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AUTOMATED GEOTECHNICAL INSTRUMENTATION AND MONITORING FOR LINEAR PROJECTS: APPLICATION EXAMPLES IN COLOMBIA

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ABSTRACT

The variables involved in geological-geotechnical processes are dynamic over time, particularly in any linear-type project. Assets constructed through slopes, fills, cuts, bodies of water, among others, must be monitored throughout their lifespan to validate their expected behavior. This presents operational, timeliness, and information quality challenges for decision-making in the face of deviations. Various technologies and practical examples of automated geotechnical monitoring in Colombia are presented, utilizing diverse sensors for linear infrastructure. These have provided real-time valuable information and enabled decision optimization.

Keywords: *instrumentation, automation, InSAR technology, geotechnics, remote monitoring, structural health, Engineering 4.0, Internet of Things (IoT).*

1. INTRODUCTION

Risk management challenges have been increasing for infrastructure projects, particularly for linear projects in the hydrocarbon sector (pipelines, oil pipelines, gas pipelines, among others). This is due to the rise in precipitation associated with changes and intensities of El Niño and La Niña phenomena. Given the unique conditions of the Colombian territory, these changes present vulnerabilities linked to its young geology and steep slopes, often accompanied by historically active mass removal processes. Additionally, the seismic activity resulting from various geological faults in the Colombian mountain ranges poses a threat that increases the likelihood of triggering ground displacements (creep) or landslides.

With the technological advancements associated with Engineering 4.0, which include elements such as sensors, databases, cloud storage, and applications for interpreting vast amounts of data using artificial intelligence (AI) and machine learning (ML), the opportunity has arisen to monitor engineering variables' real-time behavior. This allows for a better understanding of the temporal behavior of regions facing geohazards in critical areas of interest.

This document introduces several technologies that have been applied to linear projects, their main outcomes, as well as their limitations in potential future applications with similar scopes in the hydrocarbon sector.

2. GEOTECHNICAL DISPLACEMENT MONITORING THROUGH GROUND-BASED INSAR (GB-InSAR) ON THE BOGOTÁ-VILLAVICENCIO ROAD

2.1 GB-InSAR Technology Description.

For remote monitoring of large areas on slopes, cuts, or other potential instability targets, one of the most implemented solutions is the use of ground-based Interferometric Synthetic Aperture Radar (GB-InSAR).

These radars perform scanning using electromagnetic waves to compare different measurements and identify displacements in the line of sight (LOS) through continuous pixel tracking.

Pixel monitoring through linear sweep with frequencies that depend on the equipment model used and the area analysis size.

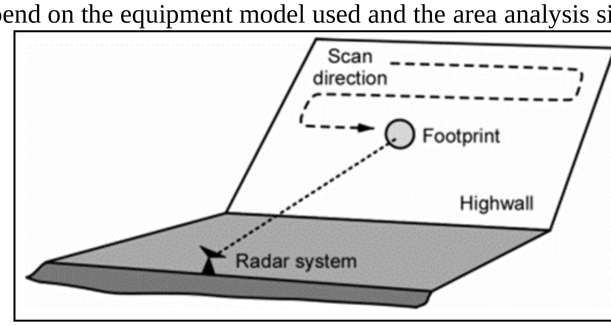

FIGURE 1: GROUND-BASED RADAR SCANNING OF A WALL. MCHUGH, E., ET AL. 2006 [1]

In the Bogotá – Villavicencio Road Corridor, one of Colombia's main routes due to its significance in cargo and tourism transportation towards the eastern part of the country, a particular critical situation arose at kilometer point 58 (K58) of this road.

At this location, there is a terrace slope comprised of heterogeneous granular materials, posing a threat to the safety of users and inhabitants of the municipality of Guayabetal. Additionally, at the lower part of this slope, a river is situated that, if dammed, could trigger avalanches, and directly affect the population just a few meters away from this critical site.

FIGURE 2: LISA TYPE GEORADAR FOR 24/7 REMOTE MONITORING OF THE K58-MESA GRANDE

2.2 LISA TYPE GROUND PENETRATING RADAR FOR 24/7 REMOTE MONITORING OF K58-MESA GRANDE

The unstable area of interest is situated in a sector where previous explorations have identified outcrops of Guayabetal quartzites and phyllites belonging to the Quetame Group Formation (PEq). Additionally, in the Mesa Grande area, there is a High Terrace deposit (Qta), located just a few meters from the municipality of Guayabetal, Cundinamarca.

