Slope Stability 2020 - PM Dight (ed.)
© Australian Centre for Geomechanics, Perth, ISBN 978-0-9876389-7-7
doi:10.36487/ACG_repo/2025_13

Evolution and management of large-scale instability: a case study from Ok Tedi

G Kennedy *PSM, Australia*

D Casagrande *PSM, Australia*

Abstract

Ok Tedi is an open pit copper-gold porphyry mine located near the upper Ok Tedi River in the highlands of the Western Provence, Papua New Guinea. The mine is one of the wettest in the world, receiving an average rainfall of between 10 m to 12 m per annum. Since 2008, the West Wall of the Ok Tedi mine has been experiencing instability with many large areas showing failure or pre-failure movements, with an estimated volume for 'Block 1A' of >8 Mm^3. These failures pose significant risk to the operation from a safety and economic perspective, with the larger areas of instability posing a huge challenge to reaching the life-of-mine design.

The failures range from small-scale ongoing erosional failures to very large and complex pit slope scale failure 'blocks', triggered initially by prolonged high rainfall events. The larger blocks are controlled by a combination of structure and poor rock mass, with movement significantly influenced by prolonged high rainfall events. Monitoring data indicates each failure block is in different stages of pre-failure movements, with some blocks in advanced stages indicating they are close to collapse.

Successful failure management requires a thorough understanding of the geotechnical model, the failure mechanism(s), triggers and behaviour; and potential post failure deformations. It also requires a comprehensive monitoring system, coupled with a detailed pit slope risk management system. Without understanding of each of the above or appropriate monitoring and risk management systems in place, continuing operations in areas within influence or potentially impacted by slope failure significantly increases the safety and economic risks to the operation.

The failure mechanism(s), triggers and behaviour evolved over time, and the evolution was identified by regular and rigorous review of multi-factorial datasets, including prism, piezometer, rainfall, radar, inclinometer and visual monitoring amongst others. This understanding allowed development of a detailed pit slope risk management system which included the use of trigger action response plans (TARPs), specified mining procedures and a detailed monitoring reporting system has allowed mining of an unloading cutback above the West Wall, which with improved surface water management has successfully mitigated the risk of multiple large-scale failures.

This paper provides an overview of the failure mechanism of Block 1A, the use of monitoring to understand the movement triggers and behaviour, and the pit slope risk management program which has allowed the successful mining of the West Wall cutback to continue with ongoing pit slope movements.

Keywords: *pit slope failure, failure management, slope monitoring*

1 Background

1.1 Ok Tedi

The Ok Tedi copper-gold mine is located near the upper Ok Tedi River in the highlands of the Western Provence, Papua New Guinea (PNG), and is one of the largest gold-rich porphyry copper deposits in the world (van Dongen et al. 2010). The mine is currently owned and operated by Ok Tedi Mining Ltd (OTML), and since its opening in 1984, has produced 5 million tonnes (Mt) of copper, 15 million ounces of gold, and 33 million ounces of silver, generating over 21 billion kina for the people of Western Province and PNG (OTML 2019).

The mine is one of the wettest in the world, receiving an average rainfall of between 10 m to 12 m per annum. Since 2008, the West Wall of the Ok Tedi mine has been experiencing instability, initially with development and progression of erosional 'chasms', which to date have deposited well over 11 Mm^3 of debris material into the Centre Pit, and since 2017, widespread complex failures with large and evolving areas, with estimated failure volumes typically in the order of >8 Mm^3 as is the case for the area known as Block 1A. These failures pose significant risk to the operation from a safety and economic perspective, with the larger areas of instability posing a huge challenge to reaching the life-of-mine design.

The Chasm failures have been covered in numerous previous technical papers and are therefore not covered in detail within. The focus of this paper is rather the large complex 'block' failure, Block 1A, which is to the north of Chasm W1, highlighted in Figure 1.

