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Horizontal Inclinometer with Fiber-Optic Applied in Embankment Construction over Soft Soil at Rodrigo de Freitas Lagoon/RJ

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SUMMARY: This paper describes the installation and performance of the monitoring of a soft clay layer treatment, where fiber optical - based instrumentation was used. The site is located at Cantagalo Park, Rodrigo de Freitas Lagoon / RJ, where the thickness of the very soft clayey soil varies from 2 to 30 m. There is information about fills being placed around the Lagoon since 1880, and at this site the main fill layer was placed about 47 years ago and the settlements are yet occurring.

The soil improvement of the soft soil was deep radial consolidation (CPR). In order to evaluate the performance of the technique, two horizontal inclinometers were installed at the site, among other instrumentations. Three fiber-optic cables were attached along one of the profiles, in which thirteen Fiber Bragg Grating (FBG) sensors were monitored. The Bragg network functions as a sensor and can be used to measure deformations or temperature variations from the modifications induced by the object to which it is associated. The main objective of the experiment was to monitor vertical settlements from the fiber optic instrumentation of the horizontal inclinometers in order to provide correlations with the results obtained from measurements carried out with a probe-type mechanical instrument.

Tests were also run in the laboratory, where a simulation of vertical displacements of a cantilever/free beam structure was performed with four FBG sensors. The laboratory results showed excellent correlations between the deformation variables (obtained through optical fiber instrumentation data) and angular variation (obtained through mechanical instrumentation data). From the angular variation it was possible to calculate the displacement value.

The field results, however, showed considerable dispersion in the deformation vs. angular variation graphs. Some factors, such as temperature variation, help explain such results. On the other hand, the experiment demonstrates the potential of application of optical fiber in geotechnical instrumentation.

KEYWORDS: Fiber Bragg Grating sensors, fiber optical sensors, soft soil, instrumentation, horizontal inclinometer, deep radial consolidation.

1 INTRODUCTION

Rodrigo de Freitas Lagoon is located at the Southern Region of Rio de Janeiro City (Figure 1). Some of the surrounding areas of the Lagoon are settling due to very soft clay deposits underlaying the fill layers.

The clay deposit thickness varies from 5 to 30 m at site of study, Cantagalo Park, a 40,000 m^2 area located at the border of the lake. The magnitude of settlements at this site, over the last 35 years, was about 2 m. During this period, the solution adopted by the city council was to level the embankment in order to maintain the grade elevation, thus coexisting with post construction settlements.

In 2011, before the earthworks, the area near the border of the lake would be submerged when the tide level was high, thus a new technique of soil improvement known as deep radial consolidation (CPR) was performed at Cantagalo Park, in order to stabilize the settlements at this region. This paper presents geotechnical characteristics of the site and the results from field instrumentation with horizontal inclinometer with fiber-optic cables installed at the improved area.

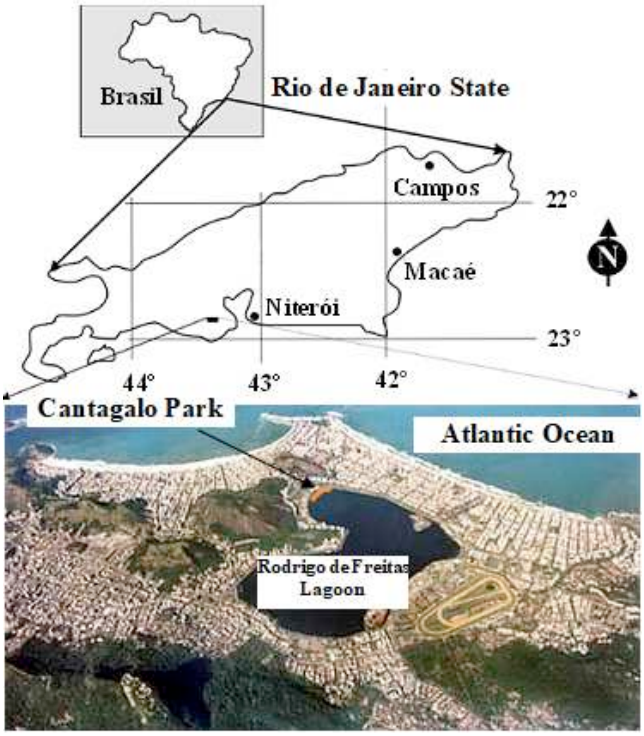


Figure 1.Site localization (modified from Souza, 2003).

2 SITE CHARACTERISTICS

2.1 Geology Formation and Geotechnical Profile

The process of formation of the Rodrigo de Freitas Lagoon is directly associated to periods of advancement and retreat of the sea - transgression and sea regression, respectively - that are repeated alternately over time. According to Muehe (1995), the formation of the coastal lagoons of Rio de Janeiro coast is due to the migration of the coastal limits to its new position of equilibrium with sea level, positioning itself between the sea and the coastal plain, which was later flooded on the occasion of a slight rise in sea level, thus forming the lagoon. Coastal lagoons, such as the Rodrigo de Freitas Lagoon, had their origin in the drowning of old fluvial basins (Amador, 1997), which resulted in coves, bays, estuaries that were later blocked by coastal sandbanks, generated by the regressive and transgressive movements of the sea, thus enclosed by the development of these sandbanks.

At Rodrigo de Freitas Lagoon, the alternation of these movements, repeated during thousands of years, provided the formation of the sandbank, where the neighborhoods of Ipanema and Leblon currently exist. This sandbank then passed to dam the waters that descended from the slopes of Carioca Mountains, which thus began to accumulate in the lower part of that basin, forming the Lagoon.

Figure 2 shows the formation of Rodrigo de Freitas Lagoon due to sea level oscillations, from the transgression Flandarina Guanabarina (a) until present day (f): the fluvial and marine low lands in its surroundings, the Leblon, Ipanema and Arpoador beaches formed during Quaternary.

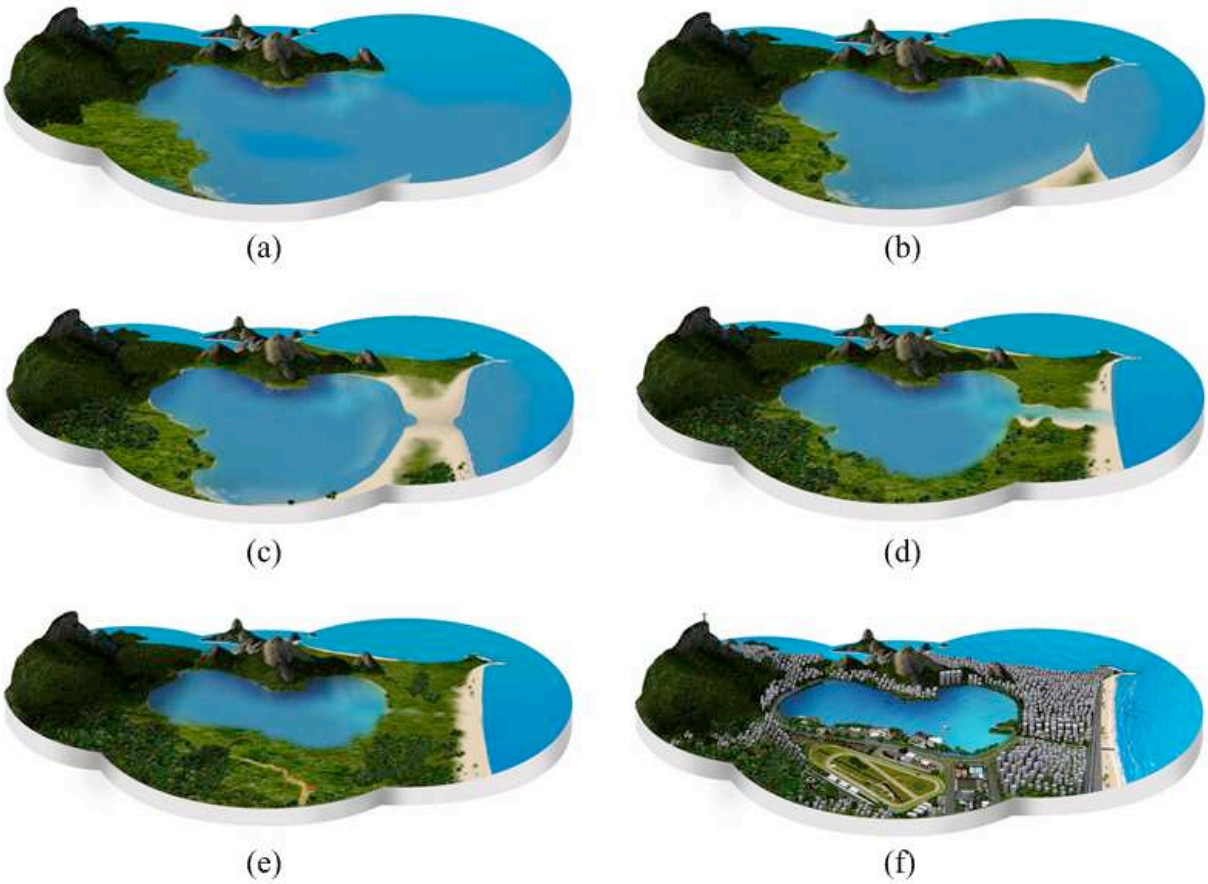
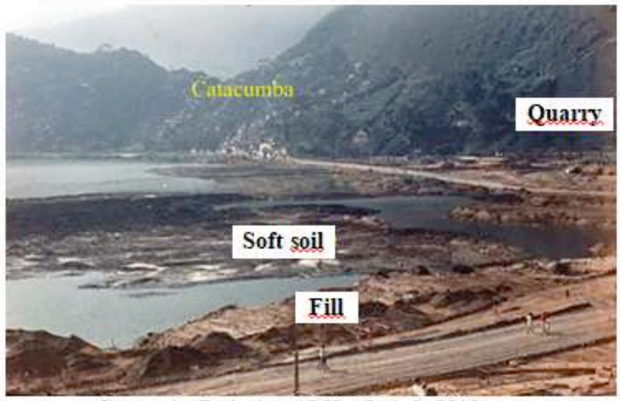


Figure 2. Rodrigo de Freitas Lagoon formation (Lagoalimpa, 2012).