Among the region's most relevant geological structures is the Jabonera Fault, which has an approximate NS orientation.

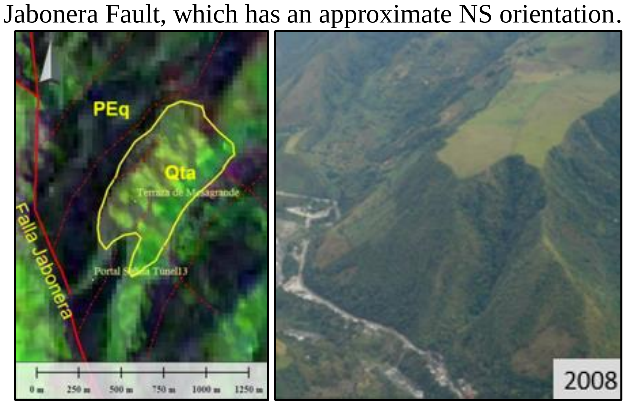

FIGURE 3: GEOLOGY OF THE MESA GRANDE AREA

2.3 Displacement Monitoring for Slope K58 - Mesa Grande

The GB-InSAR used for monitoring K58 has an operational range of 4500 m; however, the wall was situated at a distance between 600 and 700 m (lower and upper parts of the slope). The system had an elevation angle and azimuth of 60 degrees.

For this wall, measurements were taken with a rectangular pixel size of approximately 1.00 m in length and 0.50 m in width, recorded through a sweep every 90 seconds.

Each monitored pixel allowed tracking of displacement and movement trends over time, creating an early warning system. Displacement trends defined alarm thresholds as follows:

- Green Alert (Stable condition).
- Yellow Alert (Regressive condition).
- Orange Alert (Linear condition).
- Red Alert (Progressive condition).

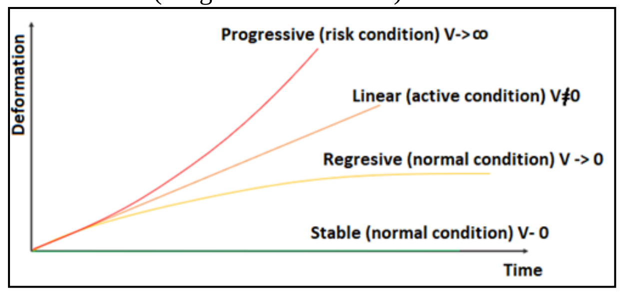

FIGURE 4: DISPLACEMENT TRENDS FOR ALARM DEFINITION

In the case of monitoring the Mesa Grande slope, during the initial 2-month period, accumulated displacements were recorded that coincided with a period of heavy precipitation and landslides on the slope, according to supplementary information.

The general trend observed in the various pixels monitored on the K58 slope was progressive (accelerating), with speeds of up to 3mm/hour recorded for the most critical points (see FIGURE 5).

Furthermore, within these initial 2 months of monitoring, the accumulated displacement reached up to 1200 mm for the most critical points.

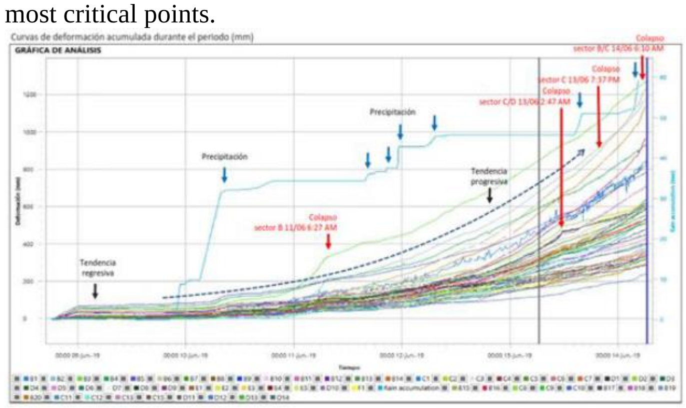

FIGURE 5: ACCUMULATED DISPLACEMENTS FOR INITIAL 2 MONTHS OF MONITORING

One of the most crucial functions of the implemented ground-based radar system was the graphical visualization of accumulated displacements (FIGURE 6), wherein each monitored pixel was assigned a color spectrum depending on the defined scale and required analysis range.

