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An overview of maintaining a database for pit slope monitoring using Ground Based Radars (GBR)

Sharla Coetsee *Reutech Mining, Cape Town, South Africa*

Priyanka Narshai *Reutech Mining, Cape Town, South Africa*

Abstract

There are several key, predefined steps to first establish and thereafter maintain a 'living' pit slope monitoring database for a Ground Based Radar (GBR). This paper discusses the key considerations that should be taken into account daily for mining operations using a GBR as part of their pit slope monitoring programme.

Practical aspects such as mechanical instrumentation health, power status and continued high quality telemetry is required in order for the system to work effectively. As the radar system collects data, one has to view this information, ascertain, then apply meaningful alarm thresholds in order to identify impending instability, or other areas of concern.

An appropriate trigger action response plan (TARP) is essential for the operation to support the required response efforts to activated alarms, and to de-escalate them depending on the trigger level, risk assessment (likelihood x consequence) and the hazard rating. In addition, custom TARP's may be necessary for specific instability modes (movement stages and patterns), seasonal changes in the atmospheric environment (heat, rainfall, snowfall, dust storms etc.). These various TARP's need to be compiled with the site characteristics in mind and communicated efficaciously to the workforce. Of great importance are the pit slope evacuation procedures, their implementation, practice and periodic review.

Daily geotechnical assessment of the radar data in conjunction with other available instrumentation is imperative to pre-emptively and proactively identify potentially sinister pit slope conditions. These tasks should be undertaken hand-in-hand with visual inspection of the pit slope. Other daily tasks include tracking and recording activities such as drilling and blasting, weather conditions, seismic events, and any other noteworthy occurrence in event logs.

Whilst these steps and recommendations are by no means exhaustive, they provide some guidance to actively managing and maintaining data being collected in real-time for a live database.

Keywords: *radar, monitoring, alarm thresholds, TARP, instability*

1 Introduction

Slope performance monitoring is integral for ensuring safe operational conditions during mining activities, and for gauging the efficacy of the slope design applied. There are a number of sensors that contribute to a slope monitoring program, for which the focus herein is Ground Based Real Aperture Radars (GBR, RAR) and specifically, the establishment and maintenance of databases/datasets captured by this type of equipment.

The maintenance of these databases are the foundation for obtaining reliable and accurate radar monitoring data. A number of alarm exceedance warnings may be applied in order to provide advance warning of pit slope conditions which may be indicative of both anticipated deformation, as well as to forewarn of unexpected or unforeseen events. *'It is these events that can have serious implications in terms of loss of life, serious injury or disruption to mining activities*' (Sharon & Eberhardt 2020).

Whilst having employed various sensors to collect data, the instrumentation (and its collected data) must be well understood, which is best described by Sharon (2020): the intrinsic parameters regarding range, resolution, accuracy, precision, conformance, robustness and reliability are *'synonymous with ensuring confidence in data, poor quality or inaccurate data can be misleading and may be worse than having no data at all.'*

One must also be cognisant of the fundamental principles of the alarming capability and assessment tools provided via the software. This entails both the physical interface itself and the concepts which deal directly with the management of the interpretation of measured interferometric phase and the removal of Refractive Index (RI) which is representative of atmospheric conditions (detailed training and certification is offered by the various service providers).

This paper provides a summary of work conducted in describing the establishment of a successful pit slope monitoring database using GBR (Coetsee & Narshai, 2022a) and then presents an overview of the maintenance of these living databases. Whilst directly applicable to Reutech Mining's Movement and Surveying Radars (MSR), these steps are also valid for other service providers, the theory and checklists can be adjusted to cater for any mining GBR system.