During the rainy season, the accumulation of water opens the sandbank that separates the lagoon from the sea, allowing a seasonal renewal of the Lagoon waters. With urbanization, a series of modifications occurred around the Lagoon, with the reduction of the wet area of the Lagoon due to the construction of landfills (Trajan, 2007). It is estimated that 1/3 of the total wet area of the lagoon has been filled. Figure 3 shows the evolution of landfill formation around the Lagoon from 1880 to present day and the earthwork in the 60's.



Cantagalo Park, late 1960s (Luizd, 2012)

Figure 3. Rodrigo de Freitas Lagoon border limits (adapted from Agrar, 2011).

Due to geological formation and the successive anthropic modifications over time at the Rodrigo de Freitas Lagoon border, nowadays, at the Cantagalo Park area the fill thickness varies from 4 to 16 m, and the thickness of the clay deposit reaching 30 m at some places, as shown in Figure 4 a and b.

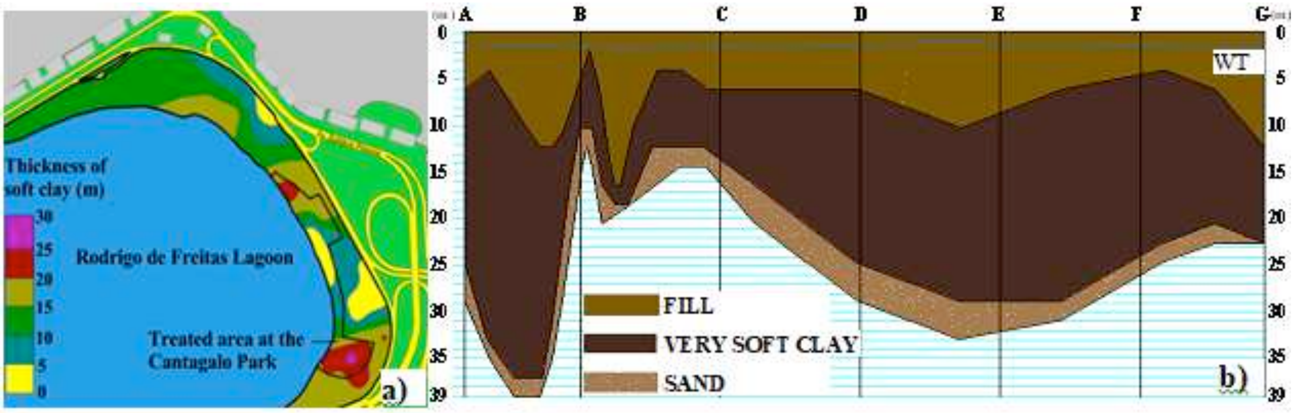


Figure 4. a) Soft soil iso-thickness curves at the Rodrigo de Freitas Lagoon b) Geotechnical profile along Cantagalo Park.

2.2 Geotechnical Carachteristics of the Soft Clay

Site investigations and laboratory tests were performed at 5 clusters in order to provide geotechnical parameters for the analyses of the geotechnical solution for the embankment at the Cantagalo Park (Figure 5). Laboratory tests included soil indexes and oedometer tests. Standard penetration tests were also carried out and the water content of the soil collected at the tip of the Raymond sampler was obtained for some boreholes. Electric vane tests, piezocone and dilatometer tests with a Marchetti dilatometer were also carried out (Almeida *et al*., 2012).

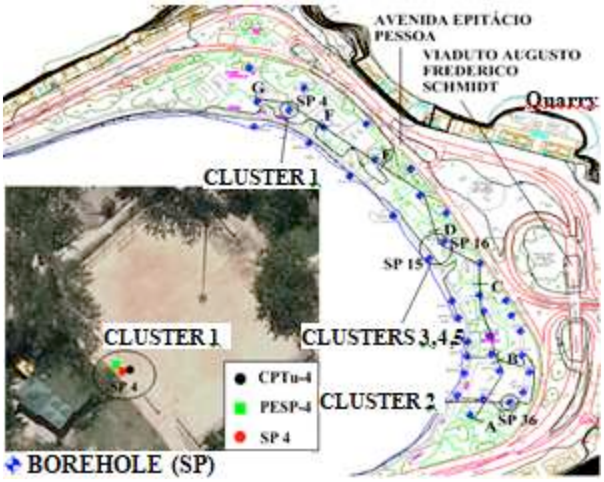


Figure 5. Field tests location

The geotechnical results obtained from Cantagalo soft soil deposit are within the range of geotechnical data of Rio de Janeiro clays (Mello, 2013). The soft clay is highly compressible, with compression ratio ranging between 0.39 and 0.63, which is common for Brazilian coastal clays (Almeida and Marques, 2013). It is very plastic clay, although its plasticity is not as high as some Rio de Janeiro clays, the water content obtained from the 34 SPT boreholes carried out nearby varies from 15.6 to 185.3%. Figure 6 shows test results from cluster 2, vertical 36.

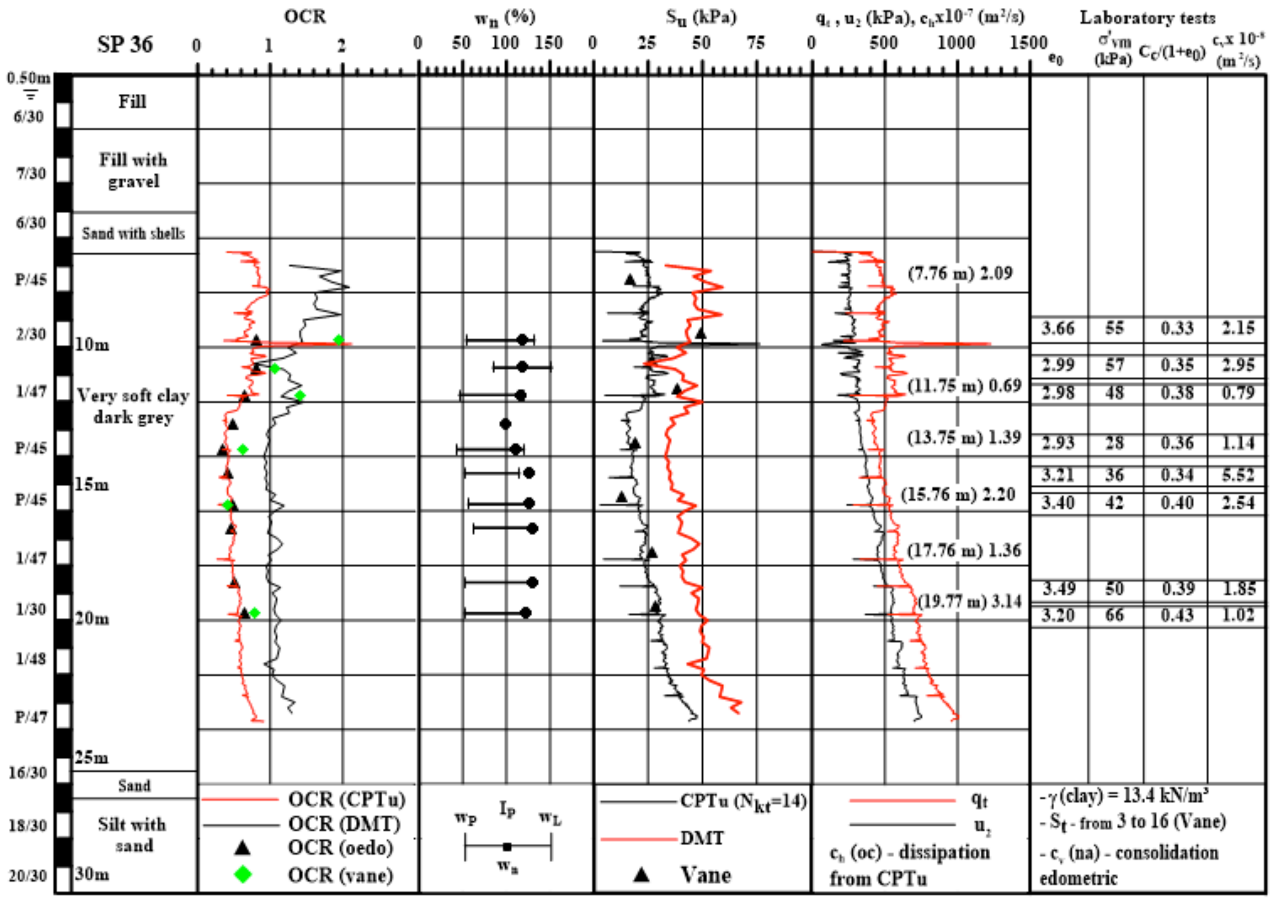


Figure 6. Geotechnical characteristics of the soft clay deposit at Cluster 2.

