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UNIVERSIDAD DE CHILE

Geotechnical Monitoring in Surface Mining

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Contents

- Monitoring and instrumentation systems – Fundamentals & LOP guidelines
- Monitoring systems with focus on safety
- Monitoring system integrated in Mining Processes
- Predictive Monitoring

Fundamentals – Why monitoring is important

"What gets measured, gets managed." – Peter Drucker

•**Ensures Safety of Operations**: Detects ground movement, slope instability, and potential failures early to prevent catastrophic slope failures, protecting workers and equipment.

•**Optimizes Mine Design**: Provides real-time data to adjust pit slope angles, mining methods, and support systems, maximizing resource extraction while maintaining stability.

•**Prevents Costly Downtime**: Early warning of geotechnical issues helps to minimize unexpected operational interruptions, reducing costly downtime and repairs.

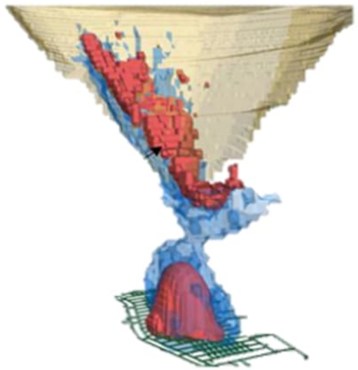
•**Environmental Protection**: Monitoring helps prevent slope failures that could lead to environmental hazards, such as landslides, erosion, or contaminant releases.

•**Improves Decision-Making**: Accurate data from instruments supports informed decision-making in mine planning and operations, ensuring the right balance between safety and productivity.

•**Regulatory Compliance**: Geotechnical monitoring is often required by regulatory authorities to ensure mining operations meet safety and environmental standards.

•**Advances in Technology**: Incorporates modern technologies such as remote sensing, drones, and real-time data analytics to monitor large and complex sites efficiently.

•**Long-Term Stability Assessments**: Helps in understanding long-term ground behaviour, crucial for post-mining land use and closure planning.



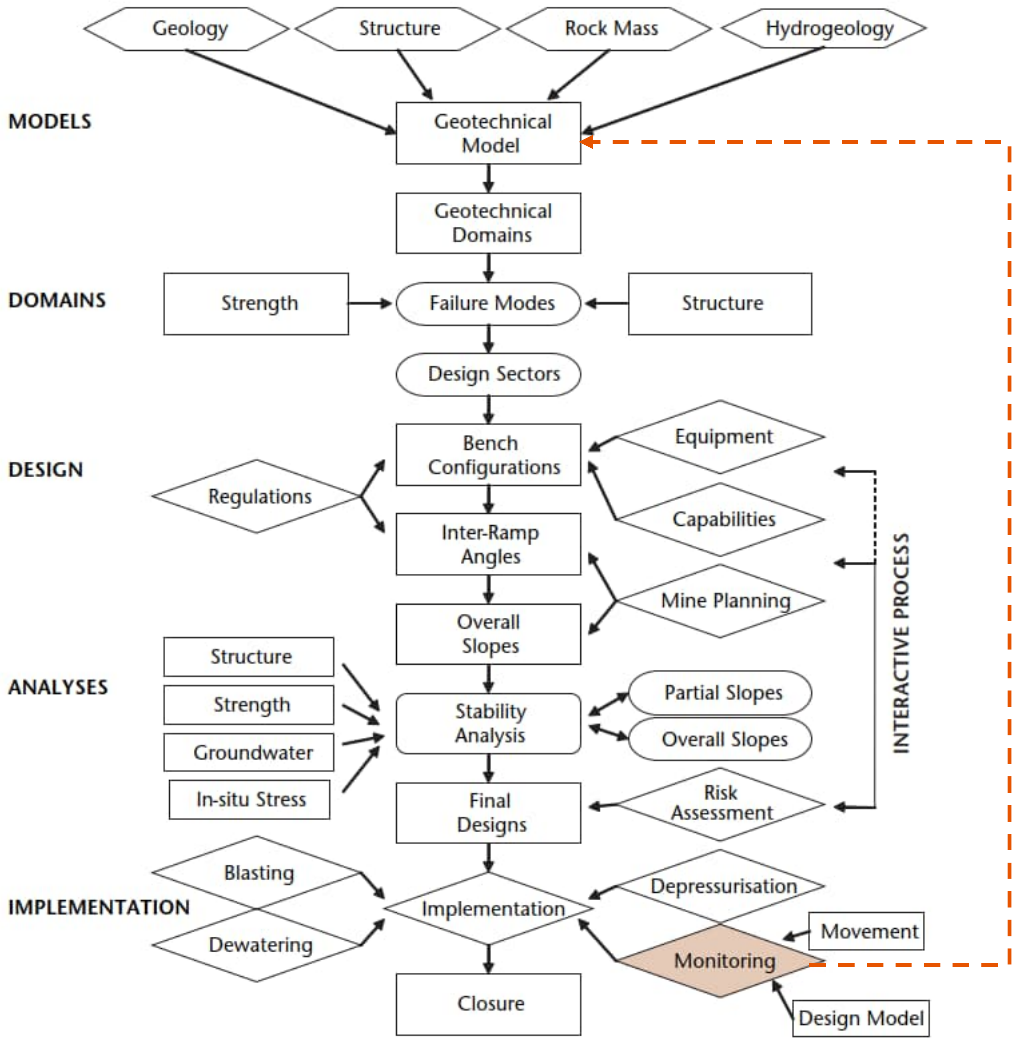
Caving induced failure in Palabora Mine, South Africa

The role of Geotechnical Monitoring

The Geotechnical Monitoring system forms part of an integral process in order to track the slope performance of what is designed (plan vs actual) focused on Safety.

Using a natural environment and rockmass as material for this excavations generates slopes with more uncertainty compared with constructions made with human-made materials where all the variables are significantly more controlled.

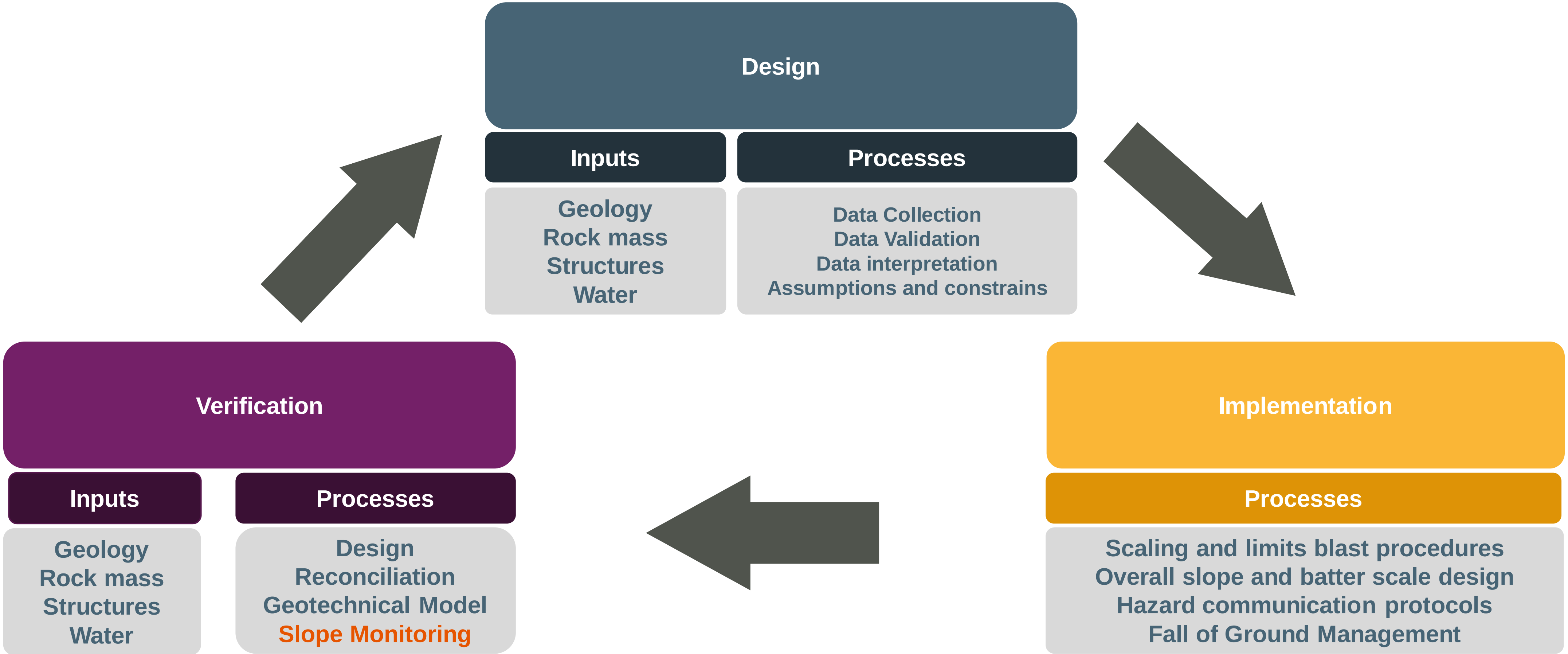
Geotechnical Monitoring system aims to detect and manage the potential instabilities of these excavations as a critical control of the design process.



Ref. Open Pit and Slope Design, Read / Stacey 2009

The Geotechnical Cycle

Design – Implementation - Verification for surface mining | Geotechnical Engineering



Modified from de Graaf and Wessels 2015

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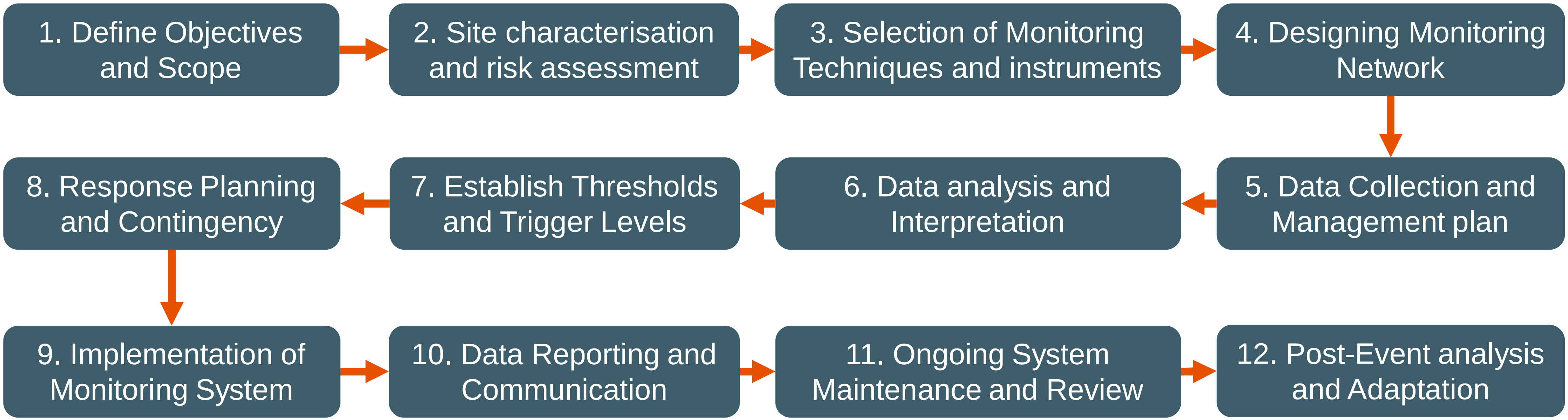
Planning a Geotechnical Monitoring System

Effective geotechnical monitoring starts with thorough planning, accurate data and proactive risk management



Planning a Geotechnical Monitoring System

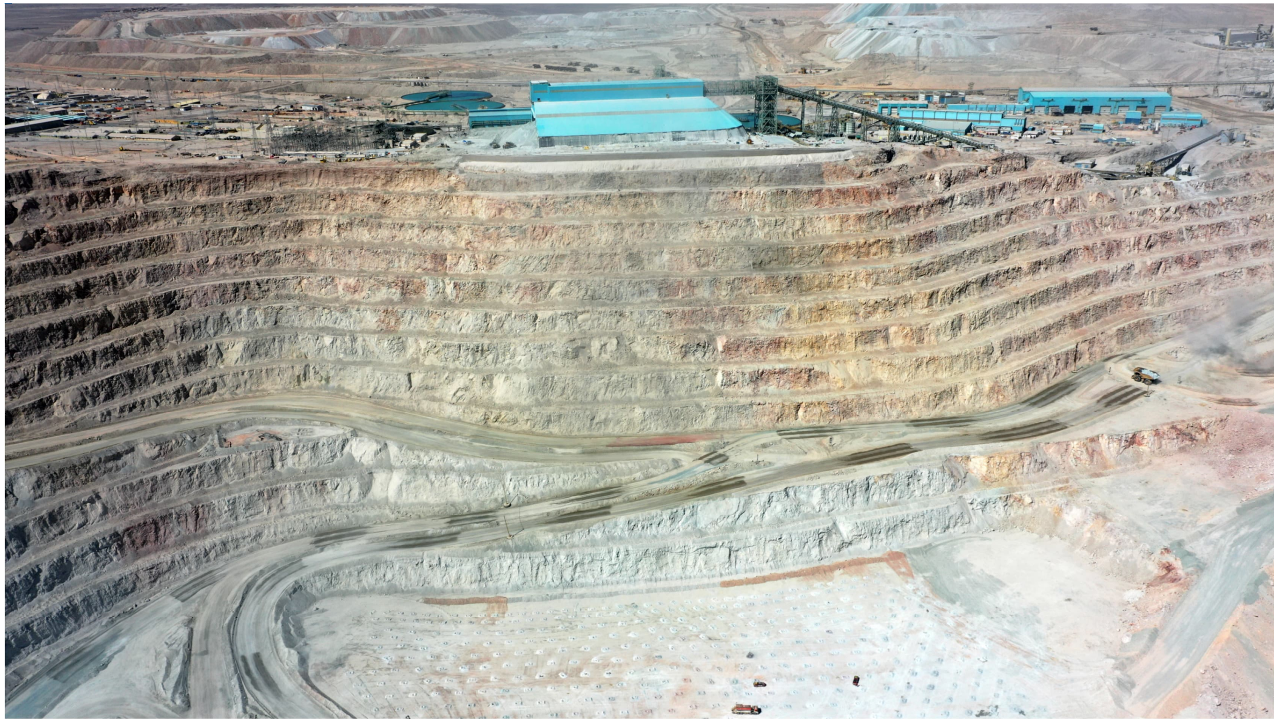
1. Define Objectives and Scope

•**Identify the Purpose of Monitoring**: Understand what you need to monitor (e.g., slope stability, ground movement, water pressure).

This is critical in terms of what physical variables we need to measure

•**Set Performance Criteria**: Establish the performance thresholds and parameters for safety and operational efficiency (e.g., tolerable displacements).

