Slope Instability Monitoring by Using Distributed Optical Fiber

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***Abstract*— Mass movements are often associated with periods of heavy rainfall that penetrate the ground causing a reduction in its shear strength parameters and generating instabilities that can lead to rupture. These instabilities when in densely populated areas can cause catastrophic occurrences with loss of human life and environmental and economic damage. This article discusses the results of ground strain measurement obtained by using a special optical cable and a Distributed Temperature and Strain Sensor (DTSS) unit. The optical cable was installed on a slope in São Paulo state, Brazil. Optical fiber technology allows instantaneous and periodic monitoring of surface strain evolution that occurs over a wide area, complementing traditional geotechnical instrumentation, made up of punctual and manual measurements, which is prone to error and requires more time for verification. The optical cable used for this study acts as an intrinsic sensor, where the cable itself acts as a sensor element, thus performing the function of receiving and transmitting information, unlike other sensors, called extrinsic, which only transmit information from a point sensor. The optical fiber sensor used are lightweight, malleable and immune to electromagnetic interference, making them ideal because they are rugged and allow for practical control and reliable results. For the optical cable analyzed for this article, the maximum strain variation and maximum strain relief values were 1528.29 microstrains and -2867.69 microstrains, respectively.*

***Keywords*— DTSS, Geotechnical Monitoring, Optical Fibers.**

I. INTRODUCTION

Slopes are often located in areas with large concentrations of people close to linear civil structures such as highways, railways and pipelines. In the case of pipelines crossing sloped regions like mountain sides there might be complications if mass movements occur. If the pipeline is damaged by the mass movement it is at risk of rupture. Then, the fluid carried by pipeline when leaking may contaminate the soil and water or cause fires and explosions. When the fluid contaminates the soil and water, with natural occurrences of rainfall, groundwater and other external factors these fluids can be carried to other nearby areas affecting not only the region of the rupture. The ambiental, economic and social impact of an accident with a pipeline could be very detrimental to the development of communities, cities and states.

Slope instabilities become apparent before rupture, signs of instability tend to start slow and gradually over time tend to intensify until rupture occurs.

When properly positioned and monitored geotechnical equipment allows the collection of data and the analysis of parameters that may indicate signs of mass movements. When risk arise, the professionals assigned to the monitoring must be able to analyze these data and with appropriate techniques control or stabilize the mass movement. However, if measures are not met in time the professionals must apply fast contingency measures.

In order to contribute to the research to improve safety of pipelines crossing slopes a complement to the traditional geotechnical equipment was installed on a site. The slope that exhibit a known instability behavior in the past was instrumented with optical fibers layered about 30 centimeters below surface. This technology has revolutionized how we monitor mass movements by monitoring mass movements in order to facilitate decisions to help minimize catastrophic occurrences.

This article presents an abstract of preliminary mass movements measurements results over time. Full results can be seen in a dissertation publication (PAULINO, 2020). That dissertation completes the objectives from a Research and Development job, evolved by Lactec with Petrobras financial support, which purpose is evaluating the use of optical fiber technology to monitoring geotechnical behavior of slope areas crossed by pipelines.

II. OPTICAL FIBER TECHNOLOGY

Since the 1960s optical fibers have been used in various ways of communication whether it be telecommunications, computer networking or long-distance communication (KREUZER, 2006). With the development of optical fibers, various ideas and techniques have been introduced and applied to different fields of studies and projects.

Optical fiber is a transparent and flexible cord that is made of either drawing glass or plastic. The optical fiber itself is encased in 2 concentric layers made of protective coating which consist of coating and cladding layers. Each layer is made and designed with a specific job and objective for the optic fiber to transmit light and read specific data points for the given project and company (KILGALLON, 2004). The most internal layer of the optical fiber is the core, made of silica, which center section is the light-transmitting region of the fiber. The middle layer as known as the cladding layer is also made of silica and this is the first layer that surrounds the core. This layer is important in helping the optical fiber completing its main objective of transmitting a light signal through the core. By creating an optical waveguide that helps confine the light in the core of the optical fiber it helps create total reflection at the core-cladding interface (KILGALLON, 2004). The coating layer is made of polymer and the purpose of this material is to protect the cladding and the core from external environmental damage. Based on what is asked of the company using optical fibers, other layers can be used as a protective barrier of external environmental damage. For example, in 2008 the company Fiberware, Mittweida (Germany) produced an external Polyvinyl chloride (PVC) layer, Kevlar layer, and PVC jacket layer (CHENG-YU et al., 2017).

