Ground-based slope stability radar for the discrimination of superficial deformation process and their correlation with environmental triggering factors

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Abstract. Landslides occur in a wide variety of forms and environments. These are a direct expression of the geology, rheology, and destabilizing forces of the slope. In particular, landslides prone to abrupt drops in shear resistance over one or more surfaces of rupture pose a major threat to vulnerable communities. Precursory signs may not be obvious and evacuation times are virtually inexistent once the failure phase is initiated. Therefore, prediction and early warning are the only viable options [*Kilburn, 2003*]. The advent of slope stability radar technologies to monitor slope movement opened numerous applications including geotechnical hazards mitigation. The interferometric radar technology was well accepted in the mining industry since 2001, in which a system to identify and quantify the slope failure hazard is a fundamental requirement to safely sustain production [*Bellett, 2013*]. This technology has started to find its way to deal with geo-technical hazards in natural geotechnical hazards and civil applications as well. Due to variability of the materials involved in slopes instability and their instability mechanisms, in many cases it is difficult to characterize their behavior through traditional geotechnical modeling methods and monitoring tools when a more practical approach is required in order to make sounding decisions regarding risk management. We present a case study in which the technology has probe to be efficient for identifying and managing the geotechnical hazards in a civil application. This case is related to unstable slopes that at given moment represented a high risk to main public facilities. We demonstrate that the radar data could be used not only as a warning system but also it allows to differentiate different dynamics and processes in challenging environments and to stablish their correlation with environmental triggering factors such as precipitation events and remediation works.

***Key words:** landslide, risk management, debris flow, slope stability radar*

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Наземный радар для определения устойчивости склонов при распознавании поверхностных деформационных процессов и их корреляции с внешними триггерными факторами

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Аннотация. Оползни встречаются в самых разных формах и природных условиях. Они являются прямым выражением геологического строения, реологических свойств и дестабилизирующих сил склона. В частности, оползни, подверженные резким скачкам сопротивления к сдвигу по одной или нескольким плоскостям, представляют собой серьезную угрозу для уязвимых населенных пунктов.

Прогностические признаки могут быть неочевидны, а времени дли эвакуации после начала фазы обрыва практически нет. Поэтому прогнозирование и раннее предупреждение являются единственными жизнеспособными вариантами [*Килберн, 2003*]. Появление радиолокационных технологий определения устойчивости склонов для мониторинга склоновых подвижек открыло многочисленные возможности, включая геотехнические мероприятия по предупреждению последствий. Интерферометрическая радиолокационная технология успешно применяется в горнодобывающей промышленности с 2001 г., в которой система определения и количественной оценки опасности разрушения склонов является фундаментальным требованием для поддержания безопасности производства [*Bellett, 2013*]. Эта технология начала находить свое применение для борьбы с геотехническими опасностями как в естественных геотехнических условиях, так и в гражданском применении. Из-за изменчивости материалов, обусловливающих нестабильность склонов и механизмов их неустойчивости, во многих случаях трудно охарактеризовать их поведение с помощью традиционных методов геотехнического моделирования и инструментов мониторинга, когда требуется более практичный подход для принятия обоснованных решений по управлению рисками. В статье представлено тематическое исследование, в котором предлагаемая технология должна быть эффективна при выявлении и управлении геотехническими опасностями в гражданском строительстве. Этот вопрос связан с неустойчивыми склонами, которые в данный момент представляют высокий риск для основных общественных объектов. Показано, что радиолокационные данные могут быть использованы не только в качестве системы оповещения, но и позволяют дифференцировать различные механизмы динамики и процессы в сложных условиях и стабилизировать их взаимосвязь с триггерными факторами окружающей среды, такими как выпадение осадков и рекультивационные работы.

Ключевые слова: *оползень, управление рисками, селевой поток, радар для определения устойчивости склонов*

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Introduction

Traditional geotechnical monitoring activities are mostly focused on measuring the movement of the ground surface, these include survey stations and prisms, extensometers, inclinometers, and distance meters. These technics aim to identify displacement patterns and characterize them in order either to validate possible instability mechanisms and displacement characteristics over time, namely: magnitude, trend and rate.

Due to the large variety of geomorphological, geological, geo-mechanical and geotechnical conditions the identification of the most suitable parameters and of the best instrumental solutions is a big challenge and many slope failures still come as a surprise because of the inability to effectively detect precursory ground displacements [*Mazzanti, 2013*]. This often stems from: limited number of measuring points; lack of ancillary data supporting the installation of a monitoring network; unawareness about the presence of ongoing instability phenomena; difficult site accessibility; economical or logistical constraints in general [*Carlà, 2019*].