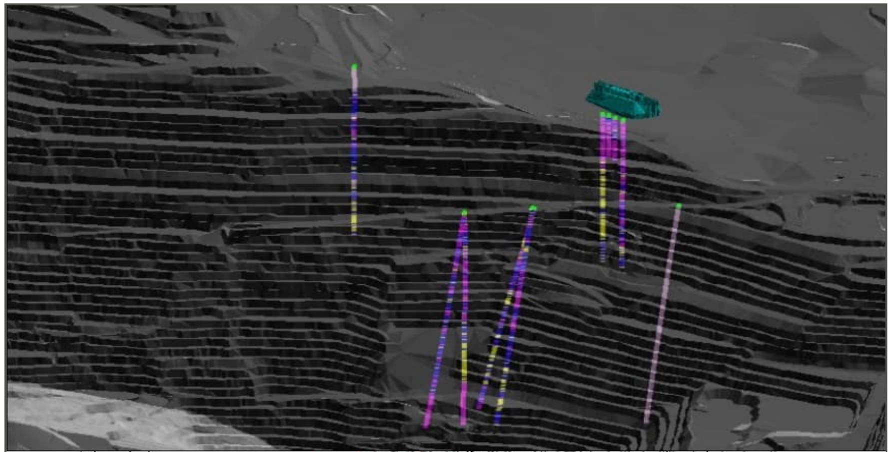
Normally, this requirement comes from Slope Stability Assessment / empirical

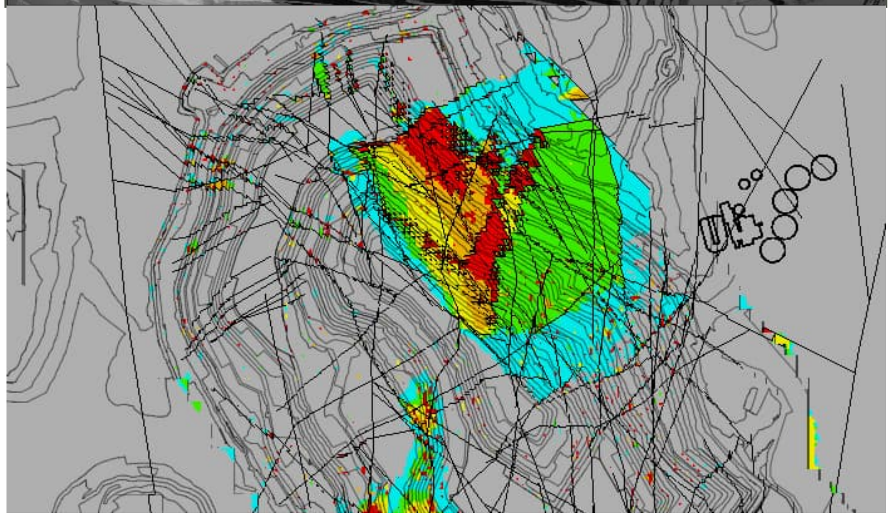


Planning a Geotechnical Monitoring System

2. Site Characterisation and Risk Assessment

- **Geotechnical Investigations**: Conduct detailed site investigations, including geological, hydrological, and geotechnical assessments.
- **Hazard Identification**: Map areas prone to instability, landslides, or subsidence.
- **Risk Ranking**: Use the gathered data to prioritize critical areas based on potential risk and impact to mine safety and productivity.





Planning a Geotechnical Monitoring System

3. Selection of Monitoring Techniques and Instruments. Critical understanding about expected mechanisms

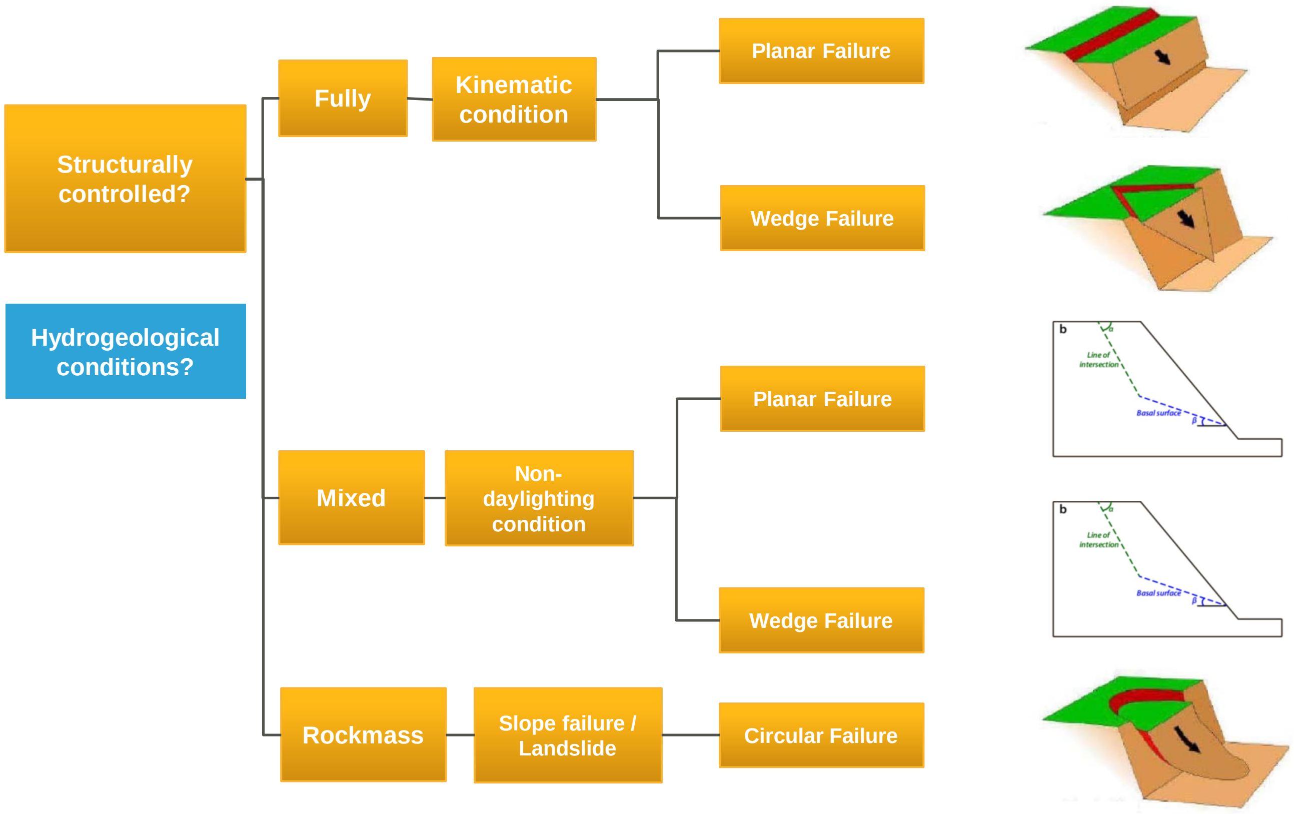
•**Determine Monitoring Parameters**: Choose the right parameters to monitor (e.g., displacements, stress, pore water pressure, vibration).

•**Instrument Selection**: Select appropriate geotechnical instruments such as:

- Slope inclinometers
- Total stations or robotic monitoring systems
- Ground-based radar
- Extensometers
- Piezometers for groundwater monitoring

•**Technology Integration**: Use advanced remote sensing technologies (e.g., LiDAR, drones, or satellite-based monitoring) for large-scale, real-time data acquisition.

Potential Failure modes and variables to be measured

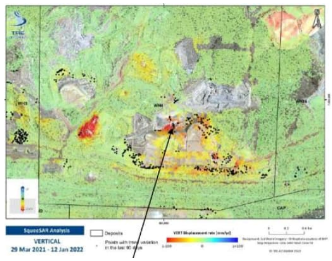
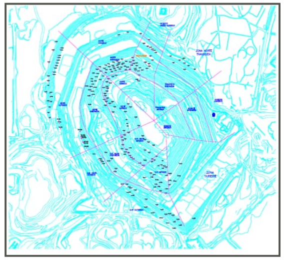
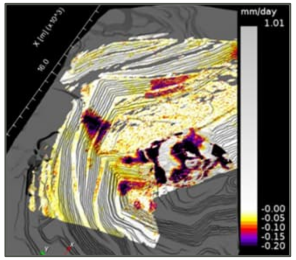
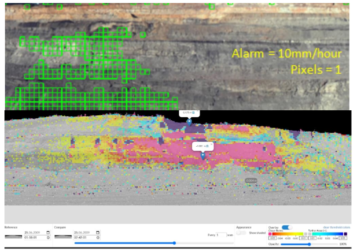
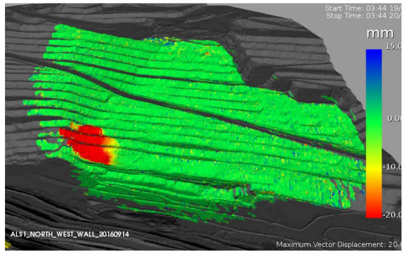


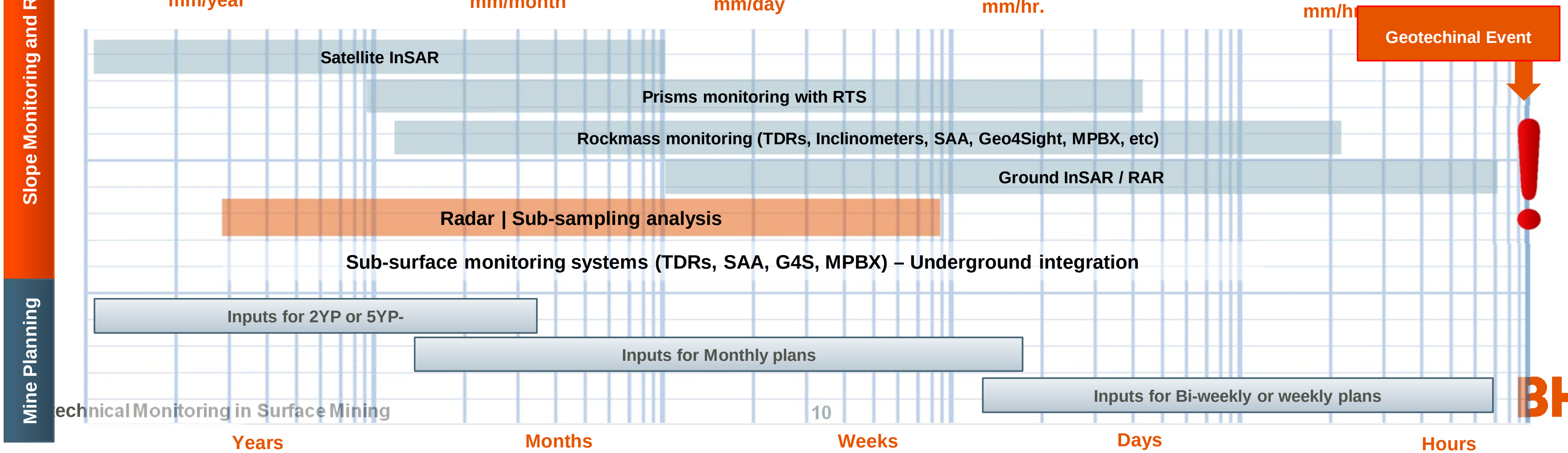
Planning a Geotechnical Monitoring System

3. Selection of Monitoring Techniques and Instruments

Strategic Monitoring → **Tactic Monitoring**

Slope Monitoring and Rockmass monitoring

Satellite InSAR	Prisms	Sub-sampling analysis for radars	Ground InSAR / RAR / Laser scanning	Ground InSAR / RAR mobile
				
Range	Range	Range	Range	Range
mm/year	mm/month	mm/day	mm/hr.	mm/hr




Instrumentation
Satellite InSAR
(Ground Deformation)
LiDAR
(Displacement)
Piezometer
(Pore Pressure)
GNSS
(Displacement)
Inclinometers
(Sub-surface Displacement)
TDR / SAA
(Sub-surface deformation)
Radar
(Ground Deformation)
Crackmeters
(Displacement)
Geotechnical Monitoring in Surface Mining
Robotic Total Station
(Slope Displacement)

Planning a Geotechnical Monitoring System

3. Most common Geotechnical instrumentation for surface mining

1.1 Extensometers: Measure changes in distance between two points within the rockmass to detect movement

1.2 Crack-meters: Measure the widening or closing of surface cracks on the slope

1.3 TDRs: Detects changes in the dielectric properties of soil or rock, corresponding sub-surface movement

1.4 Inclinometers / Shape Arrays (SAA) / Geo4Sight: Measure the tilt or angular displacement of a borehole, indicating sub-surface movement

1.5 Piezometers: Measure pore pressure within the slope, helping to assess the impact of groundwater on potential slope instabilities

1.6 Prisms with Robotic Total Stations (RTS): Measure slope displacement by monitoring changes in the position of prisms installed on the slope

2.1 Ground-based SAR and RAR (Radars): Provide real-time monitoring of slope movements across large areas in surface mining. These instruments are capable of detecting very small displacements (sub-millimeter-scale) over long-range and large areas.

2.2 Interferometric Synthetic Aperture Radar (InSAR): Satellite based remote sensing used for large-scale and long-trend ground displacement (mostly vertical displacement).

2.3 LiDAR (Light Detection and Ranging): Provides high-resolution 3D mapping of slope surface in a systematic near-real time acquisition detecting changes in slope geometry (less accurate than Ground-based Radars).

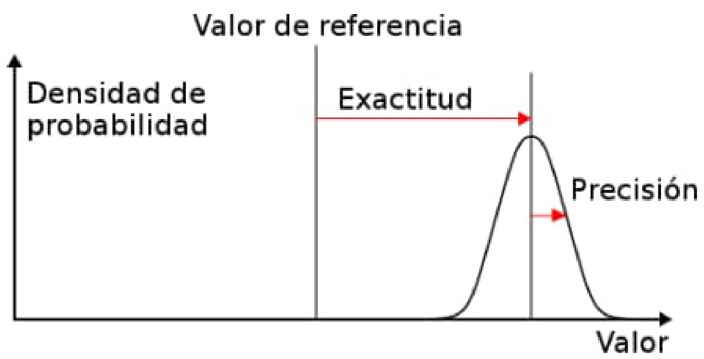
2.4 Fiber Optic Sensors: Measure strain, micro-seismicity, temperature along fiber optic cable installed either on slope or boreholes.

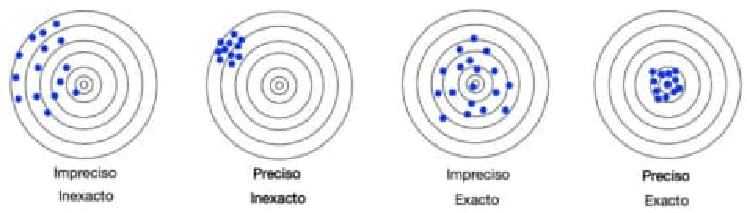
2.5. Global Navigation Satellite System (GNSS) Monitoring: Uses GPS or GNSS receivers to measure ground movements in real time with high precision.

Precision vs accuracy

Precisión: Se denomina precisión a la **capacidad de un instrumento de dar el mismo resultado en mediciones diferentes** realizadas en las **mismas condiciones**.

Exactitud: Se denomina exactitud a la capacidad de un instrumento de **acercarse** al valor de la **magnitud real**





Errors in Instrumentation

1. Instrumentation Errors

1.1. Calibration Errors : Occur when monitoring instruments are not properly calibrated or drift out of calibration over time.

•**Implications:** Calibration errors can lead to inaccurate readings of displacement, tilt, or pressure, potentially masking early signs of instability or overestimating stability. This can result in delayed responses to slope movement or unnecessary interventions.

1.2. Sensor Malfunction or Failure: Instruments may malfunction due to environmental factors, damage, or wear and tear.

•**Implications:** Malfunctioning sensors can provide false data, leading to incorrect assessments of slope behavior. In extreme cases, critical slope movements may go undetected, increasing the risk of slope failure.

1.3. Measurement Resolution and Precision Errors: Some instruments have limited resolution or precision, meaning they cannot detect very small movements accurately.

•**Implications:** Low-resolution measurements may miss subtle changes or slow movements in the slope, leading to an underestimation of potential instability risks.

Errors in Instrumentation

2. Data Collection Errors

2.1. Human Error: Errors introduced by personnel during data collection, such as incorrect readings, improper instrument setup, or data entry mistakes.

•**Implications:** Human errors can lead to inaccurate or incomplete datasets, which can distort the analysis of slope behavior and lead to incorrect trigger levels or action responses.

2.2. Environmental Interference: Environmental factors such as rain, dust, temperature changes, or vibrations can interfere with instrument readings.

•**Implications:** Environmental interference can cause temporary spikes or fluctuations in data, which may be misinterpreted as actual slope movement, leading to false alarms or unnecessary responses.

2.3. Poor Data Quality or Inconsistency: Occurs when data is collected at irregular intervals, or the quality of data is inconsistent due to variations in instrument sensitivity, positioning, or environmental factors.

•**Implications:** Inconsistent data can make it difficult to identify trends or patterns in slope movement, reducing the effectiveness of monitoring and increasing uncertainty in stability assessments.

Errors in Instrumentation

3. Data Processing and Analysis Errors

3.1. Data Transmission and Communication Errors: Data transmission errors occur when there is a loss or corruption of data as it is transmitted from instruments to the central monitoring system.

•**Implications:** Incomplete or corrupted data can lead to gaps in monitoring, making it harder to detect early warning signs of instability or changes in slope behavior.

