INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

The paper was published in the proceedings of the 13th International Symposium on Landslides and was edited by Miguel Angel Cabrera, Luis Felipe Prada-Sarmiento and Juan Montero. The conference was originally scheduled to be held in Cartagena, Colombia in June 2020, but due to the SARS-CoV-2 pandemic, it was held online from February 22nd to February 26th 2021.

Remote sensing monitoring applications for landslides in infrastructure projects in Colombia.

Hector A. Salazar and Víctor H. Restrepo

Grupo Geoandina CEO & Geoandina i SAS Technical manager

hsalazar@geoandina.net, vrestrepo@geoandina.net

Abstract

Landslide monitoring using remote sensors has been applied to evaluate the behavior of slopes in critical areas where the evidence of displacements can trigger further consequences specially to human lives and infrastructure maintenance and operation. The different scope of different technological applications can give appropriate insight to consider on the behavoiur of the phenomena studied and to take action when necessary if data shows high risk of collapse.

This article presents InSAR and TInSAR technologies applied into an active geological and geotechnical processes of the eastern zone of Colombia with power line infrastructure and on an active landslide to show its main features, technical data obtained, advantages and limitations to consider for infrastructure operation, maintenance and decision making regarding risk and asset management.

1 INTRODUCTION.

In the different stages of infrastructure projects, considering stability is a continuous duty to be able to guarantee the security and service level of assets designed to achieve their specific purpose. There are different engineering approaches to guarantee the stability of slopes, and one of greater relevance for rapid decision-making, is the monitoring of infrastructure behavior in relation to its geological and geotechnical context.

This approach has allowed technological developments for the measurement of parameters such as displacements, water pressures, precipitation, accelerations, among others, to be increasingly available and provide detailed information over time to check its behavior and trends that may manifest subsequent consequences if a collapse develops.

This article presents the remote sensing technology and the specific applications of satellite interferometry (InSAR) and terrestrial interferometry (GB-InSAR) with specific application in two infrastructure projects in Colombia.

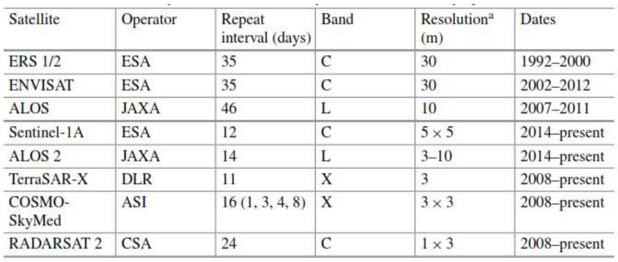
2 REMOTE SENSING.

In his article, Moore G (1979) presents a historical journey of this technology. Remote sensing since its creation mainly with the military technological advances of World War II and subsequently since 1960, have been designed to operate in almost the entire electromagnetic spectrum.

They basically consist of using the emission of electromagnetic waves and their reflection to measure physical properties of distant objects. The science of remote sensors requires obtaining absolute and relative measurements, processing information, interpretation and obtaining conclusions from the data taken. It is supported by other previous technologies such as photography, photogrammetry and airborne geophysics.

3 INSAR TECHNOLOGY.

Since 1980, the first satellite with the synthetic aperture radar (SAR) was put into orbit. Later, in the 1990s, most commercially available satellites were launched that keep orbiting today. The following table lists some satellites, their operator, orbit frequency, electromagnetic frequency band, resolution and measurement time window for reference.



Satellite	Operator	Repeat interval (days)	Band	Resolution^a (m)	Dates
ERS 1/2	ESA	35	C	30	1992–2000
ENVISAT	ESA	35	C	30	2002–2012
ALOS	JAXA	46	L	10	2007–2011
Sentinel-1A	ESA	12	C	5 × 5	2014–present
ALOS 2	JAXA	14	L	3–10	2014–present
TerraSAR-X	DLR	11	X	3	2008–present
COSMO-SkyMed	ASI	16 (1, 3, 4, 8)	X	3 × 3	2008–present
RADARSAT 2	CSA	24	C	1 × 3	2008–present

Table 1. Characteristics of some InSAR satellites in orbit.

Source: Parker A. (2017).