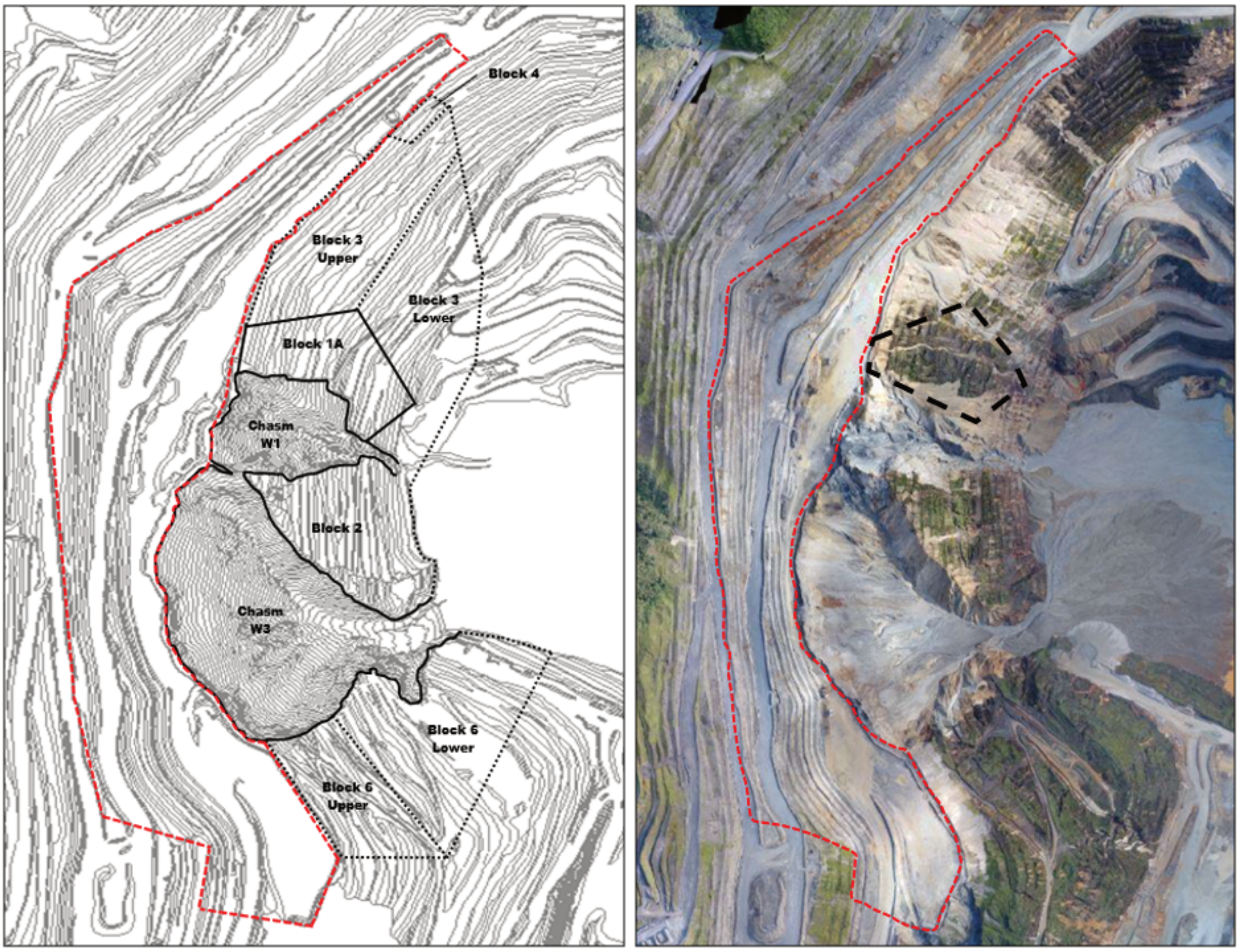


Figure 1 Schematic map illustrating West Wall chasms, failure 'blocks', and area (dashed red line) which unloading cutback has excavated since July 2017. Block 1A is illustrated in dashed black