The core layer can hold either multimode or singlemode fibers. Depending on what the specific projects call for, the optical fiber can be either multimode, singlemode or a combination of both fibers. Multimode fibers have the prefix “multi” because light rays travel through multiple paths called “modes”. Singlemode fibers allows light to travel straight through the fiber, according to the smaller diameter when compared to multimode fibers. Typically, the diameter of multimode and singlemode fiber is broken into two diameters, the first measurement is for the core layer and the second measurement is for the cladding layer. Multimode have (50/125) µm or (62,5/125) µm and singlemode have (9/125) µm.

In addition, optical cables can be manufactured according to its application, which may indicate different layers with different amounts of optical fibers in its interior. The most traditional optical cable types are tight buffered and loose tube cables. In Tight Buffered cables each fiber composed by core and cladding layers receives a thermoplastic coating layer, which keeps the fiber attached to this layer. Then, the fibers are grouped inside a traction element, like Kevlar, which protects the other layers against physical damage.

In the case of loose tube cables, the coating layer placed around the fiber have a much larger internal diameter than the fiber, that means fiber is free within optical cable subunits. Then, the space between the subunit and the fiber is filled with a gel that allows free movement of the fiber within the tube. This type of cable is widely used when it is intended to evaluate the temperature variations suffered by the fiber, because they are free, the fibers do not suffer interference from strain, for example.

For a better understanding of optical fibers, one must know the importance of bandwidth and the role it plays in singlemode and multimode fiber. Bandwidth is the data-carrying capacity of an optical fiber, it is a product of distance and frequency (KILGALLON, 2004). Because light in multimode fibers take different paths in the core of the fiber there is a risk in mixing the fibers information. This could lead to unrecoverable information at the exit of the fiber, that is why the information in these fibers must be sufficiently spaced, differently from the singlemode fibers, where the information can be closer because light propagates in just one mode.

With the growing use of optical fibers, it is beneficial to know the advantages and disadvantages of the technology. Optical fibers have increased bandwidth which allows for greater information-carrying capacity, the fiber also provides lower attenuation than copper conductors. In the process the optical fibers allow for fewer repeaters, this allows the optical fiber to transmit information over long distances. Optical fibers also have decreased sizes compared to other transmitting material. Optical fibers are lightweight and easy to transport, compared to copper its approximately 10 to 15 times lighter; it also allows for easier and faster installation (KILGALLON, 2004). In contrast, optical fibers are rather fragile and over long distances of connection optical fibers

https://dx.doi.org/10.22161/ijaers.78.4 ISSN: 2349-6495(P) | 2456-1908(O)

can become more vulnerable to damage compared to copper wiring. Optical fibers can also malfunction if the pigtail connection in any way get disconnected, dirty or gets damaged, usually the pigtail is connected to a system; for example, DTSS. This system tracks and keeps a count of deformation suffered by the optical fiber.

In Brazil, Lactec, one of the largest centers of science and technology, a reference in development and innovation, conducts research and development projects in partnership with companies from different areas, focusing on proposing technological solutions to some existing problems. In the geotechnical area, regarding the main theme of this article, optical fiber technology, Lactec engineers, researchers and former students from Lactec postgraduate program has already developed and published a lot of relevant documents regarding the use and improvement of the technology in the tracking of mass movements. Among these documents, it is possible to cite dissertations from Buras (2013), Silveira (2017) and Favaro (2018).

In the dissertation of Buras (2013), the development of a mass movement areas identification system through fiber optic technology using DTSS is presented. The author performed specific experiments to simulate mass movements in the laboratory, where the unstable zone was identified through the deformation of an optical cable installed in the ground. The results obtained by Buras in the laboratory allowed the estimation of an effective theoretical model for the identification of stable and unstable areas on a slope by installing distributed optical fiber sensors in trenches excavated on the slope face, longitudinally, transversely or both ways.

Silveira (2017) in his dissertation exposes his methodology to analyze deformation monitoring data of a natural slope crossed by a pipeline. Following the rupture of a pipeline in 2001 due to mass movement, in August 2014 Lactec installed distributed optical fiber sensors on that slope, in the context of one of Lactec's numerous research and development projects developed in partnership with Petrobras and Transpetro. Data were collected between January 2015 and May 2016 with DTSS equipment and treated using MatLab, Excel and Surfer software. The results indicated that the slope suffered strain of 784 microstrains and strain relief of -515 microstrains. According to the author, the recorded values are relatively low and, being a methodology applied in experimental phase, it cannot be affirmed if such deformations correspond to displacements in the slope.