3.2. Data Interpretation Errors: Occur when monitoring data is incorrectly analysed or misinterpreted by engineers or analysts.

•**Implications:** Misinterpretation can lead to false conclusions about slope stability, resulting in either unnecessary operational changes or a failure to take action in response to real slope movements. This increases the risk of unexpected slope failures or operational inefficiencies.

3.3. Software and Algorithmic Errors: Errors can occur due to faulty algorithms, software bugs, or incorrect data processing within data management systems.

•**Implications:** These errors can lead to inaccurate trend analysis, incorrect predictions, or failure to trigger alarms, potentially resulting in delayed responses to critical slope instability.

Errors in Instrumentation

4. Systematic vs. Random Errors

4.1. Systematic Errors: Consistent and repeatable errors that occur due to flaws in the measurement system, such as calibration issues, instrument bias, or environmental influences.

•**Implications:** Systematic errors can lead to consistently biased data, affecting the accuracy of long-term trend analysis and potentially resulting in incorrect slope stability assessments.

4.2. Random Errors: Unpredictable errors that occur due to various uncontrollable factors, such as environmental changes, instrument noise, or data entry variability.

•**Implications:** Random errors introduce variability and uncertainty in the data, making it more challenging to identify true trends or changes in slope behaviour. While individual random errors may have less impact, they can accumulate over time and affect the reliability of the monitoring system.

Implications of Errors in Surface Mining Geotechnical Monitoring:

•**False Alarms:** Errors, especially due to environmental interference or sensor malfunction, can trigger false alarms, leading to unnecessary interruptions in mining operations, increased operational costs, and reduced productivity.

•**Missed Warnings:** Calibration errors, data transmission failures, or interpretation mistakes may result in missed or delayed detection of critical slope movements, increasing the risk of unexpected slope failures and endangering personnel and equipment.

•**Reduced Confidence in Monitoring Data:** Frequent errors or inconsistencies can reduce trust in the monitoring system, leading to hesitancy in decision-making and potentially undermining the effectiveness of slope stability management.

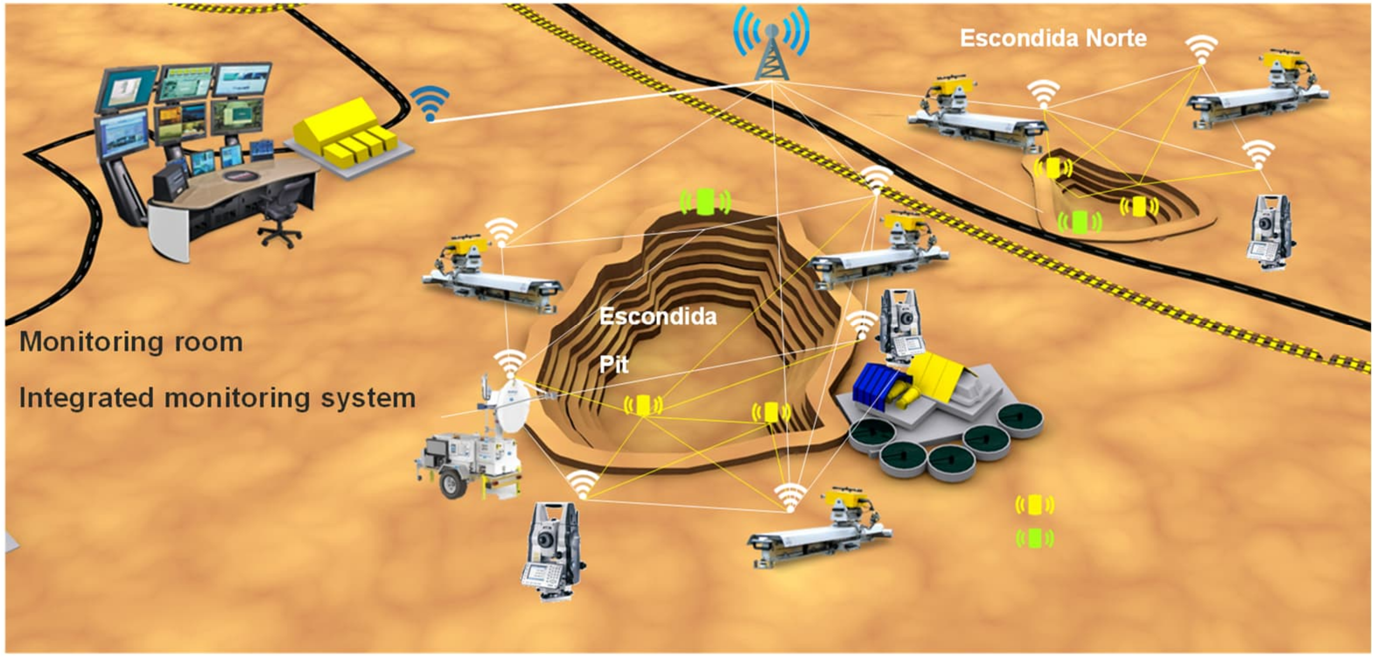
•**Inefficient Resource Allocation:** Responding to false alarms or misinterpreted data may result in the misallocation of resources, such as unnecessary evacuations, stoppages, or reinforcement measures.

Planning a Geotechnical Monitoring System

4. Design Monitoring Network

•**Placement of Instruments**: Optimize the layout of monitoring equipment based on identified risk zones, geological features, and operational constraints.

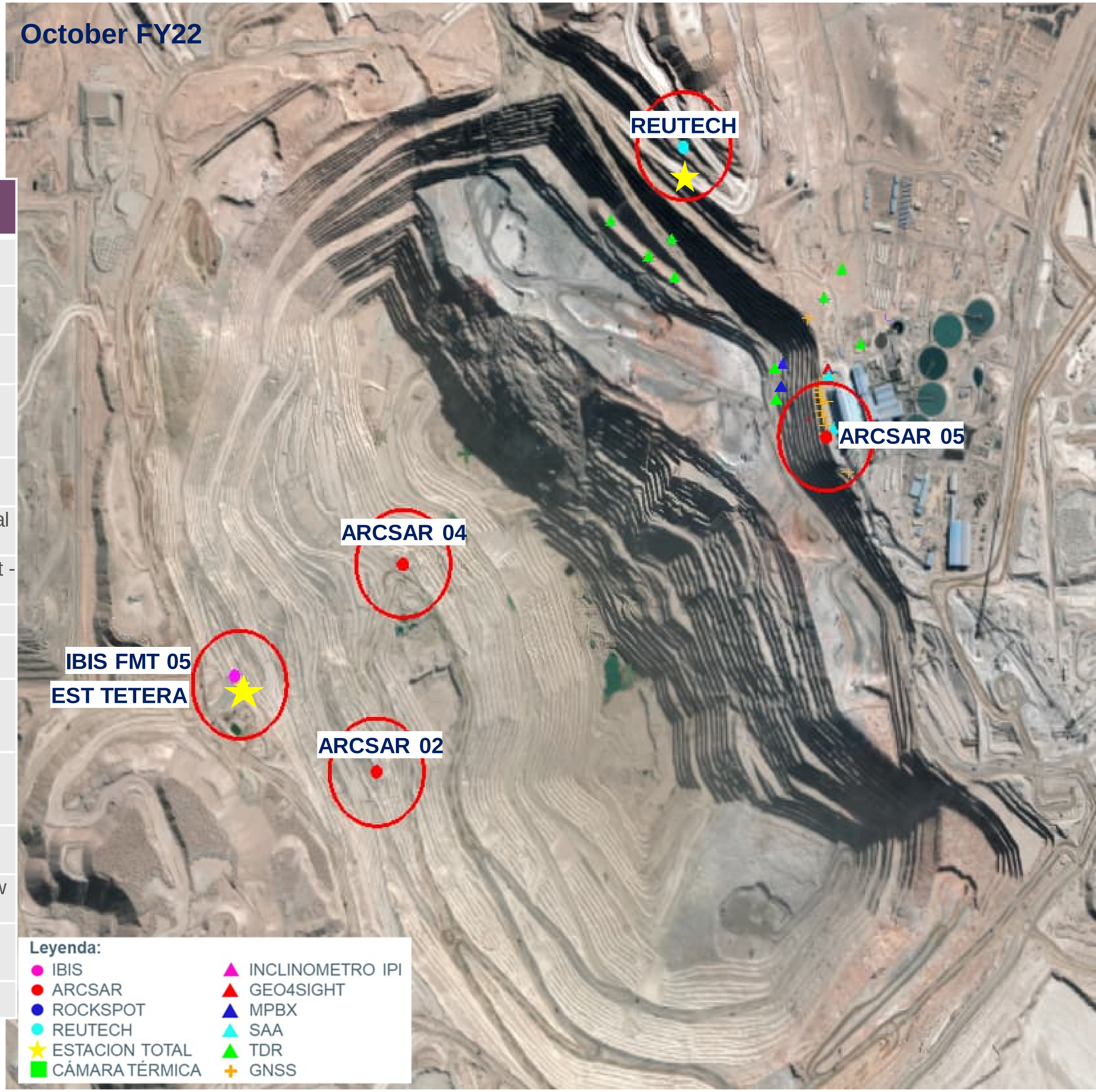
•**Redundancy and Cross-Verification**: Ensure redundancy in critical areas, using multiple monitoring methods for cross-verification of data.



Escondida

Location of instrumentation FY20

Type of instrumentation	ID	N°	Area of interest	Objective
Radars	ArcSAR 02	1	S-W-N wall	Surface displacement monitoring E6S / N16W / SW / W wall
	ArcSAR 04	1	SE-E and NE wall	Surface displacement monitoring Bottom pit in E wall / E6 / E7 / PL1S
	ArcSAR 05	1	SE-E and NE wall	Surface displacement monitoring Bottom pit in E wall / E6 / E7 / PL1S
	FMT-5	1	NE wall	Surface displacement monitoring NE failed area / PL1 pushback / N16 - PL1 interaction
RTS + prisms	-	252	Active pushbacks	Surface displacement monitoring
TDR	-	6	PL1	Rockmass in deph (cutting faults in Structural model)
GNSS	-	12	Los Colorados	Surface displacement monitoring in PL1 crest - Minipit (absolute values)
Geo4Sight	G4S1	75	Los Colorados	150 m. depth in Stock Pile Los Colorados
	G4S2	75	Los Colorados	150 m. in PL1. Understanding damage / deconfinement
SAA	D-2328	300	Los Colorados	150 m. rockmass deformation monitoring below Los Colorados Plant Fault 240
	D-2329	300	Los Colorados	150 m. rockmass deformation monitoring below Los Colorados Plant Fault 240 and M15_NE_01
MPBX	1	4	Los Colorados	230 m. rockmass deformation monitoring below Los Colorados Plant
	2	4	Los Colorados	230. rockmass deformation monitoring below Los Colorados Plant
Satellite interferometry	-	-	Whole pit	Surface displacement monitoring
Piezometers	-	36	Whole pit	Pore pressure



Escondida

2YP for Geotechicnical Monitoring

Monitoring plan is reviewed on annual basis (FF05), updating if is required 5YP CAPEX and F08 for budget.

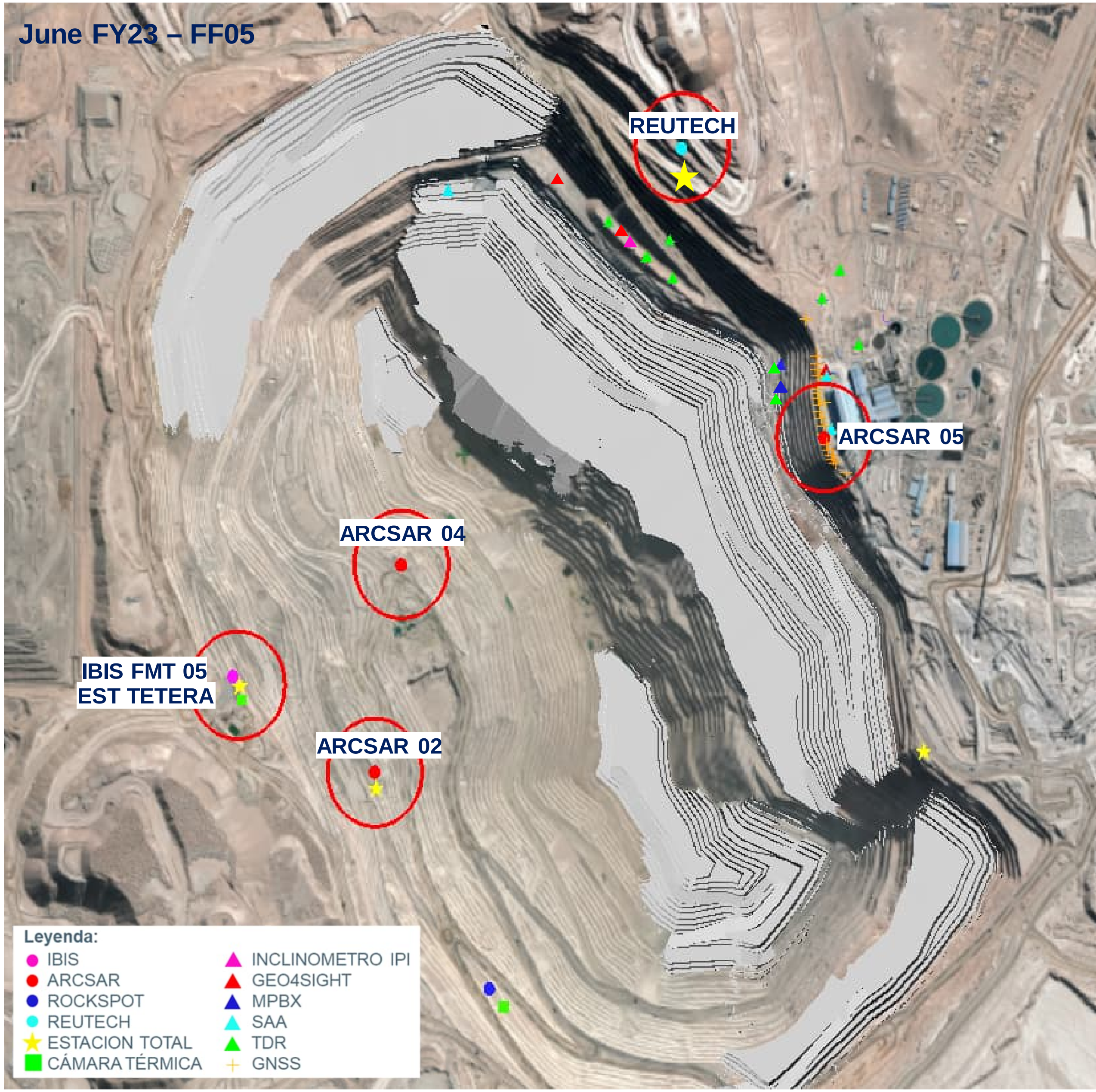
It is recommended to install the thermal camera and Rockspot® considering the interaction between PL1 and E06 and E07 with E06 according with Forecast

One SAA will also be installed on the north wall of PL1, the other one will be a backup in case any of the 3 installed SAAs fail.

The IBIS 05 radar will be renewed according with CAPEX plan

Additional GNSS sensors will be added to the Los Colorados system.

