Optimization of a large-scale slope monitoring system by the correlation between interferometric radar and geological compartmentalization

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ABSTRACT: The implementation of a monitoring system able to catch geotechnical events in large-scale open pits is challenging and requires a combination of different technologies, since rock masses are heterogeneous. Traditional monitoring systems commonly treat rock masses as a discrete and homogeneous domain, which is not representative of the global slope failure process with differentiated deformation along the structure, due to different rock types, joint families and rheology. Interferometric radars have been used as a potential tool in monitoring large-scale geotechnical failures, since they could give a rapid response in all scale deformation, characterize the behavior of the movement, and predict failure time using tools, as inverse velocity. Regardless of the scale of slope monitored, the data obtained is rarely associated with rock types and rheology. This article presents an optimization of a large-scale slope monitoring system, correlating interferometric radar and geological compartmentalization, in a real case of global slope failure.

Keywords: monitoring system, terrestrial radar, global slope failure, rock mass, sectorization.

1 INTRODUCTION

The Gongo Soco Pit is located in Barão de Cocais, Minas Gerais, Brazil. Mining activities started in the late 18th century, with the exploration of gold, and continued until the beginning of the 20th century. Around 1989, iron ore production started in Gongo Soco and continued until 2015, when all operation ceased.

The Gongo Soco pit has two main slopes, North and South Wall (Figure 1). Each one has its own geomechanical characteristics. In addition, the absence of a water pumping system after mining closure increased superficial and groundwater levels, resulting in a lake on the bottom of the pit. Since 2002, the North Wall has been presenting deformations. However, in a global point of view, the slope presented low deformation rates for radar and prism data. In 2019, a major mechanism of a structurally controlled planar failure (called Primary Failure) started at the central portion of the north slope and a robust monitoring system was implemented. In January 2020, the deformation rate reached its maximum value (the peak) and the slope started to gradually fall. The Primary Failure initiated a residual deformation stage after this event. Besides that, as a consequence of the Primary

Failure rupture and a heavy rainfall season, a second failure in the northeastern portion of the Gongo Soco pit (called Secondary Instability) started a deformation process, with high deformation rates and velocity. Since then, the North Wall has been the subject of different studies and analysis, encompassing all aspects related to the rock mass as, for example, the geological properties. The present study is focused on the North Wall global ruptures and the monitoring system designed to optimize the analysis of movement and deformation, considering the correlation between interferometric radar data and the geological compartmentalization.

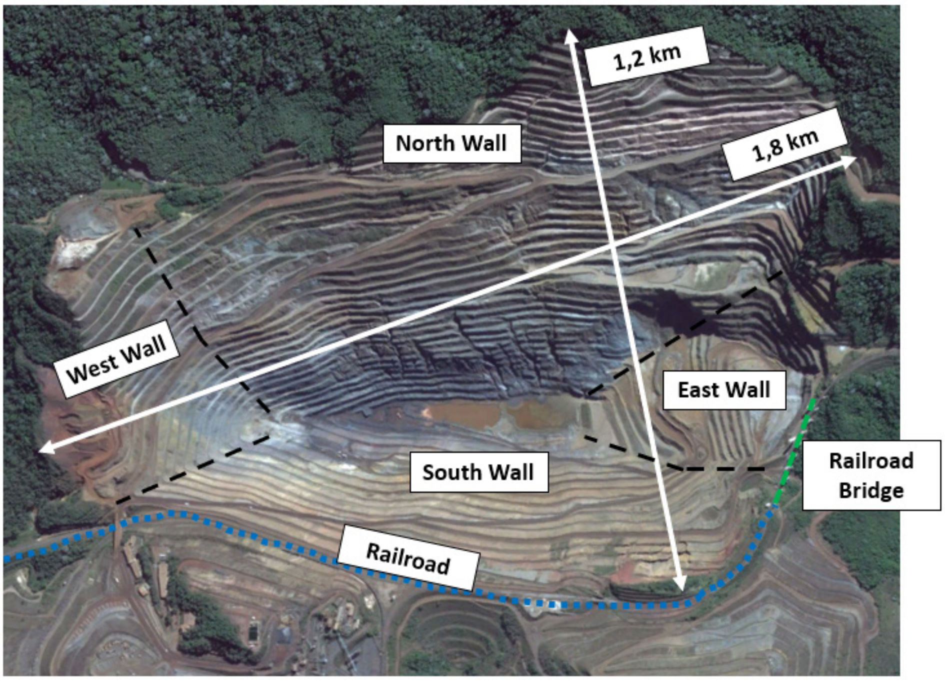

Figure 1. The Gongo Soco Open Pit and its facilities in 2015, when the mine ceased its operation.