2 West Wall

2.1 Overview

The existing west wall is approximately 2,000 m long, 1,000 m wide and 500 m deep in the area of current instability, Figure 1. The slope performance of the Ok Tedi West Wall has continued to evolve from a single bench failure (described at the time as an 'erosional gully') in 2008, to two large erosional 'chasms', with multiple very large-scale complex failures across the majority of the remaining West Wall. The complex 'block' failure areas are roughly illustrated in Figure 1, which highlights the numerous areas which were separated based on movement trends, and often bordered by tension cracks and geological structures.

Debris from the ongoing failures within Chasm W1 and W3 has continued to flow into the Centre Pit, which has resulted in debris accumulation of approximately 40 m thick in the East of the Centre Pit, and up to 90 m thick up against the West Wall at the base of Chasm W3, now totalling approximately 11 Mm^3 of material within the Centre Pit.

An important aspect of the management of the slope instability was the immediate implementation of a cutback above this failure zone after the significant tension cracking which occurred in July 2017. The unloading cutback continues above the entire West Wall immediately above the zone of instability as illustrated in Figure 1. Since this time, the cutback has unloaded approximately 120 m of the West Wall immediately above the Chasm and complex failure blocks.

2.2 Geology, rock mass model and hydrology

The West Wall is largely excavated within the following lithologies:

- Darai Limestone.
- Taranaki Thrust.
- Ieru Siltstone.
- Skarn.
- Monzonite Porphyry.
- Monzodiorite.

The rock mass at Ok Tedi has experienced a complex history of intrusions, alteration and faulting, which has resulted in large variations of rock mass quality within each lithological unit. These variations in rock mass quality and strength have been captured by creation of a 3D rock mass model, encompassing a series of rock mass unit (RMU) domains which group areas of similar lithology, location, structure and most importantly rock mass quality. The RMU system divides lithologies into five classes where appropriate, with Class 5 representing the worst and Class 1 the best rock mass quality (i.e. IS1 to IS5 for Ieru Siltstone).

The rock mass model through the Block 1A area is broadly split into the following RMU domains, annotated on the image in Figure 2, and schematically in cross-section through the West Wall in Figure 3:

- Competent Darai Limestone, above the Taranaki Thrust (LS3 to LS4).
- Weak Taranaki Thrust Zone (TTZ).
- Weak, highly altered Ieru Siltstone, below the Taranaki Thrust – West Wall Weak Zone (WWWZ), (IS4 to IS5).
- Competent Skarn (SK2/3), in the centre and below the WWWZ.
- Lower Darai Limestone.

Of note, the development of Chasms W1, W3 and Block 1A have largely been within the Taranaki Thrust Zone and underlying West Wall Weak zone. The Taranaki Thrust is a structure in itself, but from a rock mass quality perspective is modelled as a zone that comprises a poorer rock mass in the Darai Limestone above and poorer rock mass zone in the Ieru Siltstone below it. The WWWZ is a zone of poor rock mass that commences in the south of the pit and extends through the entire West Wall through to the north in across the area illustrated in Figure 2. Within the West Wall failure area, the zone lies predominantly within the Ieru Siltstone, with areas of Monzodiorite and Skarn encountered at the base of Chasm W1. The WWWZ zone does not extend into or above the Taranaki Thrust Zone. Outside the WWWZ the rock mass is better quality with a gradual increase in quality to the west and sharp increase towards the east.

The rock mass in the lower Darai Limestone is highly variable along the West Wall. There is a zone of poor rock mass centred below and slightly north of Chasm W3 and along the contact with the Skarn and intrusive bodies. The structural pattern evident within boreholes in this zone indicate it is likely a diatreme or volcanic vent.