Over the last years a strong increase of available techniques for the monitoring of landslides and ground instability processes has been observed [*Mazzanti, 2013*]. Hence, several opportunities are now available to monitor landslides processes. Moreover, some of these innovative techniques are opening new frontiers in the monitoring and analysis of landslides.

Among these techniques, ground-based slope stability radars have proved to be a unique tool for surface deformation monitoring. All slope stability radars use the same underlying phase-based signal processing technique called interferometry. The technique calculates the deformation-induced phase shift of the back-scattered electromagnetic signal between two acquisitions, by this sub-millimetric measurement accuracy and sub-metric spatial resolution are attained with no need to install physical instrumentation and the information is obtained and updated frequently [*Bellett, 2013*].

The sudden increase of available technologies has not been followed by a suitable development of advanced education and training of technicians and surveyor. This paper aims to illustrate and demonstrate how ground-based radar could be effective not only as a warning system but also it allows to understand different dynamics and stablish their correlation with environmental triggering factors such as precipitation events and remediation works. The first part of the document focuses in the principles of the ground-based slope stability radars technology and in the second part we present a case study in which the technology has probe to be efficient for identifying and managing the geotechnical hazards in civil applications.

Methods: Ground-based slope stability radar technique

Ground-based radar interferometry is a reliable method for spatial displacement monitoring of slopes and is especially valuable when inaccessibility prohibits the application of other traditional monitoring techniques. Slope monitoring radars have been generically described as either real aperture radar (RAR) or synthetic aperture radar (SAR). There are many differences between these radar technologies, but one of the fundamental differences is the radar dimensionality used to image and spatially map deformation for three-dimensional slope surfaces. RAR traditionally uses either a fine pencil beam to provide full 3D imaging (3D-RAR) or a fine vertically elongated fan beam for 2D imaging (2D-RAR), on the other hand SAR uses a synthetic (virtual) fine vertically elongated fan beam for 2D imaging (2D-SAR) [*Noon, 2015*].

Ground-based radars are also able to provide additional parameters that allows to understand, at some extent, some of the characteristics of the monitored surface, namely: coherence, amplitude and range. The following sections describes how these parameters are derived from the radar signals and their implications.

Displacement calculation using radar interferometry

In order to calculate the displacement, two subsequent radar signals are compared to calculate the phase difference between the two consecutive acquisitions (see Fig. 15). It is important to note that the system can measure only the component of the movement parallel the line of sight (LOS) of the instrument, thus the real displacement vector of the observed object can be calculated only if its direction is a priori known.

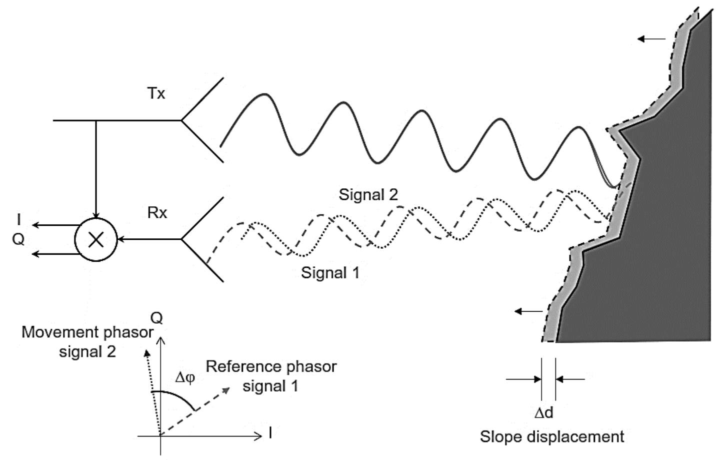


Fig. 15. Displacement calculation using ground-based radar interferometry

The corresponding displacement of the slope surface is then obtained as:

$$\Delta d = \frac{\Delta\varphi}{4\pi}\lambda, \qquad \text{Equation 1}$$

where Δd is the displacement between the consecutive acquisitions, $\Delta\varphi$ is the phase difference and λ is the wavelength of the signal. An important property of the method is the ambiguity of the phase differences, which can only vary between $\pm\pi$. Thus, displacements smaller or larger than $\pm\pi/4$ result in apparent values between $\pm\pi/4$ differing from the real value by a multiple of the full wavelength. This effect is called phase wrapping and is important for interpretation of the displacement results [*Gischig, 2009*].

Coherence

The reliability of the ground-based data is controlled by both the reflectivity of the ground and temporal decorrelation between acquisitions. Reflectivity of a surface determines the strength of the signal reflected back to the receiver by the target. It is generally low for densely vegetated areas and smooth targets not perpendicular to the line-of-sight (LOS). Decorrelation results from strong movements within a resolution cell between two acquisitions (e.g. due to unstable debris cover or differential displacements). A measure of the strength of decorrelation is the signal coherence from two subsequent acquisitions, which is defined as:

$$\gamma = \frac{E(ms^*)}{\sqrt{E(m)^2 E(s)^2}}, \qquad \text{Equation 2}$$

where m and s are the complex numbers of two acquisitions for one resolution cell, (*) denotes complex conjugate, and E signifies the expectation value. The signal coherence is a number between 0 and 1 and is a measure of the similarity of the transmitted and the received signal [*Gischig, 2009*].

