DOI: 10.3217/978-3-99161-057-1-153

Redundant Monitoring Strategies for Structural and Geohazard Assessment Using Wireless Tiltmeters and LiDAR on Linked Highway Bridges in Colombia

Víctor Restrepo[1], Héctor Salazar[2], Jean Piedrahita[3]
[1]Geoandina i SAS, Bogotá D.C., Colombia
[2]Geoandina i SAS, Bogotá D.C., Colombia
[3]Geoandina i SAS, Bogotá D.C., Colombia
email: vrestrepo@geoandina.net, hsalazar@geoandina.net, jpiedrahita@geoandina.net

ABSTRACT: The bridge system composed of Los Grillos, Puente Nuevo, and Chorro Blanco, located along the roadway connecting Sogamoso and Aguazul, near the municipality of Pajarito (Colombia), is founded on an active large-scale landslide in shale bedrock. This mass movement exhibits variable displacement rates depending on rainfall frequency over time. On August 20, 2023, the Los Grillos Bridge collapsed as a result of cumulative ground displacements that compromised its foundations and piers. Between July and December 2024, an integrated monitoring system was implemented, combining observations from an Automated Total Station (ATS), distance measurements using LiDAR, and tilt data obtained from inclinometers. The primary objective of this system is to establish correlations and track both ground and structural displacements, thereby supporting local stakeholders and decision-makers in the operational management of the remaining bridges still in service for civilian traffic. This paper presents the principal findings and illustrates how the integration of data from multiple sensor technologies enhanced the understanding of differential behavior between the ground and the structures. The analysis includes the collapsed bridge as well as the two remaining bridges in the affected area, providing timely and valuable information to support safe roadway operations.

KEY WORDS: Structural monitoring, Los Grillos Bridge, wireless sensors, landslide monitoring, Lidar ATS infrastructure monitoring, risk management.

1 INTRODUCTION AND GENERAL OVERVIEW

In Colombia, geological conditions present a wide range of engineering challenges, primarily due to the geodynamic behavior of the territory, which is heavily influenced by the presence of the Andes Mountain range across much of the country. These complex environments increase the risks that directly or indirectly affect social activities in these regions. Such risks may stem from seismic hazards, mass movements, among other factors, and have a direct impact on the design and construction of resilient and sustainable infrastructure.

In general terms and considering the current state of development in the country, one of the economic sectors most affected by geological conditions is freight transportation. Road corridors such as the one stretching from Sogamoso, Boyacá to Aguazul, Casanare—the focus of this study—are characterized by steep topography and high-mountain road networks, facing ongoing challenges in terms of mobility and connectivity.

Roadways with steep slopes, sharp curves, and unstable soils increase vulnerability to landslides, subsidence, and other impacts triggered by climatic phenomena such as heavy rainfall and thermal variability, including segments that traverse páramo ecosystems. These environmental factors significantly affect road safety, increase logistical costs, and prolong the time required for the transport of goods and personnel.

In the area located at station PR81 of the Sogamoso–Aguazul corridor, also known as the Cusiana Transversal, mass movement processes and geomorphological activity have been observed for more than two years and continue to occur to this day. These processes affect both the upper and lower zones of the surrounding slopes.

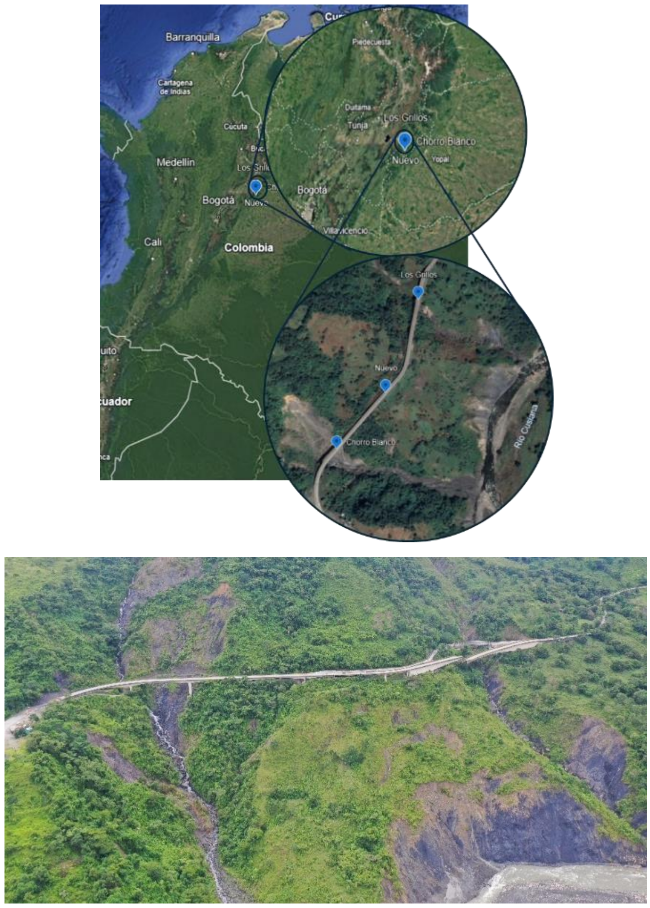

Figure 1. General location and panoramic view of the study area.