2 GEOLOGY AND STRUCTURAL GEOLOGY

Gongo Soco mine is located in the northeast portion of the Iron Ore Quadrangle. Regionally, it's characterized by five large rocks units: archean metamorphic complex, archean volcano-sedimentary sequences of Rio das Velhas supergroup, paleoproterozoic deformed sediments from Minas supergroup, Estrada Real supergroup represented for sediments of a syn-orogenic basin of Transamazonic event (2.250 – 1.900 Myr) and an undeformed Cenozoic basin. In Gongo Soco pit outcrop from the base to the top schists of archean Nova Lima group and a sequence of quartzites, phyllites, Banded Iron Formations (BIFs) and a transition unit between the phyllites and the BIF that comprise Minas Supergroup. Sediments of Cenozoic Basin called Gongo Soco Formation can be seen on the top of stratigraphic sequence. Gongo Soco mine is located on the north fold limb of Gandarela syncline, which is a symmetric structure with the fold axis NE-SW. The syncline has a northern fold limb dipping to the south and the south fold limb dipping to the north (Endo *et al.,* 2020).

Since 2002, different portions in the North Wall of the Gongo Soco pit have been presenting signs of instabilities in rock contact, specially between phyllites, the transitional unit and the BIF (Innocentini 2003), also related to the interaction between lithologies, water level oscillation and precipitation. The rupture of 2019 in the Primary Failure occurred parallel in the shear zone called 01 (Zero One – Figure 2-A), between gray phyllite and the BIFs. The Secondary Instability is delimited in the upper part by the shear zone called 02 (zero two), inside the Nova Lima Schist and deforms quartzites, phyllites, and transitional unit along the movement. Primary Failure and Secondary Instability have different movement mechanisms and due proximity between them, there is mutual influence in both displacements. The North Wall is characterized by rock's foliation and bedding planes nearly parallel to the slope direction (Figure 2-B).