The *in situ* undrained strength, S_u, was obtained from electric vane borer tests, piezocone tests and dilatometer tests. The S_u values from vane tests are varying between 9.3 and 35 kPa, and the vertical consolidation coefficient, c_v, obtained from piezocone and oedometer testsat normally consolidated range is 2.2 x 10^{-8} m²/s, which is in the upper range of c_v values for Rio de Janeiro deposits. The index tests results and some geotechnical parameters are summarized in Table 1.

Table 1. Main Cantagalo Park's Soft Clay Deposit Geotechnical Properties

Parameter	Depth (m)	
	9.5 – 12.8	13.5 – 20,0
Liquid limit – w_L (%)	99 - 152	115 - 128
Plasticity index – I_P (%)	62-78	62 - 76
G_s (g/cm³)	2.4 – 2.6	2.56 – 2.62

2.3 Soil Improvement and Field Instrumentation

The CPR technique consists of installing a mesh of PVDs along the depth of the entire saturated soft soil and then installing grout columns by high pressure mortar injection, with ranges from 100 kPa to 1,000 kPa, inside the soil in bulbs (Almeida and Riccio, 2012). These bulbs are made from bottom-up and form a composite material consisting of a stiff material (CPR columns) and a confined, compressed and consolidated soil (improved soil), as shown in Figure 7. After the improvement, an embankment with variable height (average 1 m) was executed.

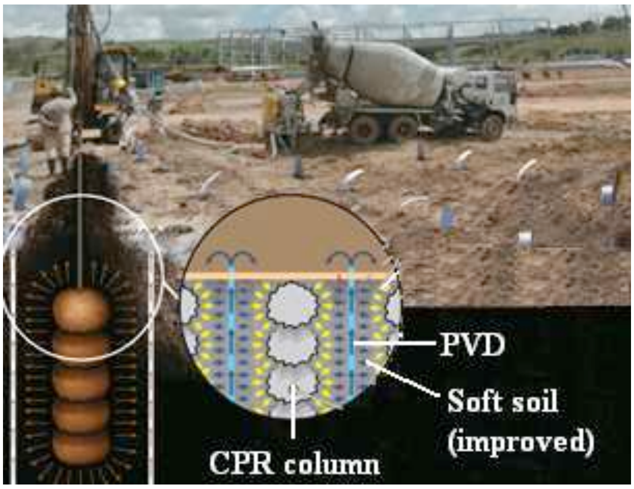


Figure 7. CPR technique schema.

Field instrumentation was composed by 2 horizontal inclinometers (111 m total length), 3 vertical inclinometers and 15 settlement plates, as shown in Figure 8. Due to the high level of pressure of the technique, most of the instrumentation was installed soon after the improvement. The monitoring of the area has been carried out for about 6 months. During execution, the pore-pressure was monitored with vibrating wire piezometer. The complete analysis of field instrumentation results, mainly combined with pore pressure results are presented by Mello (2013).

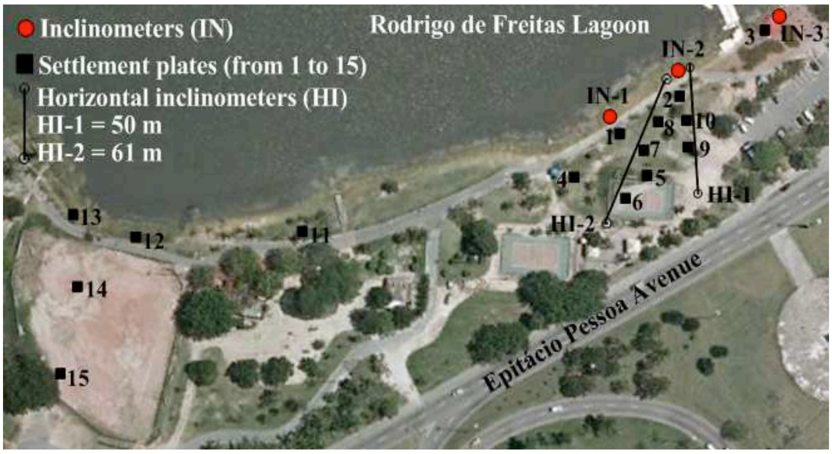


Figure 8. Instrumentation location.

3 OPTICAL FIBER INSTRUMENTATION

3.1. Geotechnical application

When an instrumented structure with FBG extensometers is tensioned, it is possible to estimate the shape that it acquires when it undergoes deformation. This technique is known as FBG 3D Shape Sensing and has a broad field of applications, such as in medicine, where it can be used in procedures such as catheterization for catheter placement in the body (Duncan and Raum, 2006). The main applications are in the field of engineering, such as the monitoring of form and force applied by wind in wind turbines, the real-time monitoring of the deformation of the wings of the aircraft (Lally *et al.*, 2012).

The multi-sensing optical fiber has seldom been used for geotechnical instrumentation, mainly due to the high reliability of traditional instrumentation and the high costs of the optical reading devices. In large part it has been used in the monitoring of the integrity of engineering structures and geotextile, and some use also in geotechnical instrumentation. The advantages of optical sensors over traditional monitoring technologies are:

- remote sensing capability;
- multi-sensing capability (measurement of temperature, pressure, pH, deformation, etc.);
- possibility of multiplexing;
- high sensitivity;
- immunity to electromagnetic interference;
- great possibility of adaptability for use in instrumentation.

It also can be used in monitoring environments with severe operating conditions, such as flammable and high voltage environments, without deterioration of the optical fiber.

Ho *et al.* (2006) fabricated an inclinometer based on Bragg networks for the measurement of horizontal displacements. Briançon *et al.* (2006) presented the application of geogrid, instrumented with FBG Grating sensors in the monitoring of deformations of a section of the railway superstructure located in the northeastern region of France.

Artières *et al.* (2010) presented the results of the detection of infiltrations, by means of fiber-optic temperature monitoring, in the experimental dikes of Peerine in France and IJkdijk in the Netherlands. Geogrids instrumented with fiber optics were also used to monitor deformations of the Dutch dike structure.

Rocha (2011), using the technique of distributed temperature sensing (DTS) along the optical fiber cable, monitored the wetting front and analyzed the variation of saturation in sandy soil, considering the importance of water as agent reducing the shear strength parameters of the soil.

Lee *et al.* (2011) used FBG sensors in triaxial test equipment to measure displacement, force and pressure in a series of triaxial tests involving both saturated and unsaturated samples.

Chang (2012) presented a detailed study identifying the potential of different technologies for monitoring transportation infrastructures. It highlights comparatively the preliminary results obtained with the use of FBG sensors and exalts the excellent cost-benefit ratio of these solutions in general.

Gomes Pinto (2015) used FBG sensors to monitor, in laboratory, the stress of steel mesh used as safety net for slope stabilization.

3.2. FBG Measurement Principles

Among the various classes of fiber optic sensors, those based on Fiber Bragg Grating stand out today as an attractive option for applications where traditional sensing systems have been inefficient, such as in environments with excessive electromagnetic radiation and applications that require multiplexing.

The FBG sensor is a fiber optic structure with refractive index of the modulated fiber core. Figure 9 shows the principle of operation of a sensor based on FBG. A broadband light source emits a signal through the fiber core, the signal incident on the FBG sensor is partially reflected from each modulation fringe of the refractive index of the fiber core. The reflections interfere with each other resulting in a resonant wavelength, called the Bragg wavelength (λ_B). Thus, for a wideband incident signal, the reflected signal is a narrow spectrum centered on the Bragg wavelength and the other components of the incident wave are transmitted through the network (Yin, 2008).