DOI: 10.3217/978-3-99161-057-1-153

Given these geological conditions, a 666-meter-long viaduct was constructed, consisting of three consecutive bridges named Los Grillos (with a span of 261 meters), Nuevo (105 meters), and Chorro Blanco (300 meters from abutment to abutment).

Due to persistent landslides in the area, these structures are currently partially or completely out of service because of multiple evident structural pathologies. In the case of the Nuevo and Chorro Blanco bridges, significant deterioration has been observed, while the Los Grillos Bridge experienced a collapse of the structure.

Based on these geotechnical and structural conditions, and with the primary goal of providing continuous monitoring through an early warning system, two complementary monitoring systems were implemented.

The first system involved tracking three-dimensional displacements using automated readings of topographic prisms and virtual points with a GMS robotic LiDAR station (Geotech Monitoring Station).

The second system focused on structural monitoring of relative displacements and rotations through the use of triaxial inclinometers and wireless laser distance meters.

Figure 2. General overview of monitoring systems in sector PR81

In the face of these challenges, engineering plays a critical role in mitigating risks associated with road infrastructure and enhancing regional connectivity.

The application of advanced techniques for slope stabilization, pavement reinforcement, and geotechnical monitoring through automated methods contributes significantly to improving the safety and operational reliability of road corridors.

2 GEOLOGY AND GEOTECHNICAL INSTABILITY OF THE AREA

The study area is located between the municipalities of Sogamoso and Pajarito, in the department of Boyacá, Colombia. Hydrologically, the region where the monitoring points are situated is primarily influenced by the Cusiana River and the Chorro Blanco stream.

According to Sheet No. 192 of the regional geological map corresponding to the surroundings of Lake Tota, Department of Boyacá, Colombia, at a 1:100.000 scale [1], the sector known as PR81 lies within a geological unit referred to as the Macanal Shale Formation (Kilm), as shown in Figure 3.

This unit is predominantly composed of black shales interbedded with thin sandstone layers, which is indicative of a deep marine sedimentary environment typical of the Lower Cretaceous.

This paleoenvironmental interpretation is supported by field evidence, particularly the abundant presence of ammonite fossils, which serve as index fossils for this geological era.

The shales of this formation are fine-grained, rich in organic matter, and exhibit well-developed foliation, making them particularly susceptible to weathering processes and deformation under load or saturation conditions. These geomechanical characteristics significantly affect slope stability, subsoil behavior beneath structures, and the design of foundations or roadways that traverse such materials—factors that may account for the various active geotechnical processes currently observed in the area.

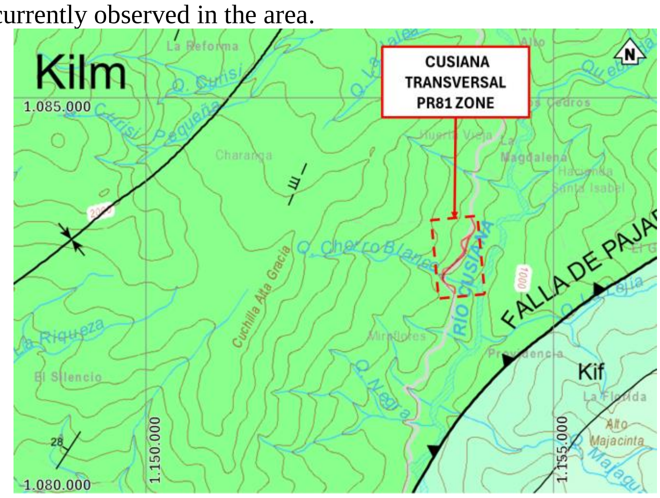

Figure 3. Regional geological map of the study area PR81 [1]

For years, the area has exhibited significant and progressive mass movement processes, particularly near the Chorro Blanco stream and along the slopes leading to the Cusiana River channel. This suggests that torrential flows from these tributaries may act as a triggering factor for the landslides and fissures observed on the slopes.

Figure 4. Evidence of geomorphological processes in sector PR81

 DOI: 10.3217/978-3-99161-057-1-153

3 STRUCTURAL COLLAPSE EVENT OF 2023 AT LOS GRILLOS BRIDGE

Due to the previously mentioned geodynamic conditions, among the three structures that comprise the viaduct, the Los Grillos Bridge exhibited the most significant deterioration. This was primarily attributed to its structural typology in conjunction with the landslides occurring in the area.

Since late 2022, multiple structural pathologies had been identified, raising concerns about the bridge's stability [2], with clear evidence of progressive structural degradation.

In 2023, following a series of seismic events with magnitudes ranging from 0.70 to 6.10, a collapse occurred on August 20 in a central section of the Los Grillos Bridge deck, located at the midpoint of the main span. This failure may have been influenced by a combination of factors, including material fatigue and cumulative effects of regional seismic activity.

The occurrence of these events underscores the critical importance of implementing continuous monitoring systems at the earliest signs of deterioration, integrating both geotechnical and structural data to enable comprehensive assessments and timely interventions.

Figure 5. Evidence of mass wasting processes near the foundations of the PR81 corridor bridges

Figure 6. Los Grillos bridge structural collapse.

4 IMPLEMENTED MONITORING SOLUTIONS

Considering the geotechnical challenges of the area, specific contingency measures were established to mitigate the risks faced by both the local population and construction personnel. Among these measures, a dual early warning system was implemented to monitor the displacement behavior of both the bridge superstructures and the surrounding slopes.