Favaro (2018) describes in his dissertation the procedures for instrumentation and monitoring strain in a slope crossed by a pipeline. In addition to soil characterization laboratory tests, an optical cable was installed on the slope face in the longitudinal and transverse direction, producing an optical fiber mesh, according to the theoretical model suggested by Buras (2013). Monitoring was performed on four different dates using the DTSS equipment. The data obtained were compiled with Matlab software and the results showed relatively small deformations with strain of 1334.04 microstrains for the longitudinal stretch and 940.62 microstrains for the transverse stretch and strain relief of -1137.74 microstrains for the longitudinal stretch and -881.21 microstrains for the transverse stretch. The author concludes that these values do not allow to affirm whether such deformations indicate movements on the slope.

In addition, were also published articles, project reports and several event participations, linked to research and development projects, which form a constant basis to further expand this knowledge and were fundamental for writing this article. A summary of those publications can be seen on TABLE 1.

Table 1: Summary of optical fiber publications

Author	Title	Objective
Buras, Silveira and Rocha, 2014	Laboratory tests for monitoring natural slopes with fiber optic technology [Testes de laboratório para o monitoramento de encostas naturais com a tecnologia de fibra óptica]	The authors developed a split metal box (shear box) and specific anchor systems in laboratory to evaluate the efficiency of distributed optical fiber sensors for mass movement monitoring after their installation on an unstable natural slope using the DTSS equipment
Marocki et al., 2015	Water level instrumentation based on fiber optic technology [Medidores de nível d'água com base na tecnologia de fibra óptica]	This research focused on the installation, field testing and monitoring of geotechnical instrumentation based on optical fiber technology for ground water level measurement
Silveira, Pretto and Buras, 2016	Technical Report 3 - R&D - ANP Project title: R&D Slope Slip Risk Analysis, Using Optical Fiber Geotechnical Instrumentation and Interactive Modeling (Process 2014 / 00442-6) [Relatório Técnico 3 - P&D - ANP Título do projeto: P&D Análise De Risco De Escorregamentos De Taludes, Utilizando Instrumentação Geotécnica De Fibra Óptica E Modelagem Interativa (Processo 2014/00442-6)]	This report, which covered the period from April 5, 2016 to August 10, 2016, presents the study areas (Parana, Santa Catarina, São Paulo and Rio de Janeiro states) covered by the project. Location data related to the areas and laboratory tests results for the soil of the slopes in question are presented. Interactive modeling and strain results for one of the selected slopes (Parana state) were also presented
Silveira, Buras and Pretto, 2017	Technical Report 4 - R&D - ANP Project title: R&D Slope Slip Risk Analysis, Using Optical Fiber Geotechnical Instrumentation and Interactive Modeling (Process 2014 / 00442-6) [Relatório Técnico 4 - P&D - ANP Título do projeto: P&D Análise De Risco De Escorregamentos De Taludes, Utilizando Instrumentação Geotécnica De Fibra Óptica E Modelagem Interativa (Processo 2014/00442-6)]	Continued from report 3, this report, from August 11, 2016 to January 25, 2017, presents data for the second selected slope (Santa Catarina state). It is possible to find the area topographic survey and the procedures for installing the optical cable on the slope, as well as the installation of the water level meter and piezometer
Buras et al., 2017a	Technical Report 5 - R&D - ANP Project title: R&D Slope Slip Risk Analysis, Using Optical Fiber Geotechnical Instrumentation and Interactive Modeling (Process 2014 / 00442-6) [Relatório Técnico 5 - P&D - ANP Título do projeto: P&D Análise De Risco De Escorregamentos De Taludes, Utilizando Instrumentação Geotécnica De Fibra Óptica E Modelagem Interativa (Processo 2014/00442-6)]	Continued from report 4, this new report, which runs from January 25, 2017 to June 19, 2017, presents the installation of the optical cable on the two remaining slopes (São Paulo and Rio de Janeiro states). The procedures for checking optical cable integrity for slope strain measurements in Santa Catarina state are presented. It is also informed that augmented reality will be used in the next steps of geotechnical monitoring of the project slopes