In the electromagnetic spectrum, satellites with InSAR radar sensors take information orthogonally oriented to the direction of the orbit. The angle of inclination of the antenna with respect to the nadir is called off-nadir angle that varies between 20 and 50 degrees. Due to the curvature of the earth's surface, the angle of incidence of the signal in a flat horizontal terrain is greater than the angle of off-nadir. Ferretti (2014).

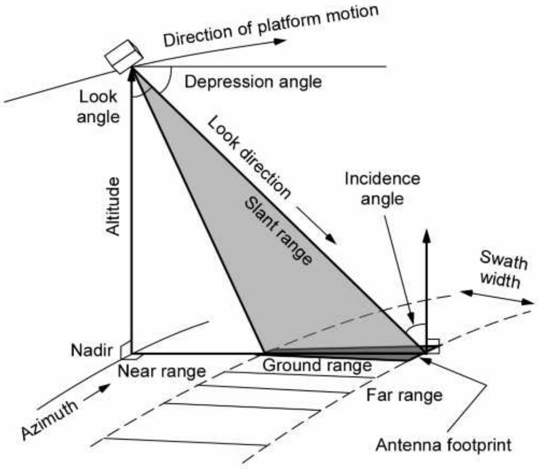


Figure 1. Radar image system geometry indicating azimuth, line of sight and footprint. (McHugh E et al 2006).

4 INSAR APPLICATION IN A POWER LINE.

For the evaluation and monitoring of the state of landslide processes and trends of accumulated displacements in the vicinity of an electric transmission line, Sentinel 1-A satellite images from the European Space Agency (ESA) were analyzed. Orbit frequency every 12 days and data analysis from October 2014 to December 2019 with a pixel resolution of approximately 13.4m x 4m was considered.

In the following images the time slot for the ascending and descending orbits in which it was possible to obtain images for analysis is presented.

Figure 2. Time baseline with image records for analysis by ascending and descending orbit, respectively.

The area of interest consisted of a strip of fifteen (15) energy towers in an area of high activity due to geological/geotechnical procesess that threaten the stability of some power transmission pylons.

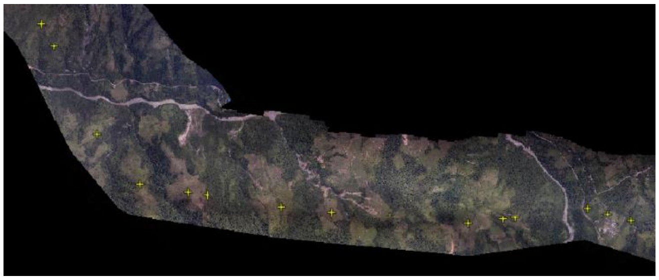


Figure 3. Power transmission corridor. Pylons studied.

The corridor runs through different geological units, among which are: terraces (Qt), sandstone formations (Pdg), shales (Pdp), phyllites and quartzites (PCAqgu). Likewise, it is in an environment of geological faults with regional influence.

For the power lines corridor analysis, accumulated displacement monitoring was done using phase change analysis of successive satellite images and analysis with amplitude changes due signal reflectance. It was possible to identify important temporarily erosion process changes, progressive landslides, deforestation and other event types for its changes evaluation over time.

As an example, in Figure 4, the image obtained for an area of interest is shown where the displacement deformation rate for the radar line of sight (LOS) is evidenced with a tendency to move away (orange to red tones) and with values of the order of 7 to 21mm/year in the analyzed time slot. The accuracy for this type of measurement is approximately ± 2mm / year.

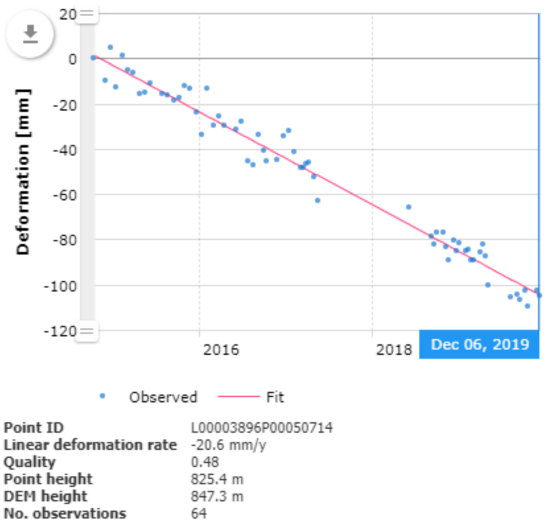
Figure 4. Deformation rates in the analysis area.

