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Risk and opportunity analysis in order to extract the maximum extractable reserve with the optimum slope using Reutech MSR-250 RAR radar results Case study: Chadormalu Iron Ore mine

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Abstract

Understanding the various levels of risk and taking appropriate control operations is the most critical aspect managing unstable walls in large open pit mines. The Hierarchy of Hazard Control gives engineers and managers a tool to effectively tackle their workplace hazards; it also reduces costs and minimizes risks.

Pyramid of hierarchy of risk control is difference for various target, but usually it is containing six items. Accordingly, for each of the geotechnical domains of the Chadormalu large open pit, a unique Trigger Action Response Plan has been prepared. Considering the importance of the wall and the consequences of the fall, distinct trigger thresholds are established for each level of the risk control. These thresholds are based on displacement criteria, instantaneous velocity, and acceleration, calibrated to the associated risk level.

Chadormalu mine is divided into five geotechnical domains. The upper and lower slope of southern wall has a static safety factor of 1.23 and 1.07, respectively. The stability of this wall is crucial as reducing the slope is not feasible, and the wall is located on a significant portion of the ore, along with a high-traffic main ramp of the mine and primary path of groundwater, which this condition is a major concern.

In order to improve safety and sustainable mining, through a comprehensive monitoring strategy including traditional, strategic and tactical monitoring systems, risk management guidelines based on the TARP has been performed during four stages: identifying, assessing, hierarchy of risk control, and reviewing control measures to ensure their effectiveness.

Using traditional monitoring techniques, unstable masses were detected with a dip of 42° and 30° at the bottom and top slope, respectively. Subsequently, using strategic approach to determine the relative dimensions of the instability, also magnitude, velocity, and direction of displacement, with a suitable precision. Finally, a RAR radar was used for tactical monitoring.

The stability analysis of the wall was conducted utilizing three distinct methodologies. The outcomes of the analysis based on attributing the properties of the tectonized zone to the unstable regions yield results that closely align with the actual conditions, yielding a safety factor in the range of 1 to 1.05 for the larger unstable sections. Subsequently, the instability was effectively managed via the implementation of the TARP program and a monitoring system, allowing for mitigation with minimal associated costs and risks.

Keyword: *Slope Stability, Monitoring, TARP, Radar, Risk and Opportunity, Hierarchy of risk control*

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I. Introduction

Mining operations in open-pits rely on sustainable profits, and the primary objective of open-pit mine design is to extract the maximum economic ore deposit in a safe and stable environment, resulting in the highest profit. This requires considering economic needs and safety concerns, leading to the design of open pit mine slopes with a minimum acceptable safety factor. Achieving optimal and economic design operations for an open pit mine requires a closed cycle that involves slope stability analysis, comprehensive understanding of displacement mechanisms, identification of effective factors in the displacement, determination rock mass properties, and back analysis. Monitoring operations play a vital role in linking the design, implementation, validation, and modification cycle. During monitoring, quantitative, and qualitative measurements of the mine walls' reactions to mining operations are performed.

The decline in the quantity of mineral surface deposits, advancements in machine-building industries, adoption of novel monitoring technologies, and implementation of risk management measures - all reactive measures - have resulted in a reduction in cut-off grade and an increase in slope angles in mining designs. From an economic perspective, this reduction in cut-off grade and increased slope angles result in several benefits, increase mining depth, a decreasing Waste/Ore ratio, shorter investment return periods, increased extractable Ore deposit reserves, and more profits.

Displacement of walls is typically caused by four factors: 1) pit and wall geometry, 2) changes in the regional stress regime resulting from the excavation of the open pit (change of initial stresses to induced and effective stresses), 3) groundwater influences (such as increased pore pressure, reduced resistance parameters, softening, and swelling), and 4) stresses induced by blasting and related damage (such as expanding the zone of disturbance and increasing its factor, D).

The movement of open pit mine walls is an inherent characteristic of mining operations, with many slopes experiencing varying degrees of displacement throughout their operational or natural lifespan. Accurately predicting slope movement and associated behavior is a challenging endeavor, which necessitates the implementation of monitoring systems to track slope displacement and associated factors. Such monitoring efforts play a crucial role in managing risk and providing critical information for design and stabilization purposes.

The Bingham Canyon mine, the largest copper mine in the United States, experienced two massive landslides on April 10, 2013, known as the Manefay slides. These landslides resulted in the release of roughly 145 million tons of tailings into the open pit. The first and larger slide, involving almost 100 million tons of tailings, originated from the northeast side of the mine at 9:30 pm. The second slide occurred about an hour and a half later and was preceded by a minor earthquake measuring approximately 2.5 on the Richter scale, which occurred 11 minutes before. Despite the scale of these events, there were no reported injuries, fatalities, or equipment damage, which demonstrated a significant achievement in terms of safety and monitoring system efficacy [1].

The OK Tedi copper and gold mine in Papua New Guinea is highly dependent on rainfall, receiving an annual average of 10-12 meters. Since 2008, the mine has experienced several small-scale landslides due to intense rainfall of up to 350 mm per week, which weakened the rock mass strength parameters and increased pore pressure within structures. However, the mine has managed these incidents effectively through a comprehensive monitoring system and the TARP program [2, 3]. In 2015, a significant landslide occurred, causing a large amount of material to enter the mine pit and damaging the hydraulic shovel. This resulted in a blockage to the high-grade ore section [3].

In 2010, the West Angelas Centre Pit North mine faced a 170-meter landslide on a 40° slope. The landslide was predicted using advanced monitoring and mapping techniques, and there were no injuries or equipment damage reported. Conversely, the KOV copper and cobalt mine in the Republic of Congo experienced a fatal landslide in 2016. Although mining operations had ceased for economic reasons, the collapse of the pit wall claimed seven lives of individuals pumping water from the mine and caused damage to the water management system infrastructure [4].

The mining industry in Iran has also experienced incidents of collapse, but the most significant one was the collapse of the Anguran lead and zinc mine, which caused over 25 million tons of material to fall. However, thanks to an advanced monitoring and mapping system, the incident had been anticipated, and loss of human life was averted. The system also limited the financial damages to the mining operations and the subsequent reconstruction efforts [5].

Ground movements and groundwater behavior are commonly measured in open-pit mining operations using various techniques. These techniques are categorized based on different criteria, including surface and subsurface, large-scale and small-scale (point and area monitoring), strategic and tactical, and manual and read-out tools [6 and 7]. According to Schwartz (2020), monitoring tools are grouped into three categories based on their scanning range, and based on their data access time, they are classified into background, extended and active, and real-time [6]. Vaziri et al. (2010) presented a general chart that classified all monitoring tools according to their objectives, installation location, and scanning scale [8]. Masoumi (2014) developed a comprehensive monitoring program for open pit mine slopes that prioritized risk management and included a responsive plan [9].

The costs associated with implementing monitoring and risk management protocols are relatively minor compared to the expenses that could be incurred in the event of a failure or mining operations shutdown. These monitoring tools have the capacity to meet all the expectations of industry experts over the extended lifespan of the mining process. As a result, they provide a convenient opportunity to assess the effectiveness of mining strategies and initiatives until the end of the mine's operational lifespan.

The process of implementing monitoring programs and deploying monitoring tools is a crucial part of mining operations. This process involves several stages that must be carried out systematically and comprehensively to achieve the desired results. The first stage involves goal determination, where the objectives of the monitoring program are established. Tool selection is the second stage, and it is crucial to select the appropriate tools in terms of type and quantity. Cheaper and simpler tools are used initially to identify small-scale unstable blocks, while strategic monitoring tools are used later to identify movement location, dimension, velocity, and direction. Once the monitoring data is collected, it is analyzed, and high-risk areas are identified. Tactical monitoring operations are then performed to provide real-time, read-out, and highly accurate data. Finally, trigger thresholds are established, and risk management and emergency measures are predicted and executed [6].

The latest and most significant tactical monitoring techniques for open-pit mines include micro-geodetic methods, long-range radar slope monitoring, mid-range radar slope monitoring, laser scanning, and geodetic methods with advanced automated cameras. These methods enable the identification, scanning, risk management, and planning of appropriate reactive measures for unstable areas [6 and 7].

2- 2- Radar Monitoring

The size of pits in open-pit mines presents a practical challenge for the installation of local and subsurface monitoring systems that cannot cover all benches. Risk-based methods are employed to define the monitoring requirements for the entire pit walls [10, 11]. As a result, radars have emerged as a tool that can continuously scan a wide range, provide automatic and remote readings, and offer fast and accurate monitoring, making them the most effective means of implementing rapid warning programs in open-pit mines.

The use of Synthetic Aperture Radar (SAR) for monitoring slope stability and landslide management has been suggested by Harries and Robert (2007) [12]. Modern techniques have enabled continuous information gathering on falling zones or unstable slopes without exposing individuals to high-risk areas. The advantages of radar technology include the ability to monitor large areas with high accuracy as real-time and read-out and to identify external factors contributing to instability, such as blasting, loading, saturation, temperature changes, expansion due to freezing or precipitation, and noise-generating factors such as wind, fog, dust, and temperature. Furthermore, the extent of each effect on the rate or direction of slope movement can also be identified using radar technology.

Kumar et al. conducted a study on a risk management program aimed at reducing the risk of falls and injuries to workers and machinery through a rapid early warning system. They utilized variance techniques, specifically Analysis of Variance (ANOVA), as the mathematical model to analyze the data obtained from the SSR radars. The average velocity was used to identify critical conditions, and the critical value for rock slopes was found to be 0.4 mm/hr [13].

The investigation conducted by Klappstein et al (2014). focused on the instability of a coal mine situated in the rugged topography of the foothills of Alberta, which has a complex geological structure in a thrust belt. Two geotechnical scanning methods - "robotic mapping" and "radar" - were introduced as the most advanced scanning techniques. The analysis of their findings revealed that the evolution of geotechnical monitoring has led to significant improvements in the ability to detect failure mechanisms, displacement rates, and the timing of their occurrence. Moreover, radar monitoring enhances slope stability by providing spatial and temporal coverage, collecting large amounts of data in a short period, and improving the quality of data obtained for slope stability analysis. [14].

Barr et al. (2021) and Wang et al. (2021) conducted a review of case studies examining the practical application of Interferometric Synthetic Aperture Radar (InSAR) in open-pit mining operations where ground monitoring is limited. They found that InSAR is an effective tool for "revealing the unknown" and can be used concurrently for multiple open-pit mines as an integral component of the slope monitoring system. InSAR's ability to cover large areas with high accuracy makes it a strategic system for detecting dangerous areas. The authors used the SqueeSAR multi-interference technique, which has a conventional data acquisition period spanning 11 to 12 days. However, they noted that alternative options of 4 and 7 days are available through the use of alternative satellites. Their results were highly consistent with those obtained through the use of the 3D Slide limiting equilibrium software (Rocscience Inc.'s Slide3 Software) [15, 16]. It's worth noting that the

InSAR method used in their study is less accurate than other radar techniques (such as RAR and SAR) and lacks real-time scanning capability.