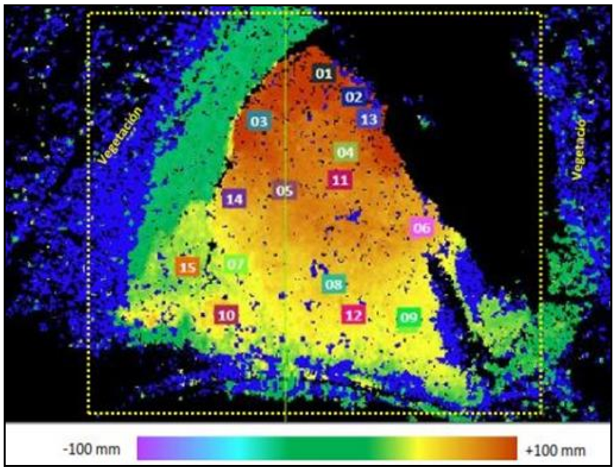

FIGURE 6: ACCUMULATED DISPLACEMENTS ON THE SLOPE (OCTOBER 2019 TO FEBRUARY 2020)

During the initial monitoring stage, high rates of displacement were recorded, and by applying the reverse velocity analysis (Fukuzono, T., 1985 [2]), it was possible to identify events with a progressive trend.

This allowed for the early prediction of potential slope material collapse and consequently, providing authorities with several hours' advance notice for risk management, see FIGURE 7.

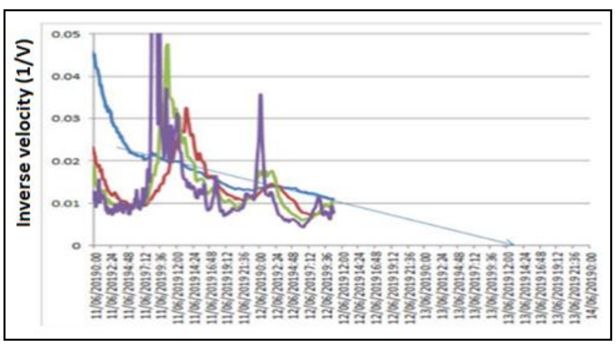

FIGURE 7: REVERSE VELOCITY ANALYSIS (ESTIMATED COLLAPSE EVENT FOR 06/13/2019 13:00)

The collapse event occurred one hour prior to the estimated time. Throughout the process, local and national risk management entities coordinated to control road operations and prevent fatalities resulting from the event.

2.4 Benefits and Limitations of the Implemented Technology

The GB-InSAR technology allowed for this project:

- Real-time monitoring of slope behavior and segmented identification of displacements, through the implementation of an early warning protocol for decision-making, ensuring the safety of users, nearby population, and road operation in the intervention area.
- Based on the early identification of displacement trends, it was possible to keep the road section operational. In the scenario of potential collapse, decisions about temporary solution alternatives for road operation reactivation could be supported.
- Having a detailed database of millions of data points (pixels) with historical records, enabling optimal analysis of daily and historical behavior.

However, despite the significant benefits, the implemented technology has the following limitations:

- For scanning areas with dense vegetation, recurring movements that may generate noise in identifying general slope displacement trends must be filtered beforehand.
- While the technology can identify areas with pronounced displacement trends, it does not register small rockfalls or localized material displacements smaller than the pixel size.

3. GEOTECHNICAL MONITORING OF DISPLACEMENTS USING INSAR SATELLITE TECHNOLOGY FOR POWER TOWERS

3.1 Description of InSAR Technology

Active satellites equipped with InSAR radar sensors capture information from the electromagnetic spectrum, oriented orthogonally to the orbital direction.

The antenna's inclination angle with respect to nadir can vary between 20 and 50 degrees. Due to the Earth's curvature, this angle is less than the angle of signal incidence on a flat horizontal terrain (Ferreti, 2014 [3]).

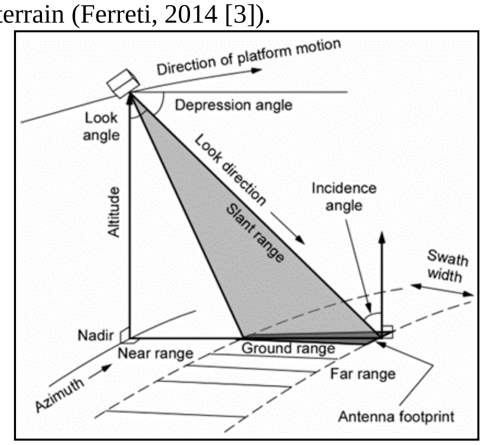

FIGURE 8: GEOMETRY OF THE RADAR IMAGE SYSTEM INDICATING AZIMUTH, LINE OF SIGHT, AND FOOTPRINT. MCHUGH, E., ET.AL., 2006 [1]

3.2 Monitoring Unstable Areas near Power Towers

Near a series of towers that are part of a significant power transmission line, historically significant geomorphological processes have been recorded. Therefore, an assessment and monitoring of landslide processes and cumulative displacement trends were conducted using the processing and analysis of data based on Sentinel 1-A satellite images from the European Space Agency (ESA).

