IPG 2023
INTERNATIONAL PIPELINE GEOTECHNICAL CONFERENCE
23 y 24 de Noviembre
Bogotá Plaza Hotel. Bogotá D.C. - Colombia

Con el auspicio de: arpel
ASOCIACIÓN DE EMPRESAS DE PETRÓLEO, GAS Y ENERGÍA RENOVABLE DE AMÉRICA LATINA Y EL CARIBE

Organiza: C-IPG ACIEM Asociación Colombiana de Ingenieros

6ª CONFERENCIA INTERNACIONAL GEOTECNIA DE DUCTOS

IPG2023-0022

TGP GEOHAZARD PREVENTION SYSTEM WITH COMMUNICATION OPTICAL FIBER CABLES: A FULL-SCALE CASE STUDY

Fabien Ravet[1], Ricard Mas Fillol[2], Alberto Melo[3], Francisco Oliveros[3], Etienne Rochat[2]

[1] Gradesens, Fribourg, Switzerland
[2] Omnisens, Morges, Switzerland
[3] Transportadora de Gas del Peru, Lima, Peru

ABSTRACT

Optical fiber cables (OFC) are well known for their use in communications. They offer long distance and high-speed transmission capabilities. OFC is the perfect element of hydrocarbon and water transportation systems as part of the activity and management of communication and SCADA services of the operating companies. As an example, the TGP system has 790 km of cables laid in its Right of Way (ROW) that have been in use since the beginning of its operation in 2004. More recently, OFCs have started to be used as sensors. In these applications, a communication cable (CC) can be applied as a continuous temperature sensor to detect leaks and erosion. A strain monitoring cable (SMC) can also be spliced to the CC for detecting ground movements and subsidence in areas of special interest. In case of major ground displacements, it is common to observe induced deformation at the CC. Existing OFC infrastructures can then be exploited to monitor pipelines. This paper describes how to retrofit an existing CC to provide information on the integrity of the TGP conveyance system. In 2018, TGP initiated an evaluation of such a possibility leading to validation of the solution by the end of 2022. The evaluation included a pilot project on an 18 km long section composed of a mix of CC and SMC. It included a detailed and experimental study of the sensitivity of CC to environmental stresses. This was followed by a full-scale implementation of the system along a 256km stretch comprising the geographical area of the Amazon rainforest and part of the Andes Mountain range. The installation of this technique was timely to increase monitoring and surveillance during the 2022-2023 rainy season, which is the most complicated season for the infrastructure crossing the Andes. The system demonstrated its effectiveness in operability, complementarity with other geotechnical monitoring systems and follow-up of the stability condition of the ROW in the instrumented section.

Keywords: geotechnical monitoring, geohazard risk mitigation, landslide, subsidence, erosion, optical fiber sensors, distributed temperature sensor, distributed strain sensor, Brillouin scattering

NOMENCLATURE

Brillouin – A fiber optic scattering & sensing mechanism
BOTDA – Brillouin Optical Time Domain Analyzer
BOTDR – Brillouin Optical Domain Reflectometer
CC – Communication Cable
DSS – Distributed Strain Sensing
DTS – Distributed Temperature Sensing
DTSS – Distributed Temperature and Strain Sensing
EFL – Excess Fiber Length
EDFA – Erbium Doped Fiber Amplifier
FO – Fiber Optic
FOC – Fiber Optic Cable
GIS – Geographical Information System
GTMS – Geotechnical Monitoring System
HMI – Human Machine Interface
IEC – International Electrotechnical Commission
ITU – International Telecommunication Union
LDS – Leak Detection System
IT – Information Technology
MLV – Main Line Valve
NG – Natural Gas
NGL – Natural Gas Liquid
OD – Outer Diameter
OO – Owner/Operators
OTDR – Optical Time Domain Reflectometer
PS – Pumping Station
ROW – Right-of-Way

SBS – Stimulated Brillouin Scattering
SCADA – Supervisory Control and Data Acquisition
SMC – Strain Measuring Cable
SMF – Single Mode Fiber
TPI – Third Party Intrusion
WDM – Wavelength Division Multiplexer

1. INTRODUCTION

In the Andes mountains, pipeline incidents caused by geohazards reach 50% of the total number of incidents while ground movement remain a minor threat (<7%) in geologically stable regions such as Western Europe [1]. The eastern side of any pipeline crossing the Andes is exposed to a high geohazard risk which have affected several natural gas transport systems [2]. In the Andes, geohazards risk mitigation is a key activity for pipeline OO's in general, and particularly for the pipeline integrity team of Transportadora de Gas del Peru (TGP) [3].

