STATE-OF-THE-ART MONITORING TECHNIQUES FOR SAMARCO TAILINGS DAMS

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ABSTRACT
Good tailings dam management becomes critical as the complexity of mining projects increases, along with the increasing global focus on safe and sustainable development. The industry standard, and fundamental benchmark for a tailings storage facility, is to provide 'safe, stable, and economical storage of tailings presenting negligible public health and safety risks and acceptably low social and environmental impacts during operation and post-closure'.

Geotechnical stability is a key consideration in many tailings dam failures, and monitoring and instrumentation of tailings dams provides valuable insights into potential tailings dam failure mechanisms. Given the extremely high costs of tailings dam failures, such monitoring and instrumentation is a cost effective means of determining the critical parameters that may mitigate the risks and potential consequences of tailings dam failures. This paper discusses the outcomes of a back-analysis of state-of-the art slope monitoring techniques undertaken at a number of sites at Samarco Mine in Brazil. The data are assessed in terms of geotechnical stability and the associated alarm levels. The ability to pre-emptively identify, and respond appropriately to slope instabilities is explored.

1. INTRODUCTION
The demand for tailings dam growth, and in turn the risk associated with these structures, is increasing exponentially with time. To address waste volume requirements, tailings storage facilities must be built (Robertson, 2012):

BIGGER: higher stresses, higher strains, higher consequences;

FASTER: higher pore pressures, static liquefaction, rushed constructed, less observed time; and

LONGER LASTING: Mine closure halts operation, but the waste facility still stands. Time-dependent deterioration must not be excluded from consideration.

Statistics have reported two to five tailings dam failures annually for the roughly 3,500 tailings dams worldwide (a probability of 1 in 700 to 1 in 1,750) (LeProude, 2015; Davies et al., 2002a). Comparatively, the estimated annual probability of failure for a conventional dam is 1 in 10,000 (Davies et al., 2002a).

In Chambers' (2016) database of the 280 dam failures recorded between 1915 and present day, the highest count of failures are in the United States of America (USA) and Chile, which are anticipated to be elevated due to the number of dams in existence and the frequency of earthquake events, respectively. It is important to consider statistics and data, as will be conveyed in this paper, by the metrics of best value. The likelihood and consequence of dam failure in terms of the social, environmental, and economic pillars of sustainability are the dominant metrics by which the risk of tailings dam failure is established. In the case of historical collation of data, the value exists for the geotechnical community in that "there have been no unexplained failures" and "in all of the cases over the past thirty years, the necessary knowledge [existed] to prevent the failure at both the design and/ or operating stage" (Davies et al., 2002). For the USA, this value is realised where gained knowledge has contributed to improved engineering practice, in turn decreasing the number of dam failures from 77 in 1960 through to 1990, to 15 between 1990 and present day.

The trend of reported deaths has also decreased significantly, although the same cannot be said for amount of tailings released, reiterating that there is still work to be done. The value of education and resilience in Chile has seen the failure of tailings dams due to seismic liquefaction reduced "from 14% in pre-2000 cases to zero in post-2000 cases: the 2010 Chilean earthquake of magnitude 8.8 did not cause any failure" (Azam and Li, 2010). In perspective, the La Ligua earthquake of magnitude 7.4 on March 28, 1965, exhibited the most widespread influence with 17 reported dam failures, 200 reported deaths, and 2.5 million cubic metres of reported release as a result.

Since 1986, the state of Minas Gerais in Brazil has had eight tailings dam failures, six of which are considered major. This state, roughly the size of France, is responsible for most of the country's iron ore production, and thus has the biggest concentration of tailings dams in Brazil. Most of the failures were found to be related to liquefaction as the coarse, sandy properties of iron ore tailings exhibit characteristically high susceptibility to liquefaction. The upstream method is the predominant method for dam construction in Brazil. Also, as Brazil was mostly considered non-seismic until recently, dynamic analyses are still incipient in the country and there are no acts or regulations that require dynamic loadings to be taken into account in dam design.

In recognising cases such as that where Brazil is unfamiliar to design considerations to which Chile has advanced, geotechnical information pertinent to increasing the knowledge and understanding of in-situ failure risk analysis should be shared in consideration of safety, livelihood, reputation, and best standard practice. This is anticipated to allow a global reach of geotechnical engineers to design, construct, operate, and maintain these structures responsibly. A communal approach from all tiers of geotechnical personnel for the betterment of stakeholder safety embraces multiple benefits. Acting in accordance with this recommendation, this research paper discusses localised tailings dam failure case studies from Samarco Mine in Minas Gerais, Brazil. With a focus on state-of-the-art monitoring techniques, in particular radar deformation monitoring, the intent is to detail how back-analysed interpretation of existing monitoring and instrumentation can benefit future dam monitoring. Improved strategies in terms of critical parameter trigger levels, and ultimately the ability to anticipate and respond promptly to tailings dam instabilities are anticipated.