For the project, a range of data was considered starting from October 2014 to the month of December 2019, with an orbit monitoring frequency of 12 days. Regarding the resolution used, rectangular pixels of approximately 13.40 m x 4.00 m were employed.

The power transmission line to be monitored consisted of a strip around fifteen (15) power towers.

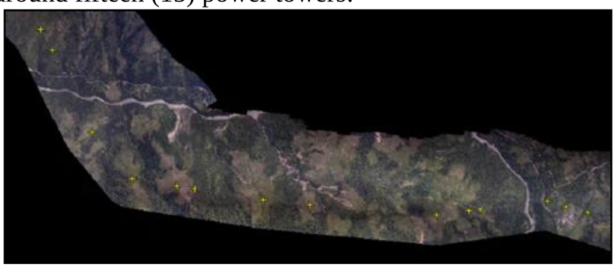

FIGURE 9: MONITORED POWER TRANSMISSION CORRIDOR

This monitored strip traverses different geological units, among which terrace units (Qt), sandstone formations (Pdg), shales (Pdp), phyllites, and quartzites (PCAqgu) were identified. Similarly, the analysis area is situated in an environment where geological faults with regional influence are found.

The corridor of the transmission lines was analyzed by tracking cumulative displacements through phase change analysis of successive satellite images, as well as analyzing amplitude changes due to signal reflectance obtained by the satellite.

Through the previous satellite image analyses, significant variations in temporal erosion processes, progressive landslide events, deforestation scenarios, and other types of events were identified for terrain change evaluation over time.

After processing the satellite data, the analysis strip was presented, showing displacement deformation rates in the line of sight (LOS) direction, trending away (orange to red tones), as shown in FIGURE 10, with values ranging from 7.00 mm/year to 21.00 mm/year.

The minimum detectable deformation scale also depends on the coherence of the obtained interferogram. Typically, in the case of coherent areas, it can be considered on the order of tens of pixels. While radar interferometry can measure deformations on the order of millimeters, the precise location of measurement points has an accuracy on the order of meters. The exact numbers depend on the type of satellite being used.

The accuracy of deformation rates obtained through this measurement method was approximately ± 2.00 mm/year, ensuring the reliability of results corroborated in the field.

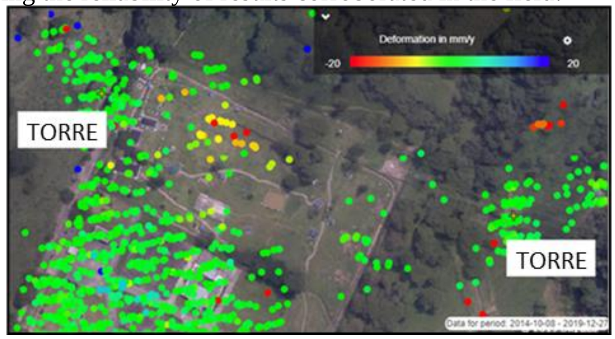

FIGURE 10: DEFORMATION RATES IN THE ANALYSIS AREA FOR THE PERIOD 08/10/2014 – 27/12/2019

Selecting a pixel with red tones allows a detailed observation of the displacement trend obtained for that area, see FIGURE 11. In this figure, the dispersion of obtained displacement data for the analyzed area is visible; however, based on these data, a clear trend could be calculated.

For applications of this technology in urban areas, due to high reflectivity, the dispersion of obtained information tends to be lower, resulting in more accurate data.

In rural areas or areas with dense vegetation, a quality criterion should be established beforehand to identify trends in displacement data.

