

Innovative use of slope monitoring radar as a support to geotechnical modelling of slopes in open pit mines

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Abstract

In the modern mining industry a comprehensive slope monitoring program, aimed at managing potential large scale instabilities and able to simultaneously detect local scale movements, should represent an integral part of every geotechnical risk assessment plan.

El Teniente provides a good example of a complex modern mining operation where stability issues have to be addressed with a slope monitoring program which is able to support geotechnical engineers not only in managing risk, but also in the interpretation of ongoing stability problems. Situated in Chile, 44 km east of Rancagua, 75 km south of the capital Santiago and at an altitude of 2,500 m, El Teniente is one of largest underground copper mines in the world and also recently integrated surface mining. The nature of the project in terms of depth, size and mining methods, and the possible interactions among the different mining processes, expose its facilities and processes to significant risk levels. Slope stability is one of the most critical sources of risk, at least in connection with surface operations. In order to cope with these risk conditions and to possibly mitigate them, new technological solutions based on process automation and innovative concepts have been adopted. This paper describes the innovative use of slope monitoring data currently under implementation at El Teniente, which is based on the combination of radar data used in an unconventional way and other geotechnical-geological analyses. Although slope monitoring radar is a well-established safety-critical monitoring practice designed to provide alarms in case of impending pit wall slope failures occurring, there is limited published information available on the use of such a powerful technology for other purposes in mining operations such as the interpretation of slope behaviour.

This paper presents the author's experience with using radar data to identify the most likely failure mechanisms and to assess and validate geotechnical models. More specifically, at El Teniente the proposed integrated approach involves calibrating the input parameters for finite element modelling (FEM) to replicate movements observed through the monitoring data acquired by radar. The paper presents the results of the use of radar to monitor different areas of the mine affected by stability issues, such as the Camino Principal (the main access road to the Rajo Sur pit) and the north walls of the Rajo Sur (potentially affected by slope movements) and how the data have been used to get a better preliminary understanding of ongoing instability phenomena.

1 Introduction

The use of slope monitoring radar is now the standard practice for the active monitoring of pit walls in open pit mines. Radar units are used effectively for safety critical slope monitoring with the aim of providing alerts in the event of progressive movements which could potentially lead to slope failure, and therefore with the aim of assessing worker safety and increasing mine productivity.

Due to radar's capability to collect quantitative information regarding slope behaviour in both the spatial and the temporal points of view, it is possible to envisage the use of such a technological tool to support the geotechnical analysis needed to achieve a better understanding of stability issues.

Modern slope monitoring radar is usually able to cover large areas with accurate georeferenced output. The capability to relate each pixel of the radar displacement map to the geographical coordinates of the pit, together with the capability to handle long-term datasets (months of monitoring data in a single project), may allow geotechnical engineers to integrate the radar data into a wide variety of geoengineering analyses.

Slope monitoring radar is used in numerous mines to support the temporal prediction of slope failures, for example by using empirical methods such as the Fukuzono or Inverse Velocity methods (Fukuzono, 1985, 1990). Data acquired through the use of radar can also support geotechnical engineers to estimate the runout distance of a potential failure mass through estimation of the volume of material involved in the movement (this typically involves combining information about the extent of the moving area with the main geological structures of the pit). More advanced applications of radar could help predict the most likely failure mechanisms by matching the deformation field identified by the radar with the outcomes of structural modelling or a calibration of numerical geotechnical models for the analysis of the slope safety factor and deformation behaviour, for example through the Finite Element Shear Strength Reduction (SSR) method (Dawson, 1999; Hammah et al., 2005).

The basic concept proposed in this paper is an attempt to match observed movements in radar data with deformations in geotechnical models in order to obtain a comprehensive understanding of rock mass mechanics which is supported by accurate real-time monitoring data over a wide area of interest.

Such an approach has been provisionally put in place at El Teniente mine, where IBIS-FM radar (IDS, 2013) data have been used to support the numerical modelling of slope behaviour. The preliminary results show that the capabilities of the IBIS-FM radar offer the possibility to use the system beyond the traditional purpose of critical safety.