3- Introduction of Chadormalu Iron Ore Mine Pit

The Chadormalu iron ore mine, which possesses geological reserves exceeding 400 million tons and economic reserves exceeding 320 million tons, is the largest iron ore deposit in central Iran and the second-largest provider of concentrate to Iranian steel factories, with an annual production exceeding 10 million tons. However, the potential for failure and resulting stock depreciation has led to a decreased risk appetite among both employers and government officials. The final pit of the Chadormalu mine is approximately circular, with a diameter of 1900 meters and a depth of 450 meters, and advances at a rate of 30 to 45 meters per year. However, limited accessibility to the ore deposit, decreased working space resulting in low maneuverability, underground mining below the water table, and wall saturation pose significant challenges. Any sudden or unforeseen instability in both operational and final areas could result in human and financial losses, as well as the cessation of iron ore production, increased waste disposal expenses, and political and social hazards. Therefore, it is crucial to monitor and document the stability of walls, structures such as crushers and power towers near the pit, and groundwater by establishing a monitoring network. This is necessary to ensure safe mining operations and continuous production.

The geotechnical and geomechanical investigations were conducted in 2013 to determine the design of the final pit slope. These investigations involved a total of 6200 meters of core drilling and extensive field surveying. The mine was divided into five geotechnical domains, as shown in Figure 1. Stability analyses were then carried out for various slope angles within each of the five geotechnical domains, using a safety factor of 3.1 as the acceptance criteria, as presented in Tables 1 and 2.

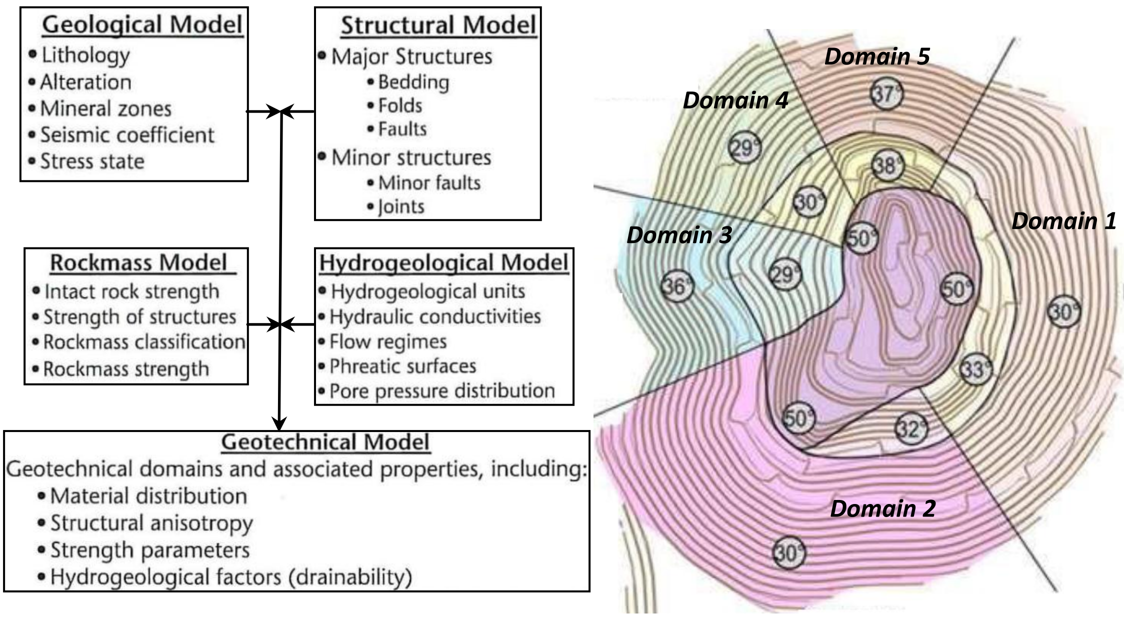

Figure 1. (Left) Component Information and Output from the Geotechnical Model [17] (Right) Chadormalu Open Pit Mine Geotechnical Domain and Final Slope Angle Value

Table 1. Typical FoS and PoF Acceptance Criteria Values to Open Pit Slope Stability Analysis [18]

Slope Scale	Consequence of Failure	Acceptance Criteria		
		FOS (min) Static	FOS (min) Dynamic	% PoF (max) (FOS < 1)
Bench	Low-High	1.1	N/A	25 - 50
Inter-ramp	Low	1.15 - 1.20	1	25
	Medium	1.2	1	20

	High	1.20 - 1.50	1.1	10
Overall	Low	1.20 - 1.30	1	15 - 20
	Medium	1.2	1.05	10- 5
	High	1.30 - 1.50	1.1	≤ 5

Table 2. SLIDE Results Based on Drained Slopes

Domain	Section	Overall		Upper		Lower	
		Angle (°)	FoS**	Angle (°)/Height (m)	FoS**	Angle (°)/Height (m)	FoS**
1	1	28	2.09	31/220	1.26	30/155	1.83
	2	31	1.42	37/136	1.34	31/179	1.34
	3	30	2.03	30/158	1.22	32/169	1.3
2	4	38	1.51	31/142	1.23	30/167	1.07
	5	31	1.81	35/259	1.72	25/118	1.12
3	6	30	1.41	40/174	3.22	26/209	1.3
4	7	31	1.42	30/155	1.16	42/160	1.51
5	8	34	1.41	36/155	1.41	40/135	1.89

4- Monitoring Process in Chadormalu Mine

The hierarchy of risk control as the most commonly used 'template' for implementing risk controls, is a system or framework used to minimize, mitigate and eliminate exposure to hazards. Understanding the various levels of Risk and taking appropriate control operations is the most critical aspect managing unstable walls in large open pit mines.

Pyramid of hierarchy of risk control is difference for various target, but usually it is containing six items. Accordingly, for each of the geotechnical domains of the Chadormalu large open pit, a unique Trigger Action Response Plan has been prepared. Considering the importance of the wall and the consequences of the fall (personnel safety, economic, political and social such as the stock market and upstream industries) the geomechanical properties of the rock mass and the history of monitoring records and the dimensions of the unstable area, distinct trigger thresholds are established for each level of the risk control. These thresholds are based on displacement criteria, instantaneous velocity, and acceleration, calibrated to the associated risk level.

Having a safety program is a necessity, but it pays to make sure that it's also a strategic one. The Hierarchy of Hazard Control gives engineers and managers a tool to effectively tackle their workplace hazards. Prioritizing control methods doesn't just make for a safer workplace; it also reduces costs and minimizes risks.

To prevent major landslides in each of the 5 geotechnical domains, appropriate slope designs have been developed. However, open-pit mines pose a high risk due to their large size, uncontrollable factors (e.g., geology, structure, weather), uncertain input data for analysis, inability to consider all details, and low safety factor compared to other structures like tunnels and dams. As per NIOSH (National Institute for Occupational Safety and Health) regulations, mining risks must be managed through hierarchical risk control, involving hazard identification and risk control measures.

The research team has endeavored to create the most thorough and cohesive monitoring strategy for open pit mine walls, as illustrated in Figure 2, by scrutinizing articles and incorporating existing flowcharts and tables. The highlighted items in yellow denote the tools and techniques accessible for the Chadormalu mine.

The main goal of this research work is to introduce a monitoring program and TARP (Targeted Action for Risk Prevention) program that take into account the risk levels involved in managing instabilities on the southern wall of the Chadormalu mine. To illustrate the implementation of these programs, a case study is presented, which involves identifying and measuring the size and location of a failure, predicting the timing of a collapse, and managing wall instability using visual inspection, micro geodetic methods, and RAR radar.

For effective monitoring of the mine, a risk-based approach is essential. In this instance, the selection of tools and methods for monitoring and responding is based on the level of risk and the potential consequences of failure. As shown in Figure 2, Chadormalu mine employs a comprehensive behavior monitoring strategy for risk management. This approach includes visual inspections, traditional monitoring systems, strategical and tactical monitoring, and surface impressions across four stages which are:

1. Identifying hazards
2. Assessing risks
3. Implementing a hierarchical risk control program

4. Reviewing control measures

Monitoring systems for open pit mines

Traditional monitoring Manual Reading Local monitoring Input and hazard ID 1 st pass monitoring indicators	Strategical monitoring Identify areas with potential for instability Hazard ID Trends analysis Calibration of slope design Mine-to-plan design, reconciliation	Tactical monitoring and alarming Able to provide early warning of slope failure Real time monitoring and 24/7 alarm monitoring	1 st Response/reaction, operational and technical accountabilities Plans Tactial monitoring with alarm trigger thresholds linked to first and emergency response plans with geotechnical intervention	Mine evacuation and emergency response plans Tactical monitoring with alarm trigger thresholds linked to first and emergency response plans without geotechnical intervention
1-Ground Monitoring **1-1- Surface** Visual inspection Face mapping & integration maps Crackmeter Pins indicator Tape extensometers Tiltmeter **2-Water monitoring** **2-1- Surface** Visual Inspection Face mapping & integration maps Precipitation monitoring Other climatology monitoring Water tracing monitoring ✓ Artificial: Any additives to groundwater during the study period ✓ Natural: Physical-Chemical water properties, Stable & unstable isotope Seepage and Spring Flowmeter Sump Water Level & Dewatering Rate **2-2- Subsurface** Observation Well Open hole Piezometer Standpipe Piezometer (single- or multi-level) Vertical profiles of water properties and chemical constituents Ground water tracing monitoring **3-Blasting monitoring** **3-1- Surface** Visual Inspection & Data Gathering	**1-Ground Monitoring** **1-1- Surface (Often automatically, Large Scale)** Manual Prism Survey Monitoring (Prism) Automated Motorized Total Station (AMTS) for Prism Monitoring Global positioning system (DGPS) (RTK, PPK, O-RTK, Static) Photogrammetry Remote Video Laser scanners (LiDAR) Radar slope monitoring (RAR, SAR) Interferometric Synthetic Aperture Radar (InSAR) **2-1- Subsurface (Manual reading, Local monitoring)** Inclinometer Time domain Reflectometry Extensometer Acoustic emission Load cell Strain gauges Shape accelerometer arrays (SAA) **2-Water monitoring** **2-1- Subsurface** Vibrating Wire Piezometer Horizontal piezometers; and/or Multi-level measurement and sample collection systems (e.g. Westbay piezometers) **3-Blasting monitoring** **3-1- Surface** High-resolution and standard-speed video cameras mounted on small UAV drones (the best method to study overbreak) **3-2- Subsurface** Limited Seismic monitoring systems (Determination SD and PPV, blasting effect on the movement and rate of displacement)	**1-Ground Monitoring** **1-1- Surface (Read-out, Real-time reading Large Scale)** Tactical/long range radar slope monitoring Real Aperture Radar (Pencil-beam RAR) Synthetic Aperture Radar (Wide-beam SAR) Long Antenna Real Aperture Radar (Fan-beam RAR) **2-1- Subsurface (Read-out, Real-time reading, Local monitoring)** Inclinometer Time domain Reflectometry Extensometer Vibrating Wire Extensometer Shape accelerometer arrays (SAA) Network Smart markers (Geo4Sight NSM)-Wireless in-ground monitoring platform **2-Water monitoring** **2-1- Subsurface** Multi-Point Vibrating Wire Piezometer (Fully grouted) TDR (Monitoring Groundwater Levels Using a Time-Domain Reflectometry Pulser) **3-Blasting monitoring** **3-1- Surface** Seismic monitoring systems (Consist of a number of geophones installed in the pit slope, which record all microseismic movements down to 0.001mm, long-term monitoring system)	Tactical/long range radar slope monitoring Real Aperture Radar (Pencil-beam RAR) Synthetic Aperture Radar (Wide-beam SAR) Long Antenna Real Aperture Radar (Fan-beam RAR) Automated Surface Extensometers with Remote Alarm	