FO monitoring solutions have been used and implemented as prevention tools of integrity programs along several pipelines [4]. These pipeline monitoring solutions reduce the risks caused by malicious or accidental TPI as well as make possible the early detection of leaks. It also proves helpful in the mitigation of natural hazard risks. Following TPI, natural hazards such as landslide, subsidence or erosion are the most common risk that pipelines are facing and are the detection objectives of the GTMS. Landslide and subsidence are detected thanks to strain monitoring using DSS interrogators while erosion is pinpointed thanks to DTS interrogators. Very often, an equipment combining both strain and temperature sensing can be built and is known as DTSS. The GTMS is the combination of these interrogators with a processing software that triggers alarms [4, 5, 6, 7].

Retrofitting a pipeline ROW with a GTMS is a simple task when the transport system uses a CC for its regular telecommunication and its SCADA. One pair of the fibers can be made available to connect the GTMS to its dedicated strain sensor (SMC). The same pair acts as more than a simple communication channel in the sections where no SMC is installed. In fact, the interrogators can provide temperature readings and inform about erosion as the CC is by design immune to mechanical loads but still sensitive to temperature. Such CC immunity is not true anymore when loads become very high as the ones induced by large soil movements. In these cases, the CC can be used as an alarming tool for sections that are not specifically equipped for strain monitoring [8, 9].

The current works present the implementation of the GTMS for the surveillance of CC. It is an extension of the work started in 2011, continued in 2018 and developed recently. The 2011 and 2018 steps have been discussed in [8]. The article presents the main challenges that needed to be addressed. One was the requirement to share the same fibers with other services. The other was to handle excessive fiber loss induced by the unstable terrains. To resolve these difficulties two optical technologies were introduced, which we believe to be for the first time in pipeline monitoring applications. The fiber sharing was achieved by using Wavelength Division Multiplexers (WDM) [10]. The loss compensation was completed by the installation of optical repeaters based on Erbium Doped Fiber Amplifiers (EDFA) [10, 11]. Therefore, due to the technology novelty, additional and dedicated training was required for the personal involved in the project. The work finally presents the monitoring operation since it has been started at the end of 2022 and shows early monitoring results as some events that were detected.

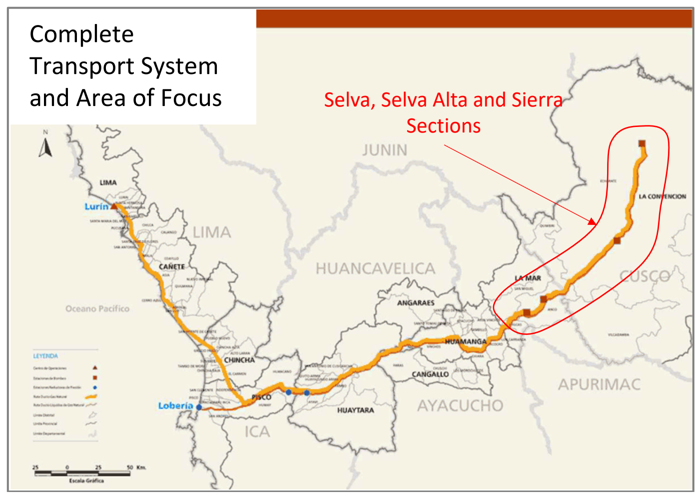

FIGURE 1: TGP TRANPORT SYSTEM ROUTE AND THE REGION WHICH IS THE OBJECT OF THE MONITORING (HIGLIGHTED IN RED).

2. THE TGP CASE STUDY

The analysis for the identification of alternatives to improve the geotechnical monitoring system was developed in conjunction with TGP integrity and information technology teams (FIGURE 1). To ensure a rigorous validation, laboratory tests were carried out on a sample of the CC model that is installed along the first 256 km of the TGP system. In that region, the system crosses the Amazon rainforest and the Sierra where the geohazard risk is important (FIGURE 2).

The TGP System is a project that has a sophisticated integrity program that includes, in a general way: permanent remote monitoring through its control room, frequent execution of internal inspections, development of predictive and preventive control plans, as well as adequate integration of the different social, environmental and technical factors [3]. With regard to fiber optics and communications services, it presents an adequate continuous communication model, which allows monitoring the conditions of the system in all its sectors, including the jungle sector.

FIGURE 2: TYPICAL JUNGLE LANDSCAPE AND PIPELINE ROW (RED DOTTED LINE).