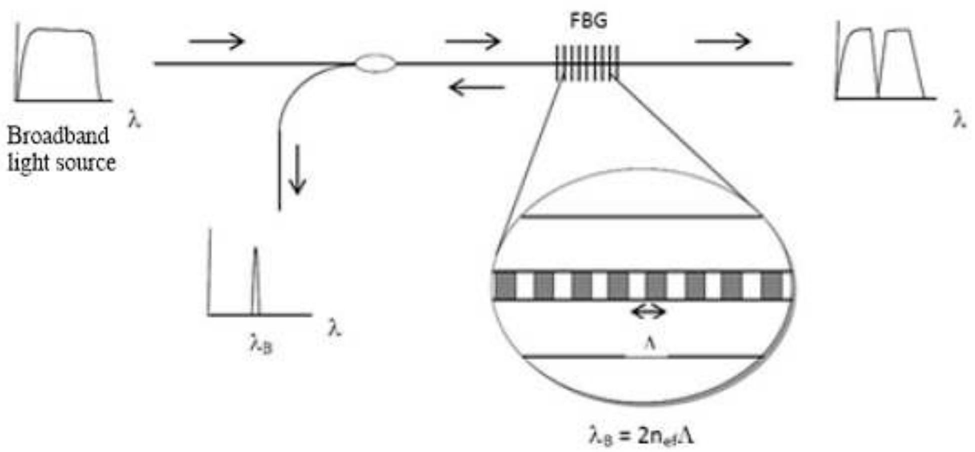


Figure 9. Operation principle of a FBG sensor (Gomes, 2011).

A representation of the effects of traction and compression on a Bragg network can be seen in Figure 10, which shows the example of a Bragg network acting as a sensor.

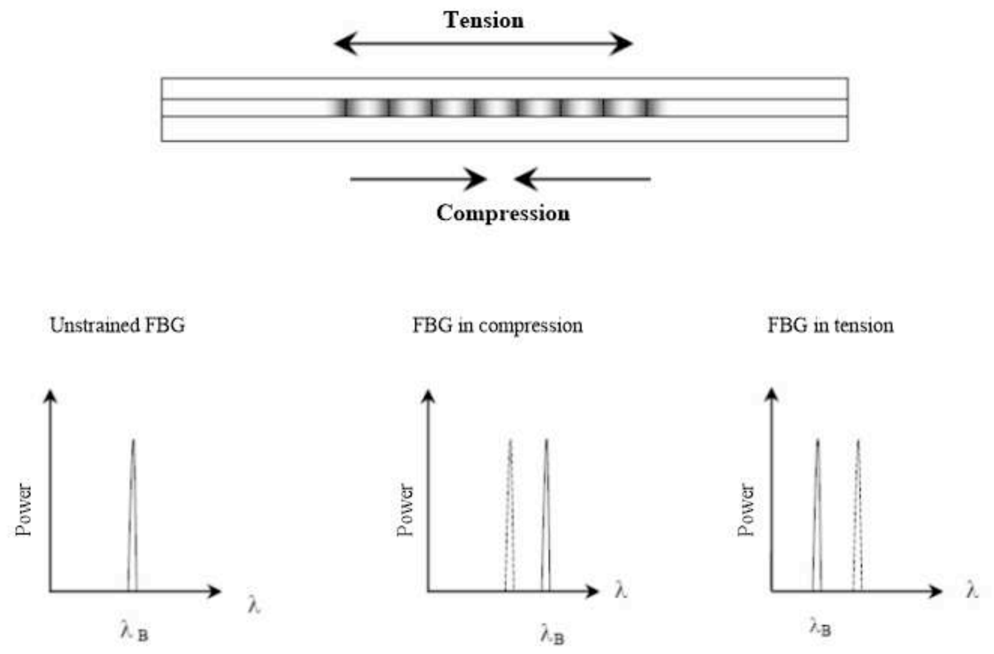


Figure 10. Schema of spectral displacement of a FBG sensor when under traction and compression (Quintero, 2006).

The variation of wavelength in relation to mechanical stresses and temperature variation can be summarized in an approximate linear way as:

$$\frac{\Delta\lambda_B}{\lambda_B} = 0{,}78\varepsilon + 9.10^{-6}\Delta T \qquad (1)$$

Where ΔT is the temperature change in ^{o}C and ε represents the deformation in m/m.

The attraction for the use of Bragg networks as sensors is due to the fact that the information is contained in the spectrum, which means an absolute measure and it is easy to be multiplexed. It follows from Equation 1 that, for the wavelengths commonly used in telecommunications (1300 and 1550 nm), the measurement of λ_B must be performed to the nearest 1 pm in order to measure 1 μm/m deformation or 0.1 ^{o}C temperature (Valente *et al.*, 2002).

Different procedures can be used for the measurement of deformations or temperature variations from the induced changes in the optical spectrum of Bragg networks. Valente *et al.* (2002) present the main techniques for reading the sensors of the Bragg network applied to measurements of temperature and deformation.

Due to the versatility and promising perspectives of the use of fiber optics in geotechnics, the Bragg network sensing technology was applied in the instrumentation of a horizontal inclinometer installed at the study area.

4 HORIZONTAL INCLINOMETERS

4.1. Instalation of the horizontal inclinometer tubes

Two horizontal inclinometers (HI-1 length of 50 m and HI-2 of 61 m) were installed near SPT boreholes, in order to measure the continuous vertical displacements along the section of the terrain after the CPR technique. They were also installed near the inclinometers previously installed, in order to correlate vertical and horizontal displacements. The installation of the horizontal inclinometers (HI) was conducted by the Engegraut team after the conclusion of the treatment of the area with CPR. Initially two trenches were opened with about 0.45 m of depth. Subsequently, a layer of sand was laid in order to regularize the bottom of the trenches.

The materials used and the connection process of the tubes are the same as those used when installing inclinometers, as well the reading unit. In this case, Slope Indicator's Digitilt horizontal inclinometer probe and digital reading unit from COPPE/UFRJ was used. Figure 11 shows the composition of the measuring set of the HI with the detail of the orientation plane of the probe in the tube.

Initially the measurement was carried out in A_0, and the probe was guided by a guide wire to the opposite end of the reading unit, and thereafter at 0.5 m intervals or every 1.0 m, the corresponding readings were carried out until the probe crosses the length of the HI and reached the end where the reading unit is located.

The measurement on A_{180} was carried out with the electric cable plugged into the connector 1 of the probe, which is equivalent to a 180º turn of the equipment. The sensor is led to the opposite end and a new round of readings begins. Data stored on the drive was processed using DigiPro software. Further information on the calculation procedure to obtain the vertical displacements is presented by Slope Indicator (2006). The installation of the HI was completed with the backfill of the trenches and four concrete inspection boxes were built at the ends of the lines in order to protect the HI during earthworks and against the action of vandals.

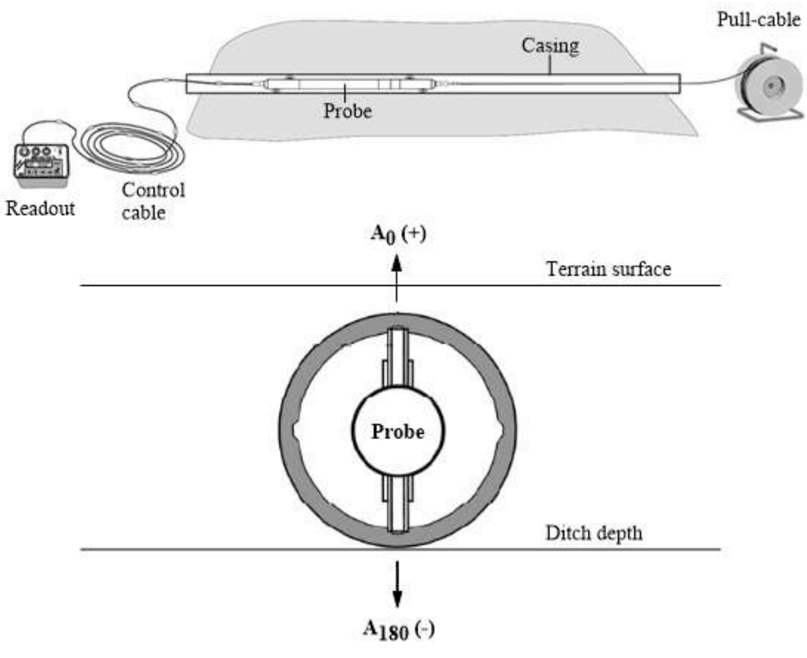


Figure 11. Probe orientation plane in the horizontal inclinometer tube.

4.2. Laboratory tests with FBG

First, the fixing and the protection material used to glue the FBG to the grooved PVC tube were subjected to laboratory tests in order to verify the compatibility of these materials when working together. These materials should have flexibility, so that the glue and the FBG deform jointly; adherence to the tube, thereby ensuring the restriction to the displacement of FBG; rapid curing and resistance to variations in temperature, humidity and abrasion.