This dual system consisted of an automated total station based on LiDAR GMS technology, which conducted three-dimensional tracking of thirty (30) topographic prisms strategically installed in various sectors within the area of analysis.

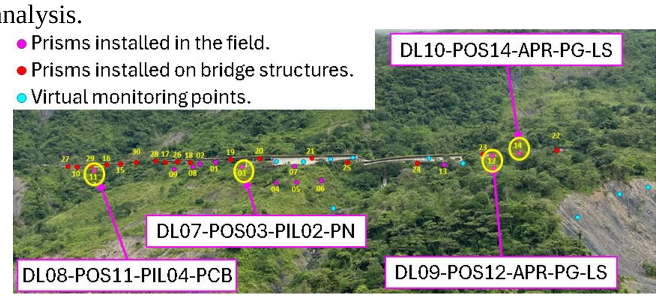

Figure 7. General location of measurement targets with GMS

Additionally, thirty-six (36) wireless sensors were installed. Of these, twenty-four (24) are triaxial clinometers used to monitor tilting at strategic locations on the viaduct bridges. The remaining twelve (12) sensors are laser distance meters equipped with triaxial clinometric sensors, designed to monitor relative displacements and inclinations.

These devices were mounted on poles located near exposed surfaces of the bridges, where topographic prisms were also installed to provide redundant data, monitored by the robotic GMS station.

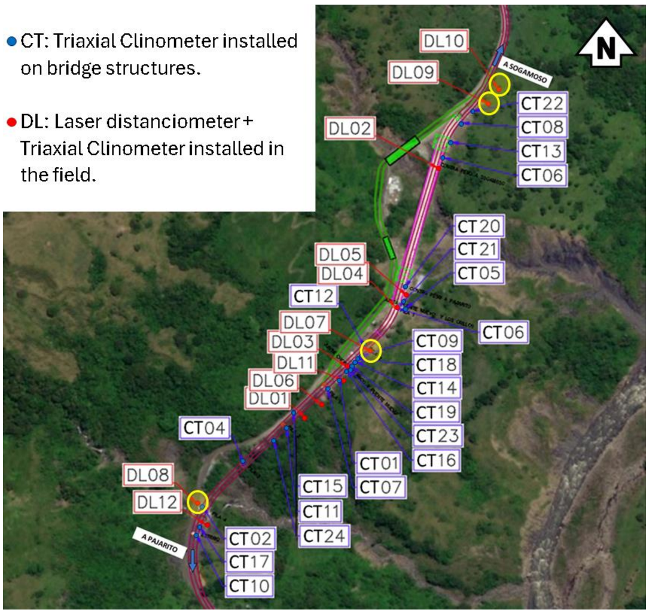

Figure 8. General location of wireless sensors

DOI: 10.3217/978-3-99161-057-1-153

4.1 *Description of robotic lidar gms technology*

This type of system consists of a state-of-the-art robotic total station capable of performing high-precision measurements of three-dimensional displacements on selected targets.

These targets may include both physical reference points, such as topographic prisms installed throughout the monitored area, and virtual points defined by pixel positions on images of exposed slopes or structural surfaces, using advanced image processing techniques.

This methodology enables continuous acquisition, processing, and analysis of displacement data within the area of interest. The resulting information facilitates the identification of incipient or progressive movements, as well as the establishment of behavioral trends in the short, medium, and long term.

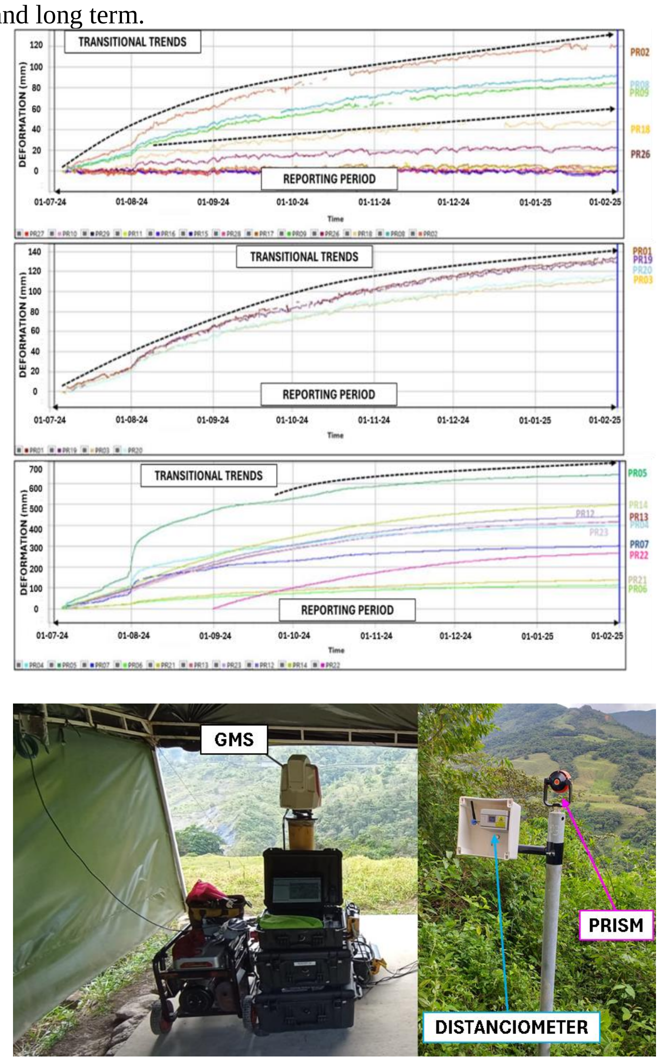

Figure 9. GMS Technology Implemented in Sector PR81

4.2 *Description of clinometric sensors and laser distance meters*

This type of system enables the monitoring of displacements (via laser distance meters) and inclinations (via clinometers) at specific points on the structures.