2. SITE CHARACTERISATION AND BACKGROUND

MINE BACKGROUND

Founded in 1977, Samarco mine iron ore in Minas Gerais, Brazil, to produce and export pellets to 19 countries in the Americas, the Middle East, Asia, and Europe. Samarco currently operates under a 50-50 joint venture arrangement between Vale S.A. and BHP Billiton Brasil Ltda.

At the time of this paper, Samarco was embedded in, and committed to the social, environmental, and economic recovery of regions impacted by failure of the Fundão dam in late 2015. As part of this recovery, and in line with the recommendations introduced, Samarco bears a self-induced responsibility and obligation to share learnings. An open discussion with both national and international peers increases awareness of the risks, and how interpretation of previous events at this mine can contribute to a safer environment.

DAM AND SLOPE CHARACTERISTICS

Each of the events described in this paper comprised real-time, radar monitoring at the time of failure. All three events occurred after the Fundão dam failure in November 2015, with data collection complemented by the availability of six radar units that were deployed to monitor for further deterioration following the event. A limitation exists where once operational instrumentation, including inclinometers, piezometers, extensometers, and survey points on the structures being assessed had been destroyed in the previous event: a strong justification in the requirement for deployable monitoring solutions. The only comparable data was that from the weather station.

SANTARÉM DAM

Santarém Dam is located 3 km downstream of Fundão dam (Figure 1). Santarém Dam is designed as a civil gravity dam: a concrete structure retaining both water and tailings. On failure of Fundão dam, Santarém Dam overtopped and sustained structural damage, but did not fail. To ensure future integrity of the dam, Samarco have constructed an earthen buttress to reinforce the downstream side. Radar monitoring detected a minor, localised failure during construction.

Dike 2

Dike 2 is located 500 m upstream of Dike 1 of the Fundão dam (Figure 1). Internal to the Fundão reservoir, Dike 2 was designed to retain the slimes component of the tailings, while sands were retained by Dike 1, both of which failed in the 2015 event. Of the 19,000,000 m^3 of material remaining within Fundão after the failure, the majority were slimes situated upstream of the breached Dike 2. In January 2016, 1,000,000 m3 of this material was mobilised from the reservoir as a result of heavy rainfall, which carried downstream uninterrupted to overtop Santarém Dam. With repair works underway on the downstream Dike 1, the risk of failure of the adjacent Selinha Dike, surrounding natural slopes, or progression of failure of Dike 2 was considered major with loss of life a potential consequence. Radar monitoring detected several minor events, of which one particular slimes collapse will be assessed.

Natural Slope

The natural slope is located 200 m downstream of Fundão dam (Figure 1). On recovery of the Fundão dam failure, a cofferdam was being constructed with the intent to drain, and allow repair works to take place downstream. Visual inspection of the worksite identified a potential circular shear failure forming on the adjacent natural rock slope. With personnel working below the area, risk assessment identified loss of life as a potential consequence of failure. No data was available on the material characteristics of the rock. Radar monitoring detected, and provided sufficient warning for failure of the circular shear failure during monitoring.

Figure 1 – Samarco site locations

TRIGGERS AND RESPONSE

On all instruments installed at Samarco Mine, parameter thresholds exist as triggers to prompt appropriate responses, dependent on the level of threshold exceeded. Piezometric thresholds correlate directly with the design factor of safety, where sensitivity analyses in computer modelling established the water table levels at which intervening action was required, prior to significant deterioration of the dam wall. Movement thresholds, on the other hand, are more difficult to determine.

Back-analysis of in-situ behaviours represents one of the most valuable approaches in establishing movement triggers. For slope stability assessment, in-situ movement data may be collected by instruments embedded in the subsurface such as inclinometers, or from the surface, by extensometers, survey points, slope stability radar, or LiDAR. Surficial readings can be convenient and readily collected indicators of internal deformation. They may also be used to confirm and/ or optimise computer modelling of anticipated behaviours, inclusive of site geotechnical variability.

Existing radar movement thresholds at Samarco are based on back-analysis of a minor failure that was captured in Santarém Dam. The basis of selection was those thresholds that allowed for greater warning prior to the event occurring. The threshold values for radar monitoring, and responses for each threshold level are summarised in Table I. It is important to acknowledge that movement velocities are reported as opposed to magnitude, as it is the accelerated change of movement that is the critical indicator of failure in the short term, with large movements over a longer duration of time able to be predicted, remediated, or otherwise remaining globally stable. Regardless of the trigger level, the Geotechnical Engineer can evacuate the structures and/ or trigger Samarco's Emergency Action Plan at any time.