In order to generate coherence value of each scan, ground-based radars will conduct a complex cross-correlation function of amplitude signature relation with range measurement. If this correlation remains the same with the next scan, the value of coherence will be 1. On the other hand, if this comparison in a successive scan exhibit a degree of difference, the coherence will have a lower value, the more haphazard the difference of the amplitude signature between one scan to the next scan, then the lower the coherence value that will be generated.

In practice, coherence value equal to 1, means that the surface of the area monitored by the ground-based slope stability radar remains intact and undisturbed. Any surface disturbance at the area being monitored by ground-based radar will be expressed by drop in coherence value below 1. The Fig. 16 illustrates this concept.

Range

Range is defined as the distance measured from the radar toward the observed target. It is calculated from the time of flight of the signal as follows:

$$R = \frac{cT}{2},$$

where R is the range, c is the speed of the light ($3x10^8$ m/s) and T is the time required for radar signal to be transmitted and reflected to radar.

Amplitude

Amplitude refers to the strength of the wave energy. In ground-based radars, amplitude measurement is based on the magnitude of the resultant phase vector formed by the incoming signal. Reflectivity of a surface determines the amplitude of the signal reflected back to the receiver by the target and it is a function of the characteristics of the surfaces such as shape and material, hence amplitude allows to understand, at some extent, some of the characteristics of the monitored surface.

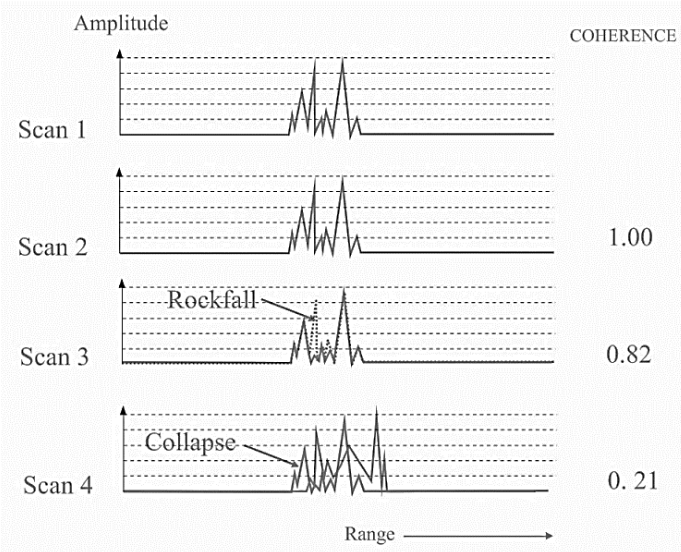


Fig. 16. Coherence calculation concept using ground-based radar data

Study area: Bogota-Medellin highway landslide

On December 2016, some minor rock falls and debris flows were observed on the Bogota-Medellin highway (K14+000) in north Colombia (see Fig. 17). Field inspections revealed some cracks in the upper hill that may be associated with a simple translational mechanism, which has presumably driven by a period of unusual adverse weather conditions for the local climate. The event partially interrupted the heavy traffic between Bogota and Medellin cities (around 22.000 vehicles/day) and since the slope showed signs of further instability it remained closed during the following days.

Fig. 17. Study area Bogota-Medellin highway (K14+000) in north Colombia

A real aperture slope stability radar was deployed at site on December 28 in order to verify the stability conditions, determine the size of the unstable area and characterize the displacement processes. The system was located around 500-800 m on the opposite side to area of concern. The Fig. 18 shows the area of concern as seen from the radar location. System specifications and acquisition parameters for this radar survey are summarized in Table 1, while campaign dates and time intervals are shown in Table 1.