Sector	Instrumentation Nomenclature	Location	Project Name	FY23 Q1	FY23 Q2	FY23 Q3	FY22 Q4
LC	Sistem GNSS Spider	PL1	GNSS monitoring system High accuracy	1			
ESC	Measurand SAA (150 m.)	PL1	Acquisition of instrumentation for Geotechnical Monitoring	1			
ESC	Measurand SAA (150 m.)	PL1		1			
ESC	IDS - IBIS FMT 05	Platform 3130 NW the ESC La Tetera	Renovation of the Mina radar system			1	



Planning a Geotechnical Monitoring System

4. Design Monitoring Network

Mechanisms of failure / risk expected in the monitored slope

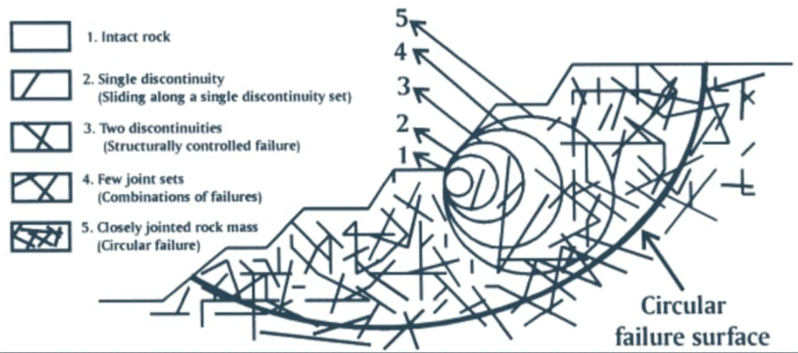
Controlled by Rockmass

Controlled by Bedding

Controlled by geological structures

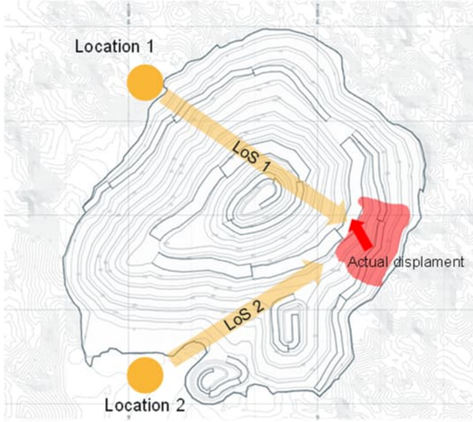
Mixed control

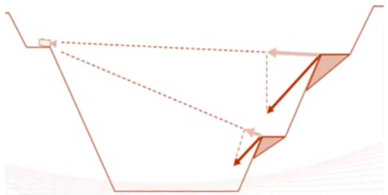
Scale of the expected failures



Ref. A Practical Procedure for the Back Analysis of Slope Failures in Closely Jointed Rock (H. Sonmez 1998)

Location of the expected failures vs radar location





* The current monitoring instruments are not reliable for rockfall detections – new technologies are on development for better results

Displacement / velocity dependency of the failed area

Planning a Geotechnical Monitoring System

5. Data Collection and Contingency Plans

- **Data Collection Protocols**: Establish clear procedures for data collection intervals, calibration, and maintenance of equipment.
- **Automated Data Acquisition**: Utilize automated systems for continuous and real-time data capture and transmission to reduce human error and improve response time.
- **Data Logging and Storage**: Ensure reliable systems for logging and storing data for long-term analysis and regulatory compliance.

Planning a Geotechnical Monitoring System

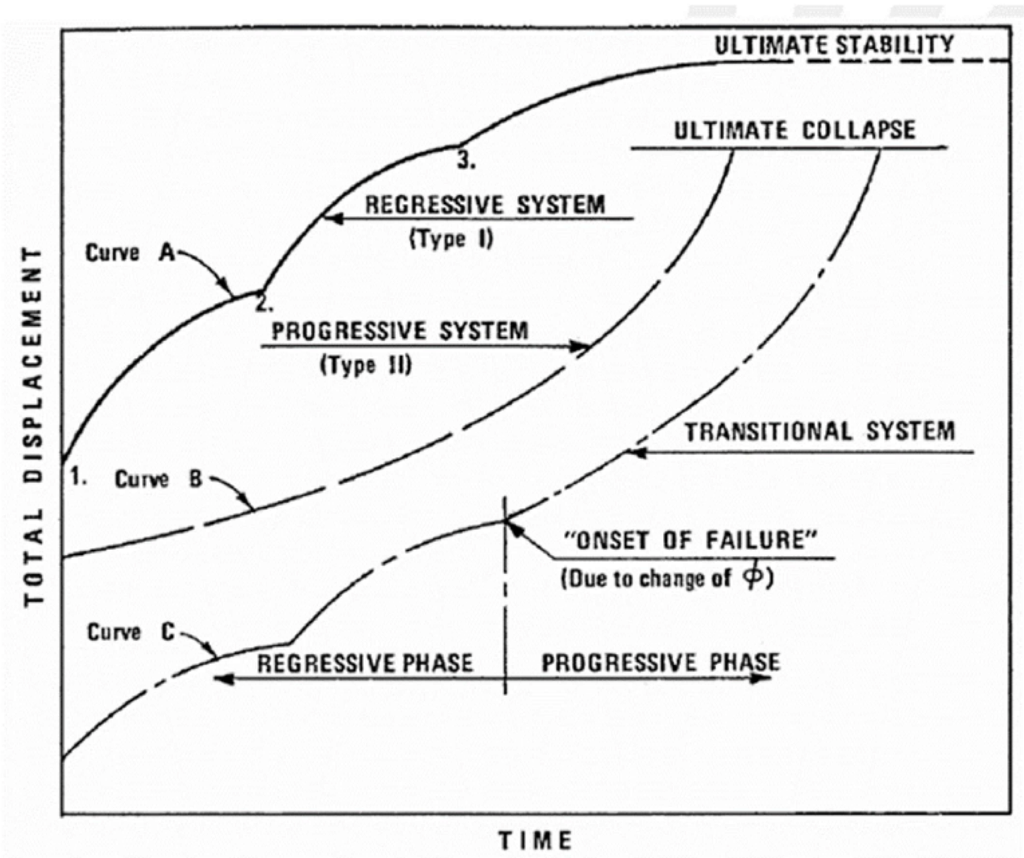
6. Data Analysis and Interpretation

•**Real-Time Monitoring and Alerts**: Set up systems for real-time analysis with automated triggers for alarms if performance thresholds are exceeded.

•**Trend Analysis**: Conduct continuous or periodic data analysis to identify early warning signs of instability (e.g., trends in displacement or groundwater pressure).

•**Cross-Correlation: Compare** data from different instruments and monitoring methods to identify correlations (e.g., between rainfall and ground movement, or between pore water pressure and slope stability).

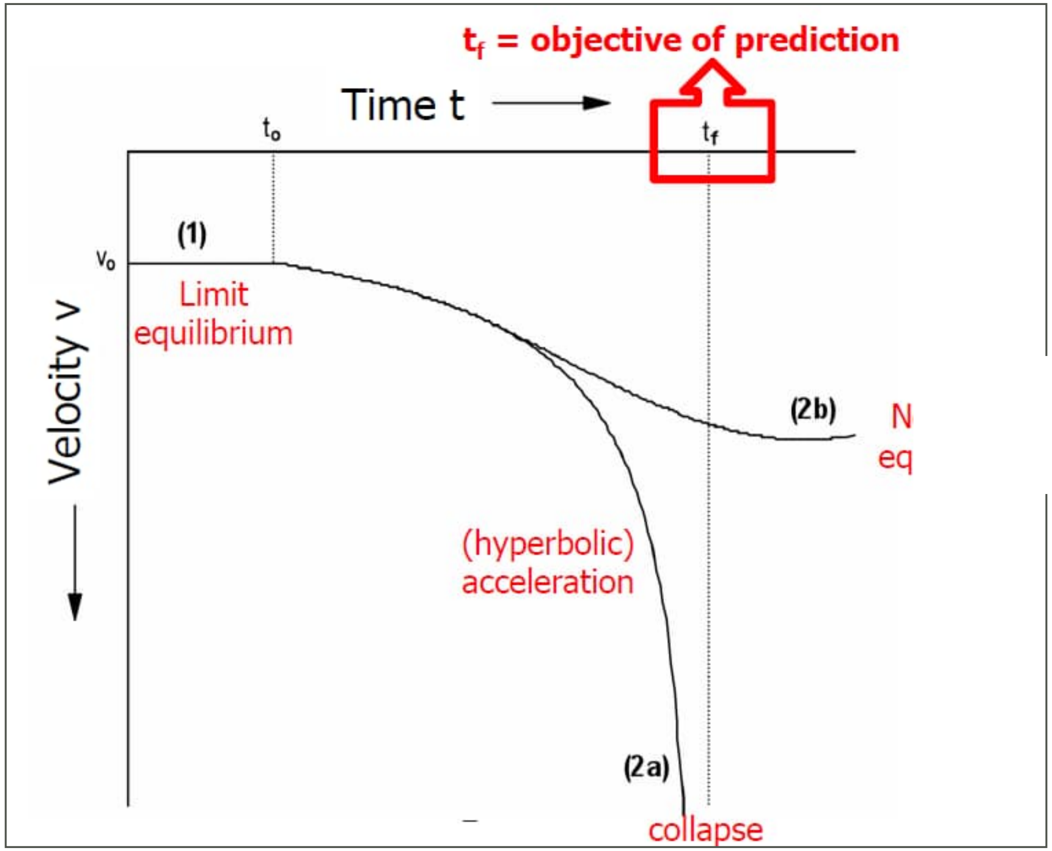
•**Predictive Modelling**: Use data for predictive modelling to simulate potential failure mechanisms or forecast future behaviour of slopes under varying conditions (e.g., weather, excavation progress).

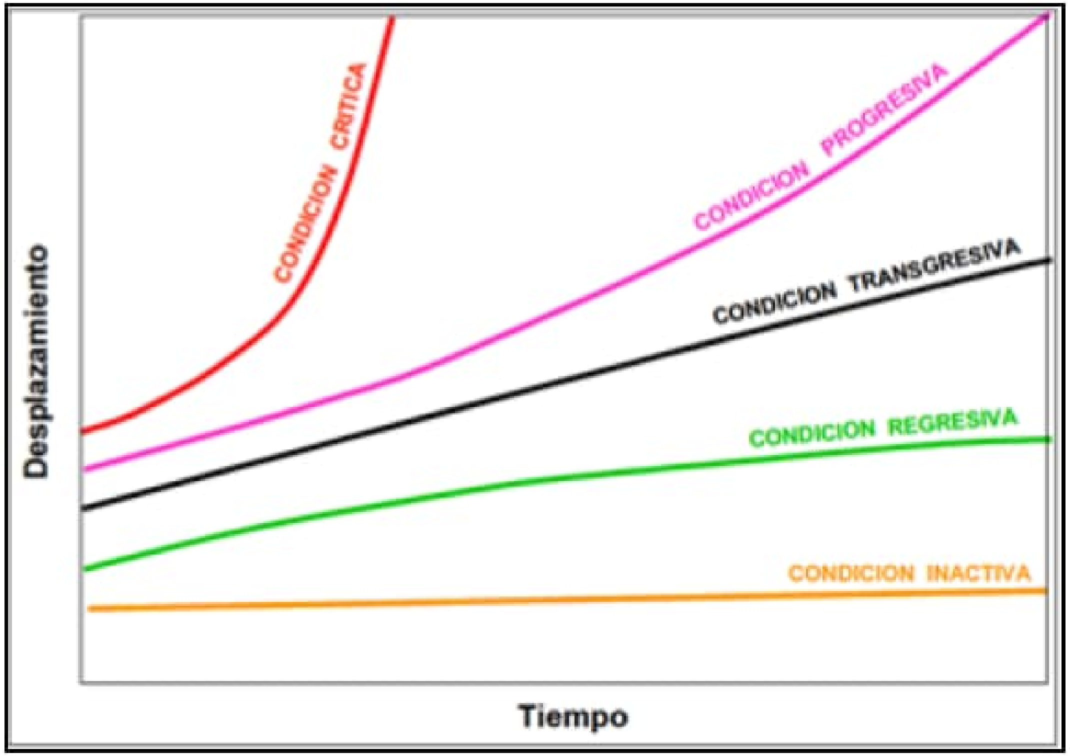


Typical displacement vs time graph (Broadbent and Zavodni, 1982).

Trend Analysis

6. Data Analysis and Interpretation

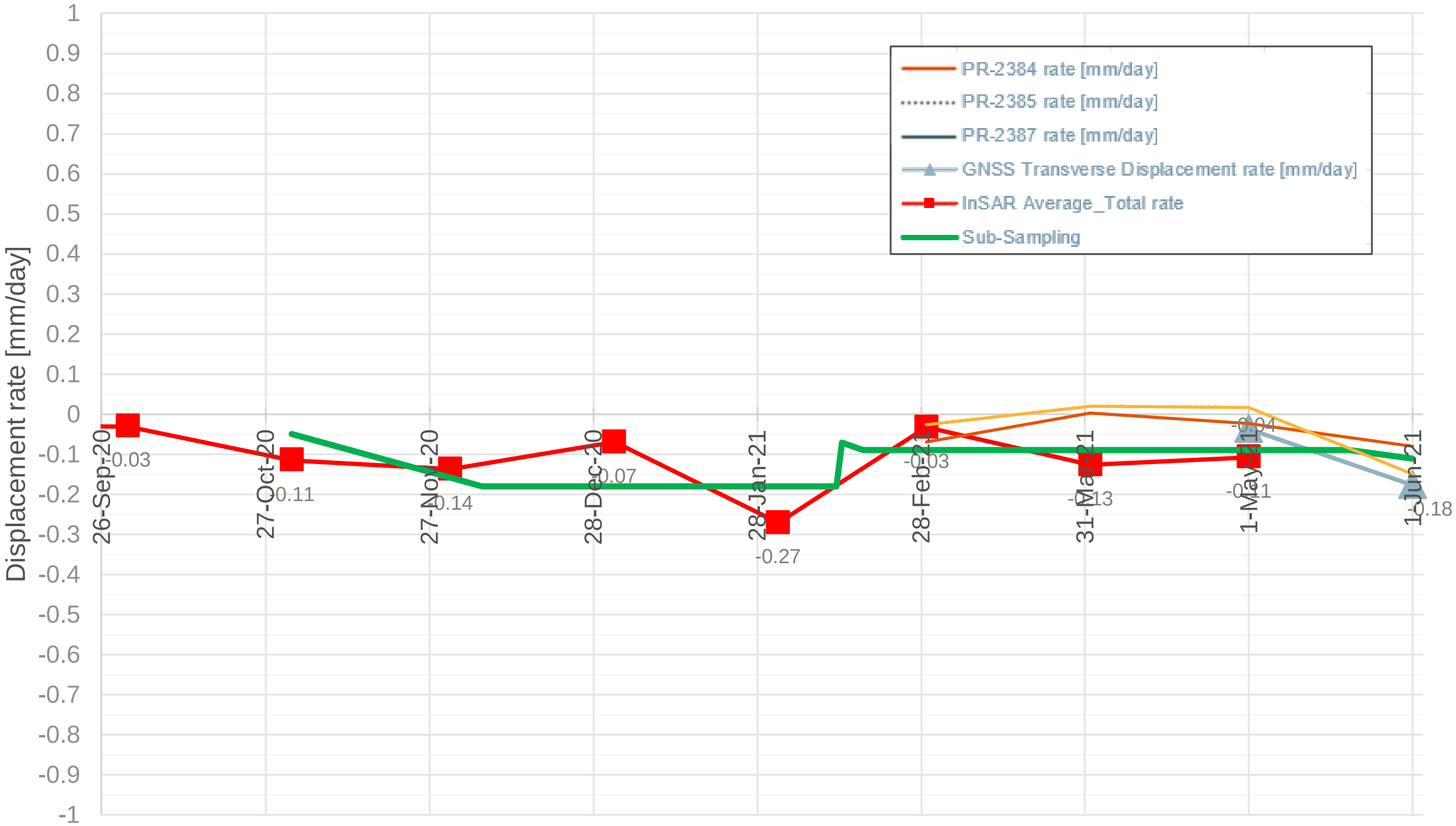




Types of trends in Slope Monitoring
This trends also applies to different physical variables (Piezometers, frequency of micro-seismicity)

Cross-Correlation

6. Data Analysis and Interpretation. Example of Escondida Mine



Instrumentation	Type of measurement	Rate of last 5 months (Jan-May 21)
Prisms	Slope distance - displacement	0.11 mm/day
IDS IBIS radar	LoS displacement Time window: 1 day	0.12 mm/day
IDS IBIS radar	LoS displacement Time window: 3 days	0.09 mm/day
IDS IBIS radar	LoS displacement Time window: 5 days	0.11 mm/day
IDS IBIS radar	LoS displacement Time window: 10 days	0.06 mm/day*
Satellite InSAR	E-W displacement Time window: 11 days	0.15 mm/day
Satellite InSAR	Absolute displacement Time window: 10 days	0.18 mm/day
SAA Vertical	Trasversal Axis (towards slope / almost west direction) 260° azimut for transversal axis	0.08 mm/day
GNSS Spider	Trasversal Axis (towards slope / almost west direction) 260° azimut for transversal axis	0.14 mm/day