Table I - Response plan for trigger levels, inclusive of nominated radar movement thresholds

		Yellow	Orange	Red
Trigger	Radar movement velocity	3mm/ h	5mm/ h	8mm/ h
Responsibilities	Monitoring centre technician	Validate the reading against specific instrument instructions*. If validated to be true, alert the geotechnical engineer of all known information by email.	As per yellow response, but also contact geotechnical engineer by phone, promptly.	Evacuate personnel from structure.
	Geotechnical engineer	If reading is validated, perform a field inspection and check surrounding instrumentation. Report on the alarm and include required actions for remediation/ response.	Investigate requirement for pre-emptive evacuation of structures. Issue report to key stakeholders.	Immediately to the monitoring centre. Evaluate threshold reading and surrounding instrumentation. Consider safety and feasibility of field inspection. Issue report as per yellow trigger.

*At Samarco, contingency is applied in the monitoring and instrumentation strategy in order to allow for this validation process. For example, automated readings from telemetry installed on piezometers would be validated by manual inspection, and Slope Stability Radar (SSR) monitoring would be validated against Interferometric Synthetic Aperture Radar (InSAR).

LOCAL ACTS AND REGULATIONS

Samarco abides by national law, called Portaria, which is authored by the National Department of Mineral Production and sets the standard for dam safety in Brazil. Portaria 416, released in September 2012, was vague in terms of monitoring and instrumentation requirements, stating only that readings from the instrumentation must be made available to the authorities should they require it, and measurement and documentation frequency should be every 15 days, at the least. A general understanding across Brazilian mines was that mandatory monitoring requirements were defined by the person or company responsible for the dam, typically to an extent that allowed design expectations to be compared against operational performance.

The most recent release of Portaria at time of this paper was Portaria 70.389, published on 17 May, 2017. This release was passed in collaboration with Samarco, where definition of the new industry standard for monitoring is complemented by the outcomes and learnings from the 2015 failure: the most significant event for Brazil in recorded history. While the monitoring requirements from Portaria 416 remain, the following requirements have been added:

- Every dam must have a monitoring system that allows the company to assess dam safety;
- The complexity of this system is dependent on dam failure consequence;
- For dams deemed of high consequence, the monitoring system must be real time, and must have video cameras, both monitored 24 hours a day, seven days a week; and
- This monitoring system, amongst other elements, must be assessed for all site dams twice per year by an external consultant.

3. MONITORING TECHNIQUE AND DATA TREND ANALYSIS

CALCULATION PERIOD

In terms of monitoring and instrumentation, calculation periods define the time duration over which the deformation data is averaged, i.e., the temporal resolution of the data. There is often an exchange between spatial and temporal resolutions; a lesser temporal resolution (considering data averaged over longer time periods) will give smooth data, but less accurate trending, while a greater temporal resolution has the potential to be distorted by data 'noise' in the system, which also has the potential to trigger false threshold alarms on isolated data spikes. For this reason, different calculation periods were assessed with the intent to establish sensitivity of the existing threshold levels at Samarco Mine, and the applicability of these in anticipating the failure event. These are represented by "Velocity over calculation period" parameters in this report. These are compared against cumulative displacement of the scanned target: a direct output of the radar technology.

SUMMARY OF MONITORING DATA FINDINGS

Santarém Dam

A minor local failure was observed on the spillway area at Santarém Dam on 12 June, 2016, at which time the slope was being monitored by slope stability radar (Figure 2). The material was displaced along a slip plane that formed two thirds of the way up the second bench. In the months preceding, GroundProbe radar surveillance reports documented negligible deformation rates that were not associated with operations, traffic, or when correlated against rainfall periods.

The compacted earthfill material exhibited regressive/ progressive deformation prior to failure (Figure 3). A regressive/ progressive (decelerating/ accelerating) failure condition can "rapidly lead to collapse" and be caused when "mining daylights a sliding surface, [when there is] breakup, or excavation of rock at the toe of a slope, or [as a result of] an increase in water pressure" (Darling, 2011). The month of June was unusually wet; 72mm of rainfall was recorded between June 1 and June 12, which is compared to the negligible rainfall that characteristically occurs during these winter months on-site. Visual inspections detected water retention on the first and second berms below the crest. No other visual anomalies were detected.

Figure 2 - Slope stability radar monitoring for Santarem Dam, showing location of local failure

The existing site thresholds for velocity proved effective in their ability to predict local failure, in particular when using the "Velocity over 60" calculation period (Figure 3). This provided warning at five hours, three hours, and one hour for yellow, orange, and red alarms, respectively (Table II). In consideration of the responses designated for each alarm as seen in Table I, this degree of notice presents a safe and feasible response time.

The regressive/ progressive trends exhibited movement for almost two days prior to failure. During the regressive trending stage, a yellow alarm was triggered for a single hour. In comparison to triggers of 2 mm/h and 1 mm/h, which would have been cautioning for five hours and eight hours, respectively, this alarm proved effective in acknowledging the increase yet not escalating the alarm beyond what a regressive trend warrants.
Further, the risk of uneventful readings in stable operating conditions exists with lower alarm thresholds. In consideration of all velocity calculation periods over the entire duration that the same radar that captured that failure was operating, 1 mm/h would be alarming on average 12.6% of stable operating time, and 2 mm/h for 7.3%.