Figure 2: Generic slope monitoring strategy

Following the risk assessment, a customized Trigger Action Response Plan (TARP) is developed for each wall or geotechnical domain, based on the Risk Control Pyramid (Figure 3). The TARP outlines a rapid response warning program aimed at mitigating potential risks in each area. Then, taking into account the geomechanical factors of the rock mass and the behavior history of each geotechnical domain, different trigger thresholds are determined based on the criteria of displacement, instantaneous velocity and acceleration and according to the degree of risk for each of the classes of the risk control pyramid.

Based on the information provided in Table 3 and considering the past mining collapses, the technical and operational response plan for the Chadormalu mine has been developed

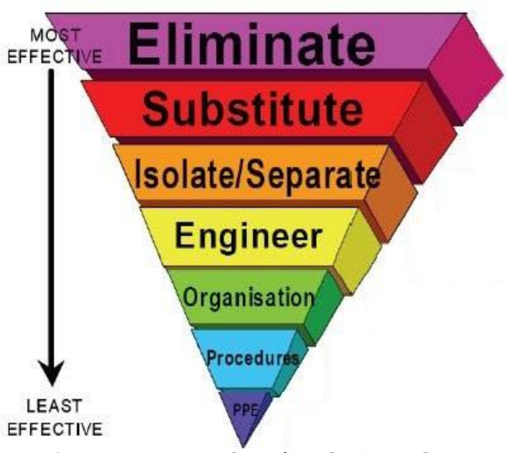

Figure 3: Hierarchy of Risk Control

Table 3. Southern wall Trigger Action Response Plan

Trigger	Conditions (criteria)	Hierarchy of Risk Control (Typical mine responses)	Monitoring systems
Displacment (mm) 10-50 mm	< 2 mm/day	1. Routine operations and planning 2. Personal Protective Equipment	Slight or no deformation Traditional monitoring Manual Reading Local monitoring Input and hazard ID 1^{st} pass monitoring indicators
Velocity (mm/day) Average velocity 7 to 14 days Average velocity of the prism or point	2-5 mm/day	1. Routine operations and planning 2. Gradual slope deformation, Constant rate (no acceleration) 3. Personal Protective Equipment 4. Making changes to the way in which people work 5. Education and training (emergency response in the event of incidents)	
Velocity (mm/day) Average velocity of 7 days Average velocity of the area	5-10 mm/day Height>50 m	1. Use Engineering Controls 2. Reduce number of blasthole, specific charge, … 3. Perform controlled blasting. 4. Mining operations management 5. Cases 3 to 5 of the second risk level	Strategical monitoring Identify areas with potential for instability Hazard ID Trends analysis Manual Prism Survey Monitoring (Prism) Strategic/long range radar slope monitoring
Velocity Ratio (VR)>1.5 VR=Current velocity/previous velocity Typically, the previous 12 or 24 hours are used for evaluating VR. Average velocity of 7 days	10-20 mm/day Height>50 m	1. Use Engineering Controls 2. Temporary Pause mining 3. Transfer of lightweight equipment and facility affected by instability to safe areas. 4. The Reduce number of blasting. 5. Mining continues under controlled conditions e.g. 6. daylight only; periods of no rainfall; spotter in place 7. Cases 3 to 5 of the second risk level	
Check the velocity for 7 days Inverse Velocity (1/mm/day) I_v=0.05 to 0.1	>20 mm/day Progressive Height>50 m	1. Isolate the hazard from the person at risk. 2. Pause mining. 3. Isolate laydown areas below failure (Remove personnel and equipment) 4. Response/reaction, operational and technical accountabilities Plans: 5. de-escalating operation, scaling of the bench surface, ripping and dozing operation with bulldozer to reduction of unstable zone slope, dewatering 6. Pause blasting under unstable area	Tactical monitoring Able to provide early warning of slope failure Safety critical Tactical/long range radar slope monitoring Real Aperture Radar (Pencil-beam RAR) Inclinometer Time domain Reflectometry
Check the velocity for 7 days Inverse Velocity (1/mm/day)<0.05 Typically, 3, 6, and 12-hour extrapolations are used to predicted time-of-failure	>30 mm/day Progressive Height>50 m	1. Emergency response plans 2. Eliminate the hazard or 3. Substitute one risk for a lesser one 4. Pause mining & blasting. 5. Complete evacuation of the mine 6. Calculate the dimensions and volume of the failure. 7. Planning for after the reduce velocity or after the failure	

5- The History and Evidence of Instability in the Southern and Southeastern Wall Based on Monitoring Results

The monitoring results of the southern and southeastern wall (geotechnical domain 2) of the Chadormalu mine reveal evidence of instability, including:

1. The presence of relatively thick alluvium and highly jointed conglomerate with water flow.
2. The schist lithology is susceptible to liquefaction due to high water absorption and low drainage under the conglomerate layer.
3. The diorite and heavily crushed granite lithology have a Geological Strength Index (GSI) of approximately 25.
4. The lithological structures and boundaries have medium permeability based on Lugeon Test (Freeze & Cherry 1979).
5. Multiple parallel and intersecting faults and permeable structures based on the results of observational monitoring (visual inspection):
6. Multiple parallel and intersecting faults and permeable structures are evident through observational monitoring. This includes matching the location of leaks with the location of structures and lithological boundaries based on surface maps and relating seepages of different levels to each other based on physicochemical characteristics.
7. The groundwater level is high as shown by the results of openhole piezometers.
8. 70% of seepages in this area occur in the groundwater path with a charging percentage of 5% to 20%, as indicated in Tables 4 and 5.

Table 4. Tritium Analyses and Recharge Estimate for Seepage of Bottom Pit (Bredenkamp 1995)

Sample Identification	3H enriched (TU)	3H Age (yrs)	Depth/ water strike (m)	Effective porosity	Recharge (mm/yr)	Ave. Annual Precipitation (1996-2017)
Bottom of pit Seepage	0.31	49.4* to 70.2**	100	0.01	14 to 20	105.0

** The initial concentration of tritium = 10 TU, its average concentration in the rains of recent years in Tehran.*
** The initial concentration of tritium=15TU, its average concentration in the rains of recent years in the Northern Hemisphere.*

Table 5. Recharge Estimate with Used Deuterium Excess method for Seepages (Alison et al 1984).

Sample ID	Location	^{2}H (per mil)	^{18}O (per mil)	^{2}H Value based on GMWL Equation	$^{2}\delta$-excess	Recharge%
S1345	Southern Wall	-40.28	-5.16	-31.08	-9.20	4.73
S1405		-34.96	-4.52	-25.96	-9.00	4.94

Geotechnical domain 2, particularly in the lower slope section, has been identified as one of the most critical walls based on rock mechanics properties, GSI values, groundwater conditions, and slope stability analysis for drained conditions. Consequently, two high-risk areas in the southern and southeastern parts have been identified through visual inspection, pin network, quantitative and qualitative groundwater monitoring (leaks and piezometers), and a regular micro-geodetic network (target deployment with a regular checkerboard pattern from the highest to the lowest level). Figure 4 displays a displacement rate of 2 mm/day in saturated areas.

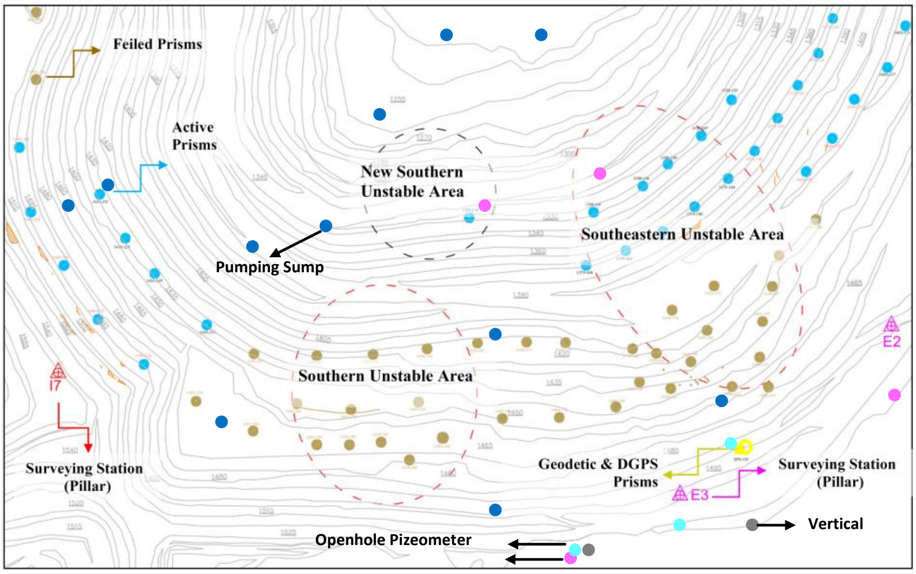

Figure 4. Monitoring Network of Southern Wall of Chadormelo Open Pit and Location of Dangerous Areas Identified based on Survey Monitoring Result (Micro Geodetic)

Between **01 Feb. to 07 Feb. 2020**, micro-geodetic monitoring identified a new hazardous area with a height of 60 meters in the southeastern pit. Based on Table 3, continuous and strategic monitoring was initiated using the MSR250 radar due to the displacement rate exceeding 5 mm/day. After 7 days, the displacement rate steadily increased and reached 10 mm/day for the lower section of the hazardous area (as shown in Figure 5).