Figure 5. shows in detail the trend obtained for a point of red color. Note the dispersion in the data for which a trend could be clearly identified. The dispersion for high reflectivity applications such as in urban areas is smaller and therefore the quality parameter tends more to unity. The quality parameter measures how well the time series of the selected data point matches the computed linear deformation model (fit). The quality measurement ranges from 0 to 1, where 1 indicates a perfect match and 0 indicates no match. A lower quality value for the selected point indicates a higher amount of noise in the time series.

In rural areas, it is necessary to determine a quality criterion that allows identifying trends such as the one shown above. For the project, the quality value was greater than 0.43, which reduced the number of pixels or analysis points.

Finally, an example of application of the method of identification of reflectance changes (amplitude) of the satellite signal allows to reconstruct the evolution of landslide processes and their progressive evolution over time.

Under this methodology it was possible to map around the power pylons processes at different dates and their temporal evolution for decision making.



Point ID	L00003896P00050714
Linear deformation rate	-20.6 mm/y
Quality	0.48
Point height	825.4 m
DEM height	847.3 m
No. observations	64

Figure 5. Accumulated displacements of the area identified with subsidence.

In Figure 6., progressive landslide events were identified that have advanced to the top of the hillside, putting at risk the energy tower located near it.

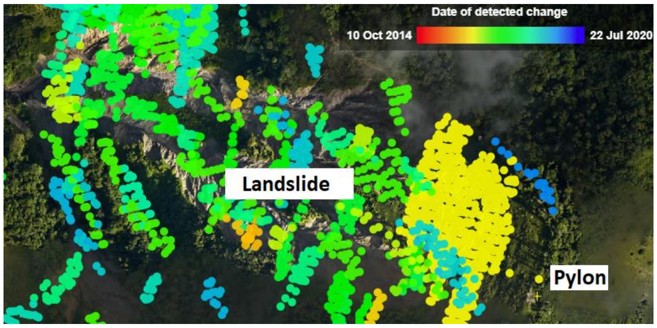


Figure 6. Event history due to changes in signal amplitude around an energy tower.

The events with blue tones are the most recent and those of yellow and orange tones are the oldest. One can observe the coincidence of the areas marked with the aerial image where active landslide processes are located close to the pylon analized.

Figure 7 shows the progress of the landslide and the location of the tower at the top of the slope.

Figure 7. Advancement of the slope degradation process near a power tower.

InSAR technology allowed for this project:

- Detailed monitoring of the history of accumulated displacements in the line of sight of the satellite for interpretation of land movements in historical critical sites and new areas not previously identified in the area.
- Identification of the history of events associated with geotechnical processes (erosion, subsidence, landslides) and the monitoring of their evolution over time for decision making.

On the other hand, technology has the following limitations:

- Periodic monitoring limited to the frequency of satellite passes through the area (12 days for the project).
- The quality criterion should be reduced due to the high presence of vegetation so that data contains trends defined for later analysis.
- Availability of satellite images (paid or free) according to trajectory and viewing angles with respect to the target area.

5 GROUND BASE INSAR (GB-INSAR)

InSAR ground radar technology or ground base GB-InSAR allows measurements to be done under the same principles applied from a satellite, but with a greater degree of accuracy in a much more limited range due to the proximity to the objective of analysis from any point in the ground.

The system to be detailed below is commonly known as LISA, which is basically a linear SAR system specially designed for use on land (Antonello G. et al. 2004). It consists of two antennas mounted on a linear rail that slides horizontally to generate the required synthetic aperture as shown in Figure 8.

Figure 8. LISA type radar installed for 24/7 slope monitoring.

An antenna generates a transmitted wavefront (TX) and another antenna has the receiver of it (RX). Figure 9.

Figure 9. Detail of antennas. Tx left and Rx right.

For the monitoring of a wall, the radar performs a sequential scan of it from left to right and from top to bottom. Figure 10.

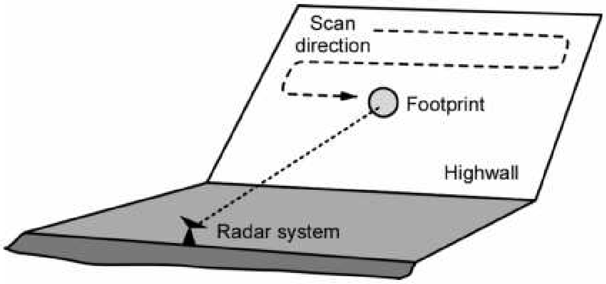


Figure 10. Sequence of scanning a wall using terrestrial radar. (McHugh E et.al 2006).