The glue, consisted of an acrylate-based adhesive, was applied to a sample of the tube, as can be seen in Figure 12. The set was subjected to increasing temperatures, reaching about 150 °C.
What was observed from the laboratory test was a perfect adhesion between the inclinometer tube and the FBG. However, due to the slow cure of the glue, the field application would slow the process of installing the optical fiber on the tube. Thus, taking into account field deadlines, it was used a polymer-based sealant adhesive, easier to apply with a glue gun. The new material tested showed good adhesion to the tube, fast curing time and formation of a structure rigid enough to protect the Bragg networks against the action of shock and / or abrasion and also flexible, in order to allow the network to deform conjointly with the tube.

In parallel, the ability of the tube to promote a response that could be measured was tested. The deformation of the material from which the tube is made should be measurable through fiber optic sensors installed therein. The instrumented tube sample, as shown in Figure 12, was subjected to various stresses whose resulting deformation could be measured by means of optical reading equipment.

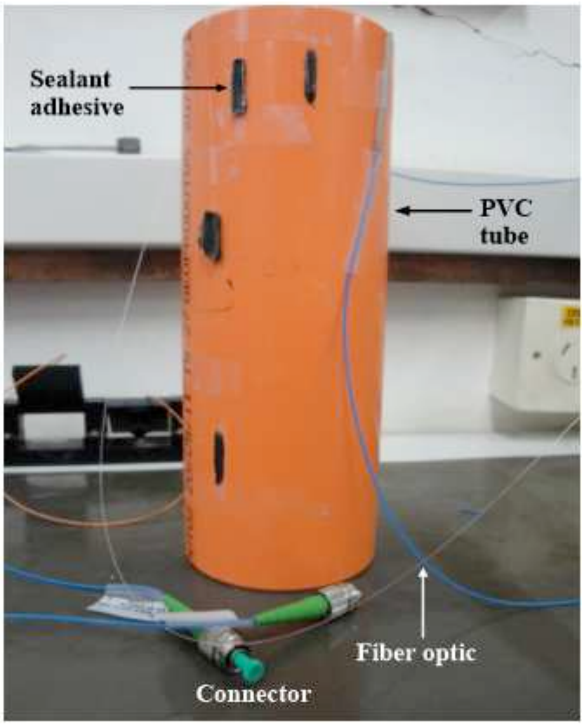


Figure 12. Laboratory tests with the FBG glued to the inclinometer tube.

Gomes Pinto *et al.* (2015) showed results of laboratory tests carried out on inclinometers instrumented with FBG and the satisfactory result obtained from the laboratory experiment with the fiber optic tube sample demonstrated the possibility of the practical use of this type of instrumentation in Engineering work.

For the instrumentation of the 61 m long profilometer line with optical fiber, it was established the implantation of thirteen Bragg networks along the tube, which would act as sensors. Figure 13 shows the spectrum obtained for the sensors. The wavelength of the nets varies in the range of 1,521 to 1,576 nm. Table 2 shows the FBG characteristics installed over the HI.

The Bragg networks were produced at the Fibra Óptica Sensors Laboratory at PUC/RJ. The process of recording the networks in the optical fiber was done through the phase mask technique. Further details about this technique can be found in Allil (2010).

The FBG were installed over the 61 m tube by PUC/RJ team, designed so that each sensor was properly positioned in the tubes of the profilometer. The FBG were positioned in the upper generatrix of the profilometer, except for the FBG 6 that was positioned inside a conduit parallel to the inclinometer. FBG 6, associated with temperature, was installed in order to correct deformation values, since the temperature influences measurements. It was decided to arrange them in three channels, that is, three distinct fiber optic lines, as shown in Table 2.

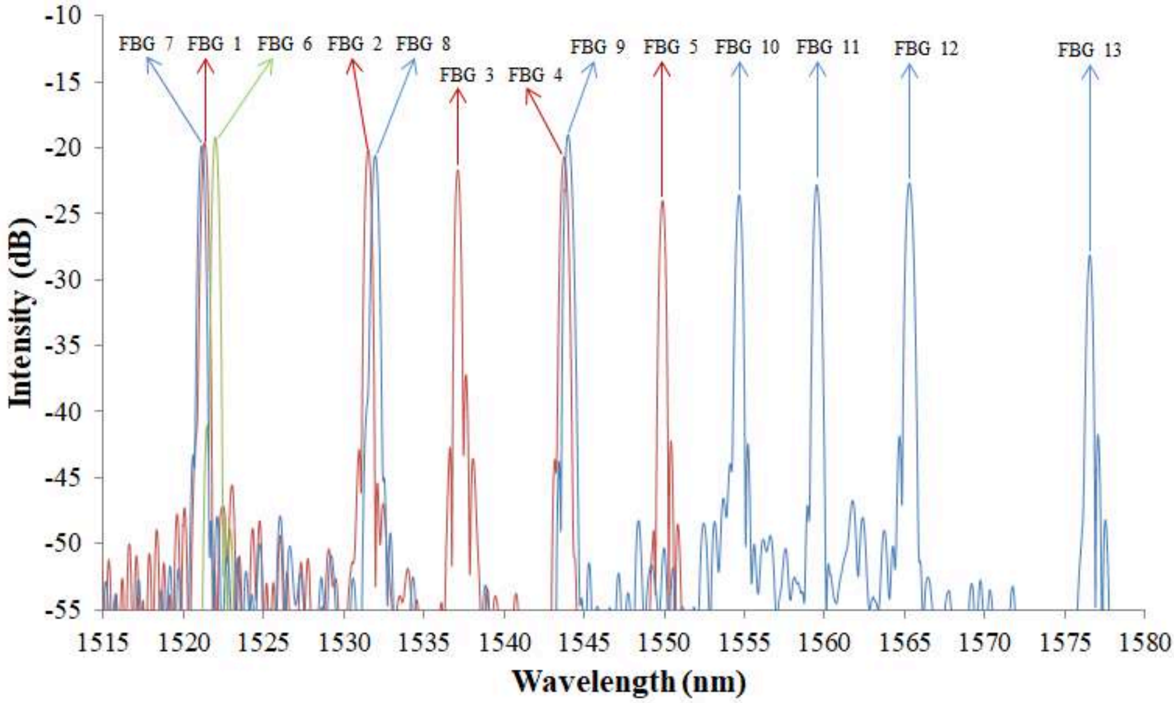


Figure 13. Spectrum of FBG.

Table 2. FBG characteristics over the HI

Sensor	Wavelenght (nm)	Location along horizontal inclinometer (m)	Location on tube and channel
FBG 1	1521.31	0.21	
FBG 2	1531.51	4.14	At the top generatrix of tube, channel 1
FBG 3	1537.10	8.05	
FBG 4	1543.74	11.99	
FBG 5	1549.89	15.90	
FBG 6	1521.97	8.05	Inside the conduit, channel 2
FBG 7	1521.13	26.84	
FBG 8	1531.94	32.85	
FBG 9	1543.98	38.46	At the top generatrix of tube, channel 3
FBG 10	1554.67	41.20	
FBG 11	1559.50	44.64	
FBG 12	1565.29	47.48	
FBG 13	1576.56	50.62	

4.3 Field installation of FBG over the horizontal inclinometer

The operational procedures for installing the optical fiber in the profilometer are described in the following sequence: cleavage, splicing, preparation of the tube, fixation of the FBG.

The cleavage consists of cutting the end of the fiber at an angle of 90º. The faces of the fibers are parallel and can thus be mended. The operation is carried out through with a cleaver, which makes a risk in the fiber, analogous to the cut of a glass. In this step, the 13 fibers containing the Bragg nets were cleaved, as shown in Figure 14 a, so that they could then be mended to the main fiber.

Fiber optic splicing is performed when two properly aligned fiber segments are fused together at elevated temperatures produced by electrical discharge emitted by the splice equipment. At this stage the fibers containing the FBG were spliced to the main fiber, Figure 14 b.

Figure 14. Cleavage and splicing of the FBG.

The preparation of the inclinometer tube consists of cleaning the surface of the tube with alcohol so that the fiber can be fixed (Figure 15 a). For the fixation and protection of the FBG, a glue based on cyanoacrylate used for fixing, and then polymeric sealant adhesive to fix and protect (Figures 15 b and 15 c).

Figure 15. Fixation of FBG over the tube: a) clean tube; b) glue application; c) Adhesive sealant applied.

A high strength adhesive tape with glass filament reinforcement was used to fix all optical wiring, Figure 16 a. In order to minimize the risks to the integrity of the fiber optic, the ditch backfill was partially sanded to the total overlay and completed with soil without gravel, Figure 16 b. The inspection boxes, located at the terminals of the profilometer, were constructed with concrete blocks (Figure 16 c), wich in addition to allow access, it has the function of protecting the tube, optical cabling and connectors against vandalism. The optical instrumentation monitoring apparatus consists of IME optical interrogator Micron Optics sm230-800, laptop computer and power generator.