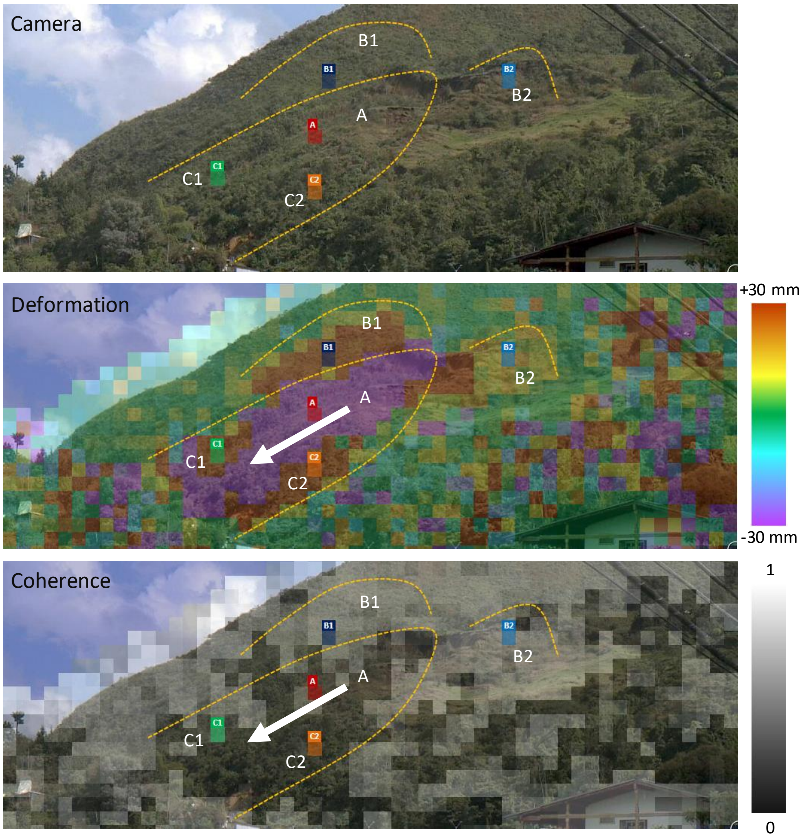


Fig. 18. Ground-based radar imagery for the first 12 hours

Table 10. Acquisition parameters for the GB-3DRAR survey

Radar type	3D real aperture radar RAR
Radar antenna aperture	1.8 m
Frequency	9.55 Mhz
Wavelength	32 mm
Target distance	500 – 800 m
Pixel size	4x4m at 500 m to 7x7m at 800m
Acquisition frequency	6 minutes (240 acquisitions a day)
Monitoring period	November 2, 2016 – August 8, 2017

The 3D-RAR information (accumulated displacement, coherence, amplitude and range) is overlain on a high-resolution camera image which allows to visually correlate this resulting information. The advantage of such integration consists in facilitating the detection of the features in the scan areas throughout the cumulated 2D imagery, hence there is no need to geo-reference the dataset or perform further surveys with other instrumentation (such as topographic stations or laser scan).

First results

12 hours after the deployment of the GB-RAR system, the radar imagery revealed the extent of the landslide area it was possible to validate the assumptions that were done by field inspection about the failure mechanism. The color scale in the radar displacement image shows displacements from −30 to +30 mm during these first 12 hours. Positive values (red to yellow) show displacement along the LOS towards the observer, negative values (light blue to violet) away from the observer, and green values represent zero displacement. On the other hand, the coherence image represents the degree of decorrelation between acquisitions. Decorrelation results from strong movements within a resolution cell between two acquisitions (e.g. due to

debris, vegetation cover or differential displacements). Highly correlated acquisitions show values close to 1.0 (white) whereas decorrelated observations will be expressed by drop in coherence value below 1.0 that will trend to zero depending on the degree of disturbance that occurred in the surface (dark grey color).

The central area of the landslide main body (zone A) form an elongated decorrelation pattern that correlates with the active debris flow channel and showed low coherence and phase wrapping ($\Delta d > \lambda/4$). Because of this, the apparent negative deformation measurements (away the radar) were considered as untruthful and disregarded during this first period. The area B (above the zone A), showed a consistent deformation pattern (also with a higher coherence) that was interpreted as a true deformation process (later this area developed a progressive trend and shaped a new main scarp). The area C also showed a consistent deformation pattern that was interpreted as the walls of the debris flow channel. Above the zone B, some data gaps occur in grassy areas due to decorrelation and shadowing but there was no evidence of other significative deformation processes.

Observation toward the deformation behavior give insight about the risk level and permits at some extent to predict failures in the future. There are 3 types of slope deformation trends: Transitional deformation occurs when an accumulated deformation vs time plot reveals constant velocity, regressive deformation occurs when the plot shows decreasing velocity and progressive deformation exists when the plot reveals increasing velocity over a time span (Zavodni & Broadbent 1980). The Fig. 19 shows the accumulated deformation plots that were generated for the aforementioned areas (A, B and C).