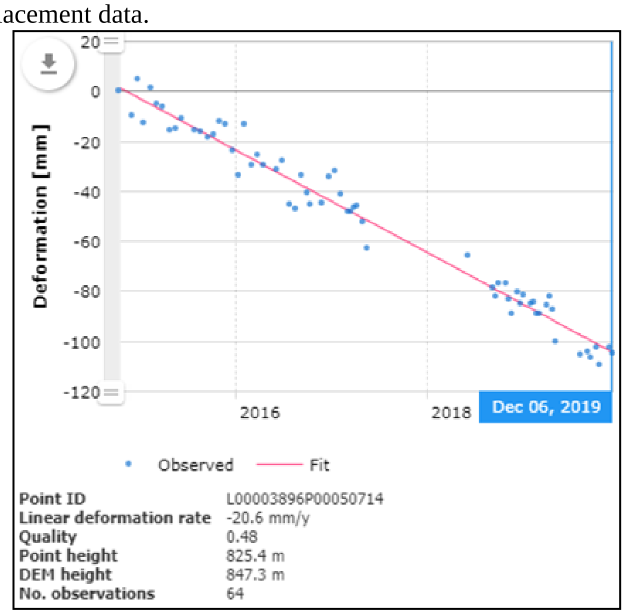

FIGURE 11: ACCUMULATED DISPLACEMENTS IN THE IDENTIFIED SUBSIDENCE AREA

On the other hand, the application of the change detection method using optical satellite signal amplitude allowed the reconstruction of the evolution of geomorphological processes and their progressive changes over time.

Therefore, these processes around power towers were mapped, serving as input for decision-making.

As shown in FIGURE 12, during the analysis period, amplitude change events associated with progressive landslides were registered. These events initially advanced (yellow to red points) from the top of the slope to the lower area, but more recently, they were affecting the area near the power tower (blue points), endangering its stability.

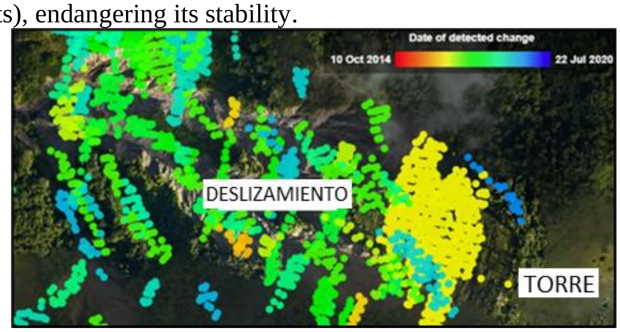

FIGURE 12: HISTORY OF EVENTS DUE TO AMPLITUDE CHANGES IN SATELLITE SIGNAL AROUND A POWER TOWER

In FIGURE 13, a photograph of the site analyzed using InSAR technology (FIGURE 12) is presented, from which the coincidence in the advancement of the landslides near the analyzed power tower can be observed.

FIGURE 13: PROGRESSION OF SLOPE DEGRADATION NEAR A POWER TOWER

3.3 Benefits and Limitations of the Implemented Technology

Through InSAR technology, the project achieved the following:

- Detailed monitoring of historical records of cumulative displacements in the satellite's line of sight (LOS), interpreting ground movements in historically critical areas, and identifying new areas of interest that could compromise structure stability.
- Historical recording of events related to geotechnical processes (erosion, subsidence, landslides) and monitoring their evolution for early decision-making.

However, InSAR technology has the following limitations:

- Monitoring is limited to the satellite's orbit frequency as it passes through the area of interest, which was 12 days for the power transmission corridor.
- In areas with dense vegetation, the quality criterion must be reduced for data to contain defined trends, or in some cases, conclusive data may not be obtained, requiring the use of other satellites with paid images.
- Availability of satellite images (paid or free) according to trajectory and viewing angles relative to the target area is necessary for detailed historical information.
- It is recommended that satellite displacements measurements would be checked on the field with surveying validation and visual inspections for correspondence.

4. ENVIRONMENTAL MONITORING IN LINEAR PROJECTS

4.1 Importance of Continuous Monitoring

Having preliminary information or a baseline regarding environmental variables that could be affected during interventions in an area through linear infrastructure projects, such as road tunnels, slope interventions, or hydrocarbon duct construction, is crucial.

This becomes significant in contexts of social, environmental, and technical sensitivity to assess potential consequences in those areas, providing objective evidence for due diligence against potential claims and demands.

4.2 Monitoring of Surface Waters for Road Tunnel Construction

Based on the hydrogeological conditions of study areas, initial conditions related to water levels (stream water depth) can be defined. During the construction phase of underground works, these levels may vary due to different rainfall regimes.