Author	Title	Objective
Favaro et al., 2018a	Geotechnical monitoring through fiber optic technology to assess the deformations of a hillside in Serra do Mar, Santa Catarina [Monitoramento geotécnico através da tecnologia de fibra óptica para avaliação das deformações de uma encosta da Serra do Mar catarinense]	This article presents the installation method developed and the data obtained in the strain monitoring using distributed optical fiber technology from a slope crossed by a pipeline operated by Transpetro in Santa Catarina state
Buras et al., 2018b	Technical Report 6 - R&D - ANP Project title: R&D Risk Analysis of Slope Regulations, Using Optical Fiber Geotechnical Instrumentation and Interactive Modeling (Process 2014 / 00442-6) [Relatório Técnico 6 - P&D - ANP Título do projeto: P&D Análise De Risco De Escorregamentos De Taludes, Utilizando Instrumentação Geotécnica De Fibra Óptica E Modelagem Interativa (Processo 2014/00442-6)]	Continued from report 5, this new report, from June 20, 2017 to December 22, 2017, presents the installation of geomechanical tube for water level measurements in a water level meter and piezometer (Santa Catarina state), the methodology of flow analysis and slope stability, scope and testing of augmented reality application, as well as some of obtained results

III. DISTRIBUTED SENSING SYSTEM

Distributed sensing systems monitor several different quantities using different technologies for analysis. This article will cover DTSS system.

With this equipment it is possible to monitor temperature and strain over long distances and on various surfaces. This equipment uses optical fiber as a sensor element.

The main benefit in using that equipment together with optical cables is in providing temperature and strain profiles along the entire optical cable rather than obtaining punctual information as in the inclinometer.

3.1 DTSS

Distributed Temperature and Strain Sensor (DTSS) is one technology used for determining the temperature and deformation in an optical fiber cable.

Over time and with contributions of natural disasters and occurrences, events like earthquakes and ground conditions can be monitored over time. With mass movements, the deformation of land can be plotted using a strain versus displacement graph. Using this form of measurement engineers can properly plot deformation of a landmass. If strain measurements are repeated multiple times on the graph, engineers or technicians can take the proper precautions to ensure the safety of the general public and structure.

A technology discovered by French physicist Léon Brillouin that is used in DTSS is Brillouin scattering, which is a type of light pattern shown in optical fiber. DTSS helps measure the entire Brillouin spectrum which in the process helps the DTSS make calculations and measurements. DTSS helps provide temperature and strain observations over a duration of time. This function within the DTSS provides real-time changes within a structure. After attaching the DTSS cable underground strain monitoring can be carried out for landslide and subsidence applications.

At the Korea Institute of Geoscience and Mineral Resources (KIGAM) optical fiber cables were experimented. Because the experiment at the university was tested in a small region of land, researchers had to improvise and used a pushing tool to activate a movement in the ground. Researchers would use weight and drop them on the surface of the test site to act as the abnormality that was introduced to the surface of the region being worked on. With the conclusion of the weight, experiment researchers discovered that DTSS will be an efficient, consistent and economical warning system for landslides and subsidence (KLUTH et al., 2006).

IV. STUDY AREA

The slope in question was selected by the Lactec research engineers together with Petrobras and Transpetro engineers, mainly because a containment structure in this area shows signs of past movements that were monitored and controlled in the upstream direction (Fig. 1).

https://dx.doi.org/10.22161/ijaers.78.4 *ISSN: 2349-6495(P) | 2456-1908(O)*

Fig. 1: Containment structure with movement indications

The area is located on the side of a highway, and is shown in Fig. 2, where it is also possible to identify the representation of the optical cable path installed on the slope.