2 A Summary of the Steps for Establishing a Successful Pit Slope Monitoring Database

A number of pre-defined steps to establish a pit slope monitoring database (refer to steps 1 – 6 in Figure 1) were developed by Coetsee & Narshai (2022a). A short description of each step includes:

1. Selecting the radar location: Items to be understood are the geotechnical conditions of the pit slope to be monitored, the monitoring strategy (strategic versus tactical), angle of incidence, line of sight and vector loss of movement calculations, scan envelope size (mechanical limits of the system), distance between the sensor and the pit slope (affects resultant spatial resolution), mechanical and logistical considerations (refueling, power sources, servicing and calibration access, communications network and telemetry), access to geo-refencing network, inspection for visual obstructions and housing for the system (if required).
2. Calculating the database configuration: Selecting the horizontal and elevation degree step and therefore the resultant point spacing or spatial resolution, understanding the consequent temporal resolution in terms of the repeatability of the scan time.
3. Assigning scan regions: Drawing the region to scan and known stable or reference regions (if applicable), applying exclusion or mask areas to mitigate false alarms, and applying user areas and point locations for further assessment.

4. Calculating area threshold parameters: The area threshold is a selected number of points (interchangeably referred to as pixels or voxels) in both height and width for which data is assessed for alarm exceedance purposes. The area threshold should represent the smallest instability size monitored, which is typically a bench height (or half a bench in height for a double bench).
5. Understanding reference time and time windowing: The reference time denotes a predetermined date and time for which the value of the measurements are set at/to 0, in order to manage detailed alarming criteria for a sub-set of the database. The concept of time windowing is that on a sliding scale, with shorter (to manage emergent situations/tactical monitoring, such as impending collapse), medium (strategic day-to-day monitoring activities) and longer (monitoring protocols, like background monitoring, for which extended data collection is required) time windows applied.
6. Alarm threshold application and viewing data: Typically, the three movement categories that alarm threshold warnings may be applied to are relative range (interchangeably called deformation or displacement), average velocity and velocity delta (acceleration or deceleration). The alarms may be either geotechnical (investigative) or critical (evacuation) level. The synthetic (data) map and trend plots should be viewed on various scales, time windows and reference times to ensure that the movement class and profile (Sullivan, 2007), as well as the inhomogeneous movement of the pit slope, are understood, identified instabilities are demarcated accordingly and areas of interest are defined.

3 An Overview of Maintaining a Pit Slope Monitoring Database

In addition to the key steps defined for establishing a successful pit slope monitoring database, the steps for maintaining it were developed as a guideline for managing day-to-day monitoring activities, and for preparing for a more detailed assessment of the collected data (either in a live format or a virtual environment for which specific events and/or historic data may be viewed). Figure 1 shows steps 7 to 12 (in conjunction with the first 6 steps) which are the maintenance component of managing these databases.

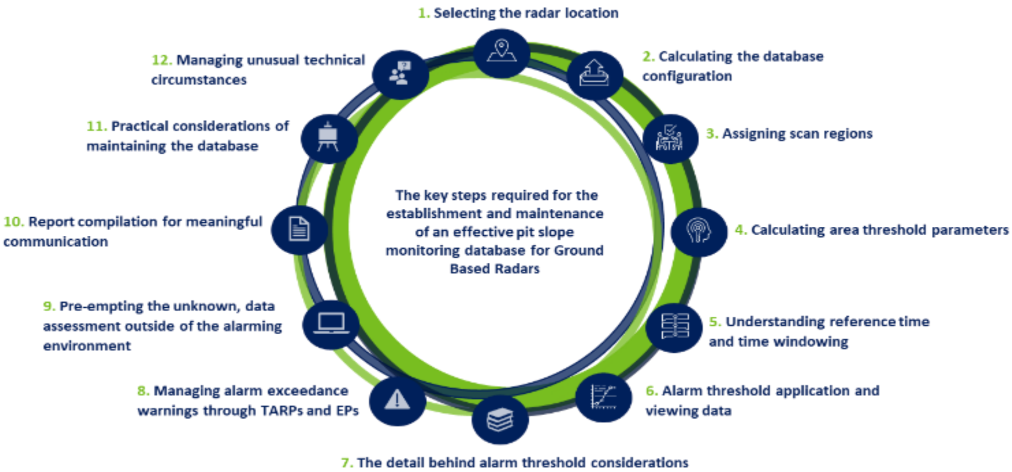

Figure 1. The 12 steps for establishing and maintaining a pit slope GBR database.