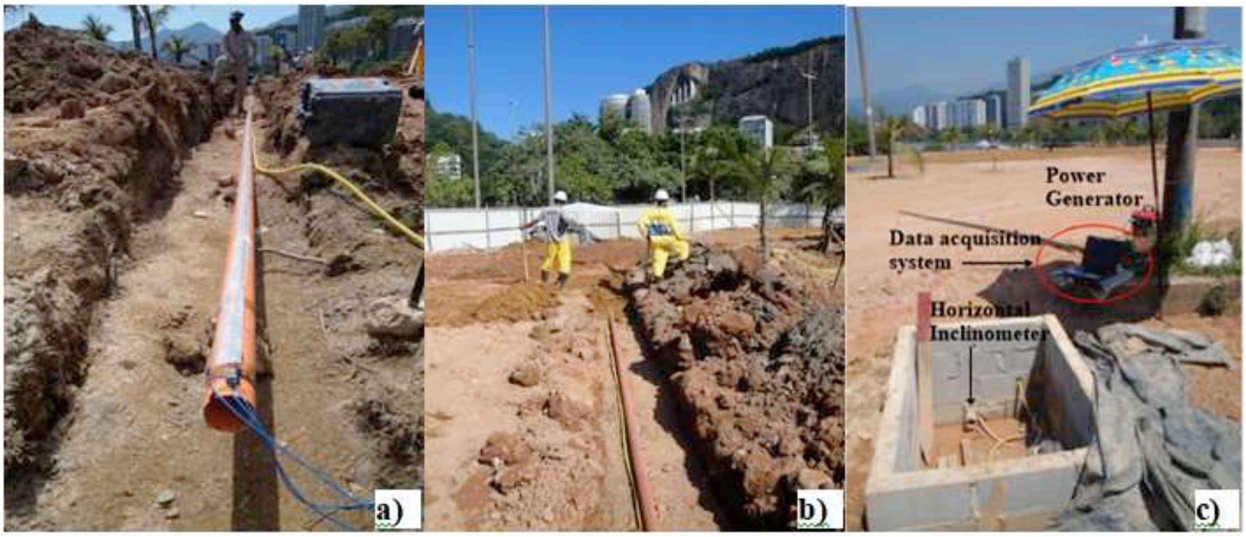


Figure 16. Tube installation: a) adhesive tape over FBG; b) ditch backfill; c) data acquisition system.

4.4 Testing the FBG

In order to verify any problems during the installation process, the sensors were tested as the FBG were installed in the profilometer. This test consisted of the verification and analysis of the signals emitted by the optical sensors with an optical spectrum analyzer called Braggmeter. All the sensors were in compliance, that is, they provided answers when the signals were acquired by the optical interrogator except FBG-3, FBG-4 and FBG-5, that were damaged when backfilling. Initially these sensors underwent attenuation process and, later total loss of optical signal power.

Figure 17 shows a detail of the optical signal acquisition system, composed of a portable computer and IME's optical reader. Initially a cleaning with isopropyl alcohol is carried out at the tip of the connectors and inside the channels of the optical interrogator that will receive the optical fibers. Soon after, the fibers are connected to the equipment channels through the connectors. Then, a network cable is connected to the interrogator and the laptop computer. Since this equipment has no battery, an electric generator is required to power it up and keep it running.

Figure 17. a) Optical signal acquisition system; b) software ENLIGHT.

The acquisition of data is through the software ENLIGHT and the FBG are automatically recognized within their respective channels when the program is accessed. The processing interval of the sensor readings is set by the user and the measurements generated are given by the wavelength measured with time for each sensor. Information can be saved at pre-set intervals and stored in the data folder created by the program in a file with a txt extension. Figure 18 shows the register of the wavelength during compaction. The vibration of the compactation equipment could be monitored with high precision.

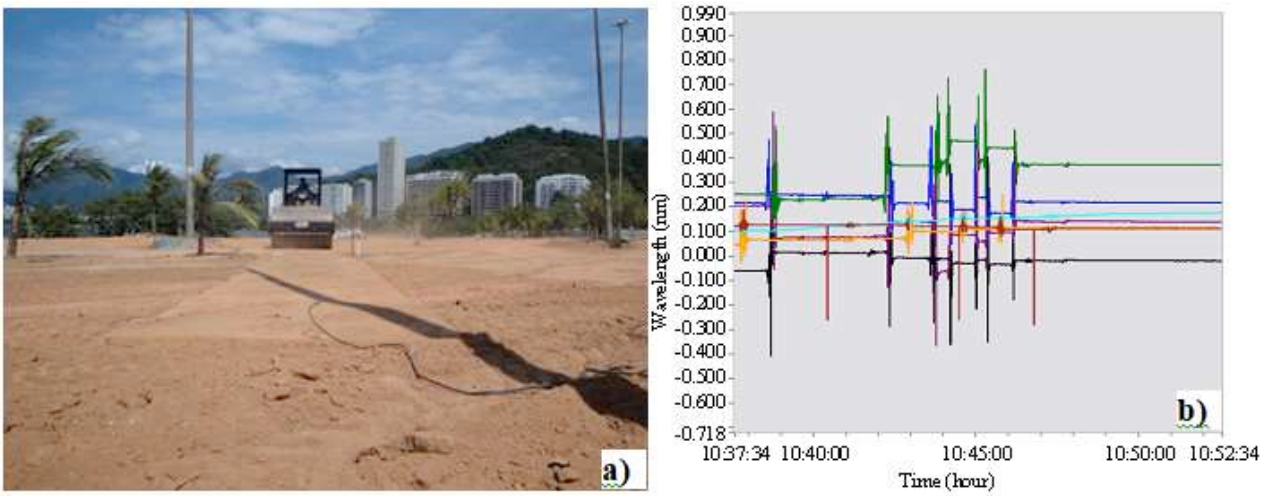


Figure 18. Real time response of FBG during compactation.

The monitoring process is complemented by the continuous temperature logging on the FBG 6, through a device called DTS, an optical system for distributed temperature measurement along 53 m of the optical fiber positioned next to the profilometer. Figure 19 shows the results, and the average temperature recorded was 25.4°C.

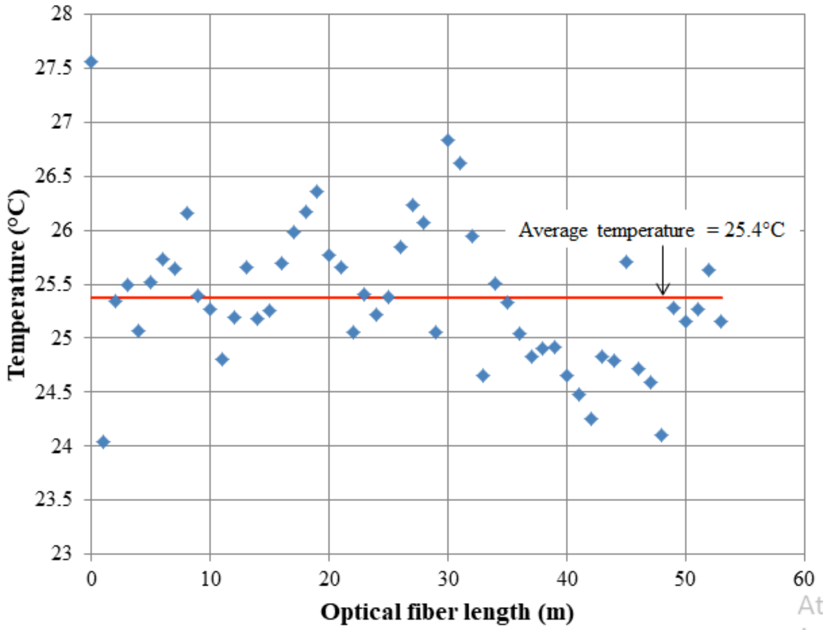


Figure 19. Temperature recording along the optical fiber.

4.5 Problems during construction

During the execution of the landfill, channel 3 stopped recording the seven sensors distributed in it, so the FBG associated with this channel was broken or bent. In order to recover it, an inspection was performed to verify the exact point on the fiber where the fault was occurring. Thus, with the use of an Optical time-domain reflectometer (OTDR) it was possible to locate the point of failure. The operating principle of the OTDR, Figure 20 a and b, is the transmission of a known electrical pulse of amplitude and duration from one end of the cable. If there is any change in the characteristic impedance of the cable, there will be reflections of the transmitted pulse.

Figure 20. a) and b) Analysis of FBG transmission with OTDR; c) local of the splicing

A sector of the HI, located 28.5 m from the monitoring point, was broken by a backhoe excavator near the instrumentation and, consequently, the fiber was also damaged (Figure 20 c). The structural integrity of the profilometer was restored with the connection of a new tube segment and the splicing of the optical fiber was carried out by a fusion process.

Another intervention was necessary due to the rupture of the FBG 6 housed in the conduit during the excavations carried out for the construction of a multi-sport court. Once again the fusion process was used. At the end of the work, due to the problems described, only the sensors FBG 1, 2, 9, 10, 11 and 12 were active.

5 RESULTS

Laboratory tests were carried out with joint readings of the optical instrumentation and the mechanical instrumentation (through the profilometric probe) in order to evaluate the behavior of the profilometer in terms of deformation, vertical displacement and angular variation when applying successive displacements at the free end of the tube, the same used in field instrumentation at Cantagalo Park.