Regarding the measurement of relative displacements, the laser distance meters project a light beam that allows for the measurement of the distance between the sensor location and a target surface, with high precision and under adverse environmental conditions.

On the other hand, the triaxial clinometers allow for the tracking of inclination angles, primarily along the two orthogonal axes, X and Y.

From this clinometric data, the displacement associated with the observed inclination can be calculated using trigonometric relationships.

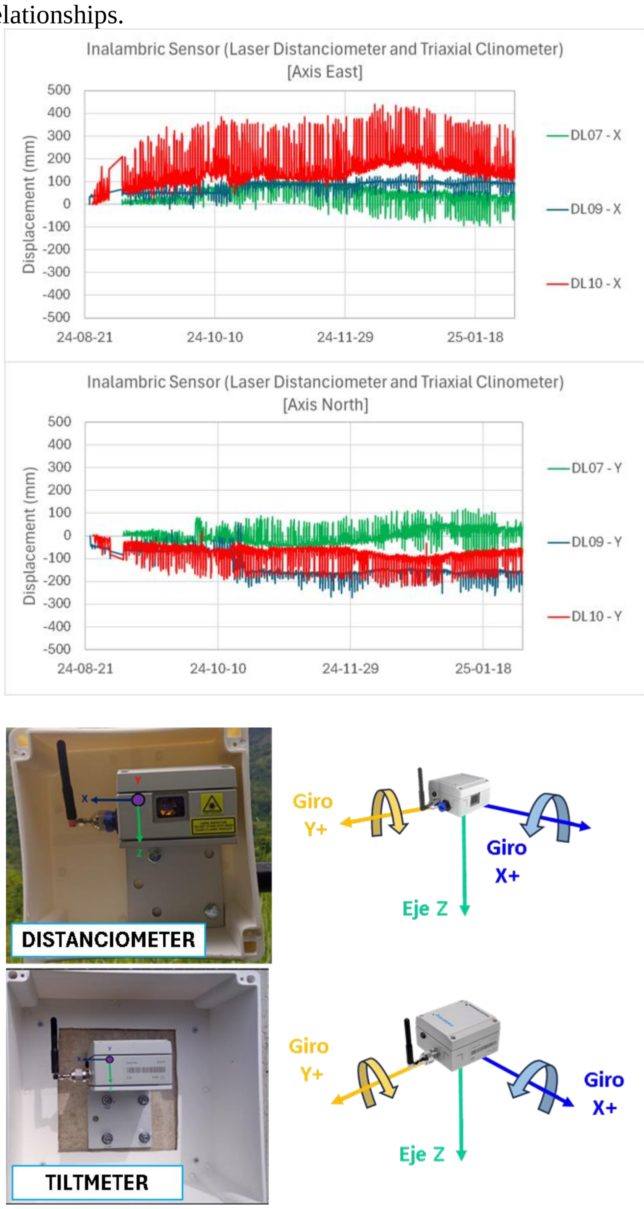

Figure 10. Sensor Technology Implemented in Sector PR81

5 RESULTS OBTAINED DURING THE GMS AND CLINOMETER MONITORING PERIOD

After nearly seven months of monitoring, primarily transient trends were observed in the study area PR81, both in the displacements recorded by the GMS equipment and in the inclinations measured by the triaxial clinometers.

DOI: 10.3217/978-3-99161-057-1-153

It is important to note that, since the monitoring points reported movement data in their local axes (X'–Y'), the recorded values were transformed into local North–East coordinates. This transformation was performed through an orthogonal axis rotation (see Figure 11), as expressed in Equation 1.

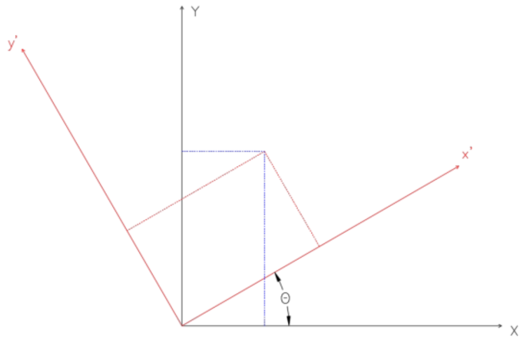

Figure 11. Diagram of orthogonal axis rotation

$$\begin{bmatrix} X\ (ESTE) \\ Y\ (NORTE) \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} x' \\ y' \end{bmatrix} \quad (1)$$

For each clinometer and laser distance meter, it was necessary to establish reference lines parallel to the bridge structures, as the instruments were installed following this alignment. Once these lines were defined, the angle between the local measurement axes and the global reference axes (X–Y), aligned with true north, was determined (Figure 12). By applying Equation 1, it was possible to transform the displacements recorded in local coordinates into the global coordinate system.