3.1 Step 7: The detail behind alarm threshold consideration

There are a number of specific concepts that must be considered when selecting and applying alarm thresholds, some of these are -

3.1.1 General alarm threshold considerations

- The temporal resolution (scan repeatability in time, Théau 2008) defines the number of measurements/samples that can be taken of the point/pixel/voxel per hour. This concept is important to understand as it defines the amount of detectable movement that the system can measure which is a function of the radar physics employed by the system as well as select database parameters applied by the user (refer to Shellam and Coggan 2020, Coetsee & Narshai 2022a and Coetsee & Narshai 2022b). In essence, the higher the repeatability of the scan, the more representative the data collected is of the slope movement taking place.
- If the scan time is longer, with less interferometric phase updates expected, it is better to use a shorter time window, or simply apply a mm/hour alarm threshold for the average velocity. By over averaging out the relative range for the average velocity alarm calculation, the sensitivity of the alarm may be lost, (refer to Coetsee & Narshai 2022a for detail on these technical concepts).
- Maintaining the length of the database for as long as possible, to ensure the full movement history of the slope is measured and recorded, is required in order to understand the pit slope condition as the slope design is implemented.
- Sensitising alarms is not limited to reducing the values applied to the relative range, average velocity and velocity delta, but also reducing the area threshold to make the 'look up' size on the slope smaller or reducing the time window.

Of practical consideration is the application of alarm thresholds viewed in conjunction with the trend plots. An example of alarm thresholds which are more applicable to the dataset illustrated is shown in

Figure 2, whereby there is a balance between geotechnical (orange line) and critical (red line) alarm exceedance points on the relative range and average velocity trend plots. It will be clear to see when alarm thresholds are too 'tight' (Figure 3) resulting in a myriad of false alarms or too 'coarse' (Figure 4) whereby there will be inadequate alarm exceedance warnings.

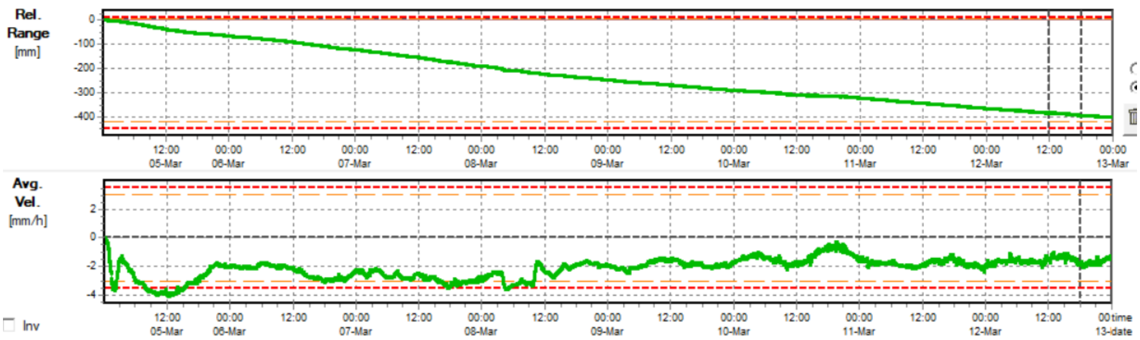

Figure 2. An example of alarm thresholds set that are more appropriate to this dataset.