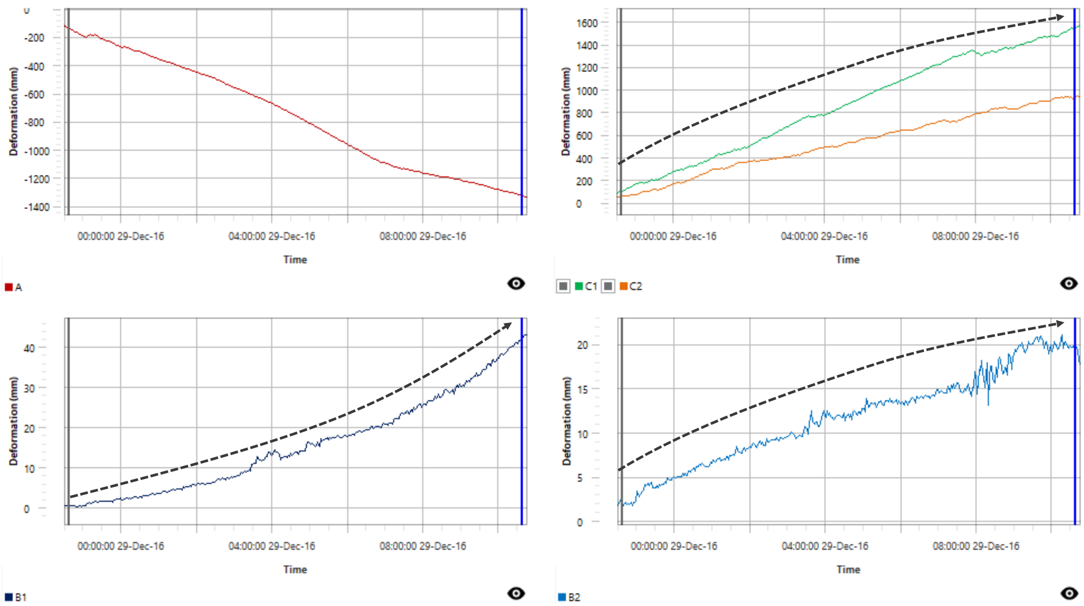


Fig. 19. Accumulated deformation vs time plots for the areas of interest

As stated, the area A showed an apparent negative deformation trend (away the radar) that was disregarded during this first period due to the low coherence and phase wrapping effect related with the active debris in this area. The area B showed a consistent progressive deformation trend that was a precursor of a future slide that occurred later in this area and shaped a new scarp. The area C showed a consistent regressive deformation trend with a lower deformation rate.

Predicting slides and falls of ground

Several authors have shown that linearly extrapolating the theoretical time of singularity in an inverse velocity versus time plot can be used to predict the time of slope failure. For this reason, monitoring activities are mostly focused on measuring the movement of the ground surface [*Fukuzono, 1985*]. Such relation is linked to the theory of damage accumulation, and to mechanisms of creep fracture by stress corrosion and power law lattice deformation [*Voight, 1989*].

As shown before, on December 29 the presented datasets revealed an accelerating trend of displacement in the area B. Expected failure-time was then derived by applying the inverse velocity method for highly coherent targets showing relevant precursors. The inverse velocity plot in the Fig. 20 was generated on December 29 around 15:00h and it shows the result of the prediction that was performed at that time. According to the forecast, the slide would happen the same day at 18:02 h. Hours later it was confirmed by field observations that the slide effectively occurred around 17:30 h (see Fig. 20).