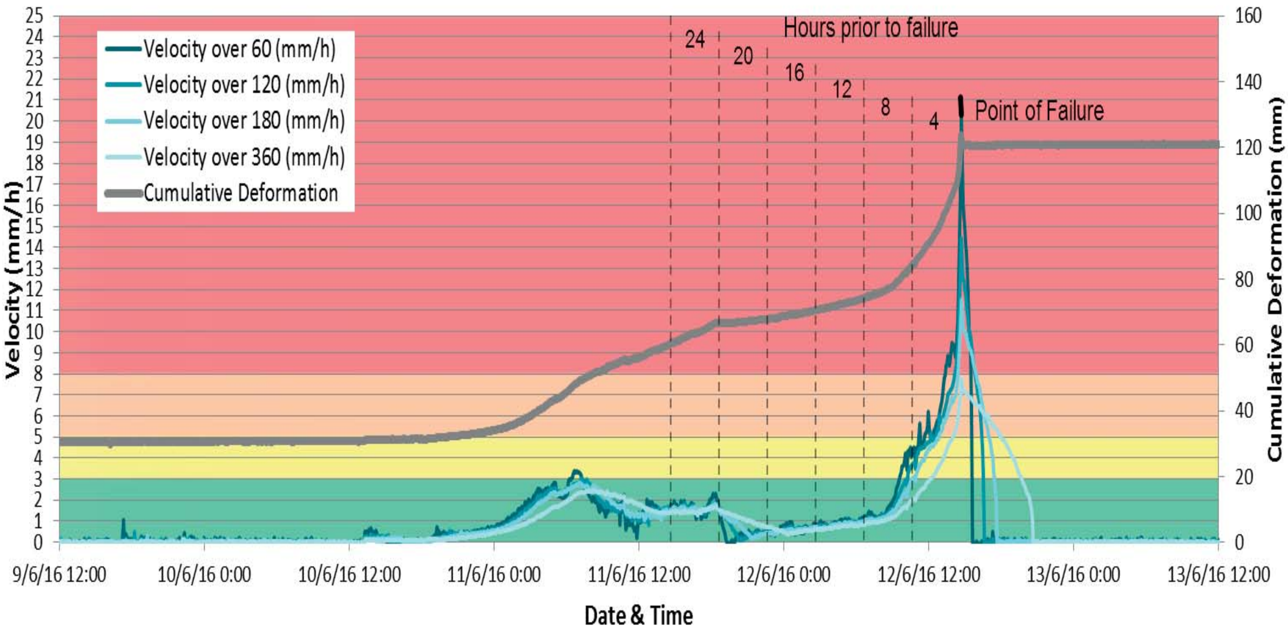

Figure 3 - Velocity and deformation data trending for Santarém Dam, velocity alarm thresholds shown

Table II - Velocity alarm assessment for Santarém Dam

	Time before event (hours)				
Trigger Level	Velocity over 60	Velocity over 120	Velocity over 180	Velocity over 360	Velocity over 1440
1mm/h	8.3	8.0	7.8	6.5	-
2mm/h	5.5	5.2	4.9	3.9	-
3mm/h	5.1	4.4	3.9	2.5	-
4mm/h	4.1	3.7	3.0	1.5	-
5mm/h	3.0	2.1	1.8	0.6	-
6mm/h	1.8	1.5	1.1	0.2	-
7mm/h	1.5	1.0	0.4	0.1	-
8mm/h	1.3	0.5	0.2	-	-
9mm/h	0.4	0.2	0.1	-	-
10mm/h	0.2	0.2	0.1	-	-

Readings designated as “-“ were not identified prior to the event.

Dike 2

A collapse of debris was observed to progress at the toe of Dike 2 over the period of six days, from 8 August 2016 to 14 August 2016 (Figure 4). Debris flow was displaced downstream in a progressive failure trend, where the rate of displacement continued to increase until collapse; approximately 50% of the total material deformation occurred on the sixth day. No significant rainfall occurred during or prior to this event.

It is anticipated that loose, saturated slimes comprising high proportions of clay- and silt-sized particles remained after the 2015 collapse. The moisture content of the slimes is typically around 30%, while the liquid limit is approximately 25%: indicating low consistency. Based on the radar deformation trends and visual assessment of the surrounding area, it is the author's opinion that hydraulic forces induced by upstream runoff flows preferentially degraded a pathway through the material; the same forces that failed an upstream earthen buttress by erosion piping two months prior.

In the author's assessment, mass collapse of the material may have been observed as a result of progressive erosion of the surrounding banks driven by decreasing confining stresses, in combination with water recharge encouraging an elevated moisture content and the associated decrease in shear strength of the slimes. In terms of the data, this mechanism could be represented by the process of shear stress gradually reducing the shear strength until the point at which the slip triggers, as reflected by comparatively elevated rates of deformation.