Predictive Monitoring

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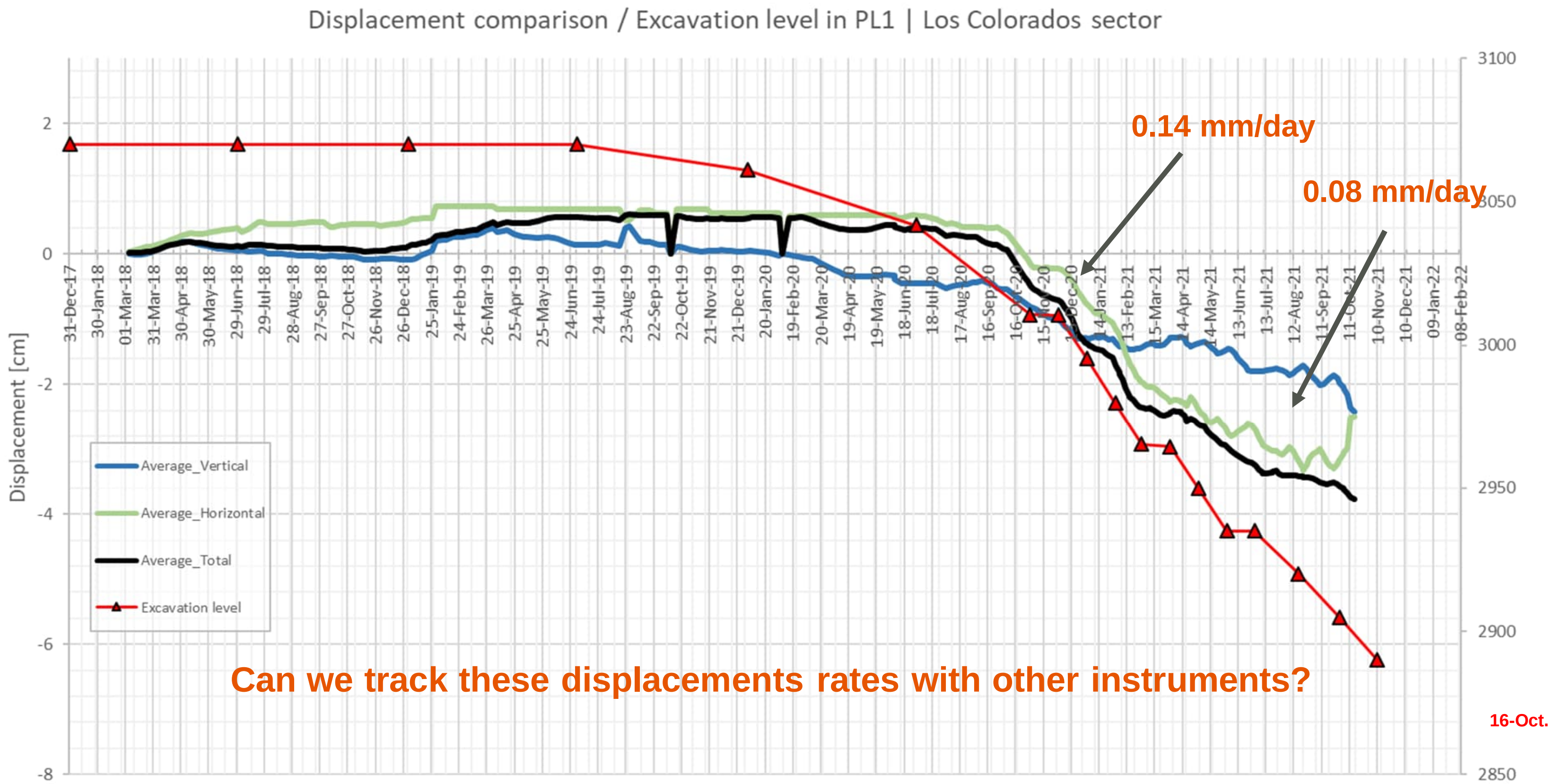
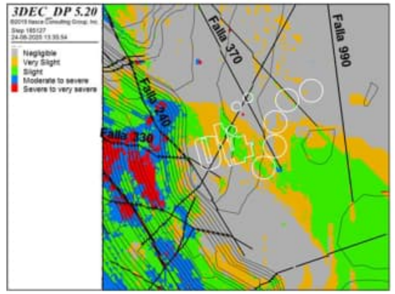
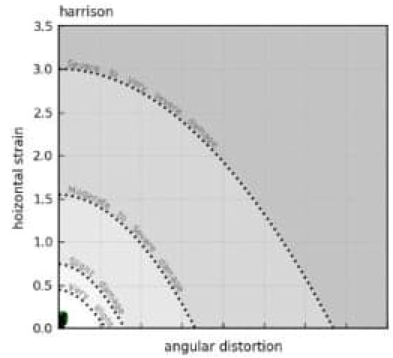
6. Data Analysis and Interpretation: The need to monitor low displacement rates (Escondida Case)



Actual displacement measured by InSAR





The following graphs shows the displacement in 2 orientations:

Up-Down displacement (negative = down)

East-West displacement (negative = west)

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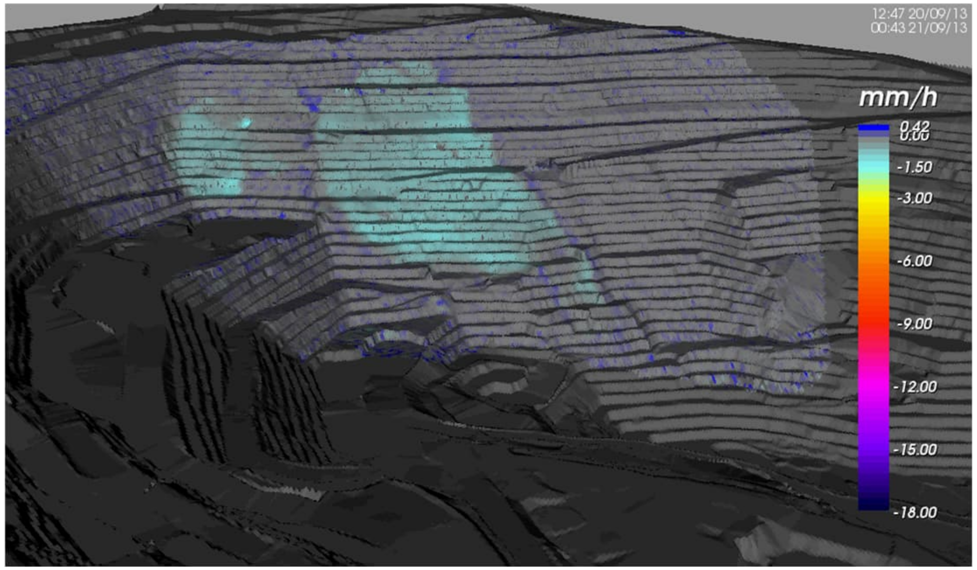
Planning a Geotechnical Monitoring System

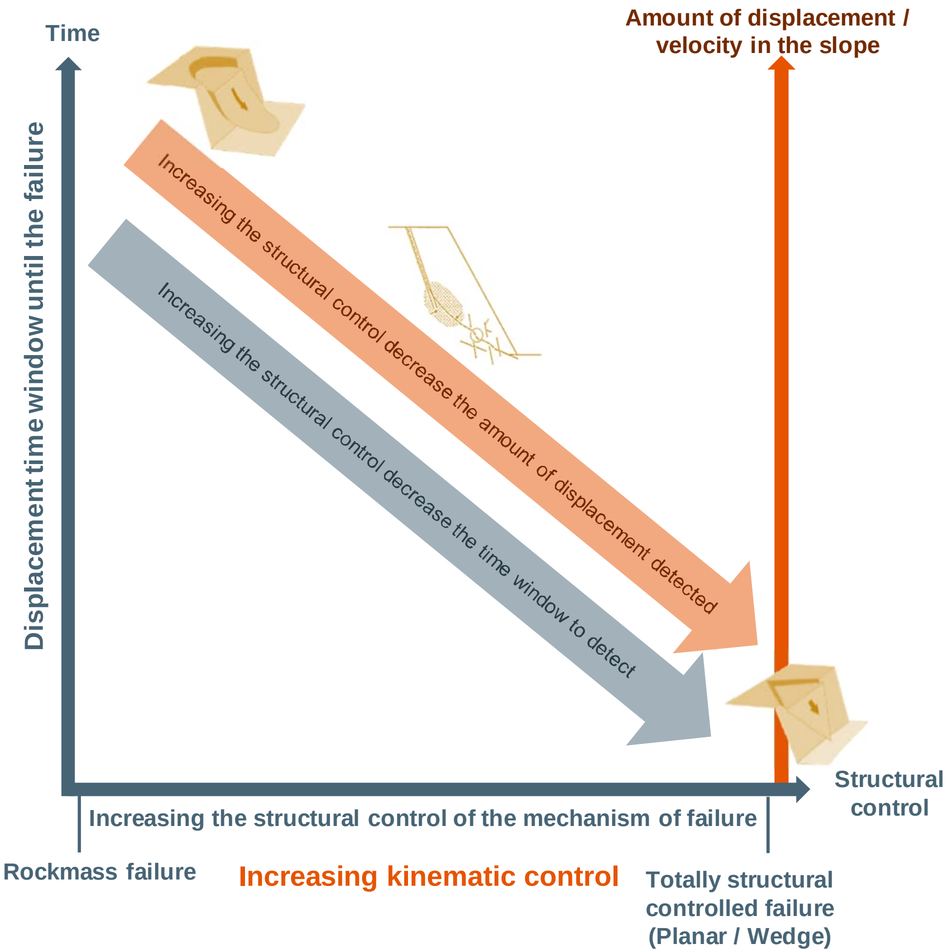
7. Establish Thresholds and Trigger Levels

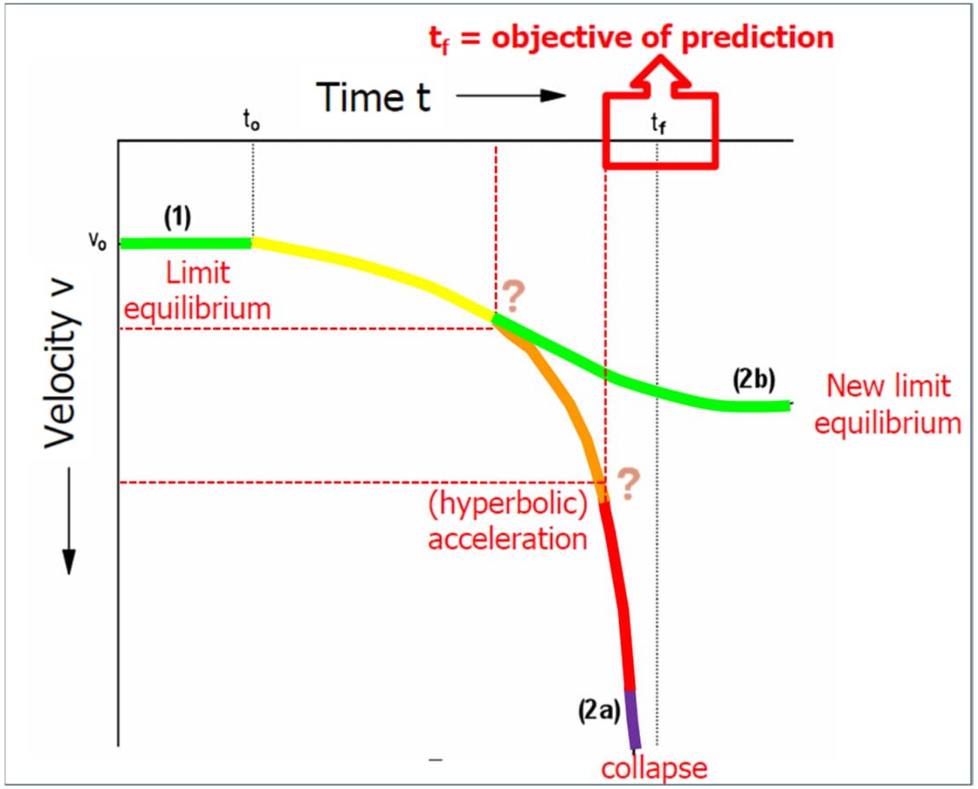
- **Define Critical Thresholds**: Based on risk assessment and historical data, establish clear thresholds for displacements, pressure, or stress beyond which immediate action is necessary.
- **Multi-Level Trigger Systems**: Implement a multi-level system of warnings (e.g., yellow for increased monitoring, orange for partial evacuation, red for immediate intervention or evacuation).
- **Stakeholder Communication**: Ensure that these thresholds and responses are communicated effectively to all operational staff, safety personnel, and decision-makers.



Time / Velocity setting Triggers

7. Establish Thresholds and Trigger Levels

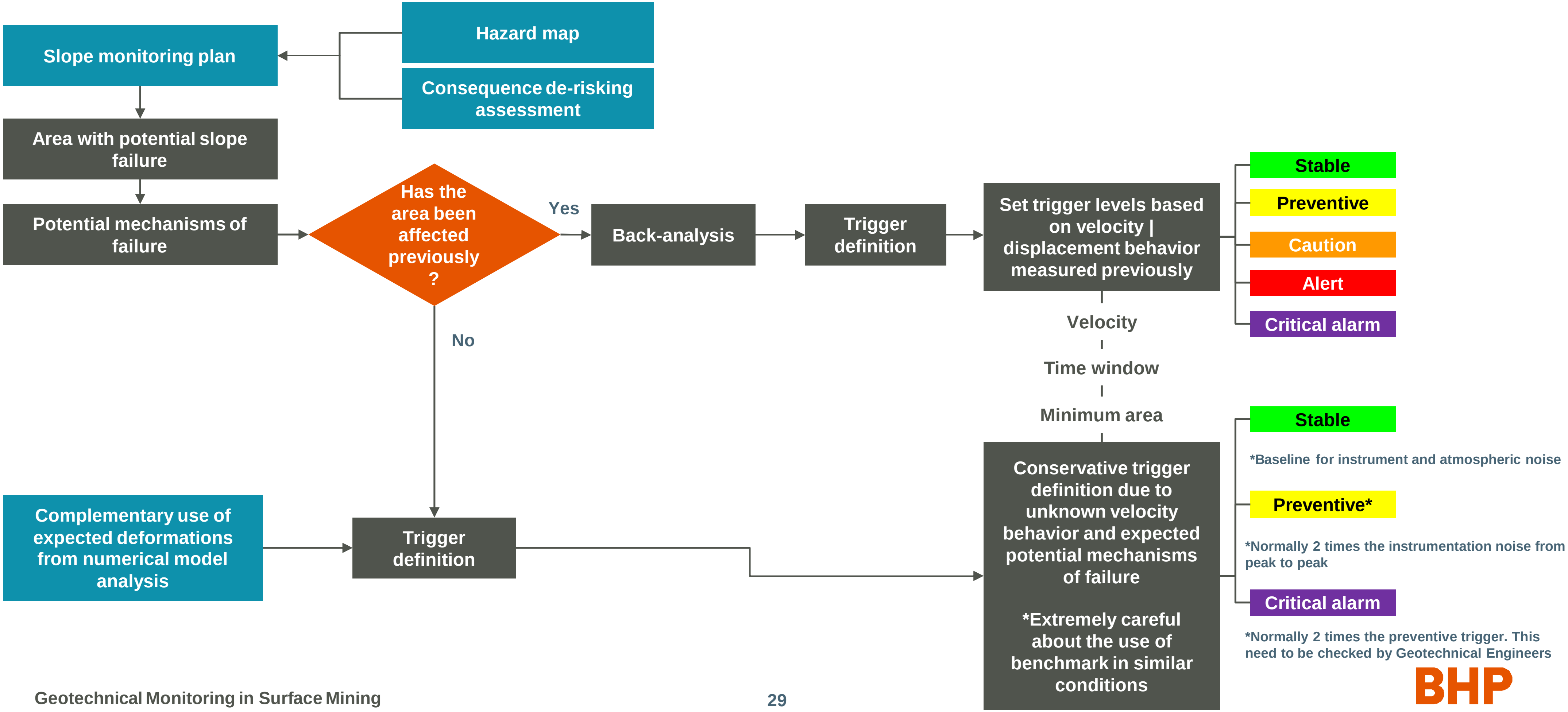




The time/velocity values depends on every site conditions (normally, all the site conditions are different)