2 El Teniente mine

El Teniente, located in Chile 44 km east of Rancagua, 75 km south of the capital Santiago and at an altitude of 2,500 m, is one of largest underground copper mines in the world. El Teniente is a good example of a complex modern mining operation. The current operation includes six underground mining blocks located at different depths. Mining methods for the underground mine include panel caving, panel caving with pre-undercut and block caving. Surface mining recently started with a first pit, Rajo Sur, in the Quebrada Diablo, and a second one will soon enter into production.

The present paper is focused on the results from monitoring critical surface areas at the Rajo Sur open pit and Camino Principal, located in the southeast of the mining area above the underground mine of El Teniente. The area of interest for mining exploitation in the Rajo Sur is located in the upper part of Quebrada Diablo, between the elevations of 2,720 and 3,140 m (Figure 1).

The ore body is contained within intrusive rocks covered by 30 m of overburden consisting of landfill and leached rocks. The geological structure of interest has a mantle shape and a thickness between 10 and 150 m, with a mineralogy dominated by pyrite, chalcopyrite and chalcocite. The resource is estimated as 34 M tons and will allow a production rate of 15 to 20,000 tons per day over a period of five years.

Other than the open pit, the main infrastructure and installations in the mine area include: main and secondary roads, transfer system, waste dump, service infrastructure and stock piles (Figure 1).