Notably, deformation trending in the surrounding areas suggests steady creep, which is anticipated to be reflective of the same influences that failed the adjacent material, and may be early stage indicators of a similar event.

In the month preceding, GroundProbe radar surveillance reports documented no evidence of significant deformation processes, with deformation rates consistently below 2 mm/day.

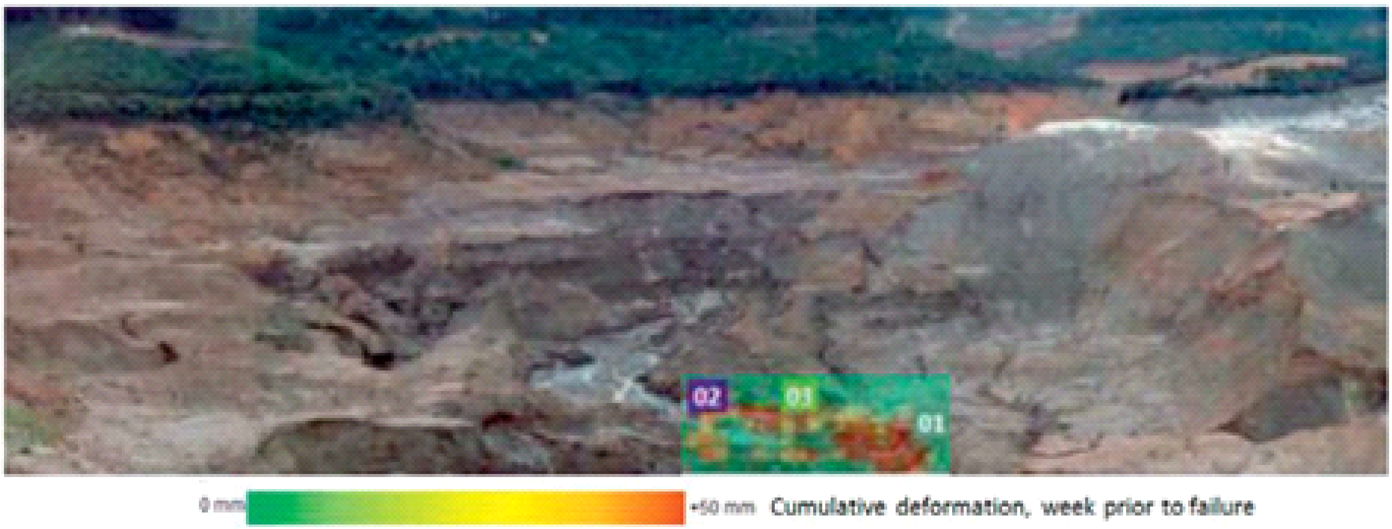

Figure 4 - Slope stability radar monitoring for Dike 2, showing location of slimes collapse

The existing site thresholds for velocity proved effective in their ability to predict collapse of the slimes at Dike 2, providing warning at up to 42 hours, 9 hours, and 1.8 hours for yellow, orange, and red alarms, respectively (Figure 5 and Table V). This degree of notice presents a safe and feasible response time. Unlike Santarém Dam, this failure was slow and ductile, exhibiting movement for six and a half days prior to failure: a duration that saw the larger calculation periods such as Velocity over 360 and Velocity over 1440 prove most effective in forecasting the failure.

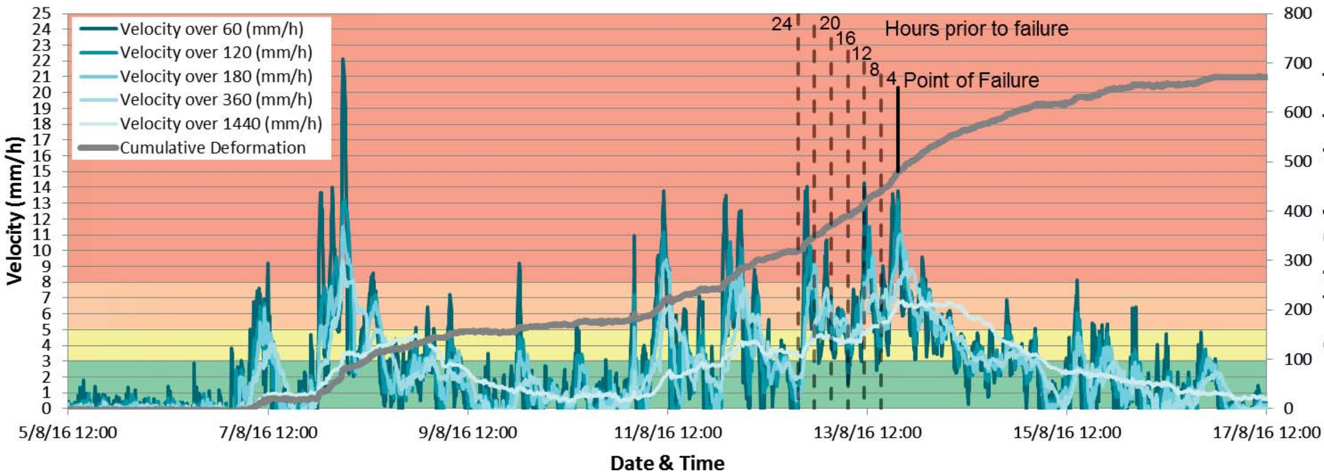

Figure 5 – Velocity and deformation data trending for Dike 2, velocity alarm thresholds shown