Defining critical thresholds and triggers

7. Establish Thresholds and Trigger Levels



Defining critical thresholds and triggers

7. Establish Thresholds and Trigger Levels

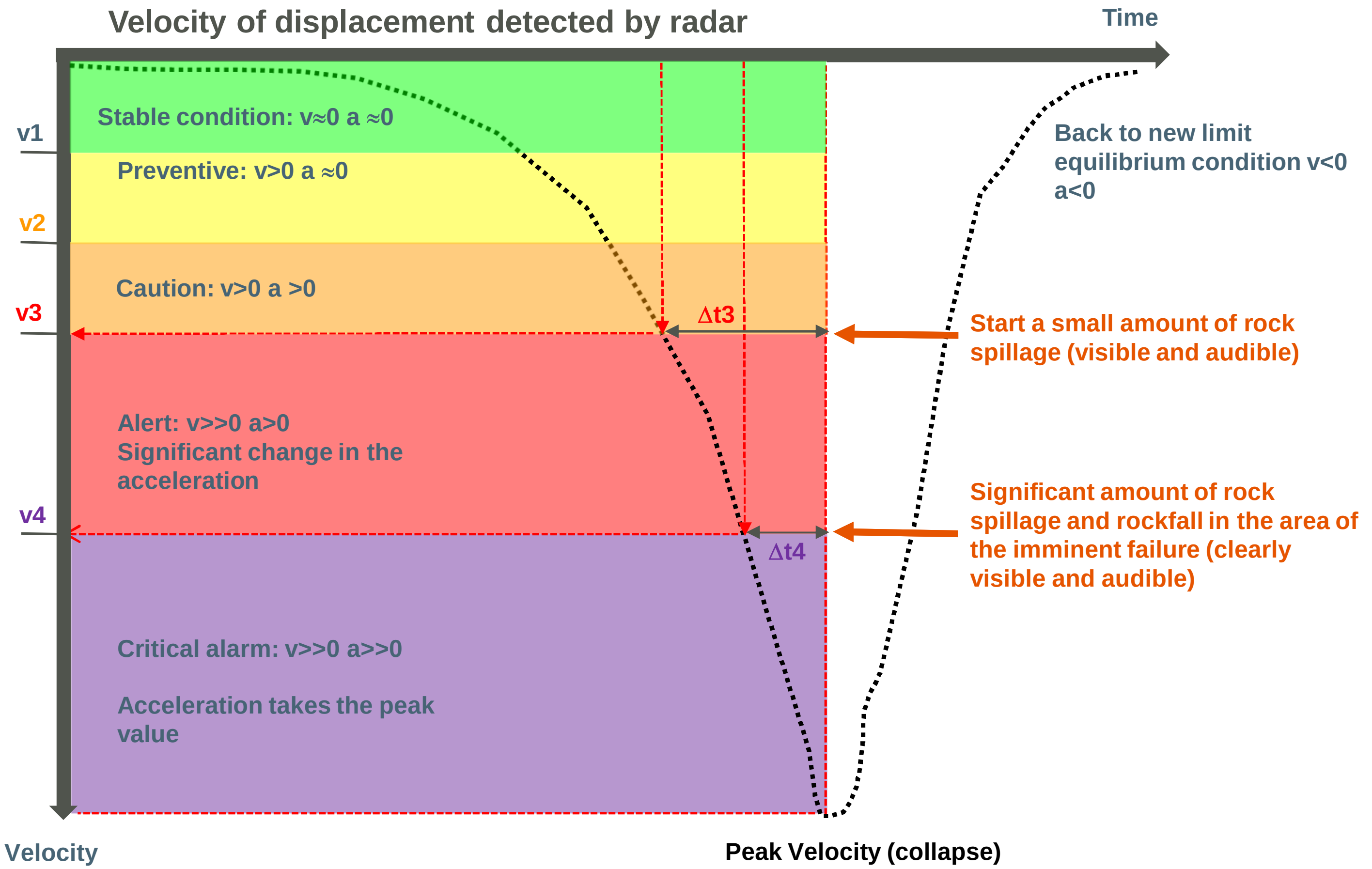
Normal condition, velocity average = 0

v1 Normally x2 the amount of noise (peak to peak) in normal operation for stable reference area

v2 Between v1 and v3 to avoid false alarms and establish the action plan for Geotech staff

Δt3 hours before the peak defines trigger velocity v3. This time is related to confirm with Geotech staff the imminent slope failure during the day (day-shift timeframe for Ground Control Engineer)

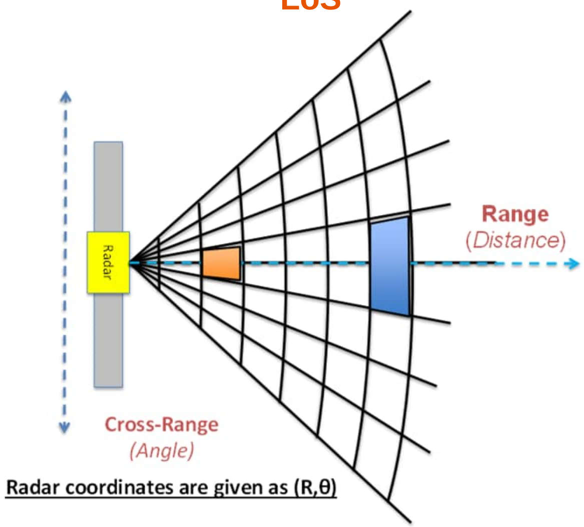
Δt4 hours before the peak defines trigger velocity v4. This time need to be defined by the time that the operation takes for evacuation. (minimum time to evacuate immediately the area). This time need to be validated with actual previous experience or drill exercises for evacuation



Defining critical thresholds and triggers

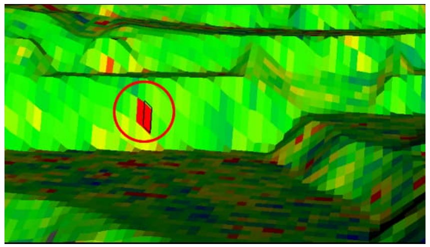
7. Establish Thresholds and Trigger Levels

Range of radar operation

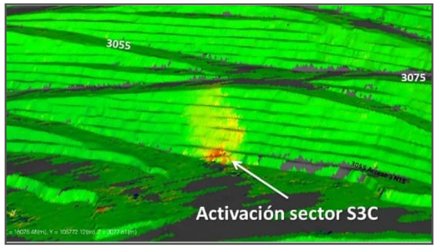


Normally from 200 m. to 2000 m.

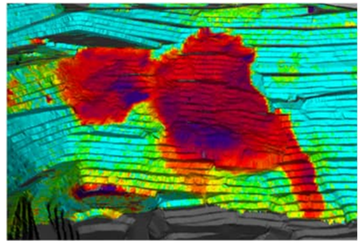
Scale of instability



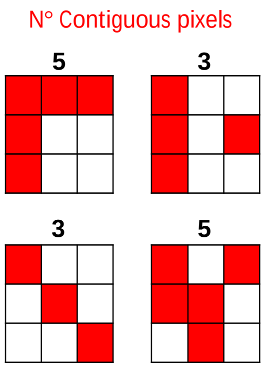
Pixel



Multi-bench



Multi-inter-ramp / Global



Pixel size depends on radar specification.
Must avoid minimum area = 1 pixel (pixels with noise)
Must avoid to much pixels as minimum area (avoid false negative)

Recommendation: 3-5 contiguous pixels (the value in m² will depend of pixel size)

Defining critical thresholds and triggers

7. Back analysis: Escondida pit case

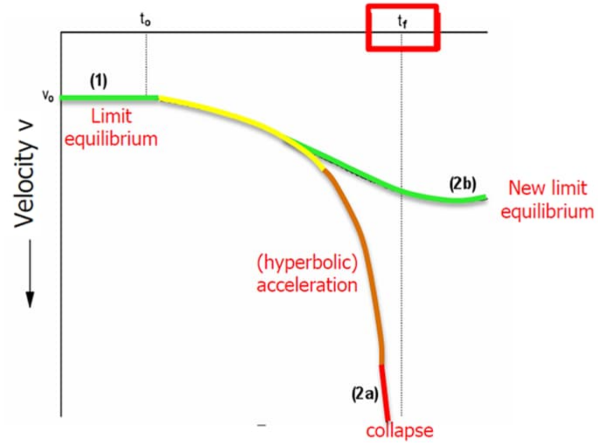
•NE Sector

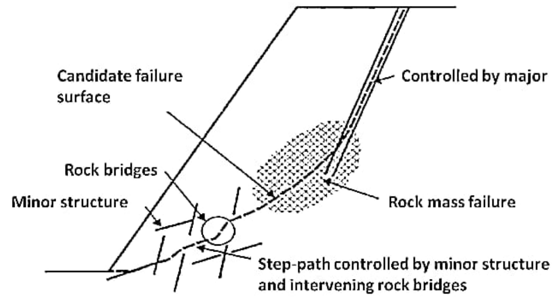
- NE (Dec. 1998)
- N10 wedge (May. - Sep. 1999)
- N12 wedge (Sep. 2005)
- N13 wedge (Feb. 2009)
- N14 wedge (Dec. 2012)
- N15 wedge (Oct. 2013)

•South Sector

- SW wedges (Sep. 2001)
- W1 wedge (Jul. 2014)
- W2 wedge (Nov. 2014)
- W3 wedge (Nov. 2014)
- W4 wedge (Apr. 2015)

Velocity behavior before a collapse





The understanding of the mechanism of failure is critical for the definition of thresholds

Defining critical thresholds and triggers

7. Back analysis: Escondida pit case

•The table and the graph resume the peak velocities per wedge and the velocity value **24 hr. before of the peak velocity**.

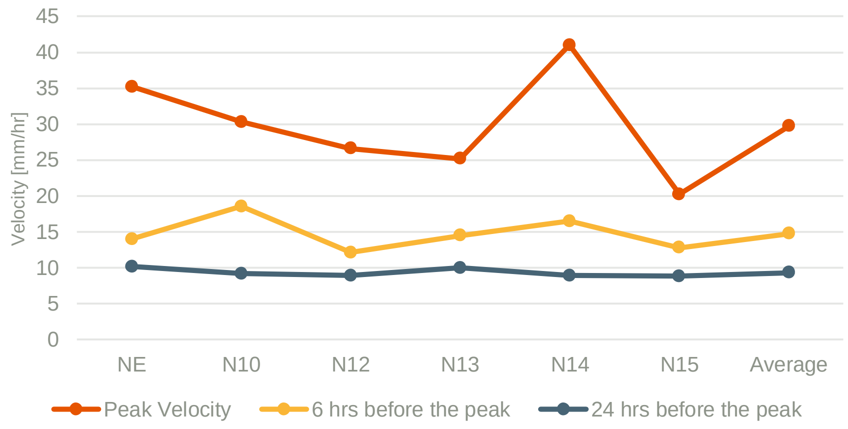
•The 24 hr. before peak data is relevant for define the critical threshold because is **sufficient time to take operational decisions** in the case of NE wall

•In the case of South Wall, the behaviour of **velocity is significantly different (structurally controlled)**. In this condition, the threshold must be defined for 12 hrs before of the peak velocity, due to 24 hrs before the peak, there are instabilities without displacements.

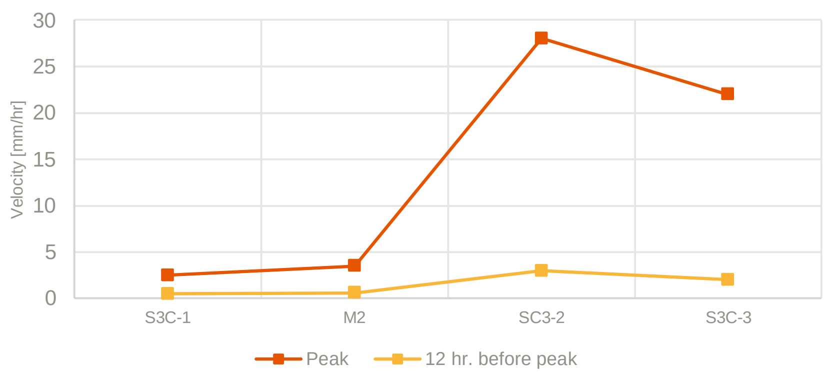
•The role of structurally elements in the instabilities is critical to understand

Geotechnical events	Peak Velocity [mm/hr]	6 hrs before the peak [mm/hr]	24 hrs before the peak [mm/hr]
NE	35.2	14	10.1
N10	30.3	18.5	9.2
N12	26.6	12.1	8.9
N13	25.2	14.5	10
N14	41	16.5	8.9
N15	20.2	12.8	8.8
Average	29.8	14.7	9.3

Velocities in historical wedges for NE wall



Peak velocities in historical instabilties SW wall



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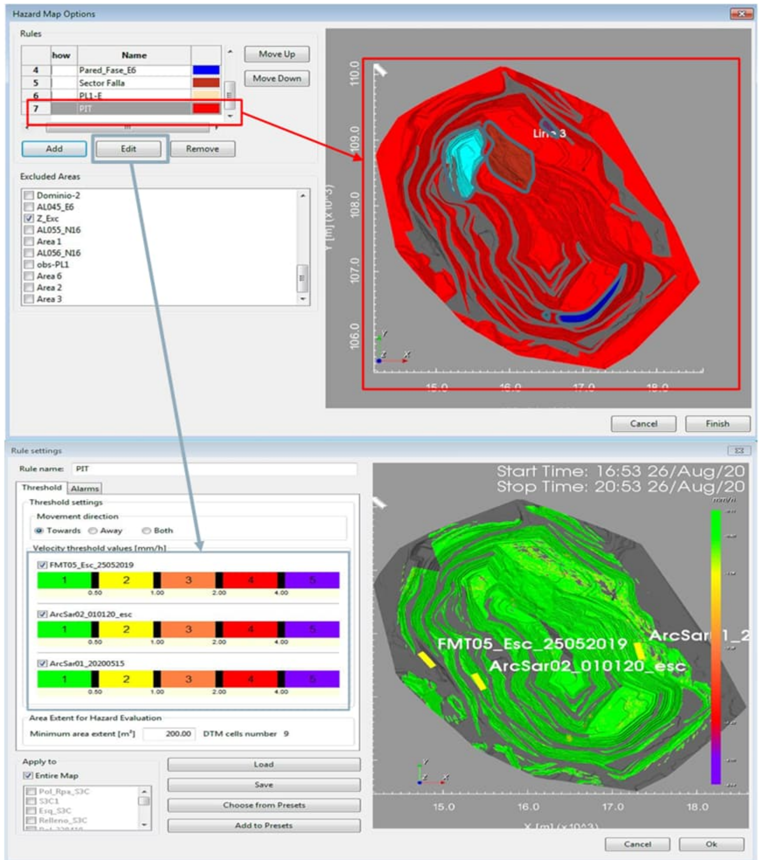
Defining critical thresholds and triggers

7. Back analysis for threshold definition

Level	Brittle Area	Creep and high deformations
1	0-3 mm/hr Ventana de tiempo de 4 hr. Área mínima para activación de alarma: 800 m²	0-0.5 mm/hr Ventana de tiempo de 2 hr. Área mínima para activación de alarma: 100 m²
2	3-6 mm/hr Ventana de tiempo de 4 hr.	0.5-1 mm/hr Ventana de tiempo de 2 hr. Área mínima para activación de alarma: 100 m²
3	6-9 mm/hr Ventana de tiempo de 4 hr. Área mínima para activación de alarma: 800 m²	1-2 mm/hr Ventana de tiempo de 2 hr. Área mínima para activación de alarma: 100 m²
4	9-12 mm/hr Ventana de tiempo de 4 hr. Área mínima para activación de alarma: 800 m²	2-4 mm/hr Ventana de tiempo de 2 hr. Área mínima para activación de alarma: 100 m²
5	>12 mm/hr Ventana de tiempo de 4 hr. Área mínima para activación de alarma: 800 m²	>4 mm/hr Ventana de tiempo de 2 hr. Área mínima para activación de alarma: 100 m²