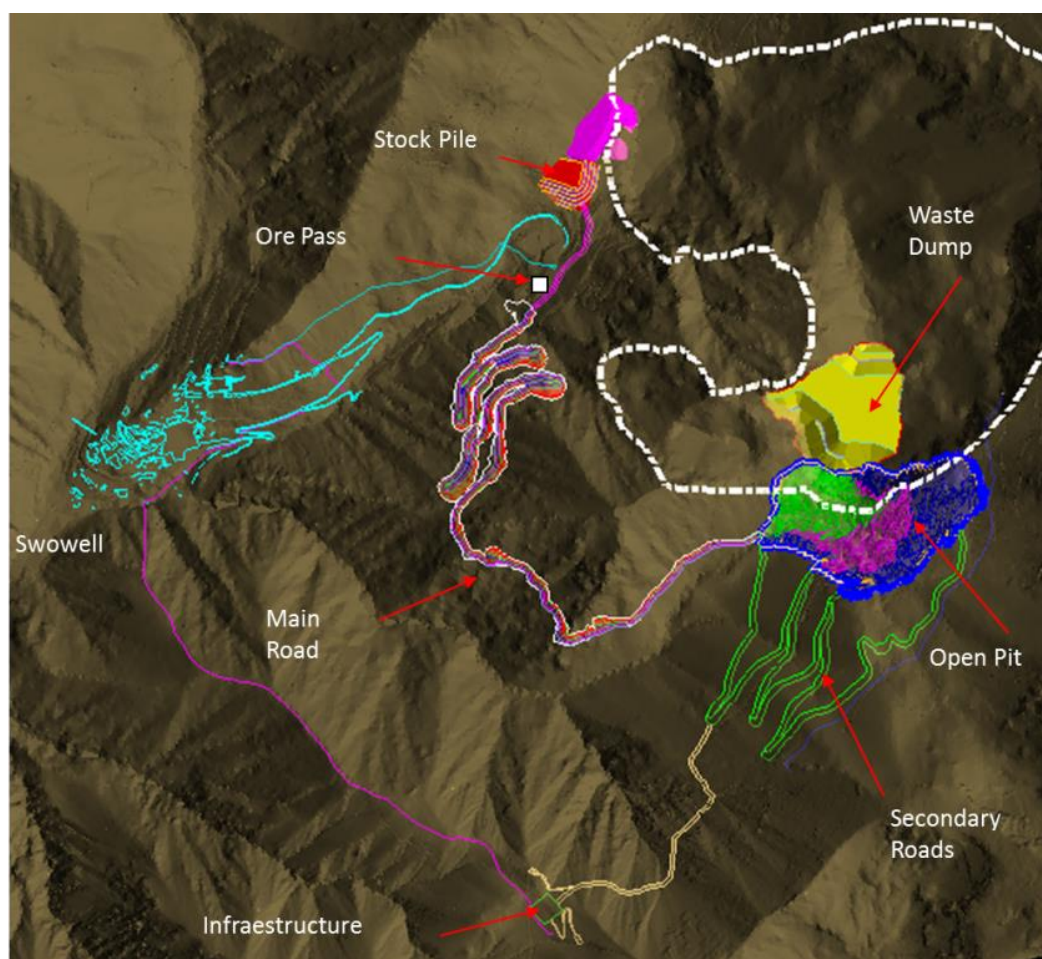


Figure 1 El Teniente Morphology and mine plan

3 Slope monitoring radar

The first type of slope monitoring radar introduced into the mining market was based on a parabolic dish-antenna radar (Real Aperture Radar – RAR) using a fine radar beam to illuminate the target over a series of small footprint areas. Various generations of Real Aperture ground-based radars (RAR) have been developed in the last few years for monitoring slope movements (Noon, 2003; Harries et al., 2006). In recent years, a new category of radar has been introduced based on a slightly different technology called Synthetic Aperture Radar (SAR) (Antonello et al., 2004; Mecatti et al., 2010; Farina et al., 2011; Severin et al., 2011) which had primarily been utilised on satellite platforms and for spatial remote sensing. Slope monitoring radars based on the terrestrial SAR technique (Atzeni et al., 2001; Pieraccini et al., 2003) are typically composed of a radar sensor equipped with two small horn antennas mechanically moved along a linear scanner and supplied by a power supply unit. The small horn antennas produce a wide beam (usually 80–90° on the horizontal plane by 50–60° on the vertical plane) which illuminates the whole monitored area a few hundred times during a single scan, each from a slightly different position as the radar sensor slides along the linear scanner. Such a mechanical scan allows slope stability radar based on SAR to obtain a full high resolution image of the observed area in a very short acquisition time (e.g. three minutes to cover an area of a 6–8 km² at a 2 km operating distance).

The present paper refers to one of the SAR slope monitoring radars currently available on the market, namely the IBIS-FM, manufactured by IDS.

The IBIS-FM system achieves a resolution cell using the full bandwidth of as small as 0.5 by 4.3 m at a monitoring distance of 1 km, has an accuracy of 0.1 to 0.2 mm along the radar's line of sight within the first km from the slope and an accuracy of less than 1 mm within 2 to 4 km. The high spatial resolution is not

only a mere technical detail, but it means higher sensitivity to slope movements and the capability to detect small areas of failure, especially in the case of sub-bench or bench-scale failures. Movements measured by the radar are in fact the average displacement which takes place within each resolution cell. As a result, small localised displacements are likely to be underestimated or washed out if they are encompassed into a single wide resolution cell. The high spatial resolution, coupled with the wide spatial coverage, enables IBIS-FM to cover a wide range of spatial scale instabilities in a slope or a pit wall.

Additionally, in open pit mines, the long range capabilities make it possible to install the system far from the mine highwalls, thus allowing the detection of both small movements (bench-scale failures) and large scale displacements from the same installation. The placement well away from the mine slopes allows the station to be set up in a stable area.

4 Safety-critical slope monitoring system at El Teniente mine

El Teniente is a mining area with several surface and underground activities. The radar based safety critical monitoring system for this site is planned to cover the two open pits, Rajo Sur and the yet to enter into production Rajo Norte, and the main access road, 'Camino Principal'. Therefore, two IBIS-FM radar systems are currently deployed on the El Teniente site. An overview of the area covered by these two IBIS-FM units is presented in Figure 2.