After completion of the works, water levels are expected to return to values like the baseline. Therefore, continuous monitoring of flow rates helps manage deviations during construction and optimize decision-making to implement timely improvements.

4.3 Water Stream Measurement Technology – Route 40 Case

Given the complexity of monitoring watercourses in remote areas with difficult access, it is crucial to implement automated systems that require minimal human intervention.

In this regard, one of the commonly used technologies involves sensors with acoustic measurement technology, that record variations in water levels in rivers and/or streams. Flow rates can be determined based on channel geometry and water depth calculations.

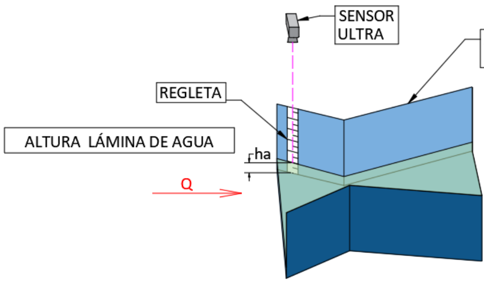

FIGURE 14: GENERAL DIAGRAM OF WATER LEVEL VARIATION MEASUREMENT SYSTEM USING ACOUSTIC MEASUREMENT TECHNOLOGY WITH PARSHALL FLUME

Then, this information is transmitted through a GPRS-4G signal gateway to cloud servers, to be analyzed and visualized using data analytics systems, and correlated with precipitation records in the area, or with interventions in the area during the construction and/or operation phase of the project.

For the road project connecting Bogotá with Girardot (Vía 40 Express / Route 40), monitoring of two streams at different points was required to demonstrate changes in the hydrogeological regime during construction.

Installation of monitoring points was carried out using sonic limnimeters that recorded the water level as it passed through previously calibrated Parshall-type flumes installed at strategic points, see FIGURE 15.

FIGURE 15: AUTOMATED MONITORING SYSTEM OF SURFACE WATER SOURCES THROUGH PARSHALL-TYPE FLUME

Through this automated instrumentation system, records of water level variation were obtained, allowing estimation of the associated flow rates. This provided preliminary information at the beginning of the construction phase of the underground project and subsequently during construction, see FIGURE 16.

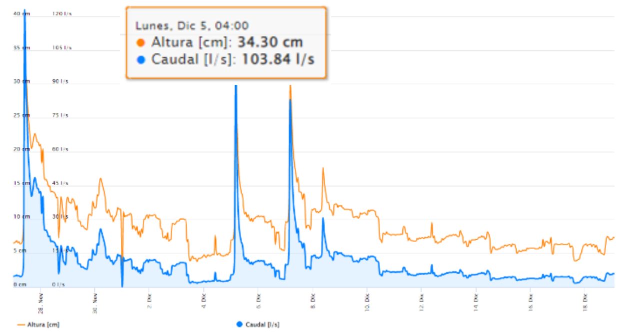

FIGURE 16: VARIATION OF WATER LEVELS AND FLOW RATES THROUGH AUTOMATED LIMNIMETERS

4.4 Groundwater Level Monitoring

Similarly, in most cases, groundwater level monitoring zones are difficult to access or far from urban areas. Therefore, the implementation of vibrating wire piezometers with automated data recording and transmission to the cloud can be a viable solution for projects.

This allows recording variations in groundwater reserves and their potential impact from anthropogenic activities or environmental phenomena, while determining the hydrogeological regime in the study area.

4.5 Description of Groundwater Measurement Technology – Route 40 Case

For the Route 40 project, groundwater monitoring points were defined using vibrating wire piezometric sensors that sent records to a data logger with electrical autonomy based on batteries.

These batteries had the capacity to provide information for over 6 months without requiring maintenance, reducing costs associated with excessive maintenance.

These data loggers then sent the obtained information via GPRS-4G to online servers that allowed real-time monitoring of the hydrogeological conditions of the monitored area.