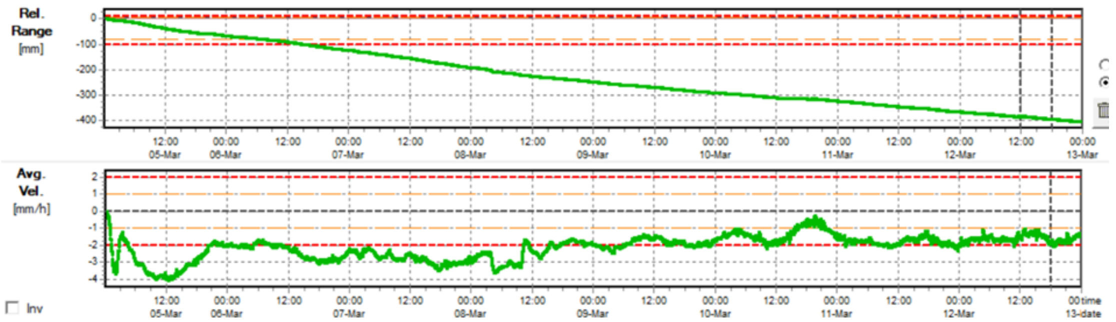

Figure 3. An example of alarm thresholds set that are too 'tight', and will result in multiple false alarms.

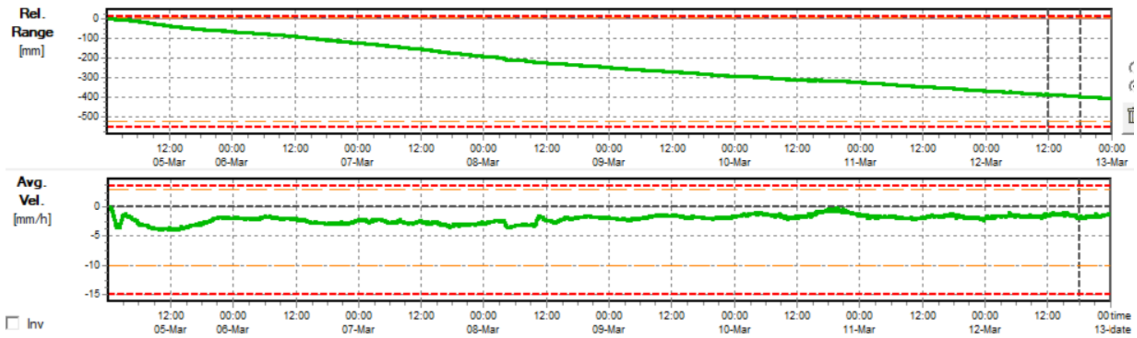

Figure 4. An example of alarm thresholds set that are too 'coarse', and will result in inadequate alarm exceedance warnings.

3.1.2 Alarm Configuration

The escalation and de-escalation of the alarm configuration may be based on:

- Switching between alert levels defined in a TARP which is dependent on the situation at hand, for example various levels based on the probability of the impact, the movement type, time to failure (Bakken et al. 2020, Coetsee et at 2020, Sharon & Eberhardt 2020, Shellam & Cogan 2020 amongst many others).
- Post-collapse monitoring for which the database reference time may be set at 0, and only post-collapse movement of the back-scarp, the failure mass and potential dislocation blocks adjacent to the instability footprint is taking place.

3.1.3 Qualifying poor data

There are techniques to qualify poor data which include the assessment of the pure amplitude, flags and confidence synthetic maps. Figure 5 illustrates good and poor quality examples for two different databases.

Examples of the synthetic maps, for a quiet monitoring scenario are shown in Figure 5 (good quality database, upper set of images) for which:

- The relative range synthetic map (50 mm scale) is quiet and does not show any major hotspots of movement.
- The amplitude (between 0 and – 60 db) is considered normal. It is possible to make out the benches and ramps for this pit slope.
- There are a few cumulative flags (data point quality interrogation) that indicate the ‘targets’ being measured on the actual slope are of good quality and are providing steady and reliable information. The ramps and berms on the other hand are visible, which is typical for this type of synthetic map.
- The confidence (scan-to-scan coherence) synthetic map shows the ramps (traffic noise) and that upper portions of the pit slope have some noise, most probably due to atmospheric effects.