Areas with different triggers in an open pit



BHP

Back-analysis of trigger for BHP Coal Operations

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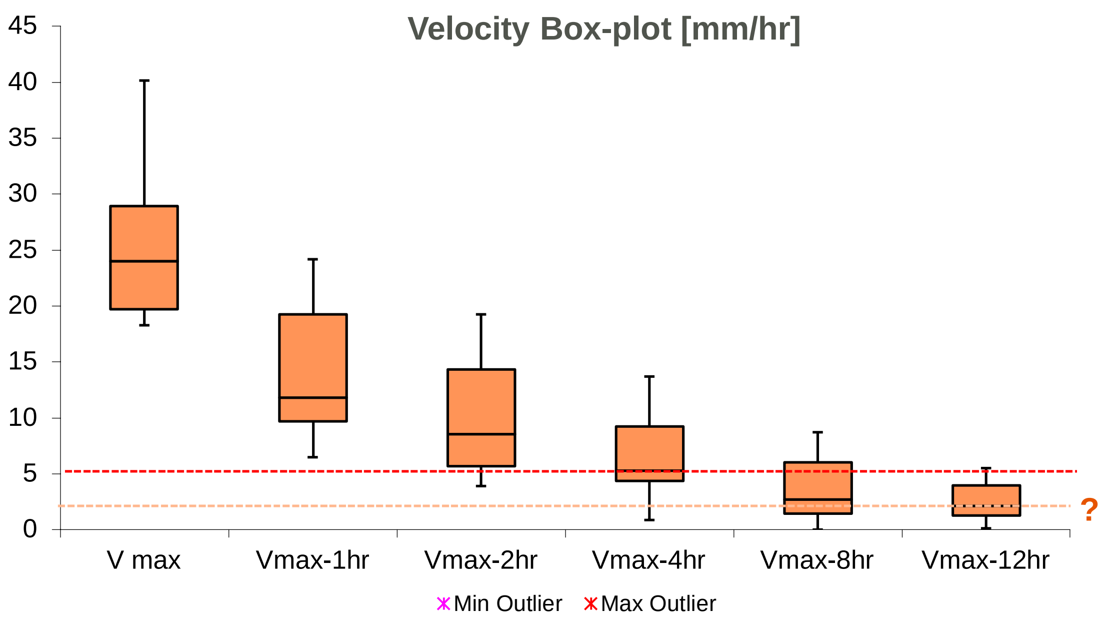
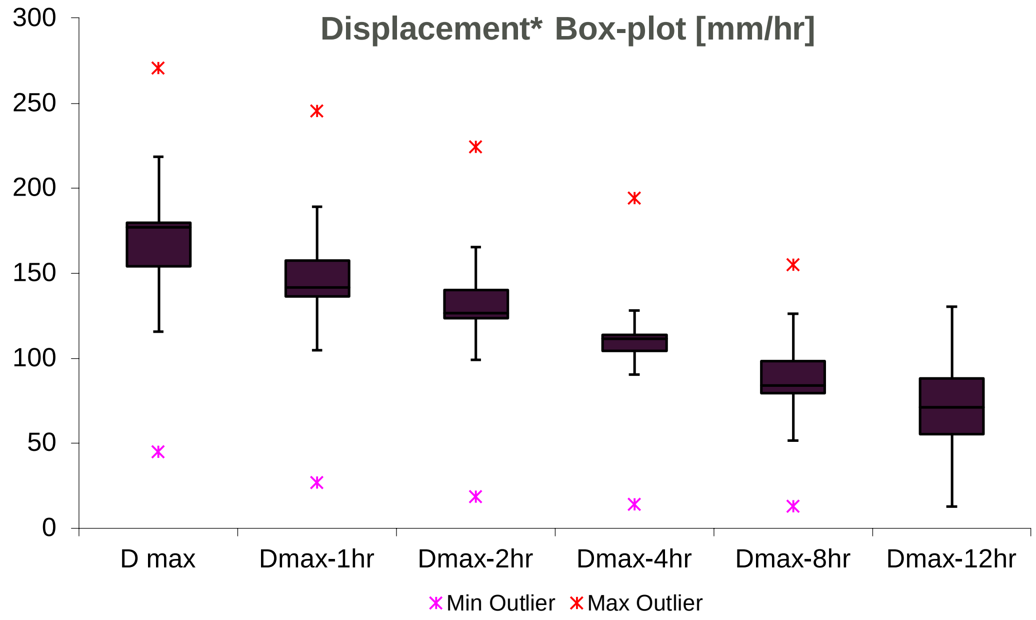
7. Back analysis for threshold definition





Labels	V max	Vmax-1hr	Vmax-2hr	Vmax-4hr	Vmax-8hr	Vmax-12hr
Min	18.3	6.4	3.9	0.9	0.0	0.1
Q_1	19.7	9.7	5.7	4.4	1.4	1.3
Median	24.0	11.8	8.5	5.3	2.7	2.1
Q_3	29.0	19.3	14.3	9.2	6.0	4.0
Max	40.1	24.1	19.2	13.7	8.7	5.5

Labels	D max	Dmax-1hr	Dmax-2hr	Dmax-4hr	Dmax-8hr	Dmax-12hr
Min	45	27	18	14	13	13
Q_1	154	136	124	104	80	56
Median	177	142	126	112	84	71
Q_3	180	157	140	114	98	88
Max	270	245	224	194	155	130

***Displacement doesn't represent the total amount of displacement due to the data starts only 24-36 hrs**

Planning a Geotechnical Monitoring System

8. Response Planning and Contingency Measures

•**Develop Action Plans**: Link monitoring data with predefined action plans, outlining steps to be taken if certain thresholds are exceeded. This may include operational adjustments (e.g., reducing mining activities), safety evacuations, or structural interventions.

•**Training and Drills**: Train mine personnel on emergency response procedures based on monitoring data and alert levels. Regular drills ensure readiness in the event of instability.

•**Review and Adaptation**: Continuously update response plans based on new data, evolving mine conditions, and advancements in monitoring technologies.

Alarm Level	Normal	Level 1 Minor Hazard	Level 2 Major Hazard	Level 3 Failure Within Controls	Level 4 Failure Exceeding Controls
Description	No specific geotechnical hazard of significance observed	No indication of potential for failure; triggers described as minor or moderate	Failure could occur; triggers described as significant	A failure (larger than isolated rockfalls) that was contained/controlled	A failure that has breached controls and had the potential to cause serious injury or equipment damage
HIGHWALL and ENDWALL Triggers (Geotechnical hazard indicators)	• Walls excavated to design • Nil to minor cracking or loose material on wall • Nil to minor rocks falling from wall • Wall is dry/free draining • No obvious signs of geotechnical instability	• Slopes >45° in weak material (Tertiary, Weathered Permian) blasted batters and soft walls not excavated to design (e.g. undercut, oversteepened) • Moderate cracks, loose material on wall • Minor cracking/heaving on bench • Increased frequency/volume of localised rock [illegible] where production has partially ceased due to [illegible] • Minor blast damage	• Significant deviation from slope design • Slopes showing signs of movement (including noise and dust) • Significant material (cling-on) left on wall in front of pre-split • Significant loose material, cracking on the wall/crest or lipping, significant floor heave [illegible] standoff [illegible] water flowing into/through drillholes or structures [illegible]	• Failure of a pit wall that was contained within standoffs or controls	• Failure of any pit wall that has affected an area outside the standoff/safe working distance (i.e. failure breached controls in place), and had the potential to cause serious injury or equipment damage

Niveles de alerta

Descripcion del nivel de alerta

Accion

Sectores/areas de trabajo

Responsible de la accion

A Trigger Action Response Plan (TARP) is essential for ensuring the safety and stability of open pit mining operations. By establishing clear trigger levels, predefined actions, effective communication, and continuous improvement, a TARP enables proactive and decisive responses to potential slope instability, minimizing risks and enhancing operational safety.

Planning a Geotechnical Monitoring System

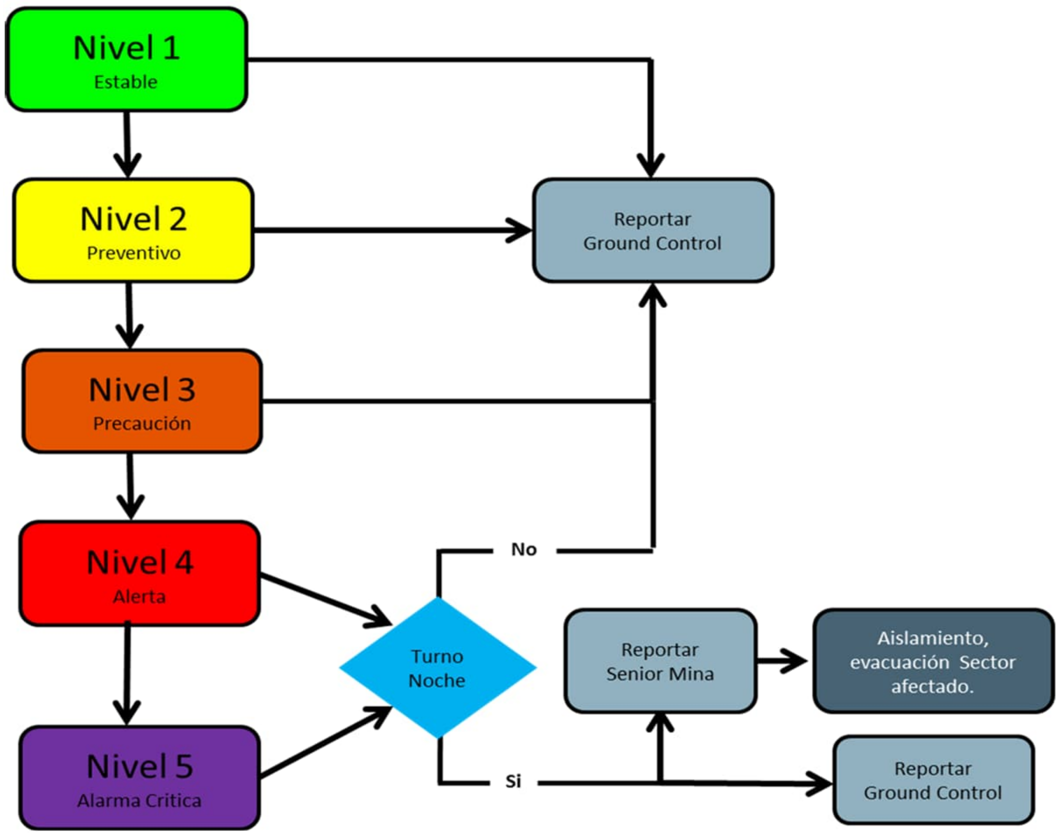
8. Response Planning and Contingency Measures

1. **Establishing Trigger Levels**: Trigger levels are predefined threshold of slope movement or deformation, when exceeded, indicate a potential increase in slope instability. Define levels: Typically three or four levels are established representing an increasing risk and escalating responses.
2. **Monitoring and Data Collection**: Continuous monitoring and data analysis to identify trends and determine if any trigger levels have been breached.
3. **Action Plans for Each Trigger Level**: Predefined actions depending on trigger levels.
    1. Normal Level (Green): Continue routine monitoring and operations
    2. Alert Level (Yellow): Increase the frequency of data collection and analysis. Conduct site inspections
    3. Action Level (Orange): Restrict access to high-risk area. Re-evaluate mine plans and adjust operations
    4. Critical Level (Red): Immediately cease all mining activities in the affected area. Evacuate personnel to safe zones
4. **Communication and Reporting**: Clear communication channels and regular reporting
5. **Regular Reviews and Updates**: Continuous improvement. Establish regular Training and Drills to ensure that all personnel are familiar with the TARP.
6. **Integration with Risk Management**: Risk Assessment and adaptive response. TARP must be flexible enough to apdt to changing slope conditions, mining stages and external factors such as weather.

Planning a Geotechnical Monitoring System

8. Response Planning and Contingency Measures

Example of Escalation process for geotechnical alarms

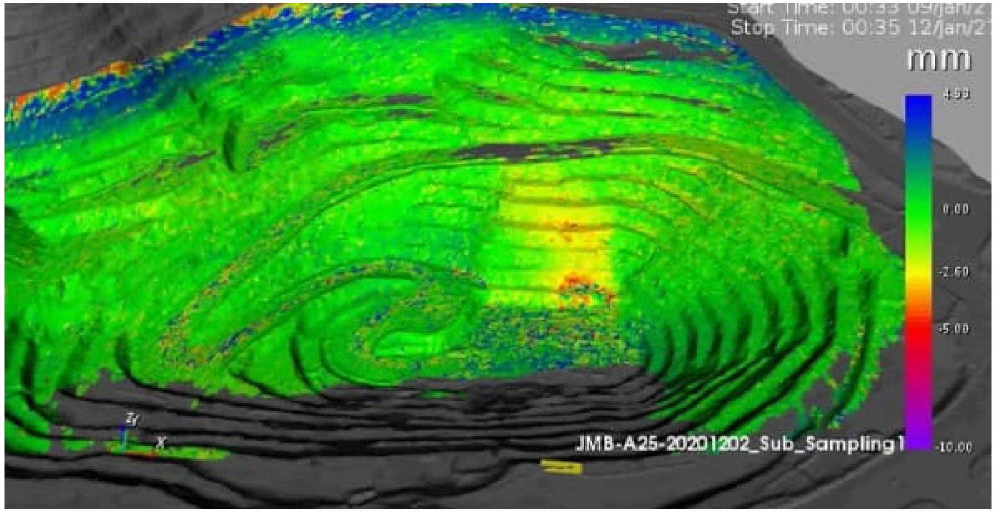


- System with 24/7 sentry in Geotech. Monitoring room

Planning a Geotechnical Monitoring System

9. Implementation of the Monitoring System

- **Installation of Instruments**: Begin the installation process, ensuring instruments are placed as designed and tested for proper functionality.
- **Baseline Measurements**: Collect initial baseline data to understand normal behaviour and deviations from this baseline, serving as a reference for future monitoring.
- **Calibration and Testing**: Regularly calibrate instruments to ensure data accuracy, and test systems periodically to verify their performance under different conditions.
- **Tracking the compliance of monitoring and instrumentation plan**: Regularly track the compliance of installation and operative condition of instrumentation