Table V - Velocity alarm assessment for Dike 2

	Time before event (hours)				
Trigger level	Velocity 60	Velocity 120	Velocity 180	Velocity 360	Velocity 1440
1mm/h	23.75	23.75	23.38	62.23	58.30
2mm/h	11.82	22.75	22.75	42.03	53.27
3mm/h	4.68	22.62	22.62	22.50	42.03
4mm/h	2.15	10.78	22.50	21.37	21.87
5mm/h	2.02	3.80	8.88	9.15	6.83
6mm/h	1.90	2.27	1.90	7.75	1.27
7mm/h	1.83	1.77	1.77	6.08	-
8mm/h	1.77	1.38	1.52	-	-
9mm/h	1.70	0.88	0.38	-	-
10mm/h	1.65	0.63	0.00	-	-

Eixo 1 – Natural Slope

Local, regressive-progressive deformation processes were observed to be drivers behind the dislodgement of material at the Eixo 1 natural slope on 14 November, 2016. The time between deformation being first observed and material failure was 7.5 days.

The slope material comprised large quantities of loose rock, initially intact but anticipated to have weathered and degraded over time. Two primary mechanisms are anticipated to have driven the regressive-progressive failure of the natural slope: breakup of rock at the toe of the slope, in addition to an increase in water pressure. With complexity added as a result of interaction between these two drivers, it is observed that the failed and exposed sections of the slope became susceptible to further degradation from weathering, in turn entering a cycle of progressive instability.

This is evidenced by the successive recorded events, all of similar behaviour, in addition to the incremental trend of movement along a preferential deformation path down the side of the slope (Figure 6).

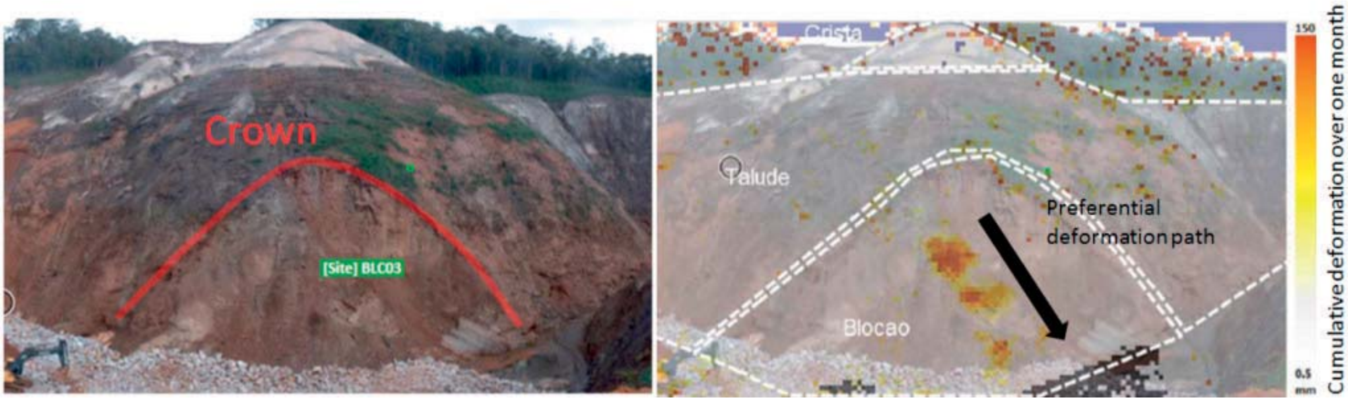

Figure 6 - Slope stability radar monitoring for Eixo 1 in November, 2016, showing location of circular slip failure

The existing site thresholds for velocity proved ineffective in their ability to predict local failure of Eixo 1. Velocity over 60 triggered a yellow alarm half an hour prior to failure, however could easily be missed if read without the knowledge that a failure were about to occur. No orange alarms were triggered.

Alternate metrics are recommended as additional control measures. Inverse velocity was investigated to also be ineffective, so an assessment of deformation triggers was conducted (Figure 7 and Table III). Deformation triggers are useful in disaggregating data noise from small deformation data, and hence will present slightly different results than the velocity analysis.