It is noted that, in the case of data obtained from the GMS (Geodetic Monitoring System), this transformation is performed automatically by the equipment, based on the predefined global axes and the relative orientation of each prism with respect to the measuring station, as determined by the laser projection

Figure 12. Axis diagram for the sensor DL02

Once the measurement results were transformed into global axes, it was possible to perform a comparative evaluation of the trends identified through both monitoring approaches (sensors and GMS).

As a summary, the data obtained for the following monitoring points are presented:

- Zone 1: Pile of Chorro Blanco Bridge (Prism PR11 – Sensor DL08).
- Zone 2: Pile of Nuevo Bridge (Prism PR03 – Sensor DL07).
- Zone 3: Sogamoso Abutment of Los Grillos Bridge (Prism PR12 – Sensor DL09).
- Zone 4: Sogamoso Abutment of Los Grillos Bridge (Prism PR14 – Sensor DL10).

For Zones 1 and 2, based on the data obtained from the dual monitoring system (GMS and sensor network), an initially positive incremental trend is observed along the X-axis (East), which subsequently tends to stabilize.

Similarly, although with an opposite pattern, the Y-axis (North) shows an initially negative incremental trend, also followed by a stabilization phase.

The global displacements recorded along both axes remain below 20 cm in magnitude, which aligns with field observations and with the presence of geomorphological indicators of slow-moving processes.

These behavioral patterns suggest a process of progressive deformation, followed by a decrease in displacement rates (as evidenced toward the end of the monitoring period), possibly associated with the seasonal transition from wet (winter) to dry (summer) periods.

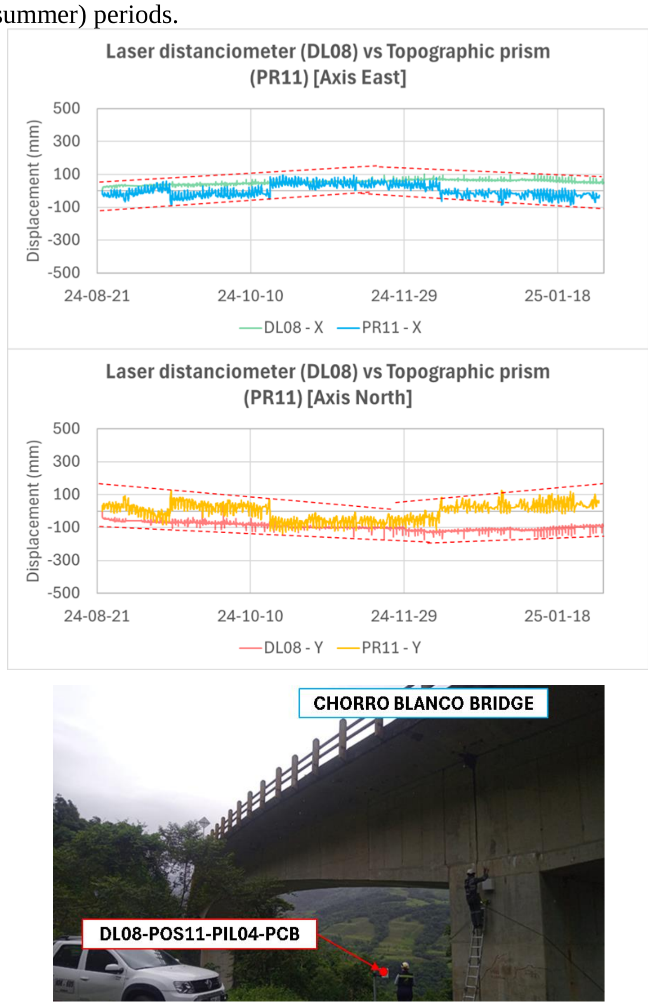

Figure 13. Location and historical record of horizontal displacements for Sector 1