An example of poor-quality data is presented in Figure 5 (poor quality database, lower set of images) whereby:

- There are line artifacts on the synthetic map caused by the phenomenon of multipathing.
- The effects of multipathing can be clearly seen as two line artifacts on the relative range, to some extent the amplitude, the cumulative flags and the confidence images.
- In this case, should there be an instability, the data would be highly compromised as the data is not reliable for the portions of the synthetic map affected.

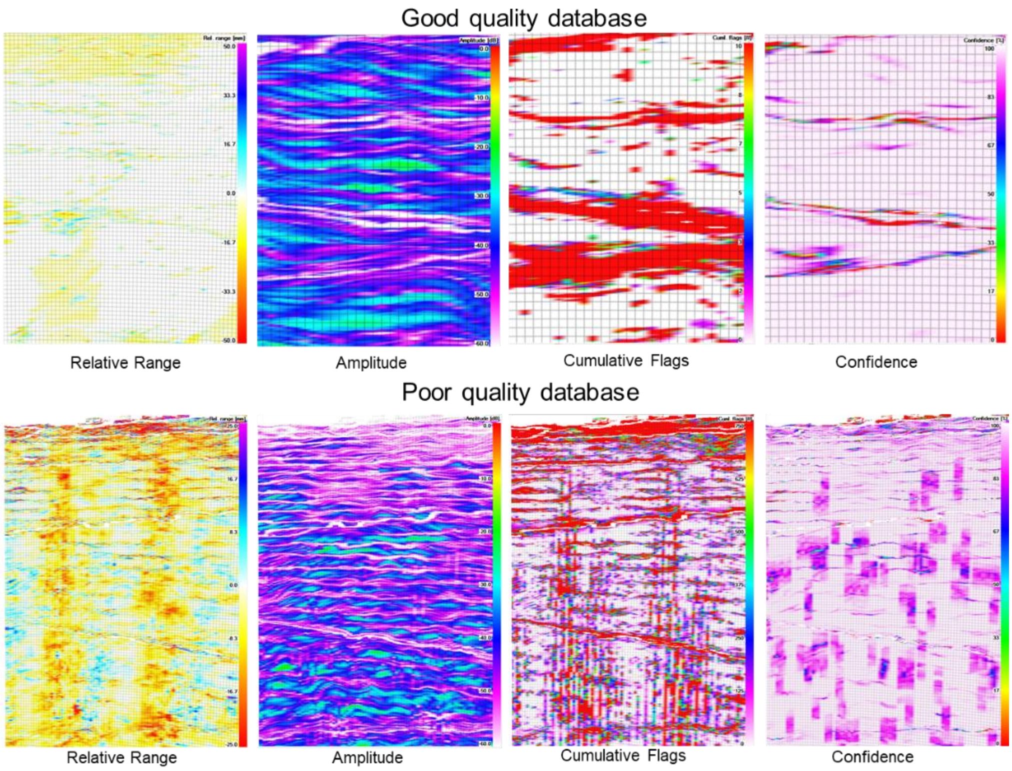

Figure 5. Synthetic maps for a good quality database (above) and a quality poor database (below).

When managing an instability, it is useful to look at the time scale for specific portions of time to understand when changes occurred to the amplitude, cumulative flag and confidence synthetic maps. This gives an indication of when movement is taking place from a signal perspective in collaboration with the movement synthetic maps and trend plots.

3.1.4 Removal of atmospheric contribution

Temperature and RI should be assessed in conjunction with the relative range in order to understand the component of the phase that is being allocated to true pit slope movement and what levels of atmospheric contribution has been removed per interferometric scan. Herein lies the importance of temporal resolution or scan time and the effect on alarming (the shorter the scan time the more effective the alarm), refer to Coetsee & Narshai 2022b for detail on how RI is removed from the total phase.

