fibre optic sensors - Part 2-2: Temperature measurement - Distributed sensing; IEC 61757-1-2: Fibre Optic Sensors - Part 1-2: Strain measurement – Distributed sensing

[30] ITU-T G.652 (11/2016) Characteristics of a single-mode opticalfibre and cable

[31] IEC 60793-1-1:2017 Optical fibres - Part 1-1: Measurement methods and test procedures - General and guidance

[32] IEC 60794-1-3:2017 Optical fibre cables - Part 1-3: Generic specification - Optical cable elements