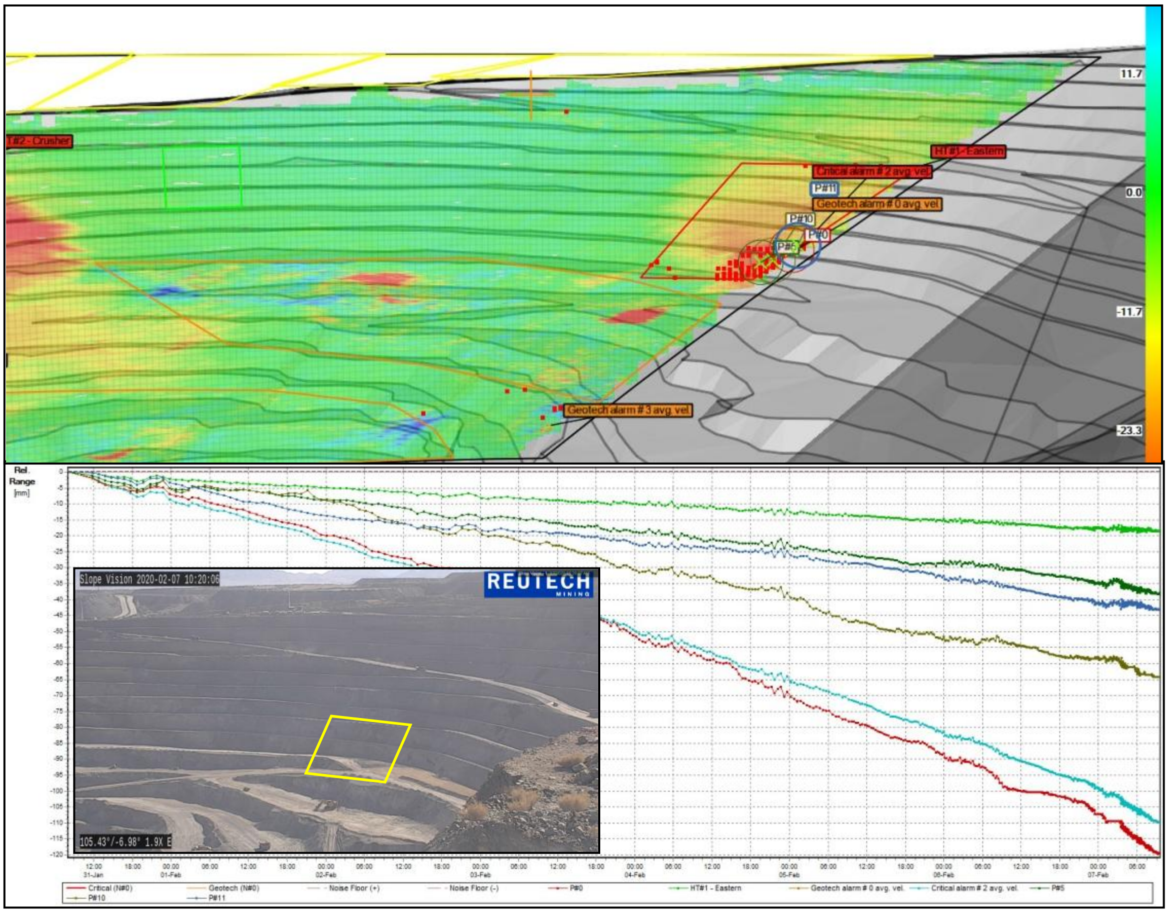

Figure 5. Location of Detected Unstable Area by MSR250 Radar (up) Scan Region & Image of Slope Vision Camera (down) Cumulative Relative Range Movement (mm)

The Trigger Action Response Plan (TARP) has implemented several measures, including:

1. Conducting strategic and ongoing radar monitoring.
2. Restricting the movement of machinery traffic.
3. Temporarily stop loading in bottom of unstable area.
4. Excavating a sump and initiating pumping.
5. Using controlled blasting methods and review blasting pattern based on GSI value and UCS.
6. Mitigating the impact of blasting by decreasing the frequency of explosions, reducing the number of blastholes, and minimizing the amount of explosive material used (minimizing PPV).

Between **02 June to 07 June 2020**, the responsive measures that were implemented resulted in a significant decrease and stabilization of the displacement rates, as shown in Figure 6. Therefore, the blasting and extraction operations were resumed.

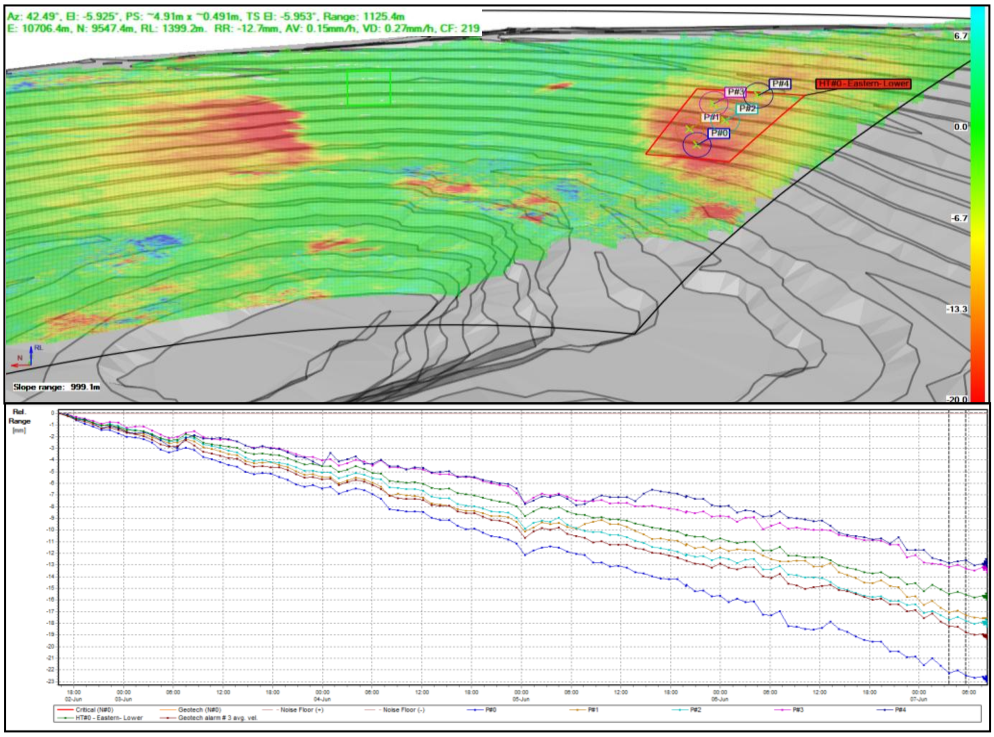

Figure 6. Location of Southeastern Unstable Area (up) Scan Region & Synthetic Map (down) Cumulative Relative Range Movement (mm)

Between **February 20th and March 20th, 2021**, the MSR250 radar monitoring showed that zones I and II were relatively stable. However, as depicted in Figure 7, a new unstable area was discovered with a displacement rate of 5.2 mm/day during this month. Based on visual inspections, the following factors can lead to instability in the levels of 1285,1270, and 1255.

- ✓ High slope of the wall.
- ✓ Narrow width of the benches.
- ✓ The presence of numerous tensile cracks in the benches.
- ✓ Penetration of water leaks into cracks and jointed rock masses.
- ✓ Saturation conditions (prone conditions for freezing, dilatation and liquefaction).
- ✓ Inappropriate pumping and dewatering operation (Figure 8).
- ✓ The explosion of large production blocks.

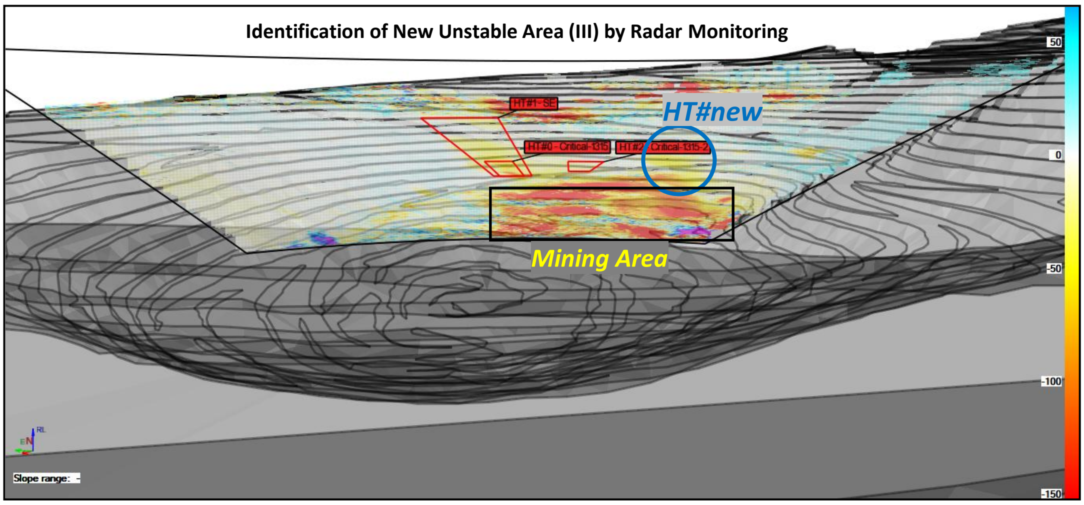

Figure 7. (Up) Scan Region & Synthetic Map (Down) Cumulative Relative Range Movement from 20 Feb. to 20 Mar. 2021 (mm)

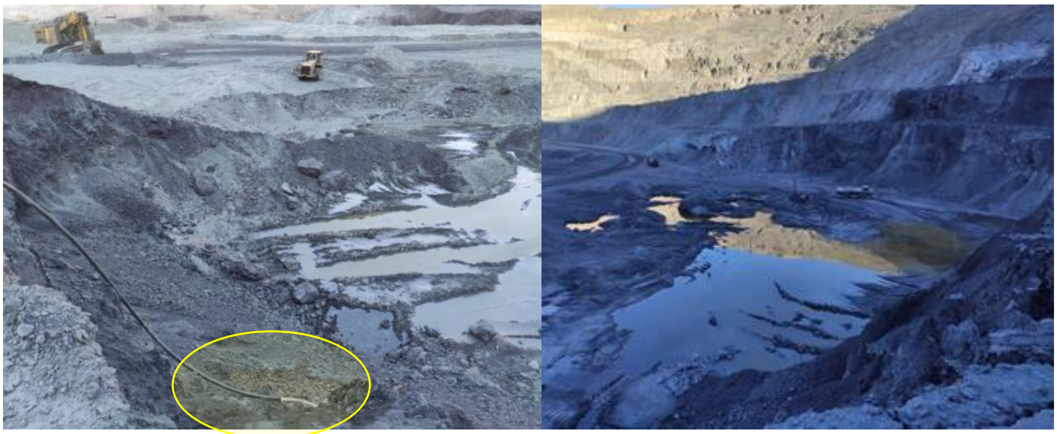

Figure 8. Unsuitable Dewatering and Wall Saturaion Condition in Downstream of New Dangerous Area (Winter)

Between **21 Mar. to 15 Apr. 2021**, a new risk area emerged in the operational zone of the southern wall, resulting in the identification of two distinct hazard zones at the top (with a height of 50 meters) and bottom (with a height of 60 meters) of the ramp. The upper part was initially identified and secured by installing a safety berm and safety ribbon in the ramp's toe to prevent any harm to transportation machinery, such as trucks, in case of a collapse. The displacement values and velocity in these zones were significantly different from other predetermined areas, leading to the identification and separate investigation of HT#4 and HT#6 hazard zones using the Reutech's RAR radar, as shown in Figure 9.