3. SENSING TECHNOLOGY

The sensing techniques used to measure the OFC in the current work rely on the phenomenon of the scattering of a lightwave. Scattering is caused by static and moving changes in the density of the medium. The scattered light spectrum of a single wavelength (λ_0) lightwave is schematically represented in FIGURE 3. The spectrum is composed of an elastic component, known as Rayleigh and two inelastic components known as Raman and Brillouin. In the present work, we are only interested in Brillouin scattering. The DTSS instrumentation takes advantage of Brillouin scattering peak frequency sensitivity to strain and temperature.

The DTSS is the core instrument of any GTMS. It relies on BOTDA interrogators. BOTDA uses SBS in single-mode fiber. Brillouin scattered light is characterized by a frequency shift proportional to both temperature and strain variations. This shift can be measured by analyzing the interaction in standard optical fibers between a pump lightwave (pulse) and a counter-propagating probe lightwave (continuous). It requires a loop. The BOTDR is another flavor of the DTSS where only a pump pulse is used without the help of a counter-propagating probe. The technique has the advantage to measure up to the fiber end or break. Unfortunately, it is limited in measurement range and operates with reduced spatial and measurement resolution. Such interrogators can use a broad variety of SMF such as the ITU G.652, G.655 or G.657. Typically, the Brillouin frequency shift at ambient temperature of such fiber is comprised between 10.7 and 11.0 GHz at 1.55 μm wavelength and varies with nominal strain and temperature coefficients of 0.05 MHz/με and 1 MHz/°C respectively. This linear relationship makes it an easy method for sensing mechanical and thermal effects, whilst the pulse nature of the pump lightwave allows for accurate localization (time of flight measurement) and defines spatial resolution (pulse duration). The discrimination of strain from temperature measurement is easily completed by using two distinct sensing cables. Telecommunication cables are generally good temperature sensors as the fibers are isolated mechanically thanks to a loose tube design with nominal EFL of 0.5%. Strain sensing is achieved with dedicated cable using tight buffered design in which thermal effects must be compensated by temperature measurements from a telecommunication cable.

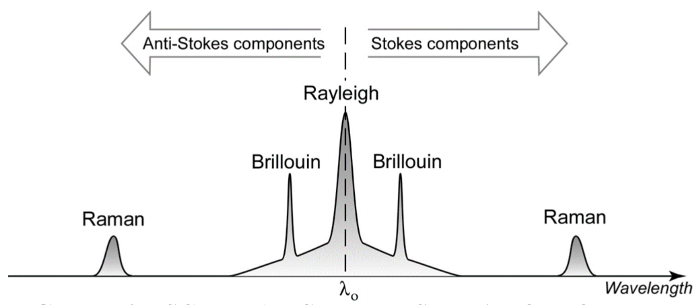

FIGURE 3: SCHEMATIC REPRESENTATION OF THE SCATTERED LIGHT SPECTRUM FROM A MONOCHROMATIC LIGHTWAVE.

TABLE 1. GEOHAZARDS AND SENSING METHODS [4].

Geohazard	Strain Measurement	Temperature Measurement
Erosion		X
Landslide [12]	X	
Subsidence	X	

Further details on the measuring unit working principle, configuration, fiber sensitivity to strain and temperature sensing parameter definitions as well as further references can be found in [13] and Appendix 1. Measurement distance range of about 80 km per sensor can be achieved for nominal attenuation of 0.2 dB/km. Longer range has been demonstrated thanks to the use of in-line optical amplification [14]. Performance parameter definitions and verification testing regarding optical fiber sensors in general and distributing sensing specifically are now formalized by the committee IEC SC 86C / WG2 [14].

4. GEOHAZARDS AND SENSING TECHNOLOGIES

The GTMS aims at detecting and locating at an early stage all the natural events that can be a threat to the pipeline. It will emphasize the early signs of these threats. Geohazards and associated sensing quantities which are either strain or temperature are listed in TABLE 1 [4], with the corresponding sensing technologies. DTS is used for temperature sensing and hence erosion detection. DTSS measures strain and temperature which is the tool for landslide and subsidence monitoring.

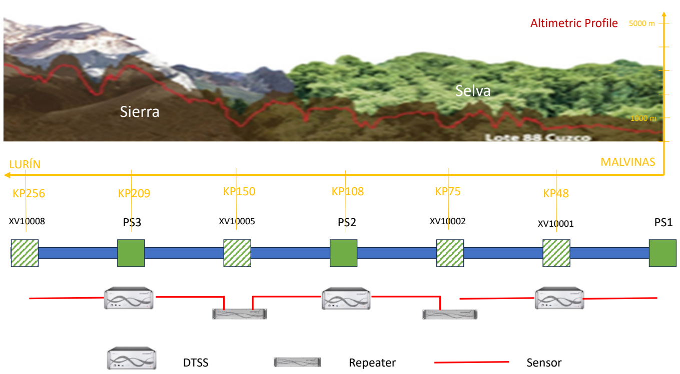

FIGURE 4: MONITORING ARCHITECTURE IMPLEMENTED IN SELVA AND SIERRA SECTIONS, FROM KP1 TO KP256, WITH ALTIMETRIC PROFILE IN RED [3].