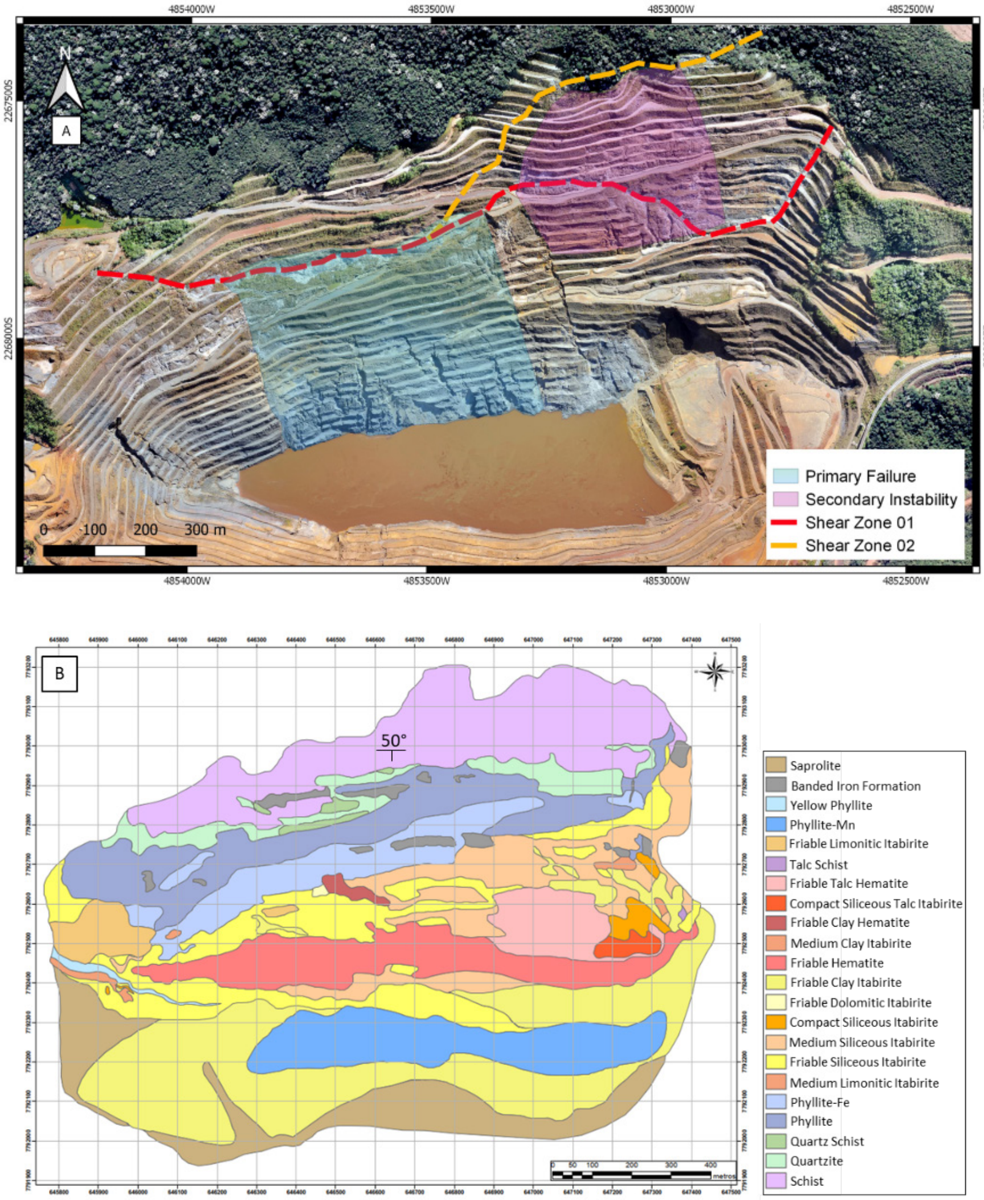

Figure 2. A- Main shear zones (Shear Zone 01 in red and Shear Zone 02 in orange). B- Gongo Soco Open Pit geological map, with medium dip direction around 50°.

3 MONITORING SYSTEM

Interferometry is a technique used to monitor slope stability by measuring the distance from radar to the slope. Each radar has a different technical specification in terms of frequency of wave, range, time of scan, etc. but in general, they present similar mechanisms. The radar transmits a signal to the structure and receives the reflected signal. The change of phase between one received signal and the next one is proportional to the movement which occurs between scans. This deformation is measured in millimeters and indicates slope stability (GroundProbe 2022).

Interferometric radars have been used in the last decade as a potential tool in the monitoring of large-scales geotechnical failures. They could give a rapid response in case of small to large deformations, characterize the behavior of the deformation (progressive, regressive, etc.) and, in some cases, predict failure time using tools as inverse velocity. Additionally, radars are a reliable method when traditional techniques are not possible due to restricted access (Torres & Kanaev 2020). However, regardless of the scale of the slope monitored (and consequently, the inherent heterogeneity and variability of the rock masses involved), the data and information obtained is, usually, rarely associated with the rock types and their rheology.

The monitoring system of the Gongo Soco pit aims to identify geotechnical events on a bench, inter-ramp and global scale using a combination of different technologies. These combinations are justified by the fact that rock masses are naturally variable and heterogeneous, characterized by the combination of intact rock, discontinuities and groundwater. Each component of the rock masses present different behavior and rheology face to a slope failure. This scenario is even more challenging when global slopes initiate the failure process, sometimes in a differentiated deformation process along the slope. In these cases, considering a large-scale slope and the possibility of different rock types, joint families and rheology within the rock mass, treat it as a discrete domain, and homogeny could not be representative.

In 2010, a Robotic Total Station were installed, and in 2013, the first Gongo Soco's interferometric radar started its operation. A current monitoring system generates robust data from an SSR-FX GroundProbe Interferometric Radar (GroundProbe 2023), a Leica Robotic Total Station (Hexagon 2023) and an IBIS-ArcSAR Hexagon Radar (Hexagon 2023). In addition, there are two cameras, orbital radar data and visual field inspections to increase the movement analysis and provide a holistic interpretation.

4 METHODOLOGY

The North Wall of the Gongo Soco pit is an interesting case study of the optimization of a large-scale slope monitoring system by the correlation between interferometric radar and geological compartmentalization, in a real case of global slope failure. Figure 3 presents initial radar data prior the sectorization showing a unique deformation mass. Considering field observation, such as cracks, subsidence, geological faults and water surgency, and geological/structural evidence (rock contacts, dip direction and shear zones), it was possible to verify evidence that led to divide the deformation into two separate sectors, called Primary Failure and Secondary Instability. After radar setup considering the two zones' boundaries, the results were analyzed over time to confirm methodology efficiency.