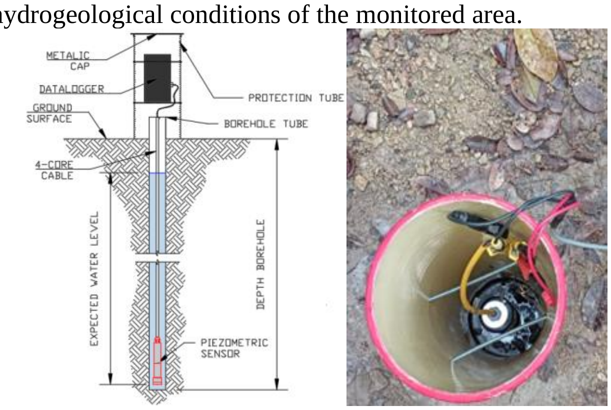

FIGURE 17: AUTOMATED HYDROGEOLOGICAL MONITORING SYSTEM

Through the installation of these piezometric sensors in Casagrande-type instruments and with the aim of obtaining information to feed the hydrogeological model of the area, slug-type permeability tests were carried out at some of these monitoring points, resulting in infiltration curves in these zones, as shown in FIGURE 18.

Subsequently, continuous monitoring of the piezometers was carried out to record variations in piezometric levels before, during, and after the execution of the road tunnel works.

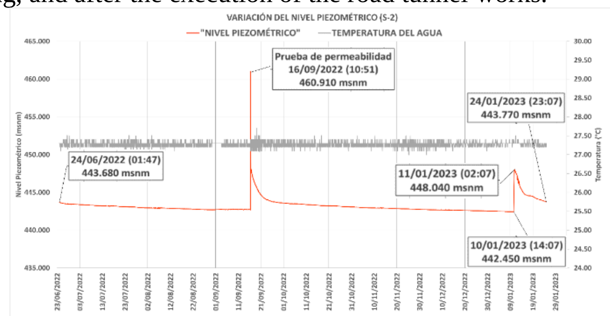

FIGURE 18: VARIATION OF GROUNDWATER LEVELS THROUGH AUTOMATED VIBRATING WIRE PIEZOMETERS

4.6 Benefits and Limitations of Implemented Technology

Through limnometric and piezometric technology, the project achieved:

- Continuous monitoring of water levels and flow rates at points of interest for streams, allowing for trend analysis of their behavior during dry seasons or heavy precipitation.
- Continuous monitoring of groundwater levels and their potential impact from the crossing of road tunnels in the area of influence.
- Collecting reference information to feed the hydrogeological models for the design and construction phase of the road tunnel project.

However, the technology has the following limitations:

- The automated transmission of collected information by the system to online servers will be limited by GPRS-4G signal coverage in the area. It is possible to implement a satellite signal with a small antenna, which can be placed inside the same station.
- Due to irregularities in the geometry of most watercourses, a system must be configured that allows sensor installation without risk of damage due to changes in the section during floods.
- In watercourses at risk of avalanches or large rock movements during floods, a system must be designed to allow optimal operation without being affected by these extraordinary conditions.
- Automated piezometers require prior drilling and well sealing activities, which, depending on the accessibility of drilling and equipment, increases installation costs.

5. STRUCTURAL PARAMETERS MONITORING IN BRIDGES

One of the most practical ways to verify the hypotheses adopted in the design phase of structures, such as bridges or viaducts, and control the construction process is by implementing monitoring systems with sensors for critical variables.

Through such systems, continuous monitoring of thermal gradients, deformations, stresses, rotations, and displacements is possible. The complexity or extent of the instrumentation network will depend on the size of the structure, access points, as well as its importance and the costs associated with installation.

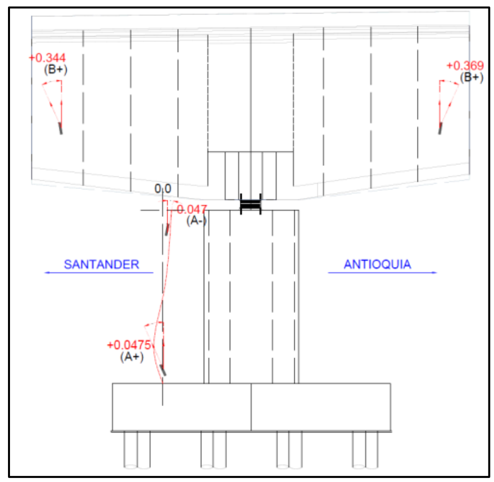

FIGURE 19: RECORDING OF ROTATIONS IN THE MONITORED STRUCTURE - RÍO MAGDALENA BRIDGE

One successful case of this technology is the Río Magdalena Bridge, for which a static instrumentation system was implemented to monitor the structure's behavior during its construction and primarily to control displacements during the lifting maneuver of the superstructure for the installation of seismic isolators on the main piers, see FIGURE 20.