DOI: 10.3217/978-3-99161-057-1-153

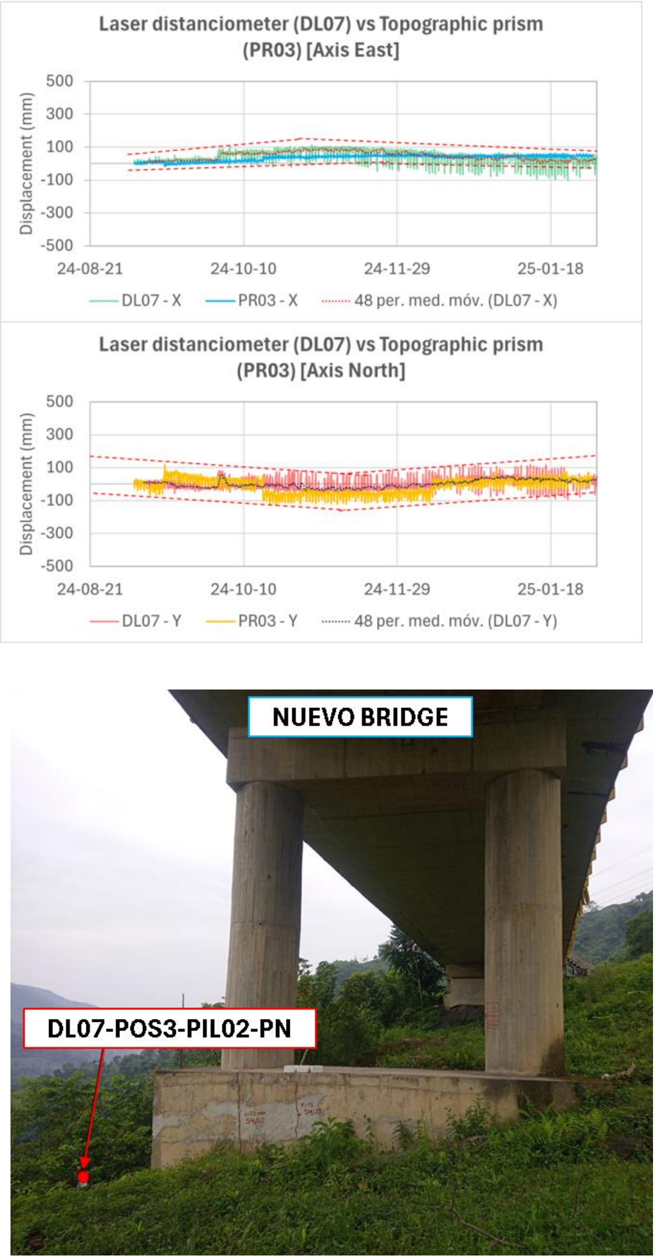

Figure 14. Location and historical record of horizontal displacements for Sector 2

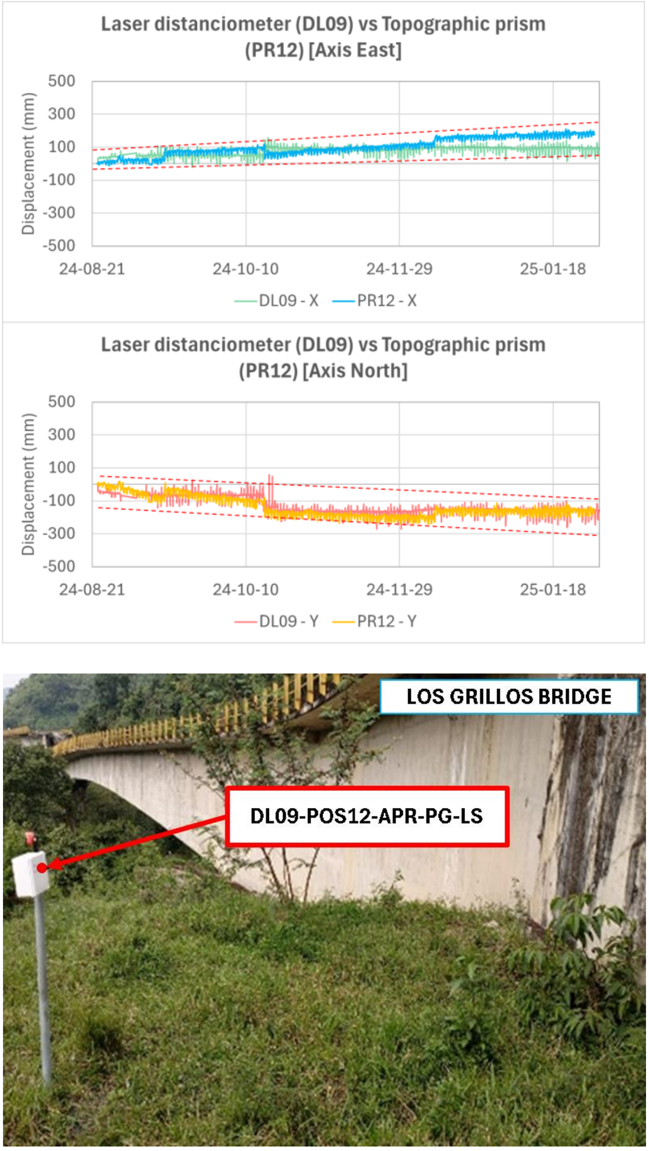

Figure 15. Location and historical record of horizontal displacements for Sector 3

On the other hand, for Zones 3 and 4, based on the information obtained during the monitoring period, mainly incremental displacement trends were identified, with more pronounced movement along the X-axis (East).

In contrast, the behavior along the Y-axis (North) tends to be more stable, exhibiting only minor variations.

The recorded displacements remained below 20 cm along the X-axis and below 25 cm along the Y-axis, values that are consistent with field observations and the documented surface morphological evolution in the area.

This behavior suggests a more active movement dynamic in the X-direction (East), possibly associated with the slope geometry, the orientation of the fracturing system, or the direction of the principal stress in the ground.