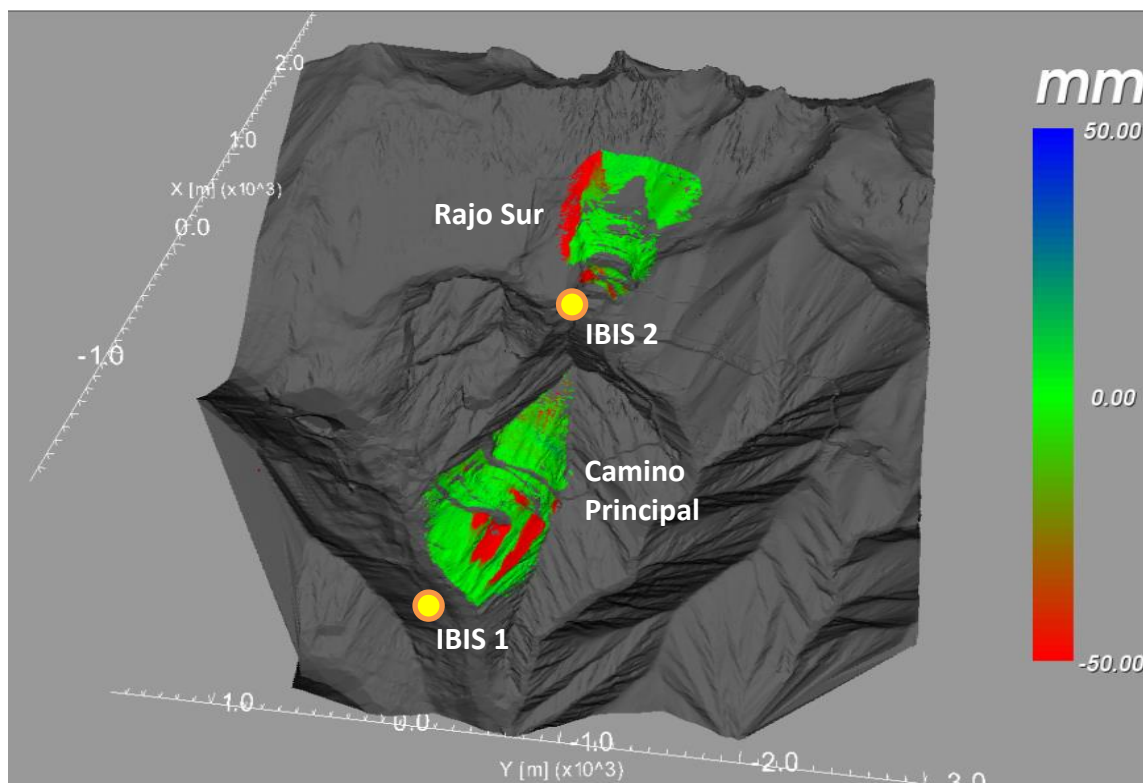


Figure 2 Three-dimensional (3D) overview of the El Teniente mining site with the two IBIS units and relative radar maps

The first radar unit, identified as IBIS 1 in Figure 2, is monitoring the steep 40° slope of Camino Principal. This unit was installed in September 2011 and has been effective in the early detection of mass movements, particularly those which occurred in the upper part of the slope (Figure 3).

The second radar unit, IBIS 2, is covering the Rajo Sur area (see Figures 2 and 4) and is mainly intended to monitor the subsidence caused by underground mining and the slopes of the open pit mine.

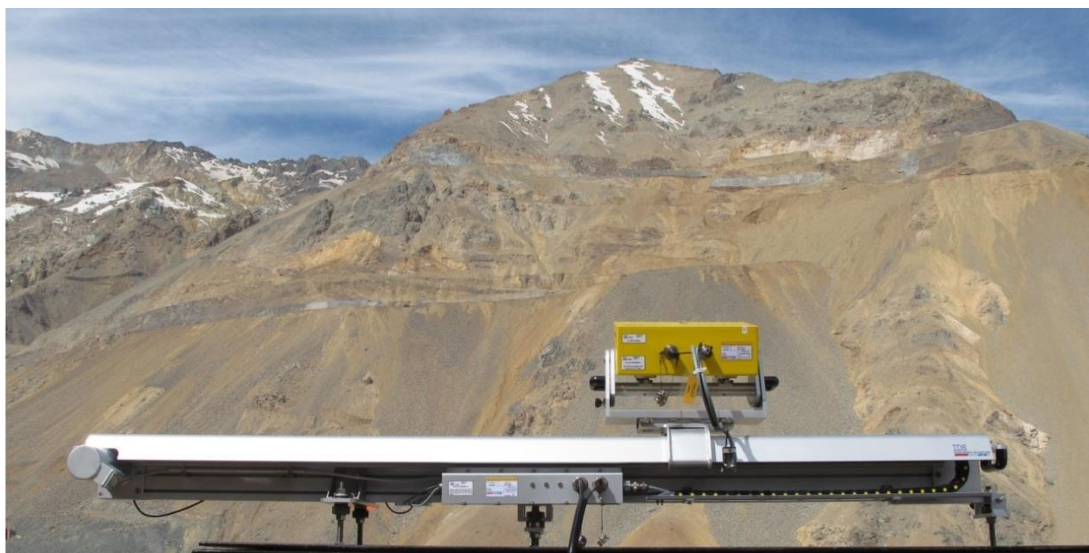


Figure 3 IBIS-FM radar installation aimed at the Camino Principal. The monitoring distance is about 2 km from the slope