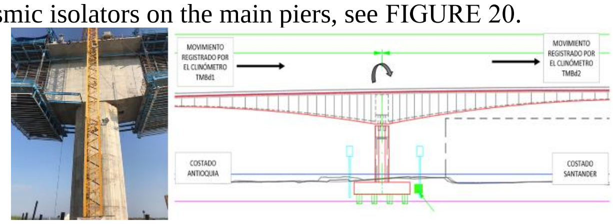

FIGURE 20: INCLINATION MONITORING DURING CONSTRUCTION PHASE OF RÍO MAGDALENA BRIDGE

Under optimal conditions, these monitoring systems can provide information both during the construction phase and the operational phase. In the latter case, they allow verification of the behavior or structural health of bridges, enabling much more effective maintenance and optimizing the time allocated to these tasks. This focus can be on critical areas identified through the implemented instrumentation.

A special case of structural instrumentation was implemented for the Yarumo Blanco Bridge, also known as La Herradura, due to its geometry. For this project, it was necessary to control the displacements and rotations of the pillars during a critical maneuver involving cutting the structural element at the base to isolate the bridge structure and install seismic isolators capable of withstanding the significant forces that were anticipated during seismic events.

To monitor the structure's behavior, wireless laser distance meters were installed to record the horizontal displacement of the structure on all four sides of the base of the piers. Additionally, clinometers were installed at different points on the structure to verify, in two directions, the relative rotation angles caused by the cutting maneuver.

These instruments recorded the variables and transmitted the information via radio frequency to two dataloggers installed on the bridge deck. These dataloggers then transmitted the information via GPRS-4G signal to an online server for real-time monitoring at a frequency of up to 5 minutes. This allowed for early alerts and timely decision-making, minimizing the risk of the maneuver, see FIGURE 21.

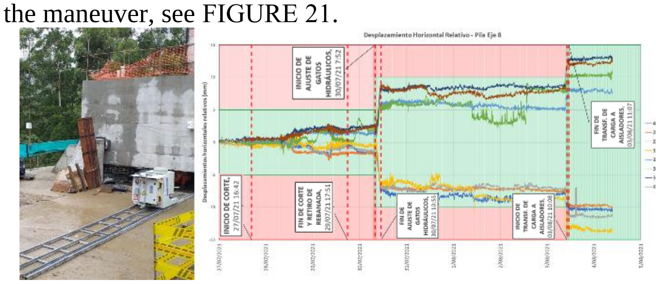

FIGURE 21: DISPLACEMENT MONITORING IN PIER DURING CUTTING MANEUVER FOR ISOLATION OF LA HERRADURA BRIDGE (YARUMO BLANCO)

6. RESULTS AND DISCUSSION

For monitoring slopes and embankments in linear projects, the most important geotechnical variables to track are ground displacements. These can be monitored remotely using technologies such as terrestrial or satellite radar, or by installing sensors such as inclinometers, extensometers, among others, directly in the field. These approaches allow for automated and remote recording of temporal variations. SAR radars provide a large amount of information for segmentation and, when combined with analytic techniques, can track trends and, in many cases, predict material collapse, as seen in the case of the K58 Mesa Grande slope monitoring.

Regarding the monitoring of linear infrastructure such as tunnels, bridges, or viaducts, the implementation of automated instrumentation systems has gained significant traction in recent years. This is driven by a greater interest in implementing good asset management practices and the aging of infrastructure.

With increased usage and external demands on structures, including geotechnical and hydrogeological forces, coupled with the progressive deterioration of structures or the action of high-intensity seismic events, having timely information allows for risk mitigation measures and the implementation of rehabilitation programs to extend the operational life of assets.

7. CONCLUSION

Linear infrastructure projects, due to their traversing of a wide variety of geological formations with heterogeneous materials (from soils to rocks) in varying states of rigidity and stability (static and dynamic), undoubtedly face a higher risk of encountering unforeseen temporal changes during construction and operation phases.

Given the rapid technological advancements and considering that the construction and infrastructure industry has been slower to adopt digital processes, there are opportunities to implement equipment and sensors that are currently available in the context of Industry 4.0. The automation of monitoring instruments allows for versatile evaluation of any asset in a linear project, ensuring real-time information that can be accessed from any device with internet access. This enables decision-makers to be notified and make informed decisions based on timely and quality information.

ACKNOWLEDGMENTS

We express our gratitude to our clients for their trust in the work carried out to implement highly precise monitoring systems in important and complex national infrastructure projects.

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