DOI: 10.3217/978-3-99161-057-1-153

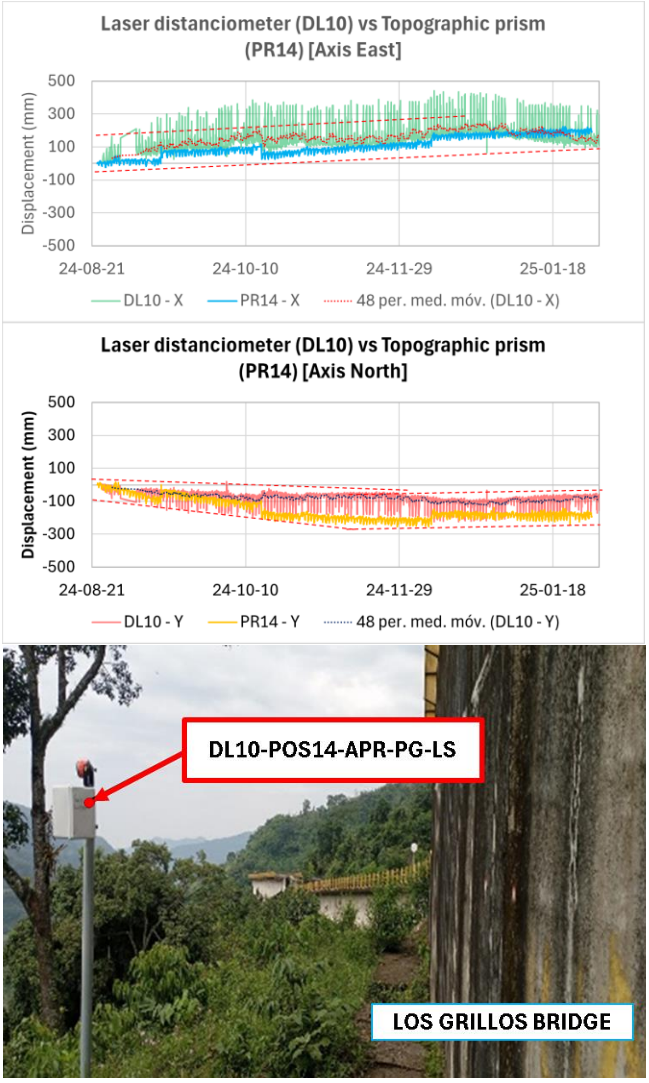

Figure 16. Location and historical record of horizontal displacements for Sector 4

5.1 *Principal displacement directions identified*

Regarding the displacement directions derived from the wireless sensors, it was observed that, as expected, movements recorded by devices installed directly on the ground exhibit greater magnitudes compared to those mounted on concrete structures.

This difference is primarily attributed to the foundation conditions of the structures, which tend to dissipate part of the deformation, as well as to the geological characteristics of the adjacent slopes, which favor greater displacement in the superficial soil layers.

Similarly, displacement behavior is also evident in the topographic prisms installed both on structural elements and on natural slopes. It is worth noting that, due to the specific conditions of the project, a higher density of prisms was installed in comparison to the wireless sensors deployed on the slopes.

This wider spatial distribution of topographic targets provides broader coverage of the monitored area, enabling a more detailed characterization of displacement patterns, particularly in critical zones of the terrain.

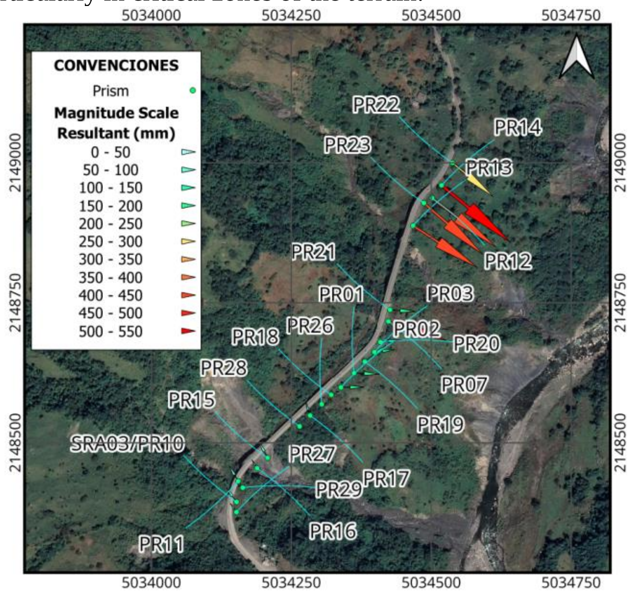

Figure 17. Principal Displacement Directions Identified Based on Measurements from Wireless Sensors

When comparing the results obtained from both monitoring systems, notable similarities are observed in the behavior of the monitored elements previously presented in this document.

These similarities suggest a degree of informational redundancy between the two systems.

The predominant displacement trends appear to be strongly influenced by the geomorphological characteristics of the area, which are generally aligned with the direction of the ongoing mass movement process occurring near the bridge foundation structures.

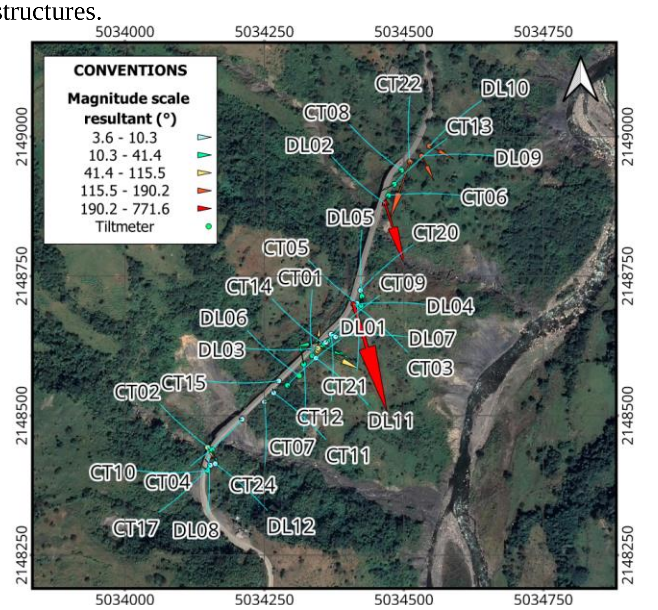

Figure 18. Principal Displacement Directions Identified Based on Measurements from topographic prism