3.1.5 Vector loss of movement considerations

The vector loss of the movement component may also require alarm criteria to be sensitised if the full movement profile cannot be captured (this calculation is discussed in Sharon & Eberhardt 2020). It has become a custom to apply a scaling factor to data collected from various sensors in order to calculate the magnitude of movement in an environment for which they are directly comparable to each other (Pienaar & Joubert 2011).

3.1.6 Informing alarm threshold selection through data assessment

Concepts to consider when conducting empirical (e.g., the strain based approach to highwall stability Newcomen & Dick 2016) or historical data assessments include:

- The date and time of the collapse.
- The spatial and temporal resolution of the database, as well at the distance between the sensor and the pit slope.
- The trigger, if known and/or observed, that may have caused the collapse.
- The geotechnical conditions and the instability type (Read & Stacey 2009, Wyllie & Mah 2004).
- Visual images (photographs, videos, etc.) and up to date digital terrain models (DTM).
- The length/duration of the database (record the date to and from).
- The height of the slope, the width of the collapse, and the volume of the failed material. A description of the failed material (blocky, fall, slide, flow, intact/consolidated, unconsolidated, etc.).
- What alarms were applied to the database and if they adequately warned of the slope stability condition/s.
    1. Ensure that a representative area that replicates alarm conditions (area threshold) are applied to the trend plots, for a number of portions of the instability (based on a visual assessment of the pit slope, and the synthetic map using the scale bar). It is known that an instability does not behave as a homogenous mass, and the differential accumulation profiles need to be measured, assessed and recorded using this method.

By following this type of assessment path, it may be determined if previously applied alarm thresholds were adequate or not, and how they should be adapted thereof to current monitoring practices.

3.1.7 A note on time of failure prediction

There are a number of techniques that may be utilised to predict time of failure, as well as warn of impending collapse such as inverse velocity (Carla et al. 2017a and 2017b), velocity ratio, and specific coherence assessment (Saunders et al. 2016). Calculating the run-out distance (Whittal et al. 2015) of the instability may also be completed. Whilst noted, a detailed overview of these concepts are beyond the scope of this paper and will be addressed with examples in future work.

3.1.8 Preparing data export for use in third party software

The data collected by the GBR can be exported as a Digital Terrain Model (.dtm) and as a 3D point cloud for which movement data is assigned. This data can then be imported into third party software packages for further specific assessment, such as Slide3 and RS3 (Roscience) for Factor of Safety (FoS) and Probability of Failure (PoF) calculations at various stages of the deformation profile.

3.2 Step 8: Managing alarm exceedance warnings through Trigger Action Response Plans (TARPs) and Evacuation Protocols (EPs)

An appropriate TARP (agreed and approved by all stakeholders, explained in detail by Read & Stacey 2009 and Sharon & Eberhardt 2020) is essential in order for the operation to support the required response efforts to activated alarms and to de-escalate them depending on the trigger level, risk assessment (likelihood × consequence) and the hazard rating.

It is also paramount to be cognisant, and plan for system health concerns which are reflected in the system status (loss of telemetry, low fuel, batteries depleted, specific hardware constraints, stabilisation scan mode (adverse atmospheric conditions), etc.). These eventualities should be included in the TARP under their own designated section, with response planning which includes actions and responsibilities.

When the system is compromised, either due to mechanical or atmospheric concerns (atmospheric system stabilisation mode), note that there may be no real-time data being received from the system, therefore, no active monitoring for which there will not be alarm threshold exceedance warnings. The system will warn the user of these eventualities in the form of a system information notification.

In addition, custom TARPs may be necessary for specific instability modes (movement stages and patterns), and seasonal changes in the atmospheric environment. These various TARPs need to be compiled with the site characteristics in mind and communicated efficaciously to all levels of the workforce when put in place due to special circumstances, as they deviate from the norm.