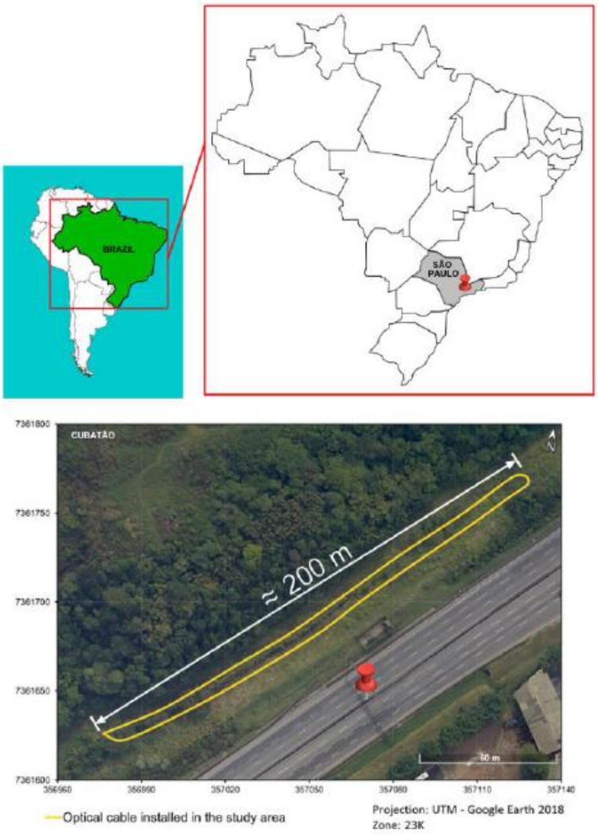

Fig. 2: Path of the optical cable in the study area

The slope was instrumented with almost 600 meters of optical cables. After the installation, a measurement was performed, which was later taken as a reference for future analysis. The equipment used on site was the DTSS from Sensornet. In subsequent campaigns, each measurement was followed by comparisons with the reference measurement values. Inside this equipment there are 407 optical sensors which when multiplied by the spatial resolution of this equipment results in 415.22 meters (407 x 1.0202) of optical cable. To this length must be added the length of the extension (50 meters) used to connect the equipment on site. All this length mentioned does not have influence in the analysis of the results. Thus, the data analysis takes place from 465.22 meters to 1028.36 meters and the preliminary results for a given length of optical cable are presented in the following item.

V. RESULTS AND DISCUSSION

Six measurement campaigns were carried out on June 11, July 12, August 9, September 13 and November 22, 2018 and March 21, 2019. As previously mentioned, on site almost 600 meters of optical cable were installed. This article presents some of the results along the optical cable.

The first campaign (June 11, 2018) was taken as a reference campaign for the other measurements. The data on this date were taken as zero as an initial slope condition and the cable pre-tensioned to allow ground compression measurements and consequently cable strain relief. Thus, the strain and stress relieve values found for the following campaigns correspond to the strain change between the deformations of the current campaign relative to the reference campaign. This way, taking the first measurement as a reference on June 11, 2018, it was possible to establish the strain variations for each campaign that followed.

Based on these variations, expressed in microstrains, six comparative images with a color scale were generated for the measurement campaigns.

In the images of Fig. 3, Fig. 4, Fig. 5, Fig. 6, Fig. 7 and Fig. 8, it is possible to see the color scale that indicates the amount of strain change between each campaign compared to the reference campaign, ranging from -5000 microstrains to +5000 microstrains, where warm tones (red) represent strain and cold tones (blue) represent strain relief. The yellow color has a value of zero, meaning that there are no variations between the strain in the analyzed campaign and the reference campaign. The longitude is informed on the horizontal axis, and the latitude on the vertical axis, both in UTM coordinates.

It should be noted that the campaign of June 11, 2018 was compared with itself, because as cited, the data on this day were taken as zero and used as a basis for calculating the strain variations in subsequent campaigns. That is why all the points in Fig. 3 are yellow, representing no strain change.

https://dx.doi.org/10.22161/ijaers.78.4 *ISSN: 2349-6495(P) | 2456-1908(O)*

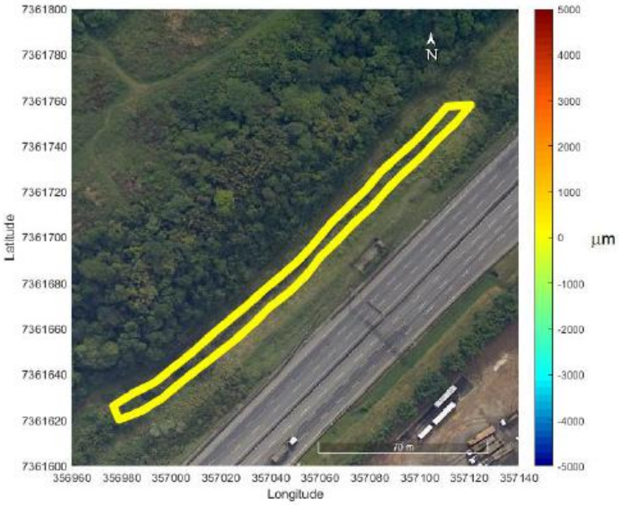

Fig. 3: Strain change between June 11, 2018 and June 11, 2018 (Reference)