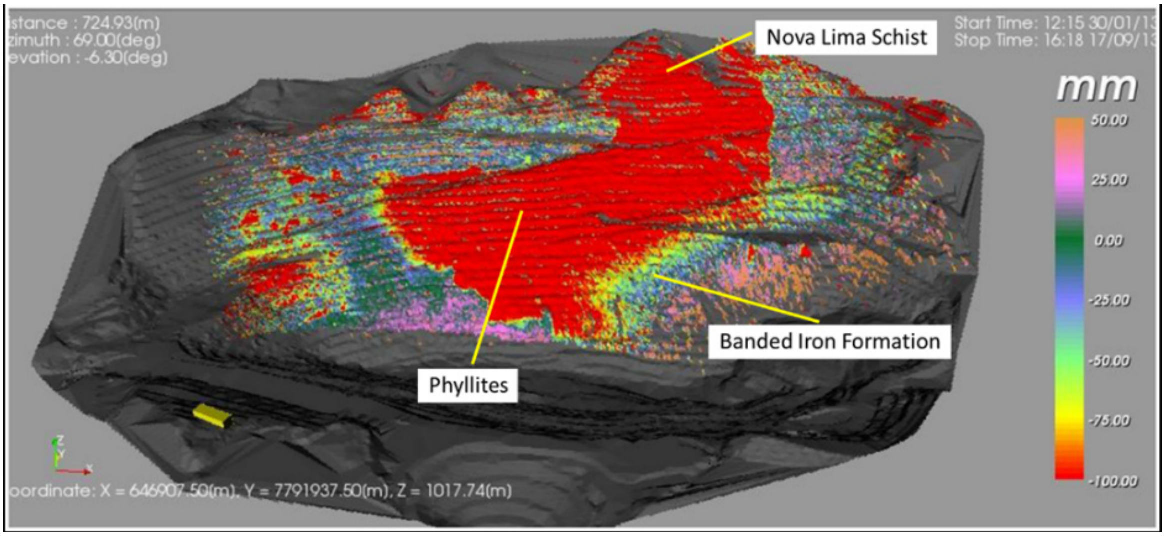

Figure 3. Interferometric radar result before compartmentalization and the main lithology associated with the shear zones.

5 RESULTS

The rock mass divided into two sectors (Figure 4) showed two distinctive behaviors in the graphs generated. The graphs presented in Figures 5 and 6 show how velocity and displacement have different behaviors in Primary Failure and Secondary Instability. The progressive movement in the Primary Failure reached higher displacement rates, possibly due to water level oscillation in the lake and interstitial water. After almost a year, this mass reached a residual movement as may be seen at the current time. The Secondary Instability has its rock deformation highly correlated with precipitation and because of that, the peaks of velocity and displacements occur during the rainy season.

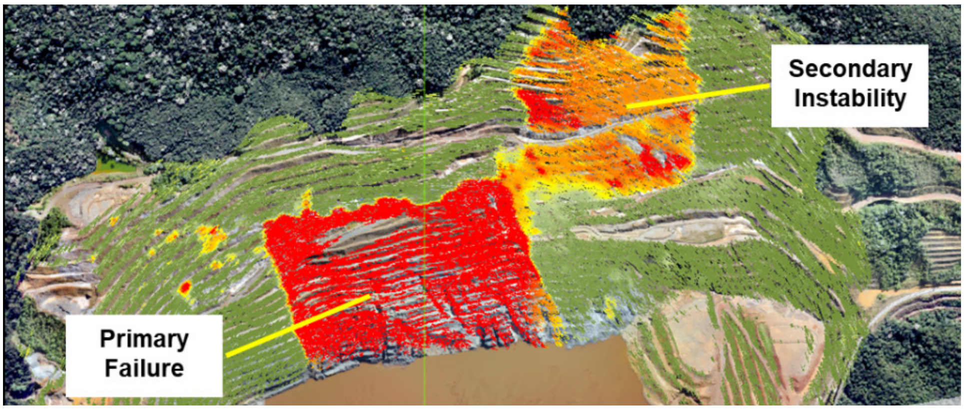

Figure 4. Interferometric radar result after geological compartmentalization showing Primary Failure and Secondary Instability.