5. TGP GEOTECHNICAL MONITORING SYSTEM

The current GTMS is composed of three DTSS interrogators installed in KP43, KP108 and KP209 respectively. The DTSS communicate with the server located in Lima. The server, model LYNX, hosts the alarm generation and management software, the GIS and the database. The software is also used to visualize the data. Over the 256km of the monitoring, most of the data are captured on the telecom FOC. Three sections were instrumented with SMC: KP8, KP91 and KP95. In the three cases, the SMC is directly spliced to the telecom FOC. The current architecture with the pipeline route altimetric profile is presented in FIGURE 4 [3].

More details about WDM and Repeater technology is available in Appendix 3.

Partial monitoring of the of the first 256 km started as early as 2011 with the focus on KP126 and KP91 and then an extension to KP95 in 2018. Details about the whole experience can be found in reference [8]. The reference discusses the validation of the sensing technology, the evaluation of the CC response to mechanical stresses as well as the report of several events and their verification by site inspections.

The CC used in the project was installed in the transport system ROW during the TGP construction phase. The CC is laid parallel to the pipeline. The monitoring intends to detect changes in the ROW that are of natural origin such as erosion and landslides. All the retrofit has been completed by implementing the DTSS interrogators and the required devices to face the two challenges of the project. All the new interrogators and the related devices are connected to the existing communication infrastructure.

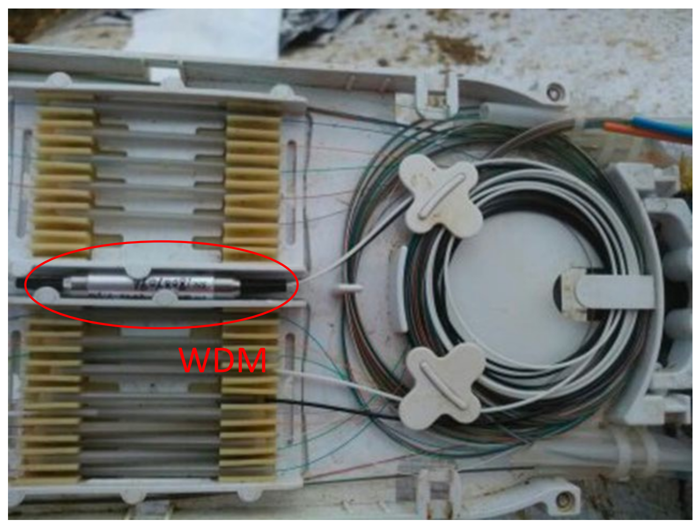

FIGURE 5: WDM COMPONENT INSTALLED IN A COMMON JUNCTION BOX.

In fact the complete GTMS implementation and operation was facing two challenges. Both could be answered to with optical fiber technology solutions. The first challenge comes from the availability of optical fibers for the monitoring. No fibers in the cable are available as they are all used by common IT services. In particular, the selected fibers for the monitoring are continuously measured by an OTDR based system used to detect fiber loss increase and fiber breaks. In telecommunication, solutions have been developed to multiplex various type of signals on the same fiber. Two signals carried by distinct wavelengths can be transmitted on the same fiber without interfering. As the OTDR operates at 1550nm and the DTSS at 1535.4nm, the signals co-propagation is then possible. The two carriers can be combined and separated by a WDM device [10], which is a component that does not require power. They are installed either in a patch panel or in a buried junction box (FIGURE *5*). In the current project, WDM were installed in KP0, KP8, KP43, KP75, KP108, KP150, KP209 and KP256.

The second challenge roots in the nature of the terrain crossed by the transport system. Soils are unstable causing large stresses on the cable. Stress is transferred to the fibers causing a loss increase. These stresses increase the risk of cable rupture and the need for additional splices. Consequently, typical attenuation coefficient for an optical fiber is 0.2dB/km at 1550nm can reach values above 0.3dB/km. Over the sensing range, which can vary from 30km to 50km, the link loss increases by 4 to 5dB. In other words, the loss in an unstable terrain is more than the double of loss in a stable terrain. Moreover, the solution brought by the WDM also contributes to the loss figure degradation. The solution can be brough by the combined use of long-range interrogators, that have a loss budget of 16 dB, with optical repeaters [10, 11] that can amplify the sensing signal at the opposite end of the sensor (FIGURE 6). They must preferably be installed in pump or valve station.