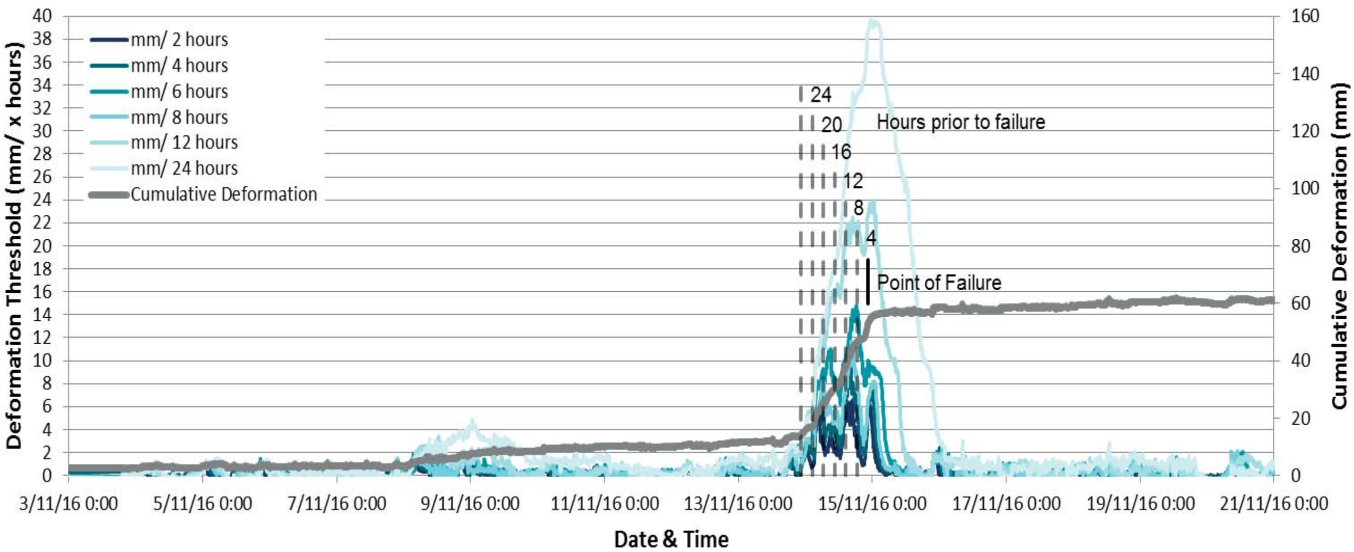

Figure 7 - Deformation data trending for Eixo 1

Table III - Deformation alarm assessment for Eixo 1

	Time before event (hours)			
Trigger Level	mm/2 hours	mm/4 hours	mm/6 hours	mm/8 hours
1mm	1.4	23.4	28.3	23.6
2mm	1.0	1.1	28.0	22.5
3mm	0.6	0.8	20.6	19.1
4mm	0.4	0.6	19.8	0.8
5mm	0.1	0.3	19.5	0.4
6mm	-	0.0	19.1	0.1
7mm	-	-	18.7	-
8mm	-	-	9.6	-
9mm	-	-	0.3	-
10mm	-	-	0.0	-

Note: Greyed out cells indicate less useful results, where these triggers were exceeded on initiation of the regression trend, and remained above the trigger level until failure.

The ability to confidently forecast developing movement in the progressive trend using the approach described in Figure 7 was not possible until at least five scans into the trend. This was because a deformation trend that is averaging movement over previous hours will capture the regressive trend prior, lagging current movement trends by a number of scans. To eliminate this, the deformation data would need to be averaged over 24 hours, which is less practical for forecasting short term events such as the Eixo 1 event as the data will simply reflect the deformation trend itself.

Calculated rates for mm/ 2 hours presented three of the more desirable warnings at 83, 60, and 36 minutes prior to failure. The risk exists that unwanted alarms will trigger at such low rates, however assessment reported that for the month prior to initiation of this event, 1.7% of operating time would be alarming for 1mm/ 2 hours, and 0% for 2 and 3 mm/ 2 hours.

It is anticipated that geotechnical engineering judgement will be applied to the deformation assessment approach, both on setup for conditional suitability of the alarm, and on response should it trigger. While this deformation trigger may be appropriate for Eixo 1, it may alarm more frequently when monitoring slopes of different material properties. In contrast, when the deformation alarm is applied to stable operating conditions for Santarém Dam and Dike 2 (analysed over the entire duration of data capture at these sites), uneventful alarms for 2mm/ 2 hours are presented 1.1% and 8.8% of the time, but would trigger approximately 8 hours and 24 hours prior to failure, respectively.

4. DISCUSSION

IMPLICATIONS AND LIMITATIONS

Opportunities

Pertinent opportunities that can be derived from the data from the three events comprise:

- Existing site thresholds for deformation velocities were effective in predicting two of the three events, up to 22 hours prior to failure. The triggers allowed for, at minimum, one hours' warning on red alarm prior to failure;
- For the Eixo 1 failure, deformations were not of great enough magnitude to assure that the velocity triggers were progressing toward a failure event. In this scenario, a second deformation metric was recommended in

order to validate the velocity triggers which allowed 1.4 and 1 hours' warning on yellow and orange alarms, respectively;
- Forecasting of slope instabilities in sufficient time allows the geotechnical engineer, or otherwise, to pre-emptively identify and respond appropriately to slope instability;
- The value in real-time monitoring techniques is realised where failure progression over a period of two through to eight days as in the cases analysed may not be identified on a bi-monthly inspection regime, for example; and
- It is not cost effective to have some real-time solutions operating 24/7 in stable conditions. Visual observations are recommended as the first and foremost control measure to be implemented. There is immense value in training operational personnel on geotechnical hazards; hundreds of eyes on the ground that can identify and advertise deteriorating conditions are invaluable, and existing, assets.