The map in Figure 8 shows the cumulative displacement of hazard zones 4 and 6. Until April 6, the displacement rate was a safe 5.2 mm/day. However, after blasting and extraction operations started in the lower area of hazard zone 6, the displacement rate increased. By April 12, it had reached approximately 6 and 9 mm/day, and by April 14, it had climbed to around 16 and 28 mm/day. Following the TARP plan, blasting was halted on April 12, and loading operations under the hazard zone were suspended on April 16. These recorded quantities were the first experience of mine monitoring, and the resulting stresses were defying description and response of the unstable mass were extremely sudden and rapid.

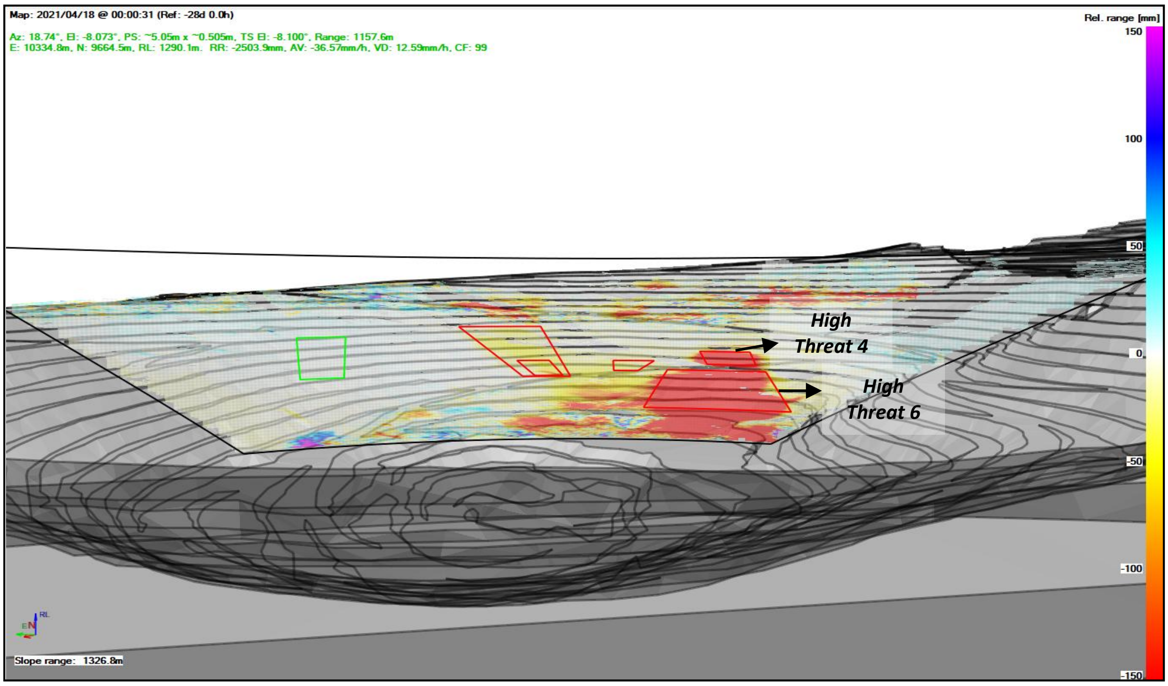

Figure 9. High Movement & Critical Condition of Unstable Areas No. 4, No. 6
(21 Mar. to 15 Apr. 2021)

On April 15, 2021, despite the suspension of mining operations, the velocity in the HT#4 and HT#6 hazard area reached 25.1 and 33.3 mm/hr, respectively. It is noteworthy that the velocity exhibited rapid acceleration, such that within a week of its identification, an emergency evacuation was declared, and a secondary response plan was implemented. Specifically, on April 16, between 7:30 and 8:45 am, the velocity in the HT#6 hazard area reached 20 mm/hr, as illustrated in Figure 10.

- Stop loading in the lower instability zone within a radius of several hundred meters;
- Conducting emergency evacuation of personnel and equipment;
- Blocking access to ramps;
- Suspending all blasting activities in the lower part within a radius of several hundred meters;
- Installing warning signs (visible day and night) at different benches;
- Expanding and enhancing the safety berm created on the ramp's toe;
- Construction a pumping sump and dewatering operations to eliminate surface flow leading to the unstable area;
- Conducting daily visual observations and inspections;
- Establishing and implementing various alarm thresholds for unstable areas in the MSR250 radar software based on velocity.

Figure 10 illustrates a map and a 3-day cumulative displacement chart of the identified risk zones, indicating the impact of implementing the Trigger Action Response Plan (TARP).

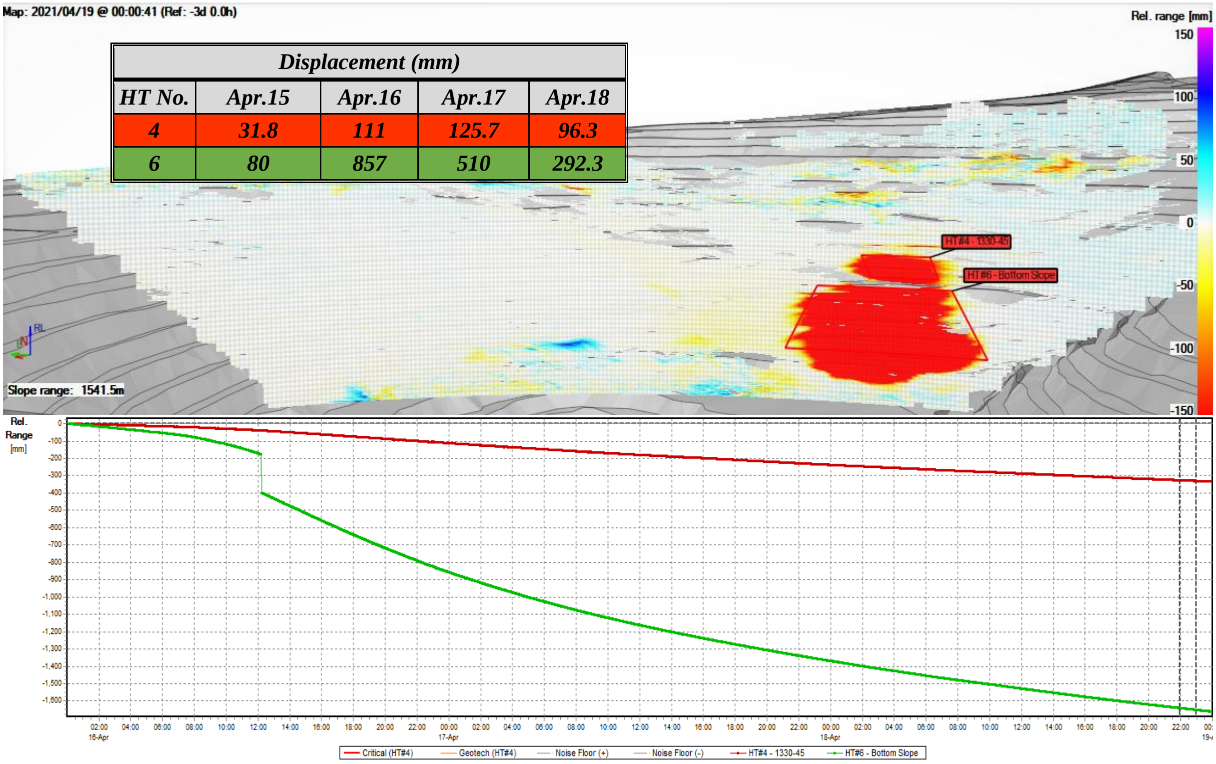

Figure 10. High Movement & Critical Condition of Unstable Areas No. 4, No. 6 (16 Apr. to 19 Apr. 2021)

As shown in Figure 10, on April 18th, after 24 hours of initial response actions for risk management, the daily cumulative displacement for HT#4 and HT#6 were 96 and 292 mm, respectively. This represents a decrease of 23% and 43% compared to the previous day.

18 Mar. to 16 Apr. 2021: The identification and investigation of effective factors in instability using monitoring tools:

Blasting and muckpile loading:

Figures 11 and 12 show the effect of the position and size of the blasting block and the muckpiles loading operation on the displacement and velocity changes of the unstable areas before and after the intensification of the instability. Initially, blasting of production blocks with large diameter holes under wet conditions and muckpiles loading operation have resulted in increased displacements (Figure 11). After a day, the trend of changes decreased, and stability was restored to an acceptable level. However, blasting of over eight blocks with 242 blastholes under the HT#6 and a large blast with 146 holes on April 12, 2021, followed by muckpiles loading operations, caused the re-exacerbation of this area (Figures 10-12).