FIGURE 6: FOUR CHANNEL REPEATER, FRONT (TOP) AND BACK (BOTTOM) PANEL VIEWS.

To the best of our knowledge, the implementation of optical technologies we introduced in this project is new for the pipeline community. Their use requires additional training of all the stakeholders involved in their installation: field engineers and of the inspectors in charge of the installation; telecom engineers and project managers involved in the design of the monitoring solution. The training is critical as any mishandling would impact the installation duration and delay the project. Training of the personal and documentation preparation was then key to the project success.

6. EVENTS DETECTED

The implementation of the GTMS was completed at the end of 2022 and its final commissioning was underway when the rainy season started. During this period, a geotechnical finding was reported on a slope at KP233 position. On-site inspection confirmed the geotechnical finding in the ROW, as shown in FIGURE 7. GTMS was not fully operational yet and strain building up could not be seen at the reported location. At least, once operational, measurements show a strain structure in KP233 area as shown in FIGURE 8. The strain profiles present a strain amplitude of 2200 □ε and a spatial extension of the event of about 50 m. As previously studied in reference [8], the observed structure and the peak amplitude is currently not problematic as the cable rupture is expected to happen when strain is larger than 10000 □ε. Actually, the cable enters in plastic regime when 8000 □ε are reached. The laboratory study we presented in 2021 shows that a strain value of 2200 □ε would be caused by a load of about 4kN [8]. It is well below the cable load rupture which commonly occurs beyond 9kN. The observed value must be considered as an early sign of the soil movement that applies a load to the cable. Moreover, the load remained stable until now. At least, such occurrence is an helpful indication to configure alarming thresholds in the monitoring software. The structure should disappear after stress relief works are conducted on the cable.

Another event could be observed in KP71 area with the GTMS. Strain profiles were collected periodically and processed until a signal degradation was reported on January 14th, 2023 (FIGURE 9). The signal degradation is caused by a localized loss increase caused by a narrow element crushing the cable (<50 cm). Civil works were conducted in KP71 to build a camp site in the ROW. It involved the driving-in of wooden post in the ground. Most likely at least one crushed the cable. The nature of the detected event is not of geotechnical origin, but it illustrates how sensitive the system is to its environment. In a rockfall a heavy stone crushing the cable would have induced similar effect.

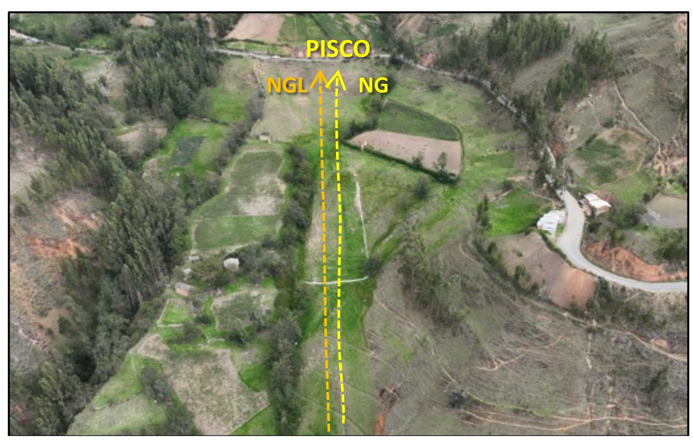

FIGURE 7: OBSERVATIONS AND GEOTECHNICAL FINDINGS MADE IN A STEEP SLOPE IN KP233 AREA.

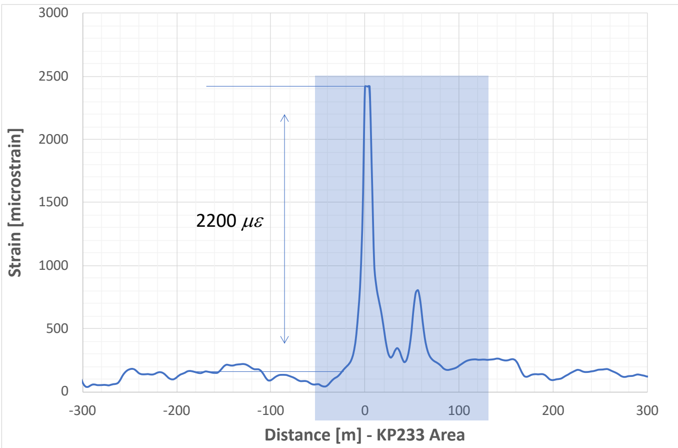

FIGURE 8: STRAIN PROFILE RELATED TO KP233 AREA OBSERVATIONS. IDENTIFIED STRAIN STRUCTURE MEASURED IN DECEMBER IS HIGHLIGHTED.