Limitations

The greatest value in monitoring and instrumentation data is in the technique of analysis, driven by operator experience, understanding of site conditions, and how these relate to an understanding of the plausible failure mechanisms and triggers for different areas of the mine. This experience must be leveraged in order to account for geotechnical variability, making appropriate considerations on the prediction of failure for:

- One conservative trigger value for each threshold, applied across the entire site, may not be effective for different types of slopes, i.e. a brittle rock failure from a sub-vertical wall will deform and fail differently than ductile flow of debris on a gently grading slope; and
- Wet weather, although often associated with geotechnical instabilities, can also produce 'noisy' radar data on smaller calculation periods, in addition to falsifying how close the material is to the radar as surficial water runoff is recorded as movement during the scan.

INTEGRATION WITH DAM MONITORING STRATEGY

The intent of the dam monitoring strategy is to assess and measure design expectations against operational performance of the dam. The opportunities identified fit with the existing dam monitoring strategy in not only validating the existing threshold parameters, but recommending alternate validation techniques to provide additional confidence to a single parameter assessment. It is anticipated that correlation of deformation parameters with other instrumentation readings would be valuable in future development of monitoring strategies.

Understandably, monitoring with no history of collapse or benchmarking data is challenging, however not redundant. The existing data at any site is of immense value: even if no failure has occurred, the data presents a range of cases within the failure envelope, where the threshold value can be set as the highest existing observed rate, and movement beyond this requires sufficient attention until the mechanisms and effects are appropriately understood.

Developing a database of site events, their trending, and the associated implications is a tool readily accessible to civil, mine, and geotechnical operators, globally. The more back-analysis that is completed on these events, the more empirical confidence can be held around understanding different types of site failure and ensuring that appropriate thresholds are in place to anticipate and respond to events appropriately.

5. CONCLUSION

This paper describes a back-analysis of three different slope instabilities at Samarco Mine, Brazil. The analysis assessed suitability of existing triggers, made recommendations for additional metrics, and consequently added to the database of failure analyses.

The yellow, orange, and red alarm triggers for radar monitored slope deformation velocities are set to 3 mm/h, 5 mm/h, and 8 mm/h at Samarco Mine. For the longer duration events, these alarms provided sufficient warning time to allow appropriate responses to take place, with evacuation of the slope area prompted at least 1.3 hours prior to failure. For the shorter duration event, which in this case was also of lower magnitude, the triggers were identified to be potentially missed. A second level of check was introduced in form of a deformation alarm, which aids to validate the velocity reading when used under the correct application.

The analyses provided additional confidence that real-time monitoring of slope stability can aid in predicting failure up to 42 hours prior to the event. The recommendation is made that applied understanding of failure mechanisms, back-analysis of monitoring and instrumentation data in terms of this, and ultimately the development of threshold triggers to prompt appropriate response should be readily integrated with the dam monitoring strategy.

In developing the dam monitoring strategy, case studies shared by other operators should be considered. With a safety focus, similarities between site conditions, new learnings, or unexpected behaviours are of value to leverage. Where previous commercial reluctance has inhibited the value of knowledge sharing, greater geotechnical community collaboration is recommended to aid in minimising repeat errors in favour of maximised diligence.

6. REFERENCES

- Australian Government Department of Industry Tourism and Resources 2007, Tailings Management, Canberra.
- Azam, S & Li, Q 2010, 'Tailings Dam Failures: A Review of the Last 100 Years', Geotechnical News: Waste GEOtechnics, p.50-53
- Davies, M, Martin, D & Lighthall, P 2002a, 'Mine Tailings Dams - When Things go Wrong'
- LePoudre, D.C. 2015, Examples, Statistics and Failure modes of tailings dams and consequences of failure, PowerPoint slides, REMTECH.
- Robertson, A.M. 2012, FMEA Risk Analysis: Failure Modes and Effects Analysis, PowerPoint slides.
- National Department of Mineral Production 2012, 'Portaria 416', Ministry of Mines and Energy, Brazil.
- National Department of Mineral Production 2017, 'Portaria 70.389', Ministry of Mines and Energy, Brazil.
- Darling 2011, SME Mining Engineering Handbook…
- Fell, R, MacGregor, P, Stapledon, D, Bell, G & Foster, M 2014, Geotechnical Engineering of Dams¸ 2nd edn, CRC Press/ Balkema, The Netherlands.