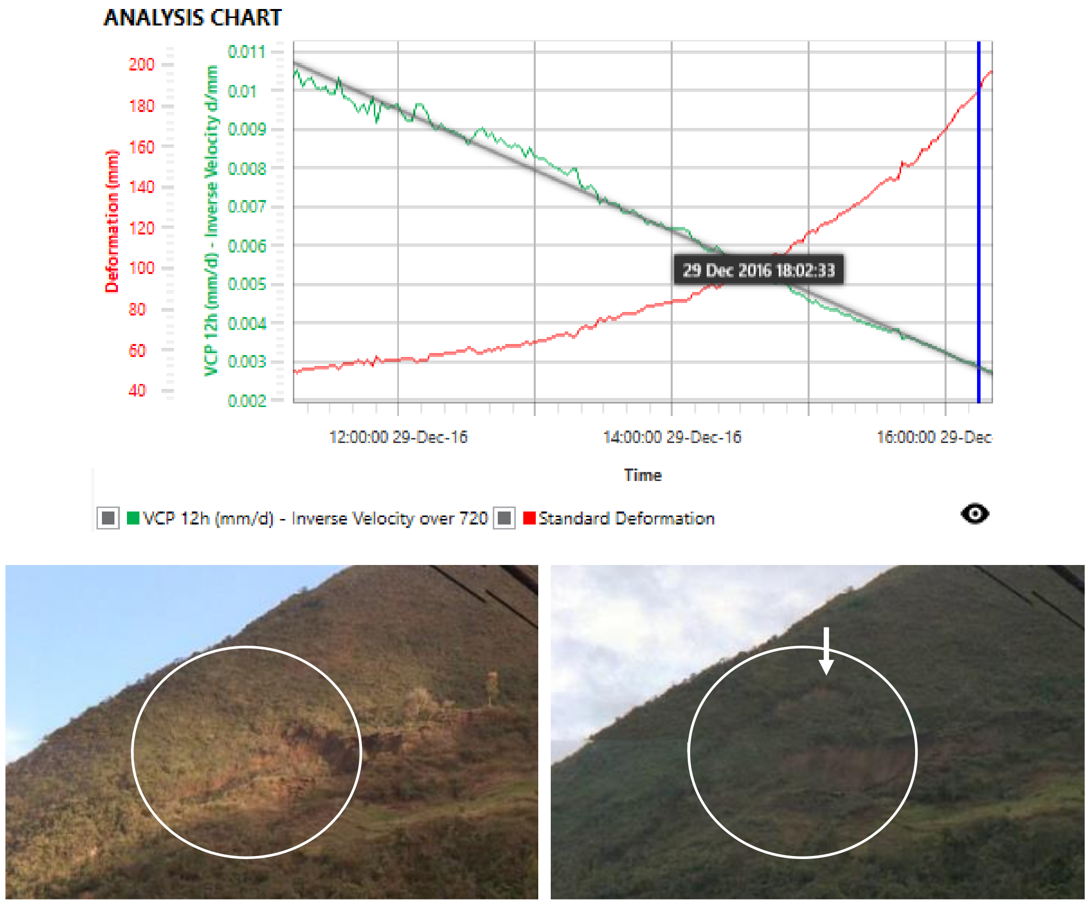


Fig. 20. Inverse velocity plot for slide prediction. Location of the predicted landslide

Unstable mass blasting

Since the area continued showing evidence of further instability during the following days and a series of transitional and progressive deformation processes and falls of ground we observed, the highway remained closed to the traffic. On January 1, the management and the local authorities try to induce a landslide by performing a blast (see Fig. 21). The set up and configuration of the blast is unknown and there was no monitoring of the vibrations in place.

Blasting is in many cases a triggering factor that effectively increases the deformation rates of both stable and unstable slopes, so it was expected this blast to lead both a generalized progressive deformation trend and a final collapse of the unstable material.

The ground-base radar information showed that the blast did not have any effect on the ongoing deformation processes, and these continued with the same deformation trends that were present before the blast.

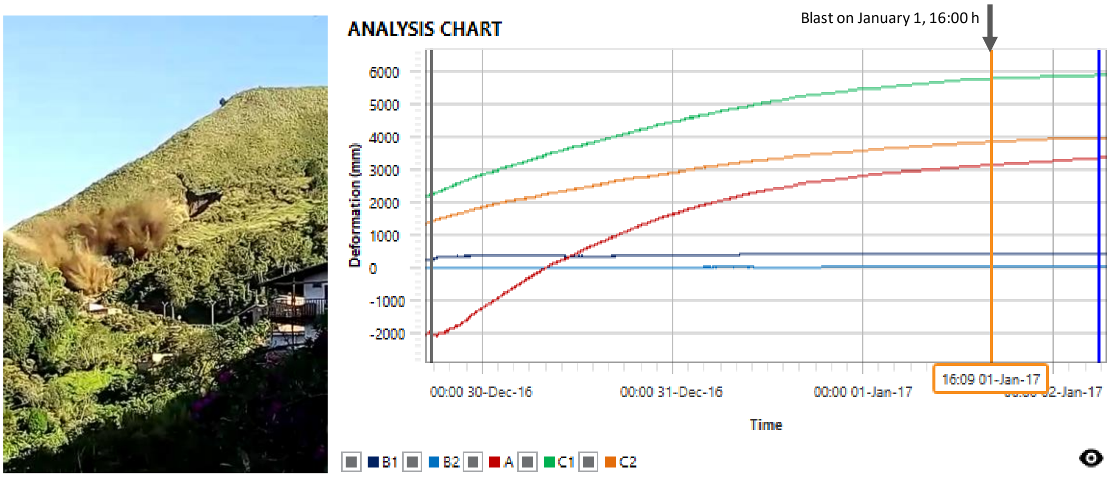


Fig. 21. Displacement analysis for the blast performed on January 1, 2017

Rainfall-induced instability processes and falls of ground

Rainfall-induced landslides can be triggered by two main mechanisms: shear failure due to build-up of pore water pressure and erosion by surface water runoff when flow velocity exceeds a critical value. Prediction of rainfall-induced landslides has relied on maps of landslide susceptibility and catalogs of landslide occurrence and corresponding rainfall amounts (rainfall thresholds). Due to their incomplete description of conditions needed to induce landslides, conventional rainfall thresholds have considerable uncertainty. Numerical modeling efforts also could provide additional insight and are expected to help extend landslide warning tools to areas where detailed historical landslide information is unavailable.