Of great importance are pit slope evacuation procedures, their implementation, practice, and periodic review. It is of little value to have a well-established TARP with no associated procedure to remove mining personnel and equipment from a perilous area in a timeous manner.

3.3 Step 9: Pre-empting the unknown, data assessment outside of the alarming environment

Daily geotechnical assessment (down to pre-set time intervals, or continuous live monitoring) of the radar data is imperative to pre-emptively and proactively identify potentially sinister pit slope conditions prior to alarm threshold exceedance. Checklists and sign-off procedures may be developed to assist with this task, as well as for record purposes (system health, shift handover, data assessment and alarm exceedance warning receipt list). These tasks should be undertaken hand-in-hand with visual inspection of the pit slope.

Some data assessment tools which may be utilised include:

- To identify and apply various scales on the relative range, average velocity, and velocity delta synthetic map to identify 'hot spots' of movement accumulation.
- Assessing a number of points/pixels/voxels to create trend plots for analysis.
- Adjusting the reference time, data viewing time period and time window to understand the movement accumulation profile.
- Allocating the accumulation profile to a movement class and pattern (Sullivan 2007).
- Comparing accumulation profiles to 'stable' portions of the pit slope to ascertain if there is background, atmospheric or mechanical noise in the data.
- Detailed assessment of historic alarm exceedance warnings, true or false alarms, location, record of alarms in that area over a period of time which may include numerous databases.

The onus is on us, as geotechnical practitioners to ensure that we are visually calibrated with the pit slope, and that we have seen and are aware of its ever-changing characteristics and behaviour. Taking time to conduct the various visual assessment techniques adds to one's own empirical knowledge, such as: incident, daily, detailed, comprehensive monthly and final highwall inspections (Sharon & Eberhardt 2020).

The radar data should also be assessed in conjunction with other monitoring instrumentation/sensors (such as prisms, precipitation sensors, satellite based InSAR etc., if available) (Zavodini 2001).

Other daily tasks include tracking and recording activities such as environmental conditions, blasting (Figure 6), seismic events, mining activities (production activities which include loading or unloading portions of the pit slope, as well as excavation at the toe) and any other noteworthy occurrence in event logs.

In addition to in house-data assessment, contacting the service provider for an overview/review of the data, or utilising an unbiased third-party review at pre-determined intervals are useful feedback resources.

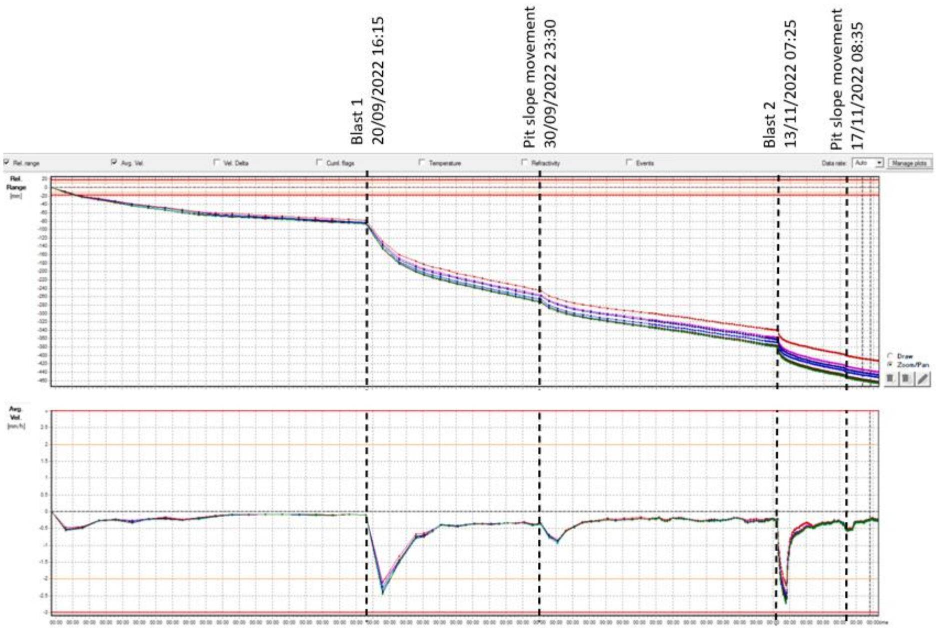

Figure 6. A schematic example of recording blast date and times on the trend plots for record-keeping purposes and data assessment.