The IBIS-FM radar covering Rajo Sur has been in commission since the start of the open pit mining operation. Block caving underground is expected to cause a surface crater with the northern flank of the crater potentially affecting the Rajo Sur pit.



Figure 4 Panoramic view of the Rajo Sur mine from the IBIS 2 installation point

The concurrence of these potential impacts at El Teniente offers the opportunity to apply in practice, and test, the proposed concept of an innovative use of monitoring data in open pit mining. Aside from the safety-critical monitoring functions, the deployed IBIS-FM systems provide the opportunity to explore the possibility to use radar data in order to improve the available geotechnical models and, consequently, the mine and production management.

The displacement datasets recorded so far by the IBIS-FM have been used for the calibration of the FEM numerical models which will be used to analyse the failure mechanisms and to provide better feedback for use in future mine design and planning.

5 Proposed methodology to integrate radar data with geotechnical modelling of pit slopes

The use of slope monitoring radar is a well-established practice for safety-critical monitoring of pit walls with the aim of providing alarms in case of impending slope failures. However, there is limited experience of using such powerful technology for other purposes in mining operations, such as the interpretation of slope behaviour, trying to assess and validate geotechnical models and identifying the most likely failure mechanisms.

The methodology proposed in this contribution is based on the inclusion of a radar-based monitoring system in an iterative workflow with the intention of:

- Continuously improving the safety of mining operations.
- Optimising other monitoring activity investments.
- Updating the pit's management on emerging instability conditions, eventually reducing production downtime.

Even though the main objective of using radar to monitor mine slopes remains the safety of workers and operations, the analysis of displacement data integrated with the results of numerical modelling, like FEM, allows other applications pertaining to the analysis of rock mechanics to be examined.

In this case study, the radar datasets acquired for safety-critical monitoring have been selected in order to calibrate as the shear strength parameters (cohesion and friction angle) used as input in a SSR FEM model. SSR finite element technique has been recently affirmed as an alternative to standard limit equilibrium analysis for the assessment of slope stability. In SSR technique the material shear strengths are progressively reduced until the numerical model does not converge anymore, i.e. collapse occurs and the critical Factor of Safety is reached. In fact, by definition, the Factor of Safety of a slope is the 'ratio of actual soil shear strength to the minimum shear strength required to prevent failure,' or indeed the factor by which rock shear strength must be reduced to bring a slope to the verge of failure (Duncan, 1996).

The current analysis consisted in adjusting the input rock mass strength parameters until the SSR model output matches the actual displacement measured by the IBIS sensor.

Finally, the enhanced understanding of instability conditions allows the adequacy of the monitoring system to be reviewed, alerts to be based on updated hazard thresholds, and eventually to possible improvements to the mine plan to be suggested (Figure 5).