The GB-RAR collects weather information that allowed to correlate in real time the displacement information with the precipitation events. It was found that the area of concern had different responses to the same precipitation events. The main body of the slide (zone A) show no evidence of any change either on its deformation trend or in its deformation rates as consequence of the precipitation events that occurred during the period (see Fig. 22). On the other hand, the main scarp and the crown area (Zone B) showed acceleration processes that could be directly correlated with some of the precipitation events (see Fig. 22). Both the long-duration and short-duration precipitation are significant in the triggering the landslides. In the zone B it is clear that the first landslide that occurred on December 29 was correlated with the rainy period, after this first slide the area remained relatively stable during the folowing days (no significant or persistent deformation trends were observed) and a second rainy period (on December 31) triggered a second slide in the very same area. This seems to confirm slope stability models that indicate that, in the initial phase, the slip surface of a landslide often occurs along the top of a relatively impermeable layer located at some depth within the soil profile. The shear strength along this surface is governed by the pore water pressure. The pore pressure is in turn controlled by water seepage through the slope from infiltrated rain. The two consecutive events may be a consequence of the infiltration processes that occurred during the precipitations that occurred in the period.

Reports of slides and falls of ground during the monitoring campaign

The monitoring campaign lasted from December 28, 2016 up to August 23, 2017. During this period a total of 18 collapses and falls of ground were reported. Most of these events were correlated with precipitation events (which seems to be more frequent during the periods of December-January and March-May) and the remedial works that were undertaken in the area as an attempt to stabilize the slope. During the period June-August 2017 the number of instability events decreased and the monitoring campaign with the ground-based slope stability radar was finished. The Fig. 23 shows a summary of the events that were reported during the monitoring campaign and the camera image of the area of study on March 2017 when the remediation works were almost completed.

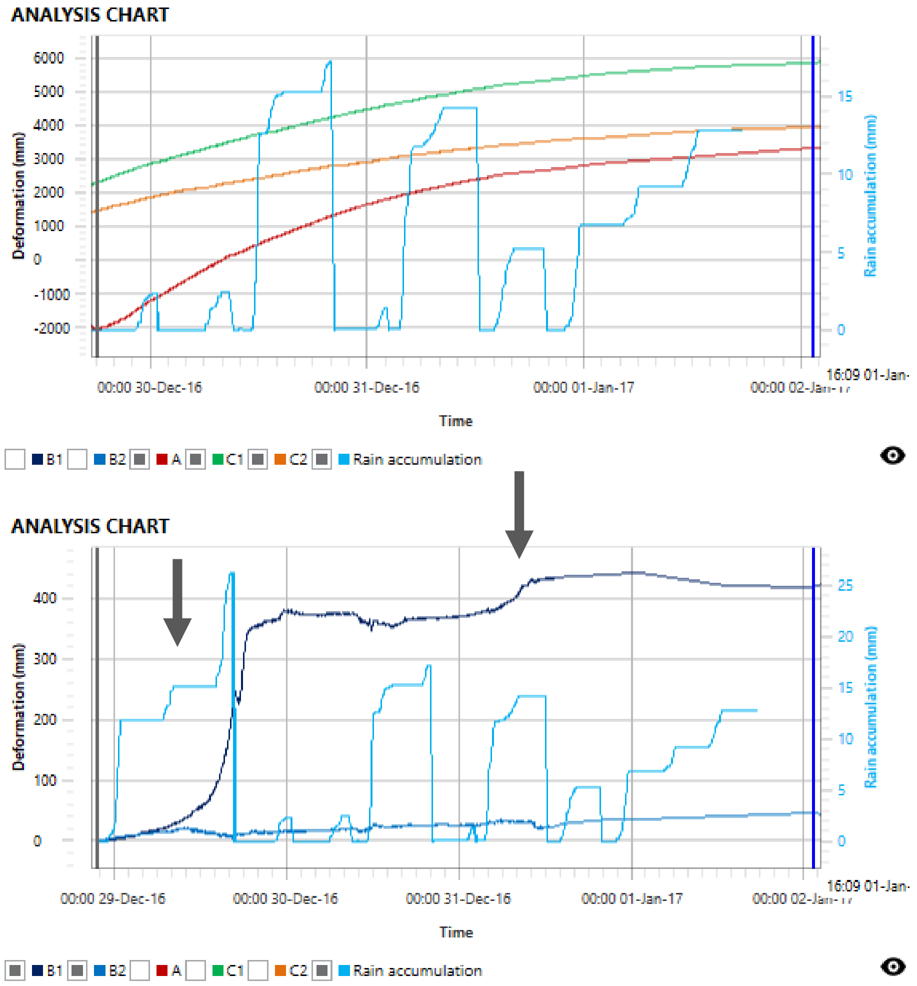
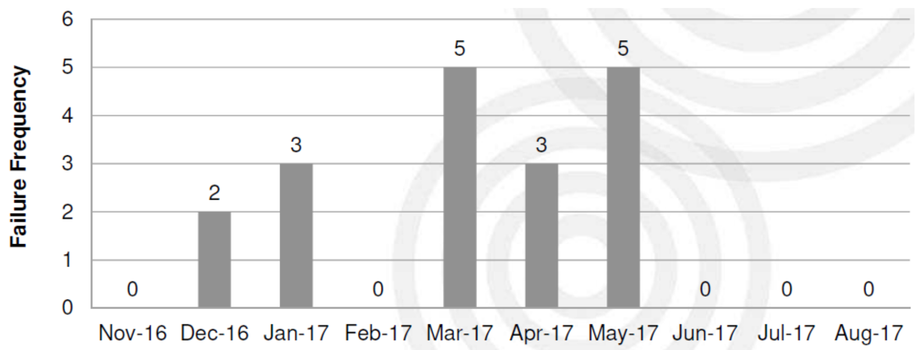