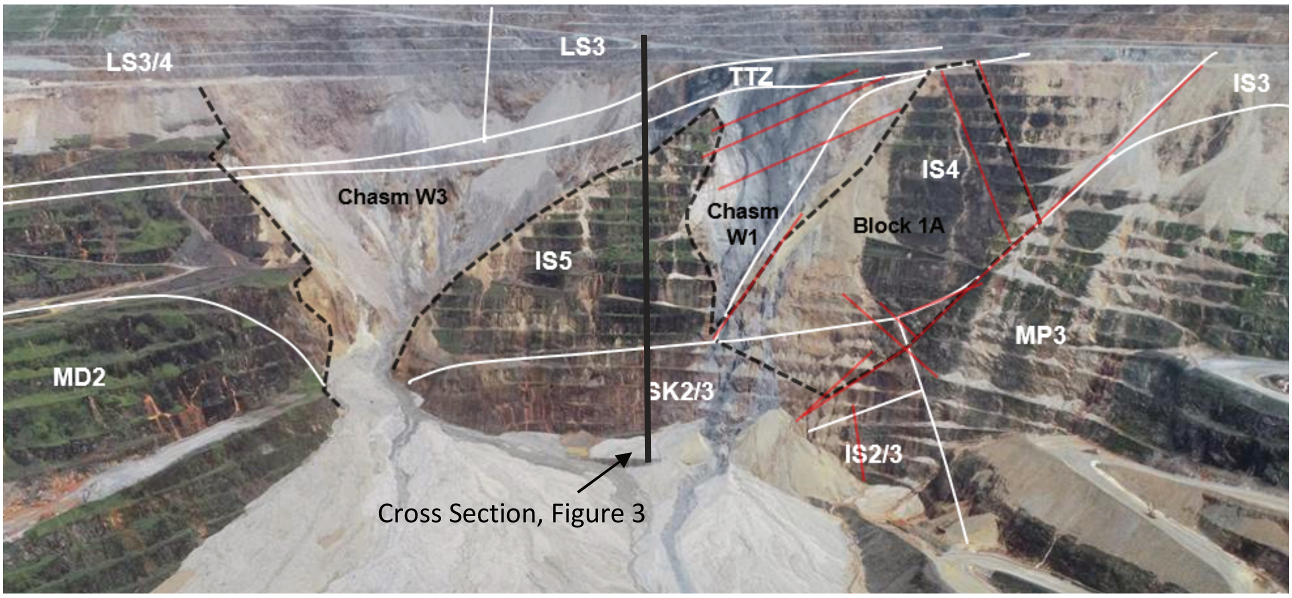


Figure 2 Rock Mass Model, Chasm W3 and W1, and Block 1A illustrated on West Wall. West Wall Weak Zone through centre, within the IS4 and IS5 rock mass