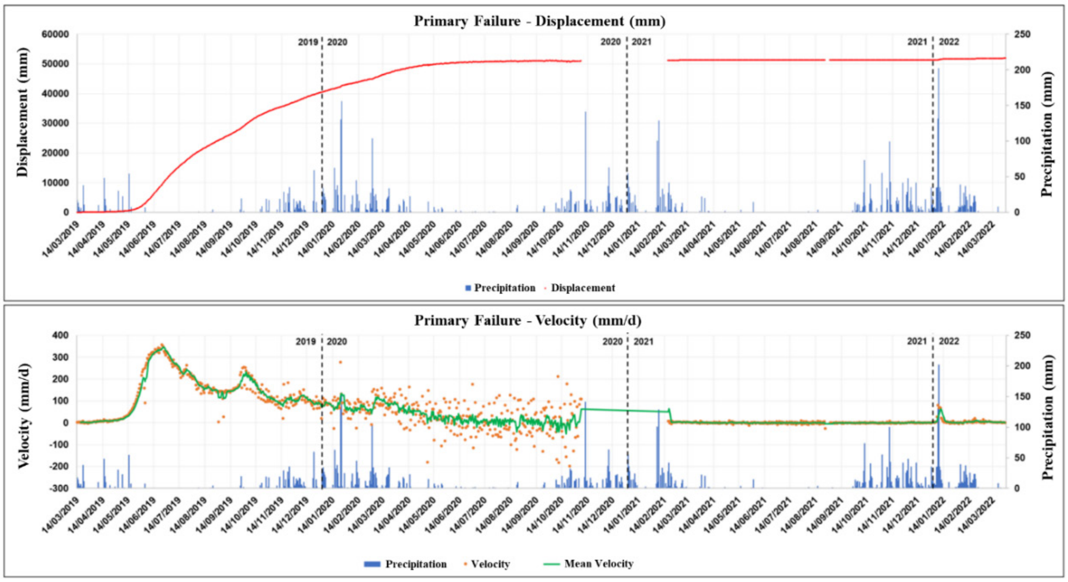

Figure 5. Primary Failure's displacement, velocity and precipitation historical data.

6 CONCLUSIONS

With geological-geotechnical information and considering the rheological behavior of the rocks under North Wall deformation, it was possible to compartmentalize the data received as a unique pattern from radar into two different global movements. This differential behavior was confirmed by historical displacement and velocity graphs. This approach enables efficient follow up of the specific limit establishment and instability evolution, leading to safer mining activities.

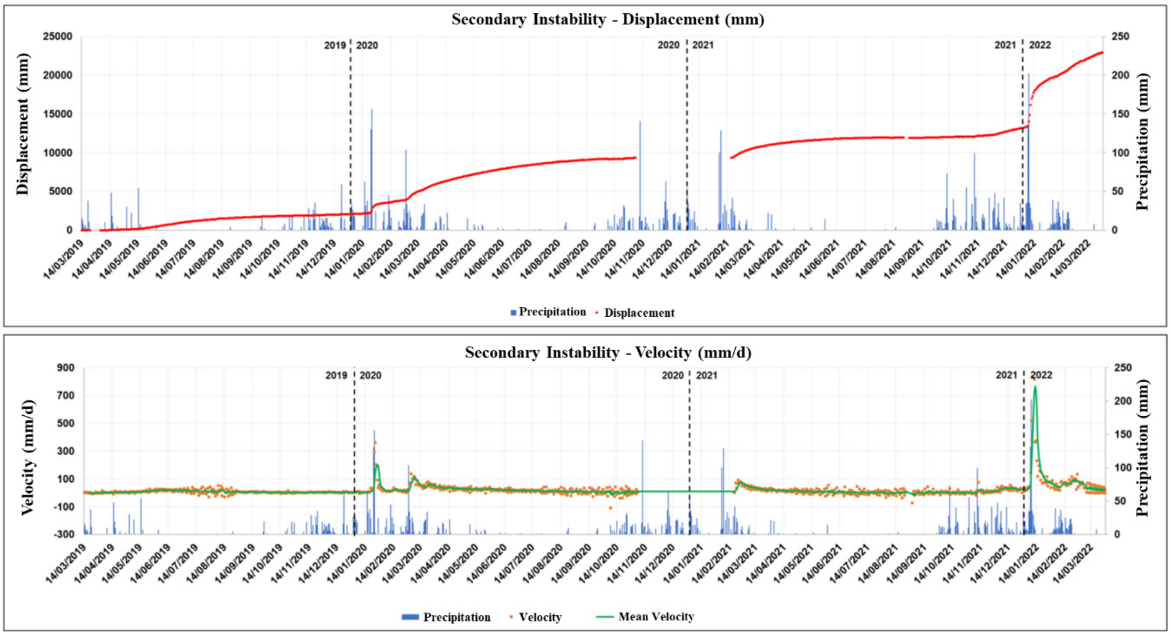

Figure 6. Secondary Instability's displacement, velocity and precipitation historical data.

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