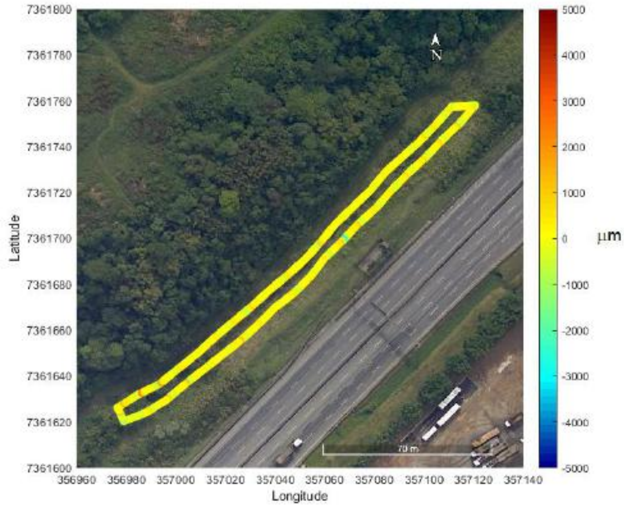

Fig. 6: Strain change between September 13, 2018 and June 11, 2018

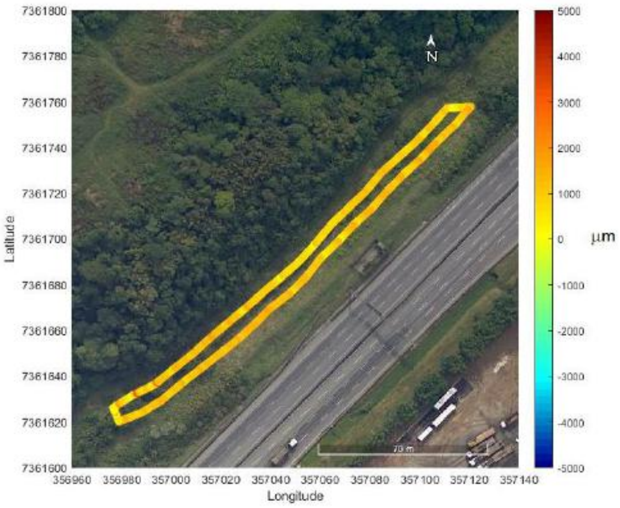

Fig. 4: Strain change between July 12, 2018 and June 11, 2018

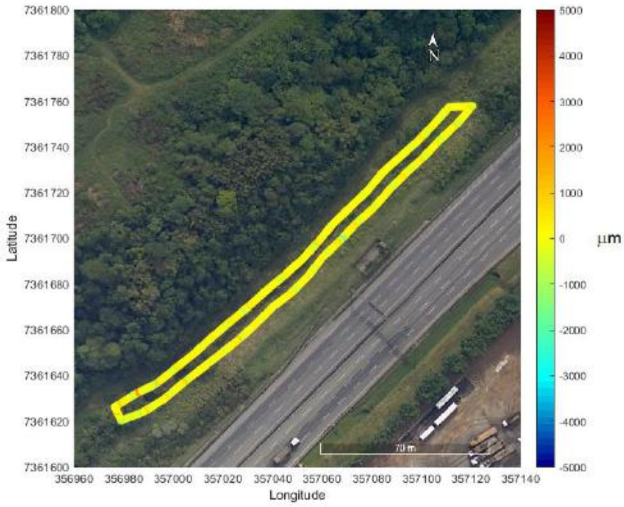

Fig. 7: Strain change between November 22, 2018 and June 11, 2018

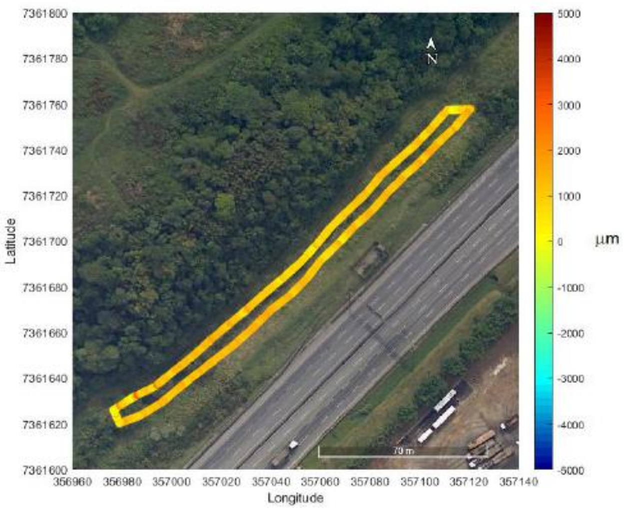

Fig. 5: Strain change between August 9, 2018 and June 11, 2018

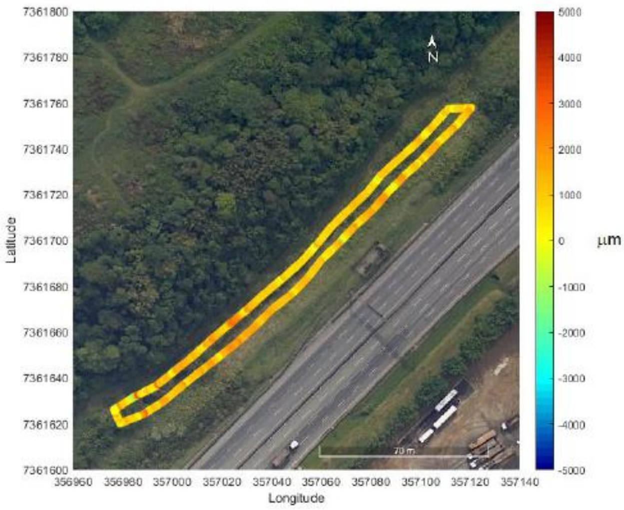

Fig. 8: Strain change between March 21, 2019 and June 11, 2018

https://dx.doi.org/10.22161/ijaers.78.4 *ISSN: 2349-6495(P) | 2456-1908(O)*

Also, considering all the measurement campaigns, were selected four points that were responsible for the highest strain changes. The graph in Fig. 9 represents these points and the strain history suffered by them during the measurement campaigns.