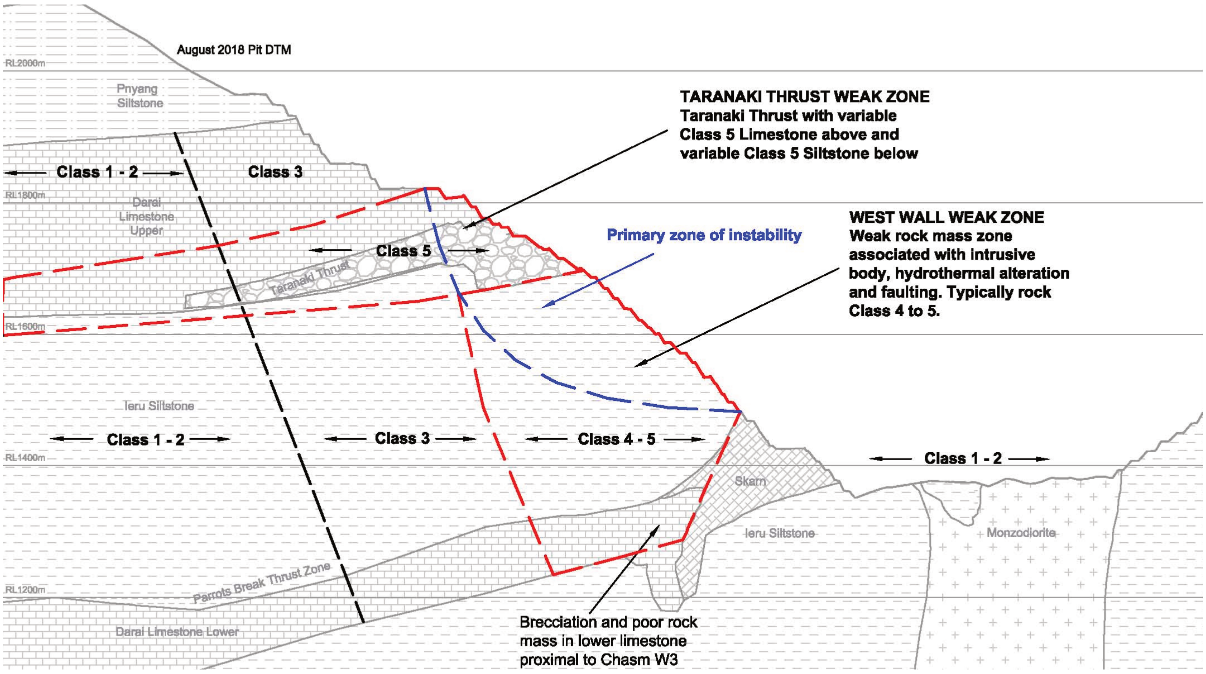


Figure 3 Geology and simplified rock mass model in cross-section, through West Wall in approximate location illustrated in Figure 2

Surface water control has generally improved over the last few years, with a recent campaign focused on designing inclined berms, benches and mining floors (sloping either north or south to shed water away from the West Wall), installation of toe drains made from old conveyor belt shotcrete in place along selected berms, and re-routing all catchments above the West Wall to flow to the north or south away from the West Wall. This has successfully reduced the surface water runoff flowing into the failure areas and reduced surface water recharge into the West Wall.

The hydrogeology regime within the West Wall is variable due to the different lithological units and permeabilities, major structures, and the effects of hydromechanical coupling which is causing transient pore pressures within the movement zones. A variable groundwater table is perched on the clay filled Taranaki Thrust within the Darai Limestone. Below the thrust, within the Ieru Siltstone and WWWZ, analyses of piezometric data indicates that considerable pore pressures are maintained within the first 100 m of Ieru Siltstone immediately below the Taranaki Thrust, near to hydrostatic, with artesian pressures noted following prolonged rainfall events (relative to the Taranaki base). Below this zone within the better quality rock mass outside of the WWWZ, the pore pressures are less than hydrostatic and variable, controlled largely by the presence of major structures.

The transient zone (movement zone) is largely within the Ieru Siltstone of the WWWZ. The transient zone is not practically applicable in some lithologies such as the Darai Limestone because it is highly permeable and transient pressures will be released quickly.

2.3 Slope monitoring system

Effective pit slope management relies on a thorough understanding or appreciation of:

- The failure mechanisms.
- Movement triggers.
- Potential maximum post failure deformations of failure(s).

Once the above aspects are understood, or at the least, the potential maximum post failure deformations for all plausible failure scenarios, a rigorous and multi-facet slope monitoring system is required which includes real time radar and rainfall monitoring. The slope monitoring system for the West Wall of Ok Tedi includes:

- Prisms.
- Radar(s).
- Direct wireline extensometer warning systems.
- Inclinometers.
- Visual monitoring.
- Ongoing recording and evaluation of the physical deformations.
- Groundwater, including drains and piezometers.
- Ongoing assessment of the changing geometry of the area due to planned (mining) and unplanned (failure) activities and events.

3 Block 1A slope performance

3.1 Overview

Large-scale pit slope movements can be categorised into the following five principal stages (Sullivan 2007):

- Elastic movements.
- Creep movements.
- Cracking and dislocation.
- Collapse.
- Post failure deformation.