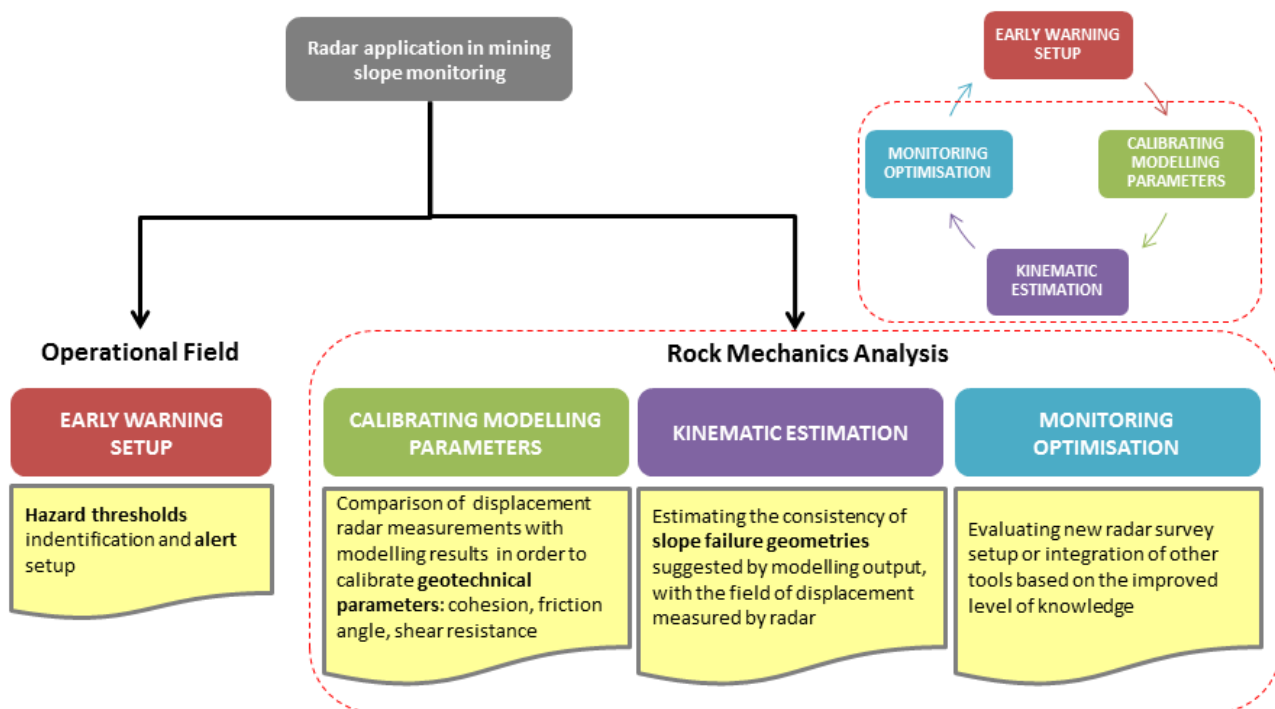


Figure 5 Iterative workflow aimed at the integration of the IBIS-FM radar system into the optimised management of an open pit mine

Based on the available monitoring data and considering the specific needs and requirements at El Teniente, this workflow has been implemented to perform the following activities:

1. Selection of two radar monitoring datasets representative of the ongoing slope deformation (Figure 6).
2. Set up of a two-dimensional (2D) SSR FEM model of the investigated slope. The finite element program Phase² was used for the numerical simulations.
3. Comparison of the modelling output with the displacement datasets recorded by the IBIS system in order to identify the possible failure mechanisms (with or without structural control). The final FEM model calibrated using the radar data provides an improved understanding of the instability mechanism, thus enabling new complimentary activities to be developed to increase the operational safety in the excavation and, if necessary, to optimise the monitoring system.

The experimental methodology takes into account the line of sight nature of the radar measurement: the values measured by radar represent the component of the 3D displacement vector projected along the radar line of sight. It is assumed here that the distribution of these values still support the hypotheses on the most common and clearly recognised failure mechanisms occurring on the slope.