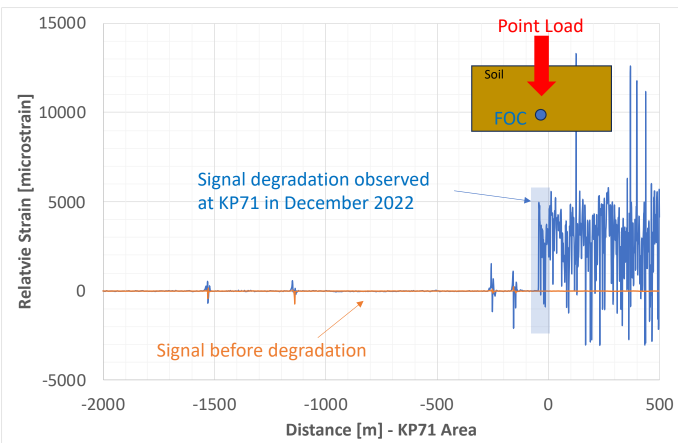

FIGURE 9: STRAIN PROFILES RELATED TO KP71 AREA OBSERVATIONS. EVENT IS FROM CONSTRUCTIVE ORIGIN: BLUE PROFILE SHOW A SIGNAL DEGRADATION; ORANGE CURVE SHOWS SIGNAL BEFORE DEGRADATION.

The detection of these events is an important information for the system configuration. The observed behaviors can be used to fine tune the alarming and the event detection thresholds. In addition to the long-lasting operational life of similar systems, these preliminary observations bring useful information which are specific to the current installation.

7. CONCLUSION

A 256 km long section of the TGP ROW has been completely retrofitted with a GTMS which uses the communication cable. The system required the introduction of advanced optical fiber technologies for signal multiplexing and optical amplification. The execution implied the training of all the parties involved.

Data captures started at the end of 2022. Events reported by site inspection or field activities could be evidenced in the measured strain profiles or in the signal quality. This information gathered at an early stage is useful in the fine tuning of the system configuration and in the improvement of its efficiency. The implemented solution is now completely commissioned and ready for the monitoring of the coming rainy seasons. It provides continuous and real-time monitoring of strain and deformation associated with terrain condition parallel to the ROW. It has low environmental impact as it is totally passive and, as no additional construction or civil works are required as it uses existing infrastructures. It is now a key element of the pipeline ROW monitoring and integrity program. It is also a tool that improves the reliability of the communication system.

ACKNOWLEDGEMENTS

The authors are grateful to TRANSPORTADORA DE GAS DEL PERÚ for allowing the publication of the work conducted during this project. They also would like to acknowledge all their colleagues who participated in a way or in another to the installation, the commissioning, and the collection of the data as well as to their respective organizations for the continuous support.

REFERENCES

1. Porter, M., Logue, C., Savigny, K. W., Esford, F., Bruce, I. (2004). “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.
2. Lee, E.M., Audibert, J.M.E., Hengesh, J.V., Nyman, D.J., (2009). “Landslide-related ruptures of the Camisea pipeline system, Peru” Quarterly Journal of Engineering Geology and Hydrogeology, Vol. 42, pp. 251–259. https://api.semanticscholar.org/CorpusID:128429033
3. Oliveros, F, Hernández, E, & Soto, G. "Application of Geotechnical Criteria for the Occurrence of Earth Flows (Avalanches) on the Right of Way of Pipeline Transportation System of Camisea in the Coast Zone of Peru." *Proceedings of the ASME 2017 International Pipeline Geotechnical Conference. ASME 2017 International Pipeline Geotechnical Conference*. Lima, Peru. July 25–26, 2017. V001T03A008. ASME. https://doi.org/10.1115/IPG2017-2541
4. Ravet, F, Briffod, F, Chin, S, Rochat, E, & Martinez, J.