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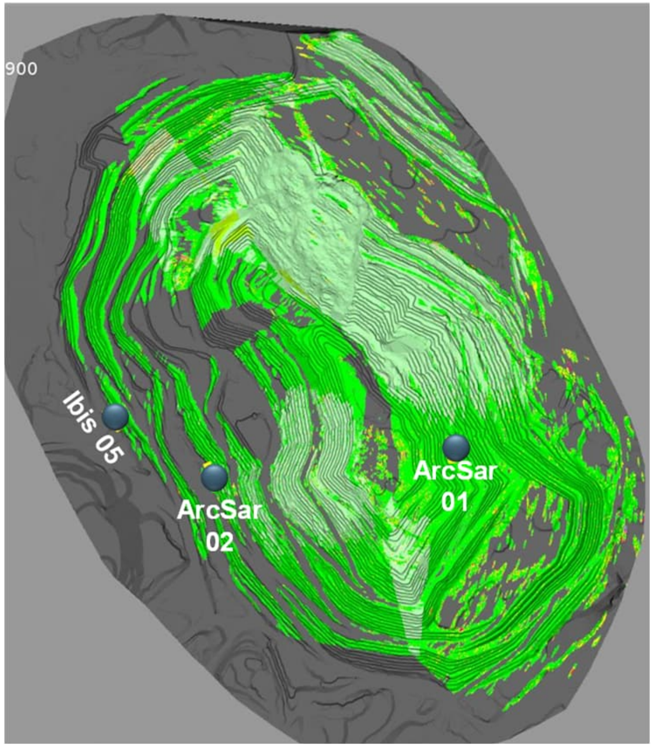
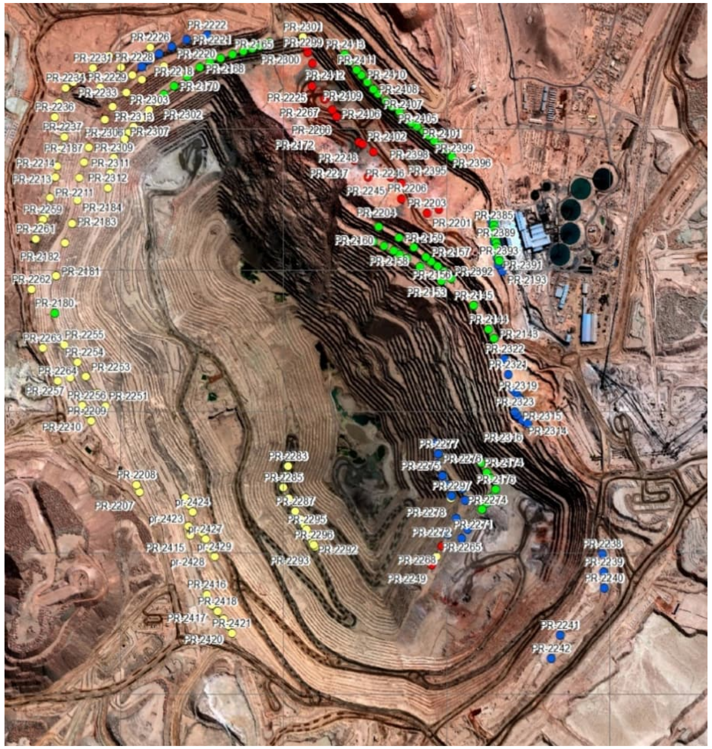
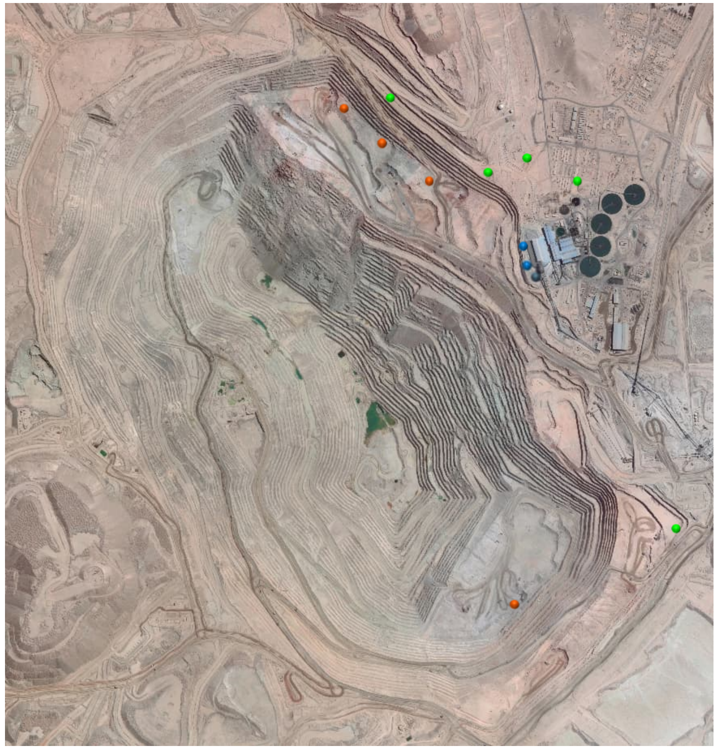
Planning a Geotechnical Monitoring System

9. Implementation of the Monitoring System: Example of Escondida Geotech. monitoring layout FY21







- Ibis Radars integrated in FPM360

  100% pit coverage

- Active prisms (52)
- Destroyed prisms
- In process to link with RTS (52)

- TDR installed during FY20 (5)
- TDR to be installed in FY21 (4) + inclinometer
- High precision GPS (x7)
- SSA Shape array (x2 250 m. each + x1 100 m.)

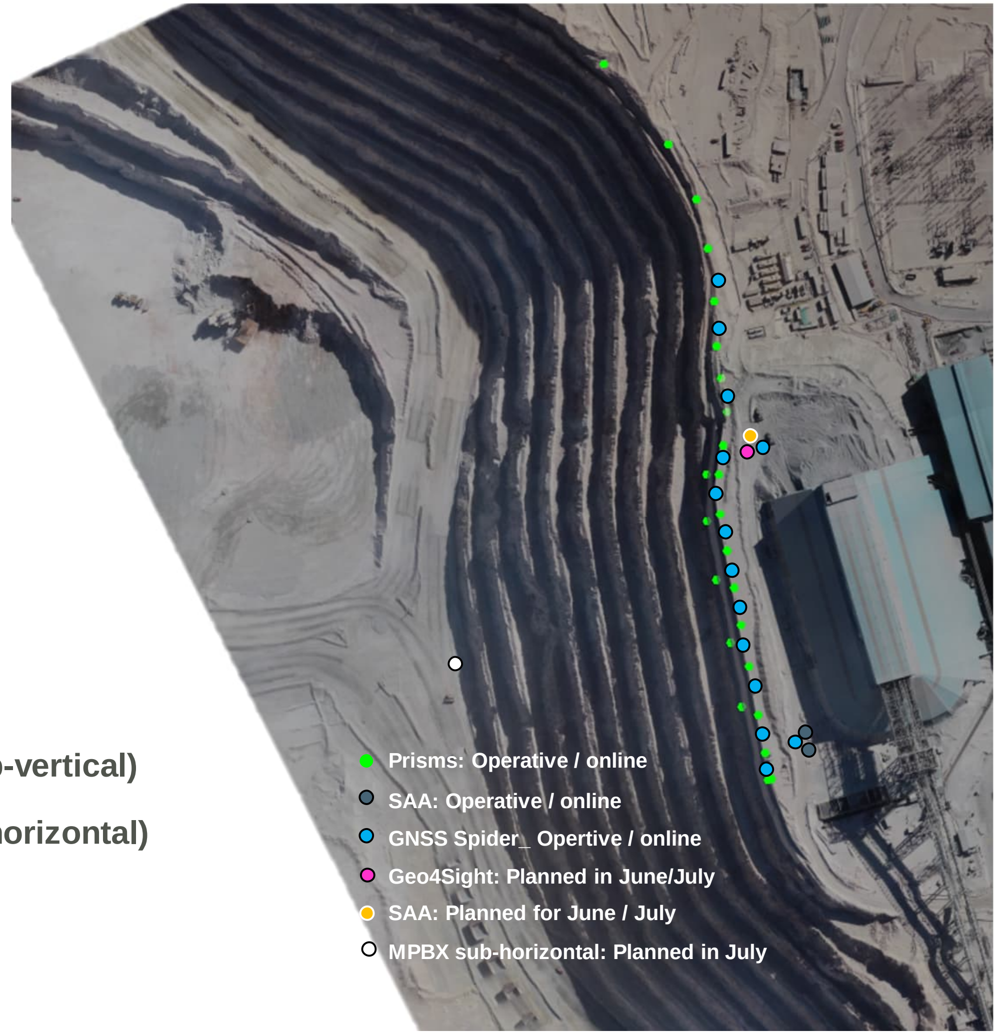
  Satellite InSAR

BHP

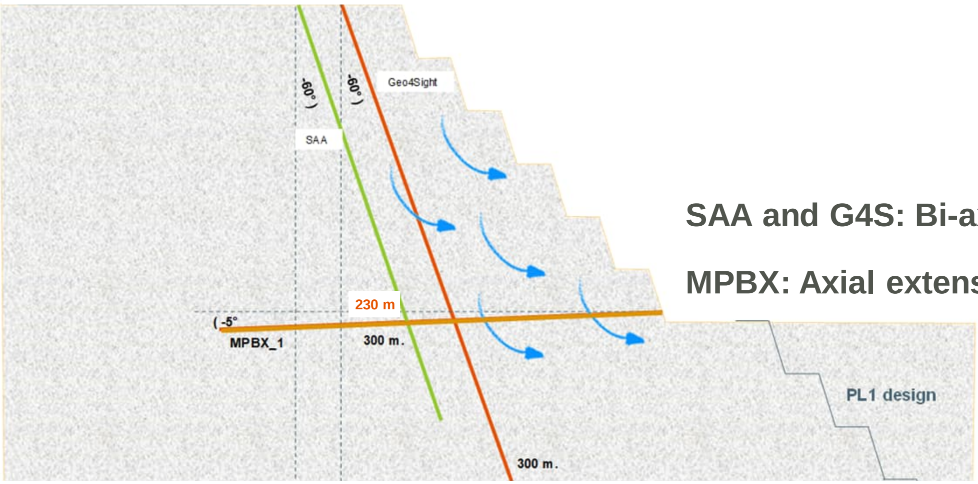
State of the art in mining for Geotechnical Monitoring

9. Deformational response: An integrated approach into the slope and rockmass

1. **Prisms:** displacements on slope
2. **SAA:** high precision sub-surface displacements
3. **GNSS Spider®:** high precision surface displacements
4. **Geo4Sight®:** high precision sub-surface displacements
5. **MPBX:** Sub-horizontal extensometers displacements
6. **Satellite InSAR:** high precision surface displacements / broad area
7. **Sub-sampling Guardian®:** high precision surface displacements / broad area
8. **Piezometers**: Hydrogeological monitoring



Expected mechanism of deformation: Sub-surface monitoring



SAA and G4S: Bi-axial tilting (Sub-vertical)

MPBX: Axial extensometer (Sub-horizontal)

Planning a Geotechnical Monitoring System

10. Data Reporting and Communication

- **Real-Time Reporting and workflow with operations for ongoing activities**: Establish channels for continuous data reporting to geotechnical engineers, management, and safety teams. Automated dashboards can provide real-time visibility into the status of the monitoring system.

- **Periodic Reports**: Prepare detailed reports on data trends, risk assessments, and any corrective actions taken. Ensure these reports are clear and accessible to both technical and non-technical stakeholders.

- **Communication Protocols**: Define communication protocols for notifying key stakeholders (e.g., mine operators, geotechnical engineers, safety officers) in the event of threshold exceedance or unusual trends.

Planning a Geotechnical Monitoring System

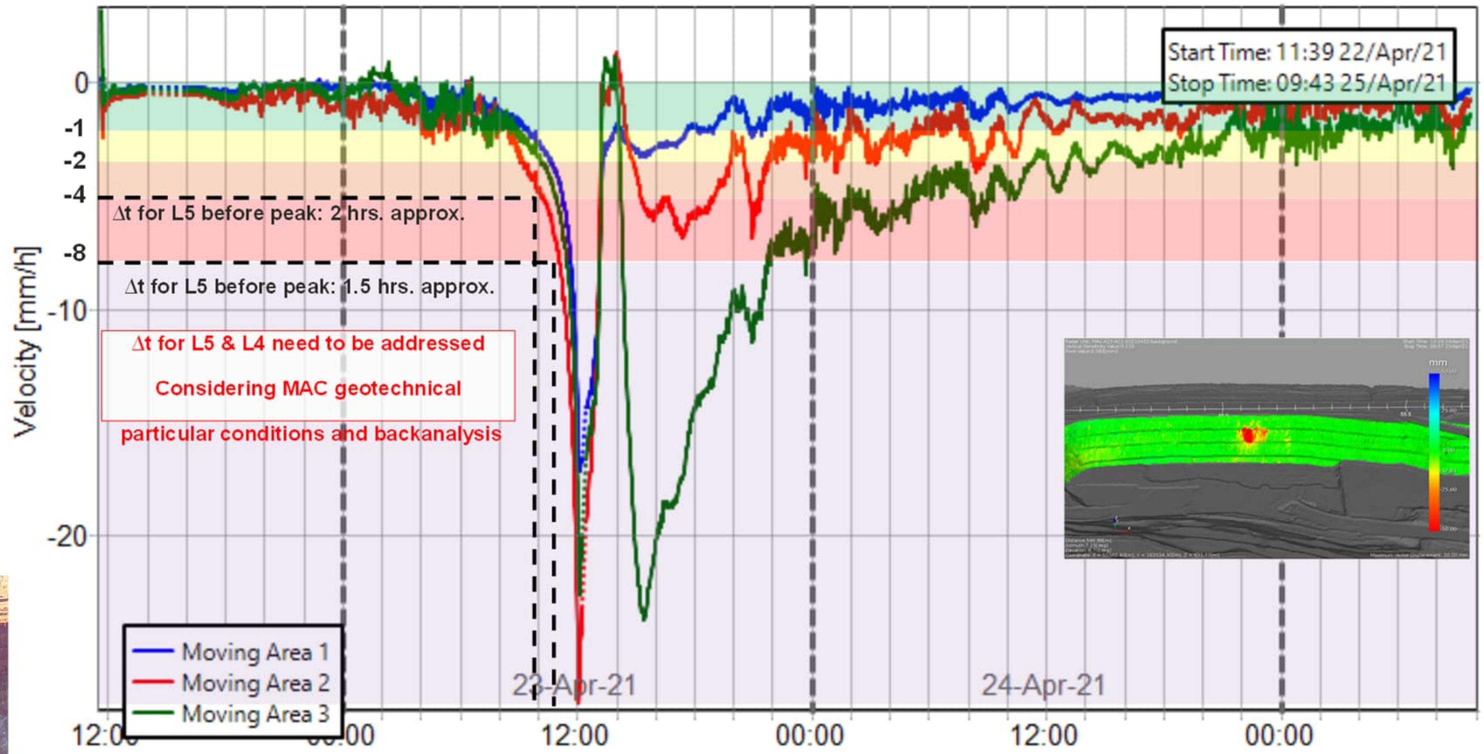
11. Ongoing system maintenance and review

- **Regular Maintenance**: Develop a maintenance schedule for all instrumentation to ensure consistent data quality, accuracy, and reliability.
- **Continuous Improvement**: Periodically review the performance of the monitoring system, incorporating lessons learned from past incidents, advancements in technology, and feedback from mine personnel.
- **System Audits**: Perform regular audits of the monitoring system to ensure it is still aligned with mine conditions, risk profiles, and regulatory requirements.

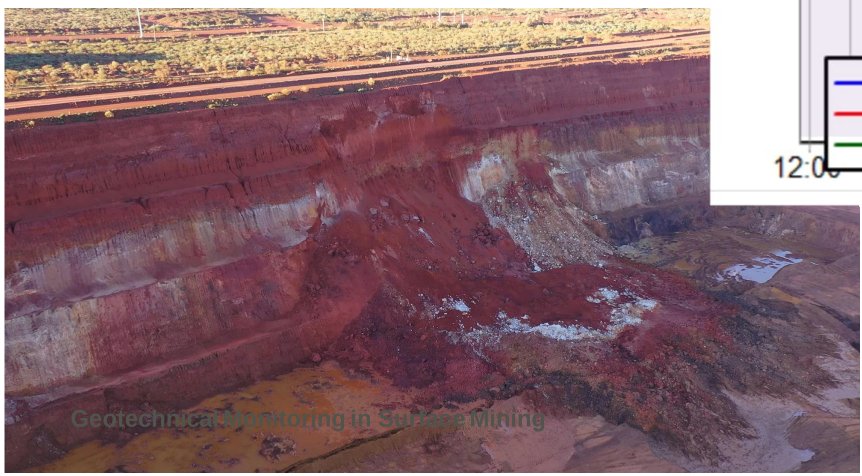
Planning a Geotechnical Monitoring System

12. Post event analysis and system adaptation

- **Incident Review**: After any significant slope failure or geotechnical event, perform a detailed review of the monitoring data to understand the sequence of events leading up to the failure.
- **System Adaptation**: Adjust the monitoring system and trigger levels based on post-event analysis to improve early warning and response in the future.



AC1 Slope Failure, WAIO, Western Australia.



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Key takeaways from Geotechnical Monitoring

- **Integration of Monitoring with Mine Planning:** Monitoring should not be a stand-alone activity but integrated into the overall mine planning and operations strategy.
- **Real-Time Monitoring and Data Management:** Emphasis on the need for real-time monitoring, data processing, and automated alert systems to respond proactively to changes in slope conditions.
- **Importance of Communication:** Effective communication of monitoring data, trigger levels, and response plans to all stakeholders is crucial for the system's success.
- **Use of Advanced Technologies:** The guidelines advocate for the use of advanced technologies like satellite-based InSAR, ground-based radar, and automated total stations to provide comprehensive coverage and real-time data acquisition.

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