DOI: 10.3217/978-3-99161-057-1-153

The largest displacement magnitudes are concentrated around the abutment areas of the Los Grillos Bridge. It is important to highlight that, despite these observed similarities, the two monitoring systems are based on fundamentally different methodologies, each with its own limitations and advantages.

The convergence of results enhances the reliability of the data and supports the use of a hybrid monitoring strategy to improve interpretation, redundancy, and validation of both structural and geotechnical behavior over time.

6 DISCUSSION OF MAIN RESULTS

Based on the results obtained, an approximate correspondence can be identified between the displacement trends recorded by the wireless sensors (inclinometers) and those measured by the topographic prisms.

Likewise, a satisfactory agreement is observed in terms of the displacement magnitudes captured by both technologies.

It is important to highlight that the differences in magnitude can be attributed to the specific accuracy characteristics of each system. In this regard, the inclinometer-based methodology, being directly installed on the ground or the structural body, offers greater sensitivity and precision for detecting angular variations and relative displacements. It has been shown that, based on properly supervised studies conducted on buildings over 50 meters high, high-precision inclinometers provide optimal performance in the continuous monitoring of sub-millimetric displacements [3].

In contrast, monitoring through topographic prisms is subject to factors such as the distance between the GMS station and the target prisms, as well as atmospheric and visibility conditions, which may reduce its accuracy in detecting small-magnitude displacements. The precision of data obtained through geodetic equipment is mainly influenced by the atmospheric conditions along the measurement path. For example, in the case of a slope monitored in Austria, a variation of 1°C or 3.6 mbar resulted in measurement deviations of up to 10 mm over a 1 km measurement range [4]. Therefore, it becomes essential that the data acquisition system incorporates algorithms capable of applying atmospheric corrections in its operation, as is the case with the equipment used for monitoring sector PR81.

7 CONCLUSIONS

The results obtained through the implementation of a dual monitoring system—comprising wireless sensors (triaxial inclinometers and laser distance meters) and topographic prisms connected to the GMS (Geodetic Monitoring System)—provide a reliable and complementary framework for evaluating structural and geotechnical behavior in critical sections of the road corridor.

The identified displacement directions and magnitudes show an acceptable level of agreement between both monitoring methodologies, particularly in the analyzed sectors, which highlight the robustness and validity of the combined approach.

It was observed that the sensors installed directly on the ground recorded greater displacement magnitudes, which are consistent with local geotechnical conditions, slope geomorphology, and the foundation characteristics of the structures.

Additionally, although topographic prisms are more susceptible to external factors such as visibility and atmospheric conditions, they offer broader spatial coverage due to their higher installation density.

The convergence in displacement trends detected by both systems reinforces the reliability of monitoring data and enables a more comprehensive interpretation of the structural behavior in response to ongoing mass movement processes, especially in the vicinity of the Los Grillos Bridge.

This confirms the importance of integrating advanced sensor technologies with traditional geodetic monitoring methods to strengthen decision-making processes related to the design, maintenance, and risk management of critical infrastructure.

ACKNOWLEDGMENTS

The authors express their sincere gratitude to all professionals, technicians, and the entire team who carried out the installation using high-access equipment in a complex geological setting. Special recognition is given to Alejandro Navarro and Cristhian Melo, whose work stood out for its passion and outstanding quality.

REFERENCES

[1] INGEOMINAS, Mapa de susceptibilidad a movimientos en masa: Plancha 192 Laguna de Tota 1:100.000, Instituto Colombiano de Geología y Minería (INGEOMINAS), Bogotá, Colombia, 2014. [Online]. Available: https://recordcenter.sgc.gov.co/B4/13010010002291/mapa/pdf/0101022911300002.pdf

[2] Infobae, "Así quedó el puente Los Grillos tras el colapso: imágenes y videos muestran el estado de la estructura," Infobae, Bogotá, Colombia, agosto 21, 2023. [Online]. Available: https://www.infobae.com/colombia/2023/08/21/asi-quedo-el-puente-los-grillos-tras-el-colapso-imagenes-y-videos-muestran-el-estado-de-la-estructura/

[3] G. De Roeck, S. Vanlanduit, M. Reynders, y B. Peeters, “Evaluation of high-precision sensors in structural monitoring,” Sensors, vol. 10, no. 12, pp. 10870–10893, MDPI, 2010. [Online]. Available: https://www.mdpi.com/1424-8220/10/12/10870

[4] P. Casagli, D. Tofani, F. Raspini, et al., “Geotechnical monitoring using total stations and laser scanners: critical aspects and solutions,” Journal of Civil Structural Health Monitoring, vol. 7, pp. 415–428, Springer, 2017. [Online]. Available: https://link.springer.com/article/10.1007/s13349-017-0250-4