The results obtained in the laboratory under controlled test conditions are shown in Figure 21. Mello (2013) showed that the curve Angle (°) versus Strain (10^{-6}m/m) in the tube section containing the FBG-3 Lab, as well 3 other FBGs, presented high correlation, with coefficients of determination close to 1.

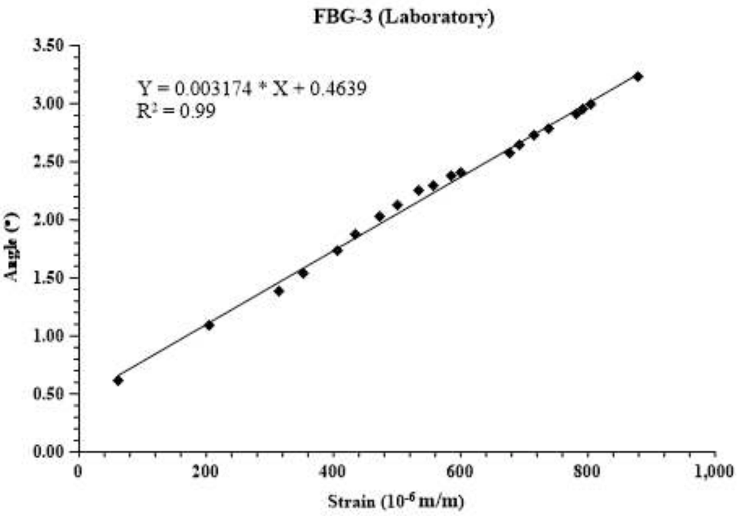


Figure 21. Angle (º) versus deformation (10-6 m / m) from laboratory test FBG-3 Lab.

The same procedure was carried out for field results for the HI and FBG, as shown in Figure 22 for each FBG.

Since the deformation is a function of temperature as previously established by Equation 1, the dispersions recorded in the graphs can be partly credited to the effect of temperature. The only measurement carried out showed that the temperature varies along the length of the HI (Figure 19). It was not possible to evaluate the influence of localized temperature, since the FBG-6, wich was positioned on the conduit at the side of the HI-1 to measure the deformations generated by the effect of the temperature variation, was broken during earthworks.

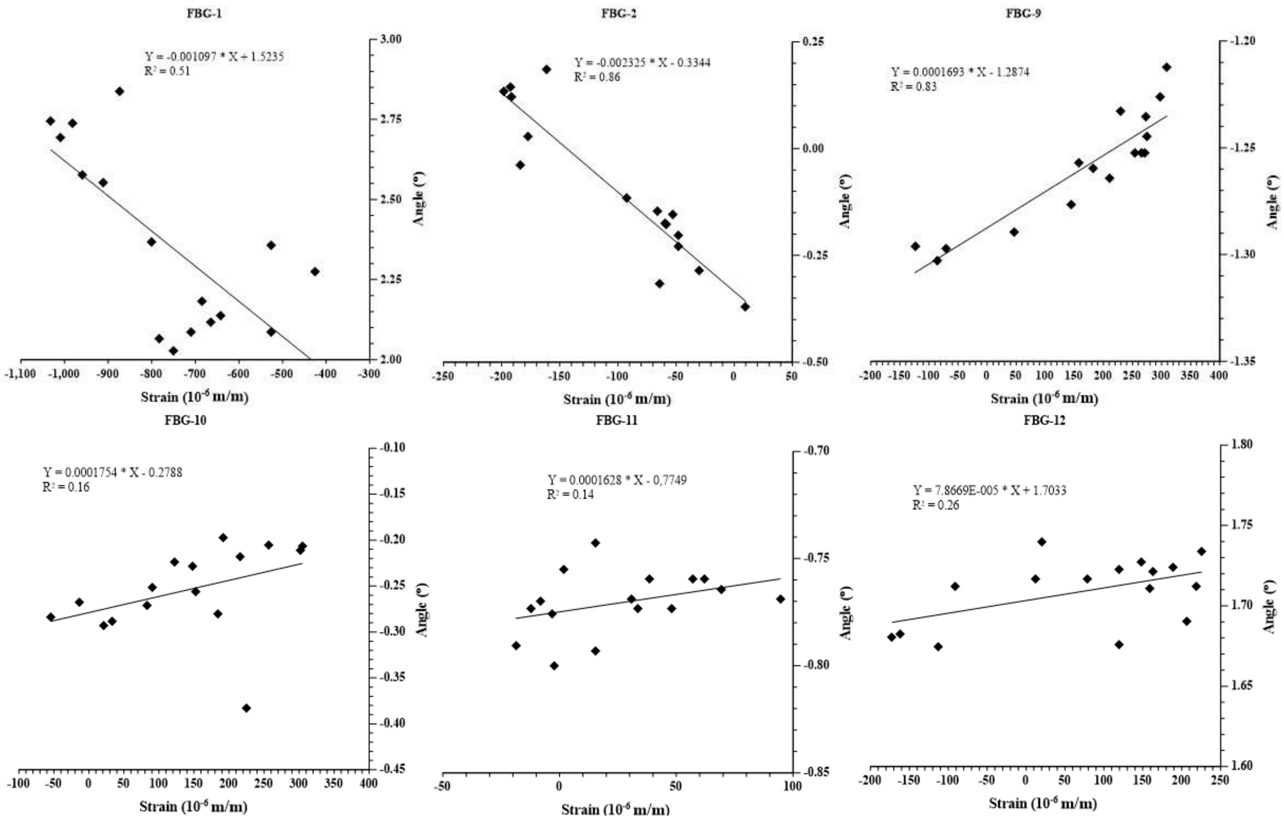


Figure 22. Angle (º) versus deformation (10^{-6} m / m) for each FBG – field monitoring.

Figure 23 show the mechanical results from HI-1(50 m) and HI-2 (61 m) with time, beginning 13 days after the end of the injection of CPR and the last read of the settlement plates installed above HI-1 and HI-2.

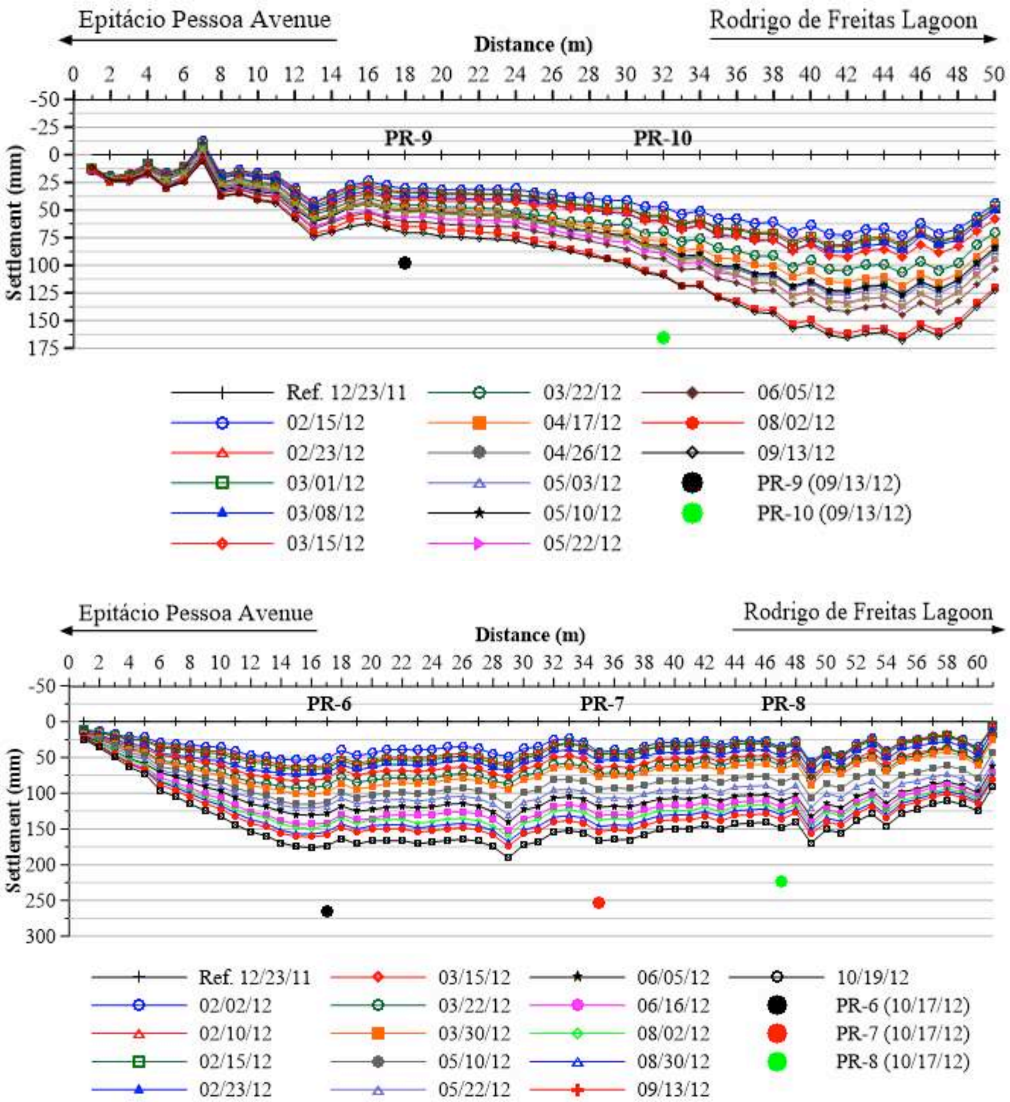


Figure 23. Results of HI-1 (50 m) and HI-2 (61 m).