Most open pit slope monitoring focuses on the cracking and dislocation and collapse stages as these present safety and economic risks to the operation and are therefore generally resourced appropriately. However, it is important to monitor slopes as soon as the slopes are excavated, as if early signs of potential instability are identified (i.e. significant or long-term creep movements), it allows the operation to plan and implement remedial measures such as depressurisation drilling, improved surface water management, slope modifications (unloading, toe buttressing, redesign), before the slope progresses through to the cracking and dislocation stage.

In open pit mining, the cracking and dislocation and collapse stages are often both referred to as failure. In practice, pit slopes which exhibit signs of cracking and dislocation can often be successfully mined or mined around without the slope progressing to collapse through careful pit slope management. Therefore, the use of the term failure for cracking and dislocation can be misleading and it is important that the two stages are differentiated (Sullivan 1993).

Identification of what movement stage the pit slope is in is completed using various slope monitoring techniques, including prism, radar, piezometer, inclinometer, rainfall and visual monitoring amongst others.

3.2 Elastic and creep movements

Elastic and creep scale pit slope movements are very slow and can continue over long periods of time without impacting the safety or economics of the mining operation. Prism monitoring is still the most reliable slope monitoring method for identifying the very low displacement rates typical of creep movements over long time periods (years).

Block 1A of the West Wall showed long-term creep movements of approximately 0.05–0.1 mm/day (~20–35 mm p.a.) from 2005 to mid-2017, with the latter part of the creep movements (2015–2016) with minor slip events for Block 1A illustrated in Figure 4. While this movement did not directly affect the mining operation during that time, it did result in significant dilation and an increase in the storage capacity and permeability of the rock mass.