6 GBINSAR APPLICATION FOR MONITORING A LANDSLIDE.

The system was installed to monitor every 4 minutes the displacement of the wall of a terrace of heterogeneous granular materials that could fall to a highway in operation. At the bottom of the terrace there is a river that could be dammed and just about 500m ahead there is a population in risk.

The GB-InSAR used has an operating range of 4500m (wall was located around 700m) and an elevation and azimuth angle of 60 degrees.

On the wall it was possible to make measurements for a pixel size of approximately 1m x 0.5m wide. Each pixel allowed tracking the displacement and the tendency of movement over time to generate early warnings.

The displacement trends defined the threshold warnings as indicated in Figure 11. Green alert (stable condition), yellow alert (regressive condition), orange alert (linear condition), red alert (progressive condition).

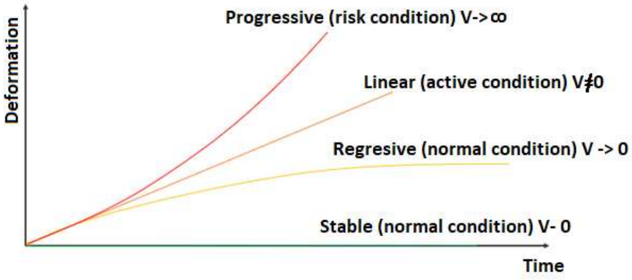


Figure 11. Displacement trends for alarm definition.

In Figure 12 there are some results of accumulated displacements in the last 4 months of monitoring that coincide with the period of low rainfall in the area.

It is observed how the generalized trend in the different pixels of the slope are of the regressive type (deceleration) with velocity around 0.20mm/day during February 2019. In the last 4 months the accumulated displacement has been between about 20 to 120mm for the pixels analyzed in the graph.

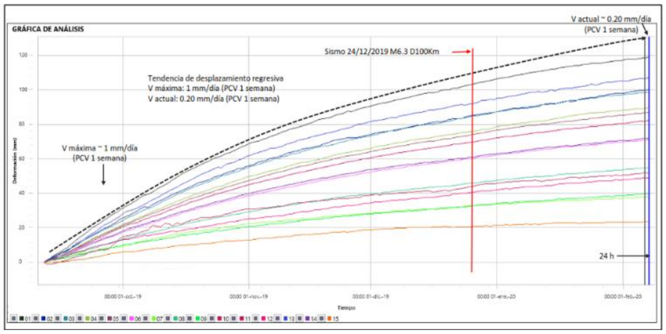


Figure 12. Displacements accumulated over a period of 4 months.

The graphical visualization on the slope of the accumulated displacements can also be observed in Figure 13 for the radar image for each pixel monitored.

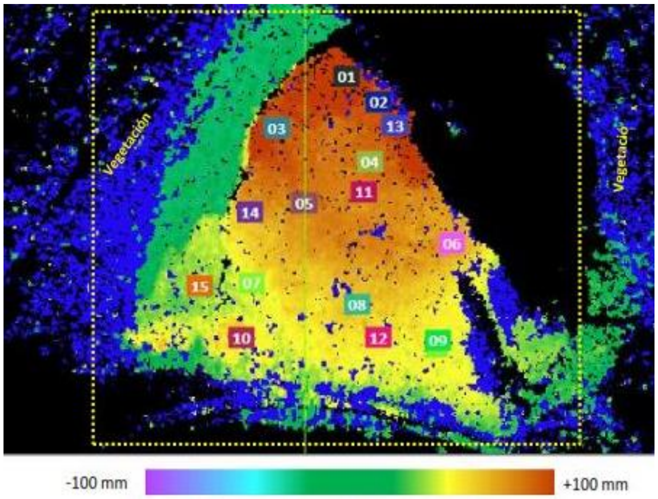


Figure 13. Accumulated displacements on the slope. Period October 2019 to February 2020.

During the initial radar monitoring stage, given the high deformation rates presented, it was possible to identify events with progressive tendency for which an inverse velocity analysis was done (Fukuzono 1985) to predict the possible collapse of material to the bottom of the slope as shown in Figure 14.