3.4 Step 10: Report compilation and meaningful communication

Reporting (defined at predetermined intervals) should not be limited to recording alarm exceedance warnings, trend plot and synthetic (data) map images for the tracking of the various movement classes or instabilities. Additional, information pertaining to the geotechnical conditions observed must be included, along with technically edited photographic or pictorial images of the area of interest. Recommendations for updating the hazard plans/maps, risk profiles, geotechnical and monitoring domains, mining sequencing, drill and blast activities, blast re-entry timing, etc. should be made periodically. Deployment records which detail the name of the system, location and database (name) as well as the contents of the database are also required as part of managing the history of the data being collected.

3.5 Step 11: Practical considerations of maintaining the database

Consideration must be made for the storage of databases (e.g. implementing automatic back-up scripts, sufficient storage capacity, central server access, etc.) to ensure retrieval and safekeeping of both current and historic data. Having these processes and procedures in place aids in the further assessment or back-analysis of data which may be required as discussed in the preceding sections.

Updating/adjusting the mask and exclusion areas and known stable regions, ensuring that benches down to the floor of the pit are monitored (as mining progresses).

Mitigation for multipathing artifacts or any other interference artifacts of the synthetic map needs to be managed as soon as they arise on a case-by-case basis. Any interference on the synthetic map compromises the quality of the data and the ability of the system to generate representative alarm threshold exceedance warnings. Multipathing and interference artifacts on the synthetic map are typically due to the presence of strong reflectors (water, metal objects, mesh, machinery etc.) in the vicinity of the scan envelope.

Pre- and post-blast trend analysis and synthetic map assessment (for safe re-entry practices) should be undertaken per blast and defined per geotechnical and monitoring domain for which the reaction of the pit slope to the blast (blast type dependant) should be described and recorded.

The system may be moved at periodic or predefined intervals in order to protect it from nearby blasting or in order to start a new monitoring campaign. A system specific checklist and redeployment procedure should be developed as part of this process, for which signoff of particular elements is required. Of particular importance is the geo-referencing of the system, and the application of custom-designed software to automatically re-align the scan regions and the three-dimensional movement data from previous deployment/s for the same database. These practices are paramount for ensuring the longevity of the monitoring database.

3.6 Step 12: Managing unusual technical circumstances

In some instances, technically challenging conditions such as highly inclement weather (snow, sleet, heavy rainfall, extreme heat), freeze and thaw, as well as expansion and contraction conditions, in-pit micro-climates, thick dust storms/haze and seismic events; present the geotechnical practitioner with additional items to consider when managing TARPs, EPs and geotechnical feedback to operational activities.

Monitoring through support or mesh, vegetation and blast spill material on the pit slope may mean that the scan region creation, TARP and associated alarm thresholds are revised to reflect the conditions being experienced. These circumstances typically introduce noise (distorted data which is known to be inaccurate) to the synthetic maps, cause false alarms, and compromise the data quality for that portion of the pit slope.

4 Conclusions

Whilst these steps, recommendations and the theory presented in this paper are by no means exhaustive, they provide some good guidance on how to actively establish and maintain data being collected in real-time for a 'living' pit slope database. Should you think we have omitted an important concept, or have any comments or recommendations, please do not hesitate to contact us. We always welcome open debate and discussion.

Scan this QR code to view the full establishment and maintenance checklist in high resolution.

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