Fig. 22. Displacement analysis for the precipitation events (December 2019 to January 2017)



	Nov-16	Dec-16	Jan-17	Feb-17	Mar-17	Apr-17	May-17	Jun-17	Jul-17	Aug-17
No. of Failure	0	2	3	0	5	3	5	0	0	0

Fig. 23. Reported slide and fall of ground events during the monitoring period

Discussion

The ground-based slope stability radar monitoring campaign undertaken has been proved effective for risk identification and management in civil applications. Accuracy in displacement measures, achievable resolution, and high acquisition rate, lead to a detailed and real-time investigation of instability behavior and its relationship with triggering factors such as precipitation, blast and remediation works. The coherence also demonstrates to be an effective parameter for discerning different dynamics in the study area.

On the other hand, some limitations related to the nature itself of the employed radar technology have to be considered during the planning phase of the monitoring campaign: 1) measured displacement refers only to the surface of the observed object that can be seen from the sensor; 2) only movements with direction parallel to the LOS of the instrument can be detected; 3) displacement trends, magnitudes and rates could be misinterpreted by the instrument due to phase wrapping; 4) the radar data interpreter need to attained full knowledge about radar parameters and images interpretation and about the slope conditions and other factors (weather, operations) which will potentially have an effect in the information. In addition, the definition of an efficient and fine-tuned monitoring procedure is essential to guarantee an effective early warning activity resulting in safety for people and prompt security measures for infrastructure.

Fig. 24. Remediation works on March 2017

Conclusion

This paper describes the effectiveness of ground-based slope stability radar as a geotechnical monitoring that allows to identify and characterize slope stability hazards regarding to civil applications. The use of accurate and real-time displacement calculation and coherence measures allowed us to identify different dynamics in a challenging area (active debris, dense vegetation cover, precipitation events, remediation works) and provide opportune information to make sound decisions during the recovery works.

Results of the proposed monitoring and the early warning that was provided in most of the instability events that occurred during the period demonstrate that it is possible an extensive application to civil engineering applications. The use of technologies and methods described in this paper results in safety for citizens and in substantial advantages for risk identification and management regarding unstable slopes.

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References

Bellett, P.A. (2013). Real Aperture Radar for Safety-Critical Slope Monitoring. GroundProbe Pty Ltd Public Green Paper.

Carlà, T. (2019). Perspectives on the prediction of catastrophic slope failures from satellite InSAR. Scientific Reports NatureSearch.

Fukuzono, T. (1985). New method for predicting the failure time of a slope. Fourth international conference and field workshop on landslides, (p. 145–150). Tokio.

Gischig, V. (2009). Identification of active release planes using ground-based differential InSAR at the Randa rock slope instability, Switzerland. Natural Hazards and Earth System Sciences, 2007-2019.

Kilburn, C. R. (2003). Forecasting giant, catastrophic slope collapse: lessons from Vajont, Northern Italy. Geomorphology, 21–32.

Mazzanti P., P. G. (2013). Traditional and Innovative Techniques for Landslide Monitoring. Tagung für Ingenieurgeologie mit Forum für junge Ingenieurgeologen, (p. 191-197). München.

Noon, D. (2015). 3D and 2D radars for open-pit slope monitoring. Slope Stability 2015. The Southern African Institute of Mining and Metallurgy.

Voight, B. (1989). A relation to describe rate-dependent material failure. Science, New Series, Vol. 243, No. 4888, 200–203.