"Pipeline Geohazard Risk Monitoring With Optical Fiber Distributed Sensors: Experience With Andean and Arctic Routes." *Proceedings of the 2018 12th International Pipeline Conference. Volume 3: Operations, Monitoring, and Maintenance; Materials and Joining*. Calgary, Alberta, Canada. September 24–28, 2018. V003T04A031. ASME. https://doi.org/10.1115/IPC2018-78047

5. Ravet, F., Ortiz, E.G., Peterson, B., Hoglund, G. and Niklès, M. (2011). "Geohazard prevention with online continuous fiber optic monitoring." Proceedings of the the Rio Pipeline Conference and Exposition, Rio de Janeiro, Brazil, Paper IBP1277_11.
6. Silva, C, & Ravet, F. "Pipeline Monitoring With Geotechnical Optical Fiber." *Proceedings of the ASME 2017 International Pipeline Geotechnical Conference. ASME 2017 International Pipeline Geotechnical Conference*. Lima, Peru. July 25–26, 2017. V001T03A003. ASME. https://doi.org/10.1115/IPG2017-2510
7. Ravet, F, Silva, C, Gil, R, Maguire, S, & Rochat, E. "Sand Dune Migration Monitoring for Pipeline Hazard Risk Mitigation: The Peru LNG Coastal Section Case." *Proceedings of the 2020 13th International Pipeline Conference. Volume 3: Operations, Monitoring, and Maintenance; Materials and Joining*. Virtual, Online. September 28–30, 2020. V003T04A015. ASME. https://doi.org/10.1115/IPC2020-9247
8. Ravet, F, Melo, A, Oliveros, F, & Rochat, E. "Retrofiting Existing Optical Fiber Infrastructure to Mitigate Geohazard Risk: The TGP Case." *Proceedings of the ASME-ARPEL 2021 International Pipeline Geotechnical Conference. ASME-ARPEL 2021 International Pipeline Geotechnical Conference*. Virtual, Online. June 21–22, 2021. V001T03A002. ASME. https://doi.org/10.1115/IPG2021-64796
9. Ravet, F., Chin, S., Briffod, F., Rochat, E. (2019), "Simple Method for DTS/DSS Data Interpretation: an Application to Pipeline Geotechnical Monitoring", paper IPG2019-5332, Proceedings of the International Pipeline Geotechnical Conference IPG2019, June 25-27, 2019, Buenos Aires, Argentina. https://api.semanticscholar.org/CorpusID:213201035
10. Rajiv Ramaswami, Kumar N. Sivarajan, Galen H. Sasaki, Optical Networks (Third Edition), Morgan Kaufmann, 2010, ISBN 9780123740922, https://doi.org/10.1016/B978-0-12-374092-2.50015-1.
11. Gyger, F, Chin, S, Rochat, E, Ravet, F, & Niklès, M. "Ultra Long Range DTS (>300km) to Support Deep Offshore and Long Tieback Developments." *Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering. Volume 6B: Pipeline and Riser Technology*. San Francisco, California, USA. June 8–13, 2014. V06BT04A001. ASME. https://doi.org/10.1115/OMAE2014-24019
12. Highland, L.M., and Bobrowsky, Peter, 2008, "The landslide handbook – A guide to understanding landslides", Reston, Virginia, U.S. Geological Survey Circular 1325, 129p.
13. Niklès, M. (2007). "Fiber optic distributed scattering sensing system: perspectives and challenges for high performance applications." 3rd European Workshop on Optical Fiber Sensors, A. Cutolo, B. Culshaw, J. M. Lopez-Higuera eds., Proc. of SPIE Vol. 6619, 66190D
14. IEC 61757-1 Ed. 2.0: Fiber optic sensors - Part 1: Generic specification; IEC 61757-2-2 Fiber optic sensors - Part 2-2: Temperature measurement - Distributed sensing; IEC 61757- 1-2: Fiber Optic Sensors - Part 1-2: Strain measurement – Distributed sensing

APPENDIX 1: Performance Parameter Definitions (as per IEC 61757-2-2)

Spatial Resolution

The spatial resolution is the ability to discriminate between two adjacent locations submitted to different temperature/ strain conditions. The spatial resolution is directly related to the optical pulse width, or the pulse length W illuminated by the pulse at a given time $w=\tau vg/2$, where τ is the pulse width and vg is the group velocity of the pulse. Spatial resolution also depends on receiver bandwidth.

Strain and Temperature Resolution – Measurement Repeatability

Strain and temperature resolutions are directly related to the measurement noise. The noise includes spontaneous, short duration deviations in output (reading) about the mean output (reading), which are not caused by temperature changes. The resolution is defined as twice the standard deviation of the noise (+/- twice the standard deviation includes 95.4% of the measurements).

Strain and Temperature Uncertainty

The Strain and temperature uncertainty is the difference between the measurement unit reading and the measurement obtained with a reference device. The measurement uncertainty depends on the calibration precision, i.e. on the quality of the calibration setup and procedure. For instance, the calibration of a piece of fiber as a temperature sensor requires a traceable reference temperature sensor with given uncertainty.

APPENDIX 2: GEOHAZARDS

Subsidence

Ground subsidence is the phenomenon described by a terrain surface moving downward relative to the surrounding soils. Subsidence can be caused by excessive ground water depletion, underground mining, limestone dissolution, natural gas extraction etc.