The maximum displacement registered by the HI-1 and HI-2 were lower than those from settlement plates. When generating vertical displacement profiles with a horizontal inclinometer, it is assumed that one of the ends is fixed and, from it, the settlements are calculated. In the field, however, displacements of the two extremities occurred, since all the instrumentation is was inside the Park, and could not be otherwise. Topographical survey of the extremities was carried out in order to assess this problem.

4 CONCLUSIONS

The use of optical extensometers in engineering measurements constituted the breaking of a paradigm, since its multiplexing capacity, and the possibility of applying several extensometers in the same cable, allow the analysis of the global behavior of the structures. In a single channel, it is possible to obtain several discrete measurements that allow inferring about the continuous behavior of the structure.

Due to the fiber-optic remote sensing capability, its application in the monitoring of the structural condition of Engineering works related to resistance (ultimate limit state) and displacements, therefore, as a system of alert against the situation of imminent rupture of the structure.

In the specific case of the present study, in spite of the dispersion of the data, associated with errors such as the non-evaluation of the effect of the temperature variation, relations between the deformation and the corresponding angular variation in the tube were determined. From these relationships, the vertical displacements (settlements) can be estimated. The reduced number of active optical sensors, 6 in total, and irregularly spaced apart, is insufficient to generate a profile of vertical displacements in a profile of 61 m in length. For this it is necessary the distribution of sensors to each meter for the initial correlation with the mechanical measurements.

There is no need to ignore traditional instrumentation, based on the principle of accelerometer operation, whose technical experience is consolidated and widely disseminated. However, the application of optical systems in geotechnical instrumentation proved possible. The laboratory experiment with the profilometer instrumented with optical sensors according to the structural model of a crimped / free beam demonstrated the possibility of its application in the instrumentation of inclinometers.

The best application for fiber optic technology in geotechnics seems to be in acting as warning systems. It can be applied, for example, to the instrumentation of inclinometers installed on slopes subject to landslides caused by heavy rains and in the risk monitoring of the structural integrity of ducts that cross regions subject to landslides. In these cases, where continuous monitoring is necessary, the possibility of remote monitoring is one of the great advantages of this type of instrumentation.

From the practical experience of the field, it was observed the great difficulty in preparing the optical fiber. The ideal is already acquiring the fiber in the standard necessary for the field measurement, eliminating the cleavage and splicing steps in the field. Another important practical aspect is to use an autonomous, battery-operated acquisition system that does not depend on the generator in the field.

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REFERENCES

Agrar. *Interconnection of Line 4 (Barra da Tijuca) with Line 1 (General Osório Station), with the subway system of the city of Rio de Janeiro / RJ*. Environmental impact study. (in Portuguese). Vol. 1, 2011.

Allil, R. C. S. B. *Fiber optic sensors with FBG technology for temperature and high voltage measurement*. (in Portuguese). D. Sc. Thesis. COPPE/UFRJ. Rio de Janeiro/RJ, 2010.

Almeida, M. S. S. and Marques, M. E. S. (2013). *Design and Performance of Embankments on Very Soft Soils*. CRS Press, London, UK, 199p.

Almeida, M. S. S., Hartmann, D. A. , Riccio, M, Guimarães, M, de Mello, M. A., Vieira, L. O. *Site investigation for stabilization of Cantagalo Park, Rodrigo de Freitas Lagoon, Rio de Janeiro, Brazil. Geotechnical and Geophysical Site Characterization 4*.Taylor & Francis Group, 2012.

Amador, E.S. *Guanabara Bay and peripheral ecosystems: man and nature*. (in Portuguese). Rio de Janeiro. Author´s edition, 1997.

Artières, O, Galiana, M, Royet, P., Beck, Y.-L., Cunat, P, Courivaud, J.-R., Fry, J.-J., Faure, Y.H. and Guidoux, C. *Fiber optics monitoring solution for canal dykes*. PIANC MMX Congress Liverpool, UK, 2010.

Briançon, L , Nancey, A, Robinet, A e Voet, M. *Set up of a warning system integrated inside a reinforced geotextile for the survey of railway*. Proc, IGC 8th, Sept.18-22, Yokohama, Japan.pp.857-860, 2006.

Chang, C. *Development of Fiber-Optic Sensor Networks for Transportation Infrastructure Monitoring*. Final Report METRANS Project 10-14, College of Engineering, California State University, 2012.

Duncan, R. G. and Raum, M. T. (2006). *Characterization of a fiber-optic shape and position sensor*. In: Proc. SPIE 6167, Smart Structures and Materials 2006: Smart Sensor Monitoring Systems and Applications, March 30.

Engegraut. Advertising material, [obtained in june 2011].

Gomes Pinto, F. (2015) *Study of the tensile behavior of steel meshes used in the stabilization of slopes of transportation infrastructure*. (in Portuguese). Master's Thesis in Transportation Engineering, Military Institute of Engineering, Rio de Janeiro.

Gomes Pinto, F. ; Mello, M. A. ; Aragão, L. A. C. M. ; Marques, M. E. S. . *Inclinometer instrumented with fiber optics for monitoring slopes*. C&T. Revista Militar de Ciência e Tecnologia, v. 3, p. 47-61, 2015.

Gomes, G. C. (2011). *Optical sensors based on fiber Bragg grids for temperature and refractive index monitoring* (in Portuguese). Master's Thesis in Electrical Engineering, Military Institute of Engineering, Rio de Janeiro.

HO, Y.-T, HUANG, A.-B. and LEE, J.-T (2006). Development of a fibre Bragg grating sensored ground movement monitoring system.Measurement Science and Technology. Vol. 16, pp. 1733-1740.

Lagoalimpa. Available in http://www.lagoalimpa.com.br/alagoa.aspx, [obtained in july 2012].

Lally, E. M.; Reaves, M.; Horrell, E.; Klute, S. and Froggatt M. E. (2012) *Fiber optic shape sensing for monitoring of flexible structures*. In: Proc. SPIE 8345, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems, 83452Y, April 26.

Lee, J.-T, Tien, K.-C., Ho, Y. T. and Huang, A.-B. (2011). *A fiber optic sensoredtriaxial testing device.Geotechnical Testing.* Journal, vol. 34, nº 2.

Luizd. Available in http://fotolog.terra.com.br/luizd:89, [obtained in november 2012].

Mello, M. A. (2013). *Deep radial consolidation applied in compressible soil at Rodrigo de Freitas Lagoon/RJ* (in portuguese). Master's Thesis in Transportation Engineering, Military Institute of Engineering, Rio de Janeiro.

Muehe, D. *Coastal Geomorphology*. In: Geomorphology: an update of bases and concepts. (in Portuguese). Rio de Janeiro: Bertrand Brasil. 1995.

Quintero, S. M. M. (2006) *Applications of FBG sensors in optical fibers in the measurement of pH and deformation of thin films* (in Portuguese). Master's Thesis in Mechanical Engineering, PUC-Rio, Rio de Janeiro.

Rocha, R. P. O. *Geotechnical instrumentation with fiber optics: monitoring of wetting front and analysis of the variation of the degree of saturation in sandy soils*. Master's Thesis.UFPR.Curitiba/PR.2011.

Slope Indicator. *Horizontal digitilt inclinometer prob*e (50302599). Washington. USA. 2006.

Souza, L.C. (2003). *Survey and characterization of Rodrigo de Freitas Lagoon zooplankton (RJ)*. Master's Thesis in Zoology, UFRJ, Rio de Janeiro.

Trajan, C. G. (2007) *Study of solutions for visualization and simulation in projects of urban evolution and urban planning: the neighborhood of the Lagoon in Rio de Janeiro* (in portuguese). DSc Thesis in Civil Engineering, COPPE/UFRJ, Rio de Janeiro.

Valente, L. C. G., Silva, L. C. N., Ribeiro, A. S., Triques, A., Regazzi, R. D. and Braga, A. M. B. *Reading techniques for fiber optic sensors based on Bragg networks*. In: 6th Conference on Equipment Technology. Salvador - BA: [s.n.]. 2002.

Yin, S., Ruffin, P. B. and Yu, F. T. S. (2008). Fiber optical sensors.2 ed., CRC Press.