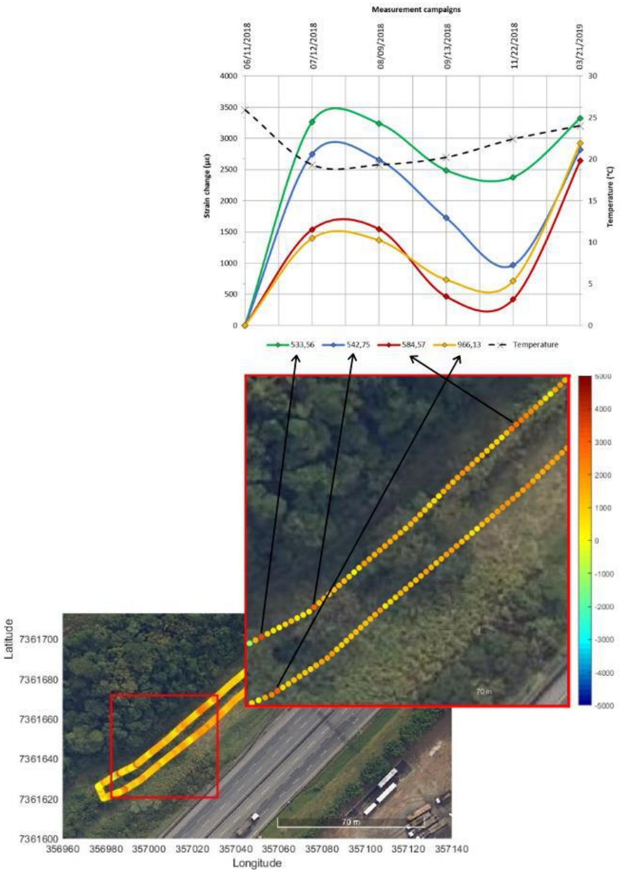

Fig. 9: Strain history for the lengths 533.56 m, 542.75 m, 584.57 m and 966.13 m

Considering the points presented and their strain history, the maximum strain was 3324.77 microstrains for the length 533.56 m. As can be seen, the same point suffered the largest strain variation in all the measurement campaigns compared to the other points according to the strain history in Fig. 9.

However, it is also important to note that the high strain variations between the first campaign (reference) and the second campaign may have occurred due to the cable re-fitting on the ground and the pre-tensioning during cable installation.