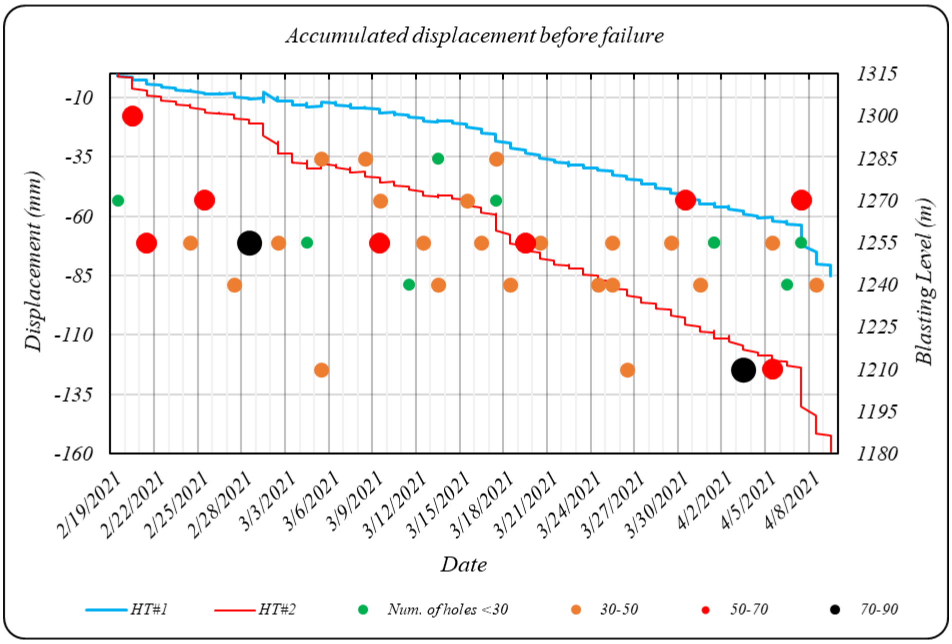

Figure 11. Cumulative Movement and velocity of unstable Areas HT # 4 and HT # 6 (21 Mar. to 18 Apr. 2021) - Based on MSR250 radar results

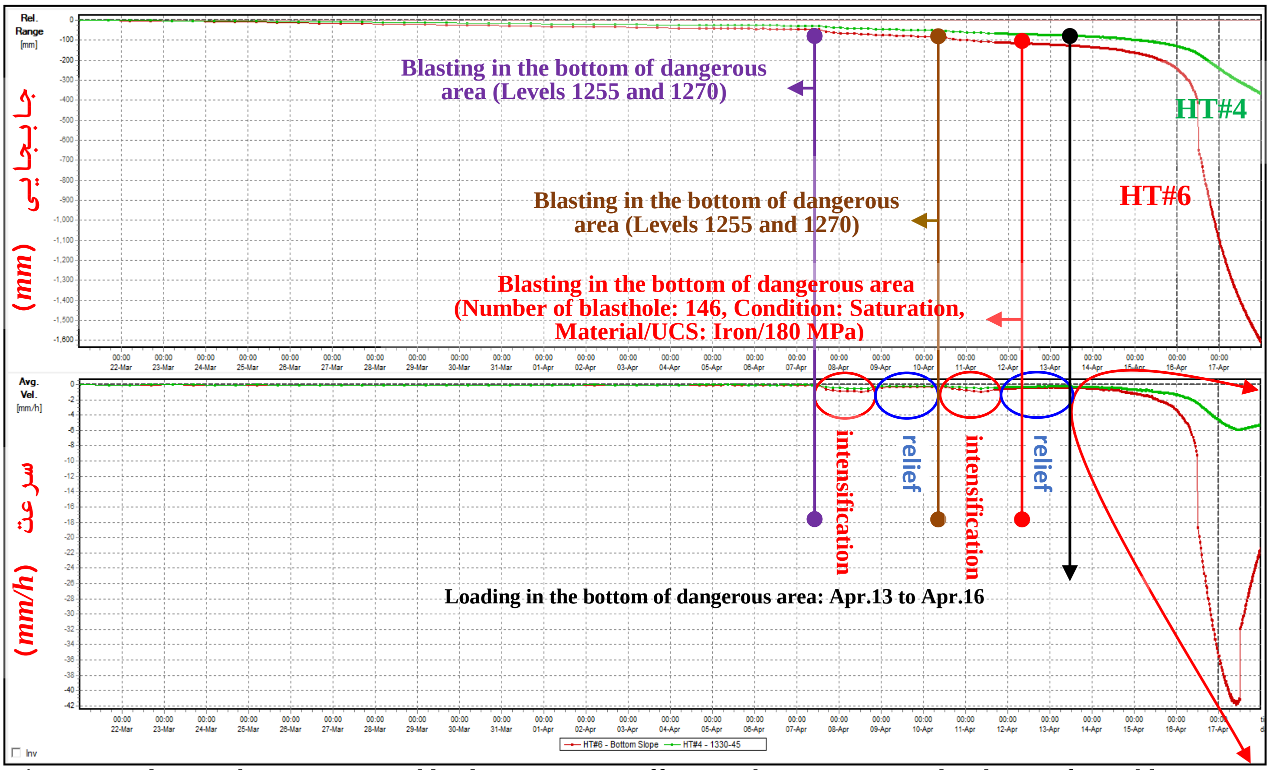

Figure 12. Blasting characteristics and loading operations effects on the Movement and Velocity of unstable areas HT # 4 and HT # 6 before the instability intensifies

Destructive Effects of Water on the Reduction of Strength Parameters (pore pressure)

The faults in this area mainly have a right-slip orientation, with a slope greater than 75º and trend northwest-southeast and northeast-southwest. Joints study in this region of the mine is practically unfeasible due to the high level of Alteration and weathering and heavy fractured rock mass (refer to Figure 13). The saturation of fault gouges and the reduction of strength parameters (cohesion and internal friction), such as increasing pore pressure, have led to the formation of an unstable mass boundary along the faults. Blasting and muckpile loading operations at the base of the faults have stimulated and displaced them, exacerbating the instability in the area.

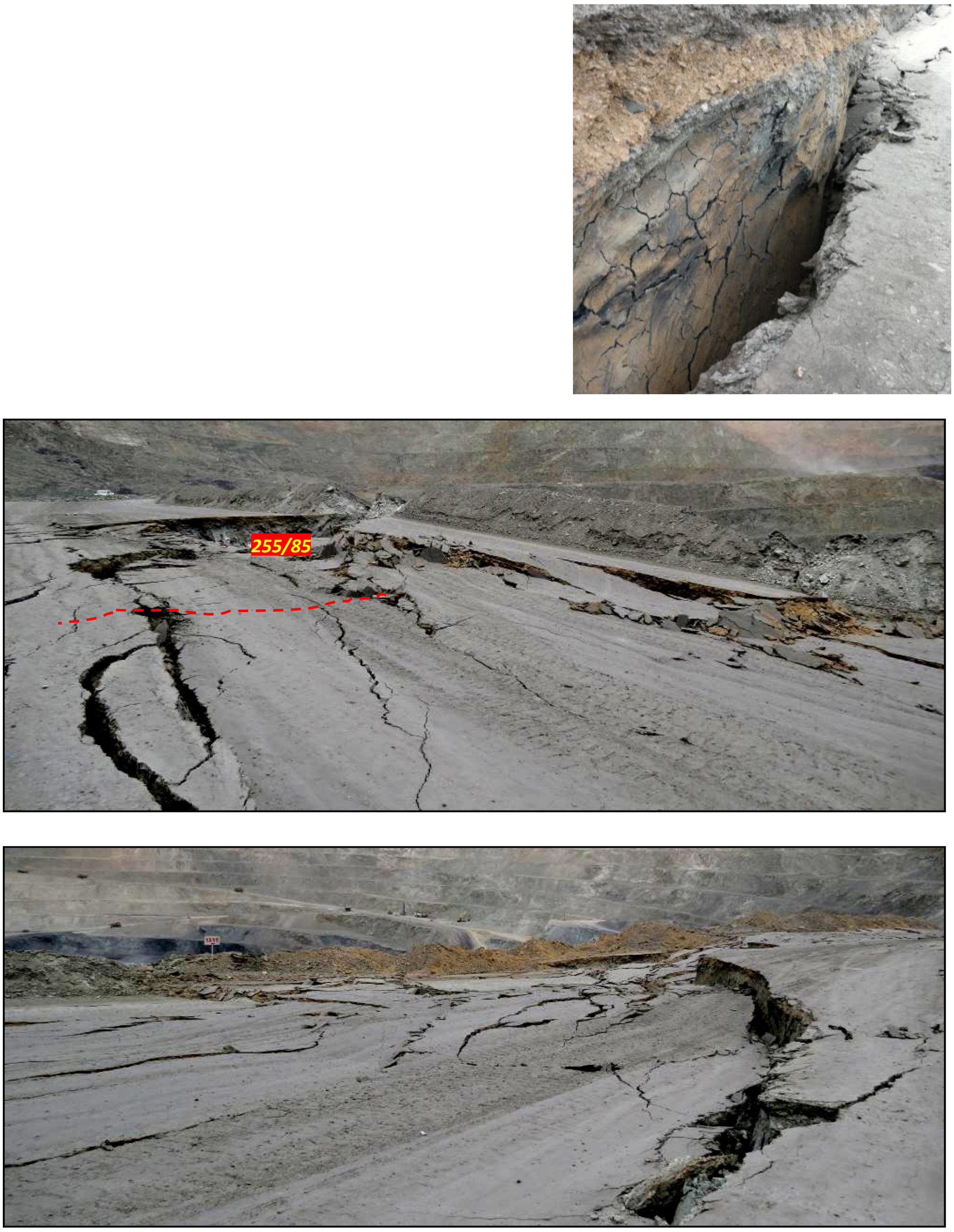

Figure 13. Adaptation of the main crack direction with faults direction in the unstable area and the destructive effect of groundwater on the strenght parameters of the gouges.

Destructive Effects of Groundwater

The pushback was performed by 130 meters in toe of hazard zone 6. the pushback causes the groundwater head and pore pressure at DP02 piezometer behind the pit slope to reduce because groundwater is draining through the pit walls into the excavation.

According to the opinion of the Read and Stacey 2009 in Figure 14, however, although the absolute pore pressure has reduced, but the low hydraulic coefficient has resulted an increase in the pressure gradient has occurred from the materials behind the pit slope to the newly toe. Consequently, this has generated a leakage force towards the interior of the pit, intensifying instability.