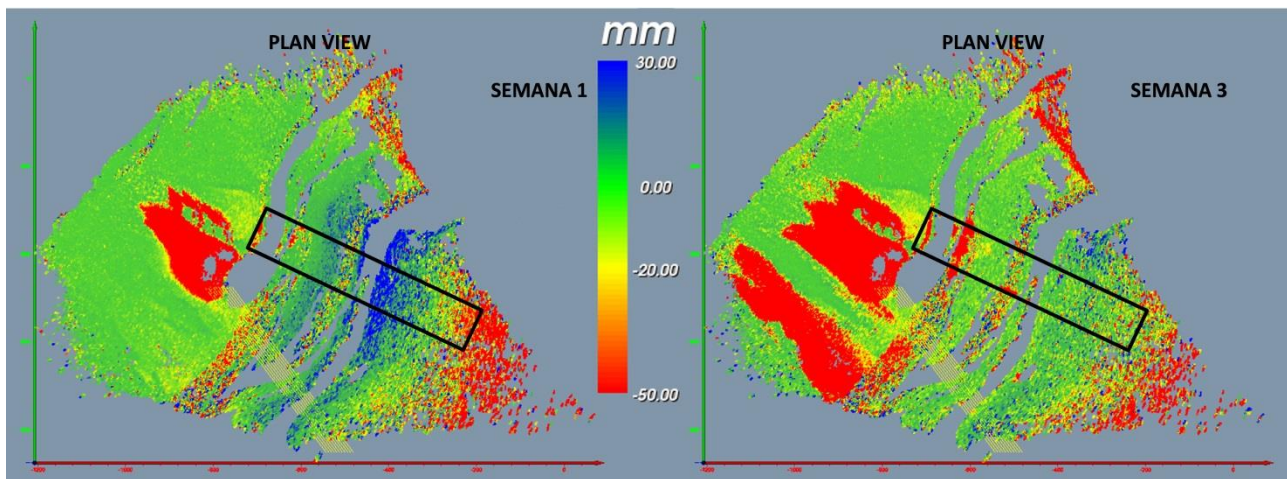


Figure 6 IBIS displacement maps of Camino Principal, relative to two different time windows used for the FEM model calibration

5.1 Calibrating the geotechnical FEM model using IBIS datasets

As mentioned above, the most innovative element of this contribution is the preliminary attempt to use radar data to improve the geotechnical models for slope stability analysis. In this test case, a representative profile from the unstable slope, well documented in the monitoring dataset, has been selected and reproduced in the 2D FEM model.

In the first stage, a previously defined set of values for cohesion and friction angle are used as inputs for the model. These initial and theoretical values are then adjusted in order to match the model's calculated deformation to the displacement measured by the radar in the field.

To provide an example of the proposed methodology, the preliminary results from the analysis carried out in this case study are shown in the following pictures (Figures 7 and 8).

Figure 8 shows the SSR model output when the Critical Strength Reduction Factor (SRF) is reached. SRF expresses the critical combination of c and ϕ beyond which the slope is supposed to collapse (i.e. the finite element model does not converge anymore).

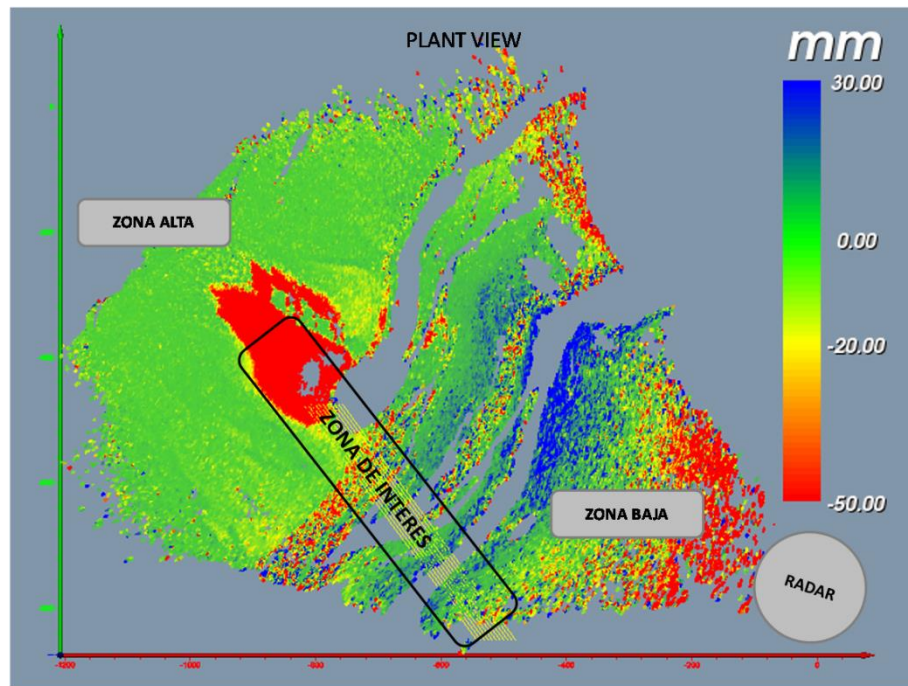


Figure 7 Example of the radar displacement dataset, recorded between the 6 and 13 September 2012, used for the model calibration