Due to these factors, it was decided to exclude the first measurement campaign and make the second measurement campaign as a reference for further strain analysis. Thus, it is possible to reduce errors arising from the re-fitting and pre-tensioning of the optical cable.

Thus, a new strain history (Fig. 10) was performed, including the points cited in the strain history of Fig. 9 in addition to another point: the one with the maximum strain relief (2867.69 microstrains) at 853.91 m.

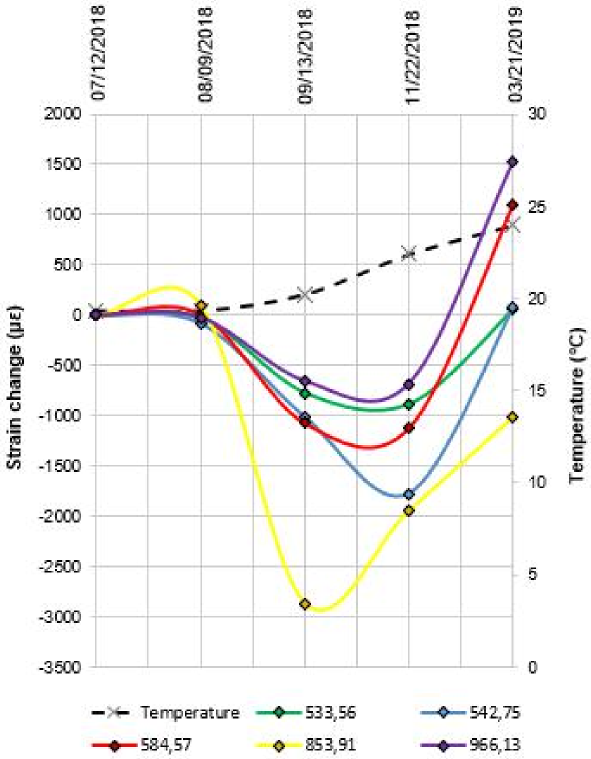

Fig. 10: Strain history for the lengths 533.56 m, 542.75 m, 584.57 m, 853,91 m and 966.13 m

As shown in Fig. 10, it is possible to notice that the strain variations between the new reference campaign and its subsequent measurement campaigns are very low, showing that the variations due to cable re-fitting and pre-tensioning were eliminated. Thus, the largest strain variation found was 1528.29 microstrains for the length of 966.13 m and the largest strain relief was -2867.69 microstrains for the length of 853.91 m.

Whereas 1000 microstrains corresponds to 0.1% strain or 1 mm/m, the maximum strain on this cable was 0.15% or 1.53 mm/m. However, although it is possible to represent such movement in mm/m, it is not possible to indicate the direction of movement.

As new measurement campaigns take place along with continuous follow-up, slope behavior will become more evident, allowing more knowledge about the performance of this geotechnical fiber optic instrumentation that will help easier decision making.

VI. CONCLUSION

This article presented the advances regarding slope geotechnical monitoring. The aim was to discuss the advantages and limitations of using optical fiber embedded in the soil to obtain internal strain profile.

From the data collected in the measurement campaigns, the data analyzed presented relatively small strain values (0.15%). The slope is moving, as visually perceived before cable installation, but so far there are no risks to the area in question as the conventional geotechnical instrumentation installed there shows. It is recommended that the slope continue to be monitored periodically by the new geotechnical fiber optic instrumentation and its data analyzed frequently.

Even with all the monitoring period and amount of data, despite the possibility of representing such movement in mm/m, it is not possible to indicate the direction of this movement and not even if the slope is really moving.

Also, the optical cable used on the slope in question allows to read strain up to 20000 microstrains. The maximum raw strain found across all the measurement campaigns was 4422.78 microstrains, reaching 22.11% of the optical cable readability.

In addition, compared to traditional geotechnical equipment, slope-mounted optical fiber technology leads to reduce installation and monitoring costs as a single cable and equipment is required to monitor a large area without the need for punctual and often difficult to access measurements.

ACKNOWLEDGEMENTS

The authors of this article thank Petrobras for their financial support, Transpetro for their technical and logistic support throughout the evolution of the Research and Development projects studies in which they work together and Lactec for the infrastructure used. The author Rodrigo Moraes da Silveira thanks the financial support granted by National Council for Scientific and Technological Development – CNPq, since he is a level 2 DT productivity scholarship holder.

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