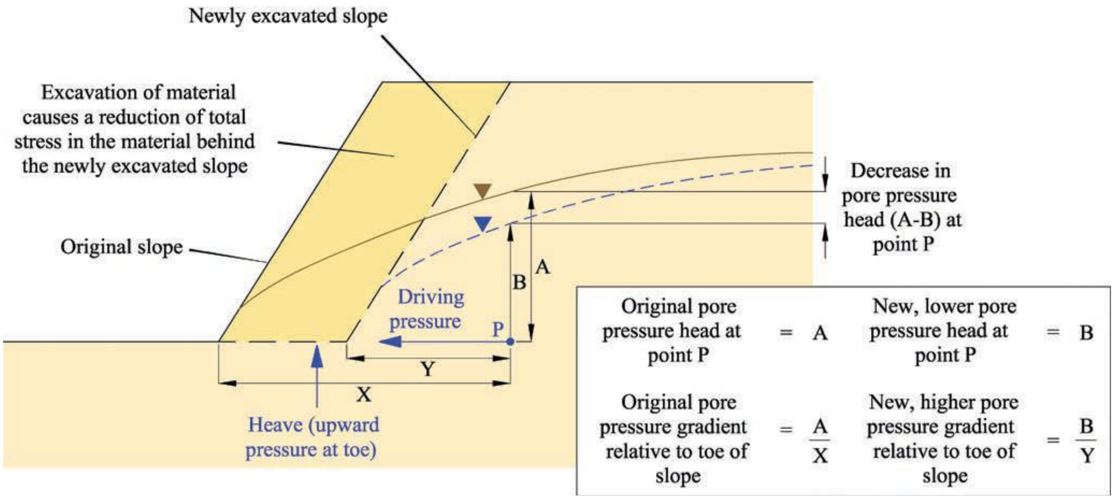

Figure 14. Illustration of dynamic groundwater flow system behind a pushback (Source: Read & Stacey, 2009)

After the instability event, two sump were excavated near the unstable area: one at the bottom of high threat 6 and another at bottom of high threat 4. These sumps were pumping and drying daily. Over an 8-day period, the 720 and 45 m^3 was pumped, respectively. This operation resulted in a significant decrease in the water level of 65 cm.

Pit Geometry

The designated operational area within the pit is characterized by a steep wall slope of 40°. However, for this specific section, the final slope is designed to be between 25° and 30°, with a safety factor ranging from 1.07 to 1.12, taking drained conditions into consideration.

Between **12 May 2021 to 14 Apr. 2021**, the displacement rate was significantly decreased by stopping the mining operation (blasting and mining) in the toe of HT#6 and ceasing the movement of machinery in accordance with Table 6 and Figure 15.

Table 6. Influence of TARP on the displacement process of unstable areas HT # 4 and HT # 6

HT No.	Apr. 14	Apr. 15	Apr. 16	Apr. 17	Apr. 18	Apr. 19	Apr. 22	Apr. 25	Apr. 30
HT#4	16.2	31.8	111	125.7	96.3	70	65.1	52.55	42.6
HT#6	28	80	857	510	292.3	177.3	145.7	109.6	78.1

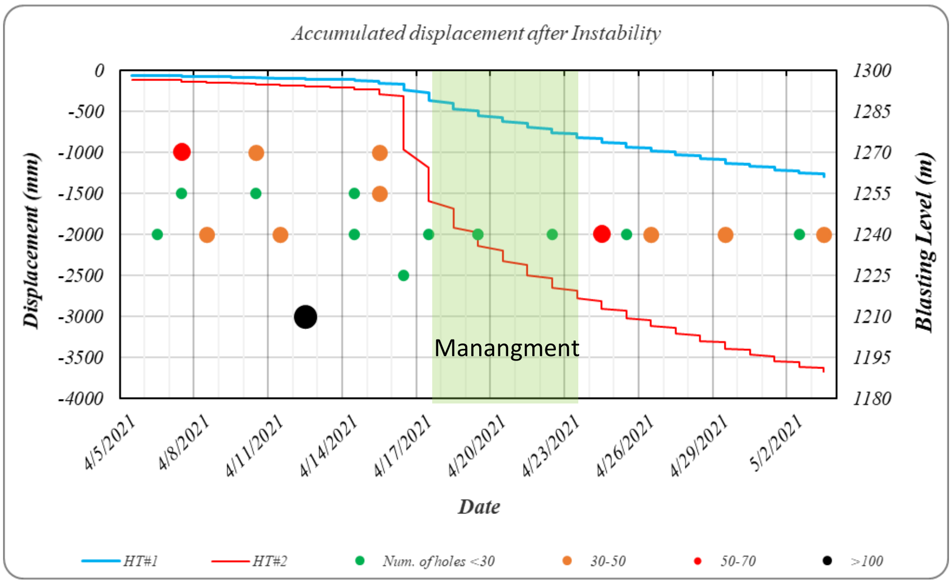

Figure 15. Influence of trigger action response plan on the displacement process of unstable areas HT # 4 and HT # 6

Based on the movement pattern of the unstable area, which involves upward movement at the toe and subsidence at the crest, as well as the rock mass's very low GSI, the characteristics of the structures and visual observations, it can be concluded that the unstable area of HT#6 exhibits a circular failure pattern. Figure 16 shows the direction of the unstable area movement.

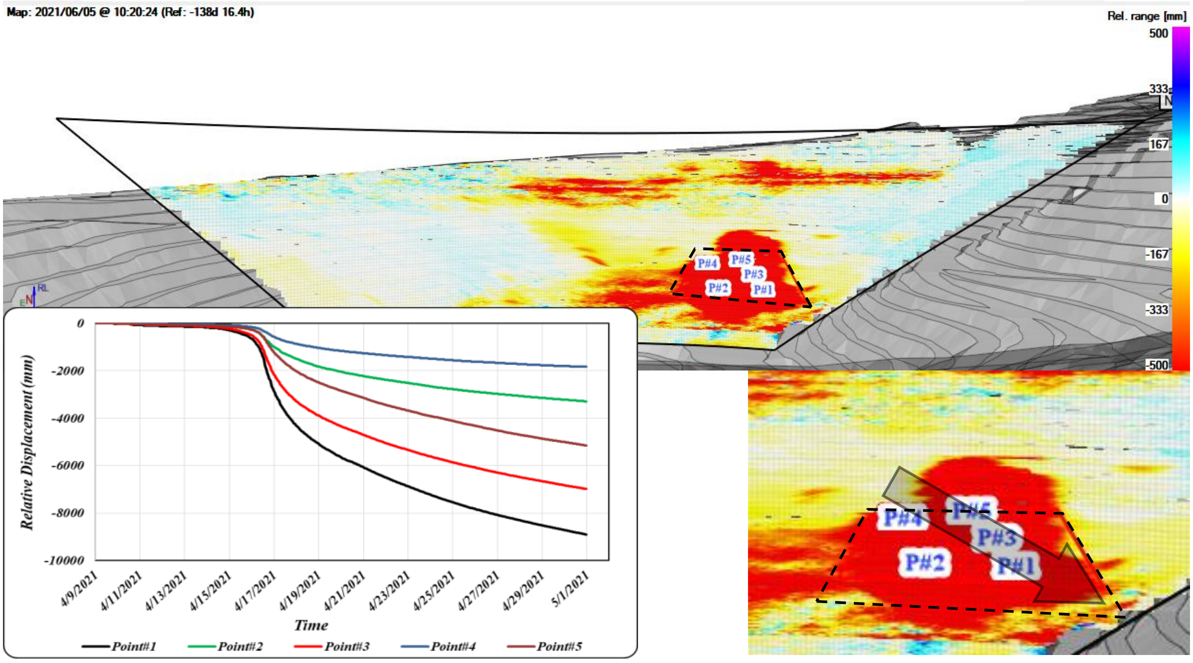

Figure 16. Displacment value in the difference parts of unstable area HT#6

6- Measures Implemented and Limit Equilibrium Analysis for the Unstable Area

Instability is occurred in the operational mining area, that is composed of very jointed granite and diorite lithology with the GSI value 25 and types of faults. To analyze the unstable area accurately and estimate the depth and extend of a potential failure, a 2D cross-section was prepared (comprising all relevant lithological, structural, hydrogeological, and geomechanical details) in accordance with Figure 17. The cross-section was used for slope stability analysis and to present an alternative mining plan.
To accurately analysis the unstable area and estimate the potential depth and extend of a failure, A model has been evaluated using the limit equilibrium approach with Slide software, which incorporated the following details:

- All lithological formations were categorized into different classes based on their GSI and IRS values, ranging from weak to strong.
- Considering that the height of the unstable area is 90 to 105 meters. Also, the nature of production blasting (uncontrolled and large-scale method), the thickness of the blast zone of 40 meters and the disturbance factor value of 0.7 were considered.
- Geological structures play a significant role in the instability of the open pit walls. Therefore, the model incorporates two methods:
  1- A one-meter-thick layer with residual strength properties based on laboratory test results.
  2- The consideration of properties related to the "tectonic zone" in the unstable area.
- Due to the high water level in the piezometer, the presence of water in all the blastholes and the presence of numerous seepages in almost all the benches of the unstable area, the area is considered completely saturated.
- To fully investigate the area, the model was executed in three scenarios, ranging from the most optimistic to the most realistic.

Tables 8 and 9 present the input parameters and the results of the slope stability analysis. In three cases where the lithologies were characterized by a fractured rock mass, the safety factor for the unstable area of HT#4 and HT#6 was less than one, resulting in the formation of a failure with a height ranging from 46 to 146 meters. The accuracy of the analysis was verified by comparing the results with those obtained through radar monitoring. The most appropriate result was obtained by characterizing the rock mass as fractured and considering the zones as tectonized zones. By applying these characteristics, the final pit walls can be reanalyzed, and if necessary, modifications to the pit plan can be made, or risk management measures can be implemented.