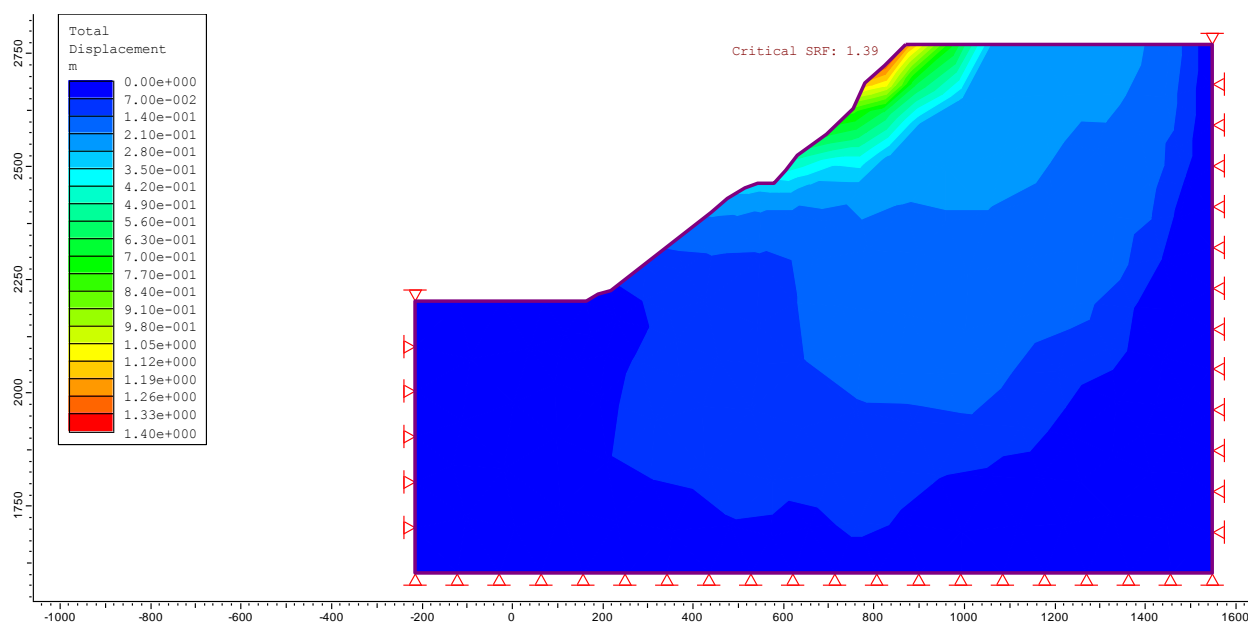


Figure 8 Calibrated SSR FEM model with validated strength parameters showing the slope deformation at the critical Factor of Safety (SRF = 1.39)

From the same analysis, the SSR FEM can also provide a probable failure mechanism/geometry. The computed movement evolution is analysed, taking into consideration the failure mechanisms documented for similar slopes and materials, in order to assess the possibility that a failure will occur. This analysis is aimed at detecting inconsistencies among possible deformation processes and the movement records, while also taking deformation rates into account.

Once both geotechnical parameters and failure mechanisms are selected and intrinsically validated, it is possible to assess the adequacy of the current monitoring system and eventually to consider new alert

thresholds for critical monitoring, to improve or better integrate the monitoring system and to schedule new activities.

6 Conclusions

The present paper introduces an innovative use of slope monitoring radar beyond the standard safety-critical purposes.

The capability of IBIS radar to collect long-term datasets, along with the capability to export georeferenced radar maps, allows its use to support the advanced geotechnical modelling required for the assessment of slope stability.

The need for numerical models to be calibrated in order to provide reliable information makes the IBIS radar an effective complementary tool. The general concept has been tentatively implemented in a practical methodology, based on real working conditions and applied in a case study at the El Teniente mine in Chile. This first example confirmed that the rich dataset provided by the IBIS radar can be used to calibrate the FEM numerical model of Camino Principal in order to validate geotechnical parameters and to identify the dominant failure mechanisms which match the movements detected by the radar.

The preliminary results will have to be further validated in different rock mass conditions and slope scenarios, but they represent an encouraging first step in the direction of a more extensive exploitation of monitoring radar data for geotechnical engineering purposes.

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