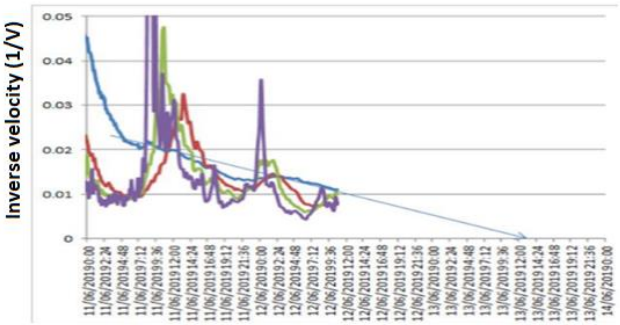


Figure 14. Inverse velocity analysis. Collapse Estimate for 13/06/2019 1:00pm.

The event actually took place about an hour in advance at the estimated time. Throughout the process, the local and national order risk management entities were coordinated to avoid any fatality.

The GB-InSAR technology allowed for this project:

- Real-time monitoring of the behavior of a landslide and sectorized identification of displacements with rigorous monitoring and subsequent activation of the warning protocol for decision making of physical safety of users, surrounding population and road operation.
- By identifying displacement trends, it was possible keep the highway on service and make decisions about temporary solution alternatives for the reactivation of the road operation.
- Detailed record of millions of data points or pixels with historical behavior for daily and historical behavior analyzes.

On the other hand, technology has the following limitations:

- For areas of high vegetation, it is necessary to filter recurring movements that generate noise in order to identify general displacement trends.
- The technology manages to identify areas with a clear trend of movement. It does not allow to identify the fall of rocks or point material with a size smaller than the size of the pixel.

7 CONCLUSIONS.

Technologies with remote InSAR type sensors from satellite and terrestrial devices have been introduced.

Technological developments of military use once again allow the development of civil applications for infrastructure projects.

Depending on the level of detail needed, monitoring area for analysis, frequency required, risk level and investment costs, the applicability of one or another technology is recommended to obtain information on landslide or slope behavior.

For the InSAR technology used for the monitoring and analysis project around the power line corridor, it was possible to identify areas with significant movement trends that were corroborated by field visits. Slope creep processes were found, as well as the monitoring of landslides degradation processes that threatened the stability of some power transmission infrastructure.

On the other hand, the application of GB-InSAR terrestrial radar technology allowed continuous monitoring of an active landslide process to support decision making of operation of the road and protection of nearby population.

Due to the level of detail that is obtained during the monitoring of each pixel, it is possible to evaluate displacement trends in a sectorized manner and in case of a temporary acceleration to obtain predictions to estimate a possible hour of material fall.

The application of remote sensing methods in the study and monitoring of landslide processes allows its descriptive study to facilitate decision-making in the operation and maintenance of civil infrastructure as in the cases presented of power transmission lines and roads.

8 REFERENCES.

Antonello. G. et.al (2004). “Ground-based SAR interferometry for monitoring mass movements”. Landslides 1:21-28. Springer-Verlag.

ESA, (2007). “InSAR Principles: Guidelines for SAR Interferometry Processing and Interpretation. Section A.”

Federico, A. (2015). “Temporal Prediction of Landslide Occurrence: A possibility or a Challenge?”. Italian Journal of Engineering Geology and Environment. Pag 41-60

Ferretti. A. (2014). “Satellite InSAR Data Reservoir Monitoring from Space”. European Association of Geoscientist & Engineers (EAGE). The Netherlands.

Fukuzono, T. (1985). “A Method to Predict the Time of Slope Failure Caused by Rainfall Using the Inverse Number of Velocity of Surface Displacemen”t. Journal of Japan Landslide Society. Vol 22. No.2.

Mazzanti P. (2012). “Remote monitoring of deformation. An overview of the seven methods described in previous G/Ns”. Geotechnical News, 30 (4):24-29.

McHugh E et a (2006). “Applications of ground-based radar to mine slope monitoring”. Report of investigacions 9666. NIOSH. Publication No.2006-116.

Moore. G. K. (1979). “What is a pictre worth? A history of remote sensing”. Hydrological Sciences Bulletin, 24:4, 477.485.

Parker. A. L (2017). “InSAR observations of ground deformation. Aplication to the Cascades Volcanic Arc.” Doctoral Thesis. University of Bristol, UK.