Landslide

Reference 12 gives a general definition of a landslide stating: "*A landslide is a downward sloping movement of rock, soil, or both, occurring in the rupture of a surface - rotational sliding or flat collapsing - in which most of the material moves as a coherent or semi-coherent mass, with small internal deformation*." The authors list and describe several type of landslides such as translational or rotational landslides as well as rock falls.

Erosion

Erosion is the phenomenon that removes soil or rock under the action of waterflow, wind or glaciers and transports the material to another location.

APPENDIX 3: OPTICAL TECHNOLOGIES

The complete GTMS implementation and operation was facing two challenges. Both could be answered to with optical fiber technology solutions. The first challenge comes from the availability of optical fibers for the monitoring. No fibers in the cable are available as they are all used by common IT services. In particular, the selected fibers for the monitoring are continuously measured by an OTDR based system used to detect fiber loss increase and fiber breaks. In telecommunication, solutions have been developed to multiplex various type of signals on the same fiber. Two signals carried by distinct wavelengths can be transmitted on the same fiber without interfering. As the OTDR operates at 1550nm and the DTSS at 1535.4nm, the signals co-propagation is then possible. The two carriers can be combined and separated by a WDM device, which is a component that does not required power. These components rely on multi-layers thin film filters which have high frequency isolation capability to reduce signal degradation at the receiver [10]. WDM operation principle as applied in the current project is illustrated in FIGURE 10 They have a small form factor. Size is like a splice protection sleeve (FIGURE 11. They are installed either in a patch panel or in a buried junction box. In the current project, WDM were installed in KP0, KP8, KP43, KP75, KP108, KP150, KP209 and KP256.

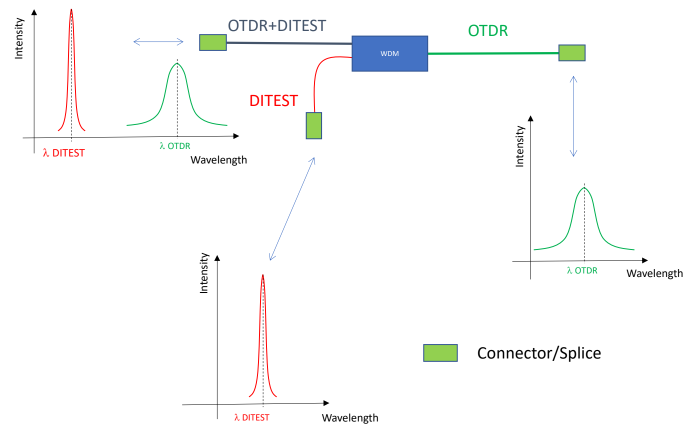

FIGURE 10: WDM OPERATIONS PRINCIPLE SHOWING THE COMBINATION OF DTSS AND OTDR SIGNALS CARRIED BY DISTINCT WAVELENGTHS. OTHER OPTICAL SIGNALS SUCH AS DATA COMMUNICATION CHANNELS CAN ALSO BE COMBINED IN A SIMILAR WAY.

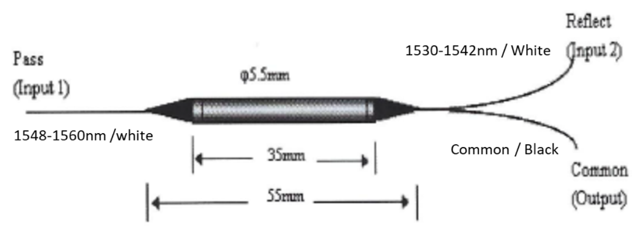

FIGURE 11: WDM DEVICE SCHEMATIC WITH DIMENSIONS.

The second challenge roots in the nature of the terrain crossed by the transport system. Soils are unstable causing large stresses on the cable. Stress is transferred to the fibers causing a loss increase. These stresses increase the risk of cable rupture and the need for additional splices. Consequently, typical attenuation coefficient for an optical fiber is 0.2dB/km at 1550nm can reach values above 0.3dB/km. Over the sensing range, which can vary from 30km to 50km, the link loss increases by 4 to 5dB. In other words, the loss in an unstable terrain is more than the double of loss in a stable terrain. Moreover, the solution brought by the WDM also contributes to the loss figure degradation. The solution can be brough by the combined use of long-range interrogators, that have a loss budget of 16 dB, with optical repeaters that can amplify the sensing signal at the opposite end of the sensor. These repeaters use EDFA based amplification [10, 11]. They are active components and hence need to be powered. They must preferably be installed in pump or valve station.