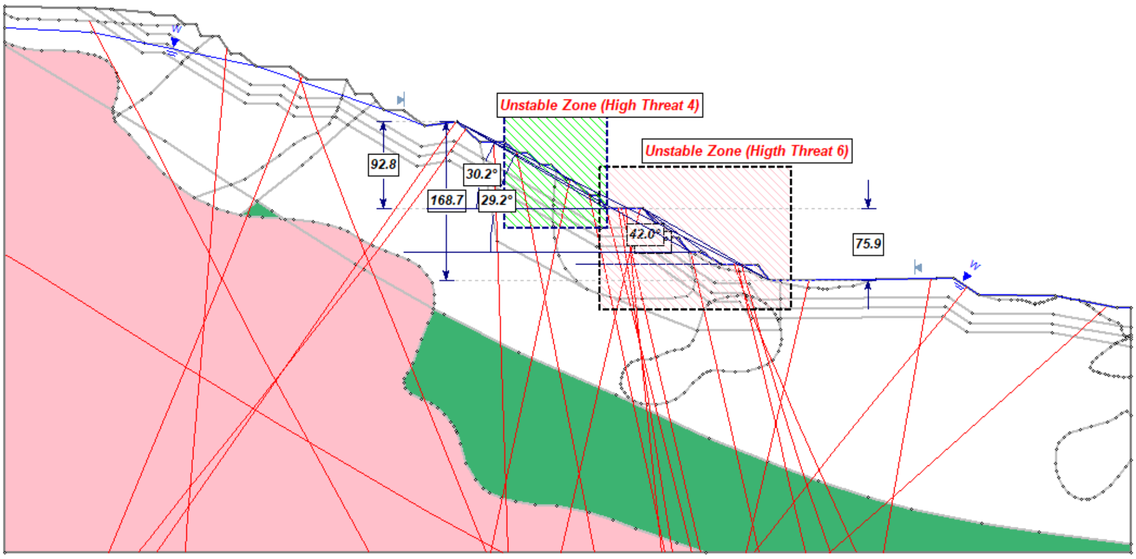

Figure 17. 2D geomechanical model for slope stability analysis

Table 8. Rock mechanical properties of rock mass in the geotechnical domain ***2***

Class	*Litho.*	*Sigc_i* *(MPa)*	*GSI*	*mi*	*D*	*Unit Weight (gr/cm³)*	*C (kPa)*	*Phi (Deg)*
General	*Schist*	*100*	*55*	*18*	*0*	*2.65*	–	–
	Diorite	*60*	*30*	*25*	*0*	*2.74*	–	–
	Granite	*80*	*40*	*15*	*0*	*2.51*	–	–
	Ore	*210*	*60*	*25*		*4.02*	–	–
General-Blast Zone	*Schist (BI)*	*100*	*55*	*18*	*0.7*	*2.65*	–	–
	Diorite (BI)	*60*	*30*	*25*	*0.7*	*2.74*	–	–
	Granite (BI)	*80*	*40*	*15*	*0.7*	*2.51*	–	–
	Ore (BI)	*210*	*60*	*25*	*0.7*	*4.02*	–	–
Fractured	*F-Schist*	*40*	*15*	*15*	*0*	*2.65*	–	–
	F-Diorite	*15*	*20*	*15*	*0*	*2.74*	–	–
	F-Granite	*30*	*20*	*15*	*0*	*2.51*	–	–
	F-Ore	*210*	*20*	*15*		*4.02*	–	–
Fractured -Blast Zone	*F-Schist (BI)*	*40*	*15*	*15*	*0.7*	*2.65*	–	–
	F-Diorite (BI)	*15*	*20*	*15*	*0.7*	*2.74*	–	–
	F-Granite (BI)	*30*	*20*	*15*	*0.7*	*2.51*	–	–
	F-Ore (BI)	*210*	*20*	*15*	*0.7*	*4.02*	–	–
Fixed for all	*Talus*					*2.18*	*10.5*	*30*
	Tectonic Zone						*25*	*30*
	Gouge (Residual)						*0*	*20*

Table 9. Limit equilibrium analysis results for high treat 4 and 6

Rock Properties	*HT#I*	*HT#II*	*HT# I, II*
	SOF/Hight	*SOF/Hight*	*SOF/Hight*
General	*3.0/93*	*3.2/45*	*2.9/149*
Lower Limit Based on Confidence Level 90% , 95% (Fractured)	*0.9/91*	*1.0/43*	*0.9/46*
Fractured with Tectonic Zone for Unstable Area	*1.0/59*	*0.9/46*	*1.1/129*

7- Proposed Solutions

According to the mentioned cases and unstable area geometry (6 to 7 benches), any blasting or muckpile loading operation could potentially cause to collapse and failure onto the underlying ore, resulting in equipment damage, safety hazards, and unsustainable development in the higher benches.
After implementing initial control measures and observing a decreasing trend of displacement, a review of the one-year mining plan was carried out to establish safe conditions, restore access to the ramp, and ensure uninterrupted ore extraction. As a result, two options were proposed:

Option 1: Stop mining operations and allow for a gradual and controlled collapse of the unstable area. This option would result in the loss of approximately 1,000,000 tons of iron ore from the Destructed area. Moreover, the closure of the eastern ramp would increase traffic on the western ramp, resulting in reduced machinery safety. Additionally, the longer transport route and the extended duration required to reopen the mine would increase costs.

Option 2: Implementation of hierarchy of risk control and TARP

A) Monitoring can be achieved with the use of the MSR250 radar, which possesses the following capabilities:
- ✓ Wide scanning area
- ✓ High scanning speed with a very short scanning time (less than 2 minutes)
- ✓ High spatial resolution (with an angle of 0.25 degrees between two acquisition points, for example, at a distance of 1000 meters, the distance between monitored points horizontally is 4.4 meters and vertically is 0.44 meters)
- ✓ Continuous and remote monitoring (up to 2500 meters)
- ✓ No need for reflectors (Unlike the survey monitoring)
- ✓ High accuracy in displacement measurement (less than 1 mm)
- ✓ Rapid warning of instability (a key feature of the radar)
- ✓ Ability to quickly manage instability, such as rapid evacuation of personnel and machinery, minimizing damages, and ensuring increased safety of personnel and equipment (a key feature of the radar).

B) Daily visual inspection by safety group, ramp improvement, scaling of the bench surface, ripping and dozing operation with bulldozer to reduction of unstable zone slope.

C) Gradual initiation of extraction operations in the upper part (benching) based on displacement chart and velocity values.

D) Blasting management and muckpile loading occurred 24 hours after the blast, following a review of the radar results and an on-site inspection.

- ✓ Reducing the frequency of blasting in unstable areas and increasing the time interval between blasts; For instance, conducting one blast in the lower instability zone every three days.
- ✓ Decreasing the number of blastholes and the amount of explosive material used, resulting in reduced PPV.
- ✓ Utilizing pre-split controlled blasting and smooth blasting techniques.

After considering all factors, the second option was chosen. In this plan, the waste materials removal operation began with a focus on the operations in the unstable area of HT#4 (Figures 19-part 2), which had better conditions in terms of the amount and rate of displacement, based on the results of radar monitoring. On the other hand, this operation reduces the load on the underlying unstable area (HT#6). The operation involved the removal of approximately 12,000,000 tons of waste material and lasted for 4 to 5 months.

Efforts were made simultaneously to enhance the ramp's stability using improvement operation, leveling of the ramp, scaling benches surface, reduce the weight of the unstable mass with unloading by using minimal machinery (Figures 19-part 3). Considering the decreasing trend of the displacement and velocity at the same time as the mentioned measures, with accepting the minimum safety factor, by creating safety berm on both sides of the ramp, the ramp was prepared for single-line passage of unladen trucks (Figures 19-part 4). By reopening a single line of the eastern ramp and implementing continuous radar scanning, it may be possible to gradually reduce traffic and transport distance.

To assess the efficacy of control measures and the implementation of the TARP and hierarchy of hazard control of plan, the results obtained from survey monitoring and radar monitoring have been utilized (Figures 19 and 20). The settlement rate before and after the intensification of instability was found to be 0.15 and 1.8 mm/day, respectively. Additionally, the amount of displacement in the direction of Electrical Distance Measurement (EDM) reflects the impact of safety and control measures in reducing the rate of displacement.

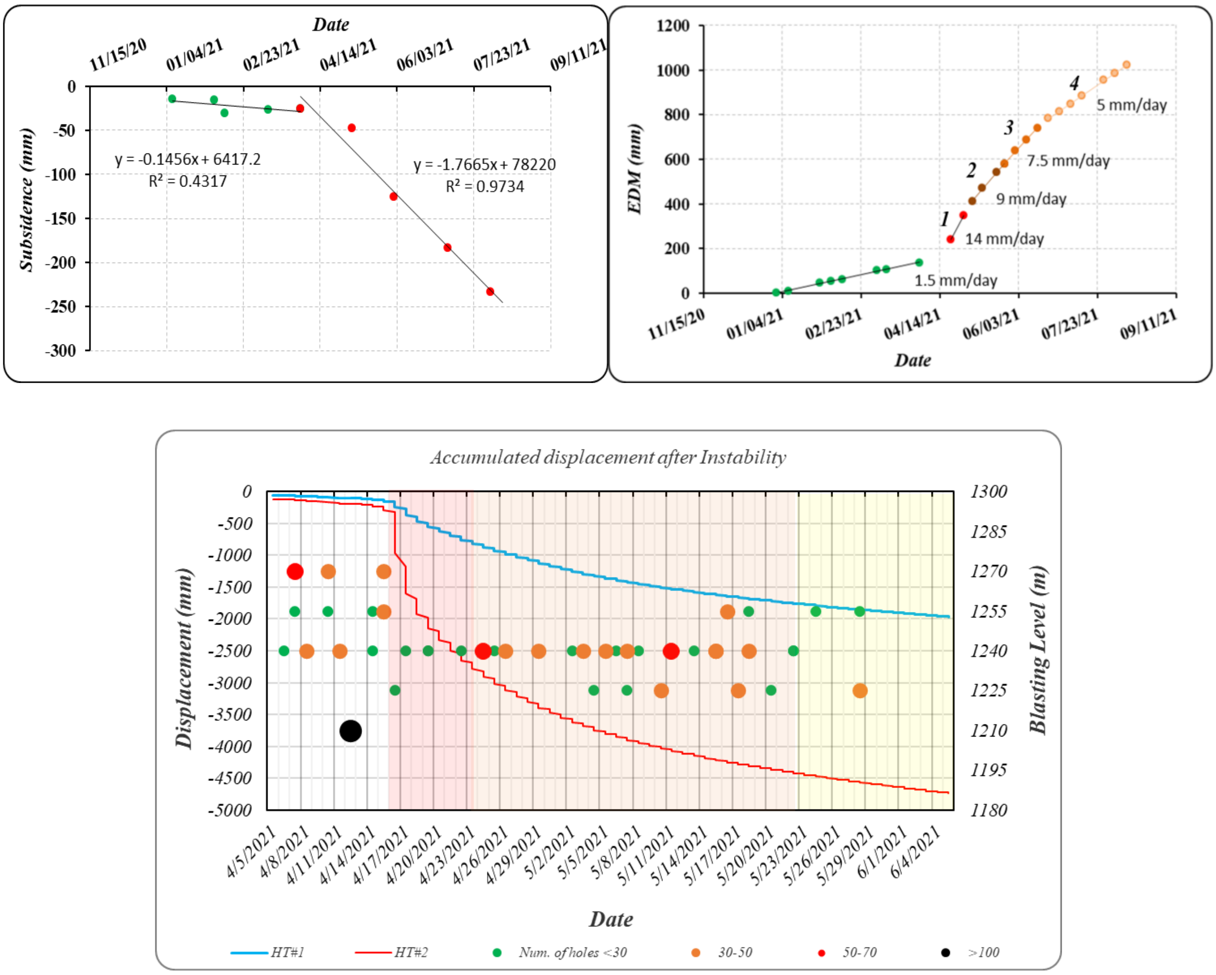

Figure 20. Impact of TARP implementation and second alternative implementation on unstable zones 4 and 6 based on radar monitoring results

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