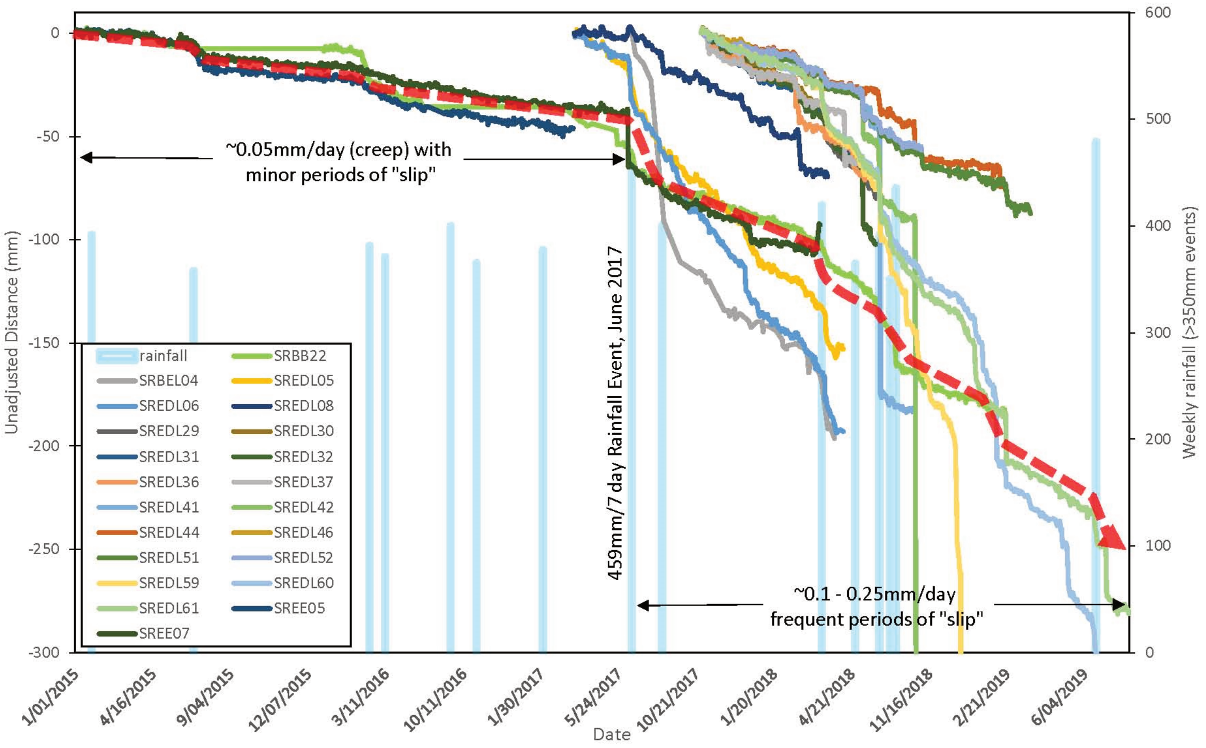


Figure 4 Block 1A Prism Movement, January 2015 to August 2019, illustrating transition from creep to advanced 'cracking and dislocation' movements in June 2017

In April of 2017, a significant tension crack (~500 mm wide) opened up in a bench 45 m above the northern edge of Chasm W3. In June of 2017, a rainfall event of 459 mm over seven days occurred which then triggered the slope to advance to the cracking and dislocation stage with movements illustrated in Figure 4.

3.3 Cracking and dislocation

The cracking and dislocation stage can be further expanded into sub-stages, which typically occur in the listed order (TD Sullivan, pers. comm. 10 July 2017):

1. Initial rises in groundwater levels/pore pressures.
2. Tension cracking.
3. High rainfalls cause sudden movement, and increased rates of movement.
4. Tension cracks become more extensive and wider. Pore pressure response to rainfall becomes faster, but levels also fall to lower levels.
5. Movements continue to accelerate.
6. Vertical scarps develop across tension cracks.
7. Evident breakup of slope and increase in small failures/slope ravelling.

In order to successfully manage a pit slope in the cracking and dislocation stage and reduce the likelihood of the slope progressing to collapse, it is important to understand how advanced the slope is through the sub-stages listed above. To achieve this in practice, it requires multiple monitoring systems, ideally installed when the slope is first excavated and before the onset of the cracking and dislocation stage. This allows a timeline of the slope and groundwater response to excavation. Prism, radar, piezometer, inclinometer, rainfall and visual monitoring are typically required to accurately quantify the above.

3.4 Groundwater monitoring

Groundwater response often precedes observable signs of pit slope deformation. As the slope continues to dilate through the creep and cracking and dislocation stages, surface cracks open, which significantly increases the rate of infiltration and rock mass permeability by providing a direct path for surface water to infiltrate into the rock mass. This leads to higher volumes of water infiltrating, and at a faster rate. Once surface cracking initiates, unless improvements to surface water management, depressurisation measures, or slope modifications (unloading/buttressing/reshaping) are undertaken, the pore pressure response and slope dilation increase with each prolonged high rainfall event. Higher pore pressures are generated within the rock mass which reduce the effective stress, triggering further slope movement, dilation, and increasing permeability with each significant event.

This increase in rock mass permeability and pore pressure response with continued dilation of the slope is evident in the piezometer data for Block 1A, Figure 5, which shows:

1. An increasingly rapid response of pore pressures (highlighted in red) in the slope with successive high rainfall events, in particular, prolonged (~7 day) high rainfall events.
2. A decreasing residual groundwater level after each prolonged high rainfall event (highlighted in blue).

The decrease in groundwater level occurs as with each prolonged and high rainfall event, further movement/dilation of the slope occurs, and the increased permeability allows the slope to drain to lower residual groundwater levels.

The piezometer data in Figure 5 shows Block 1A transitioning through sub-stages 1 through to 4. Importantly, the piezometric response is evident prior to the onset of the significant and widespread surface tension cracking which occurred during the high rainfall event in June 2017, highlighting how groundwater monitoring provides a valuable and early insights into pit slope performance.

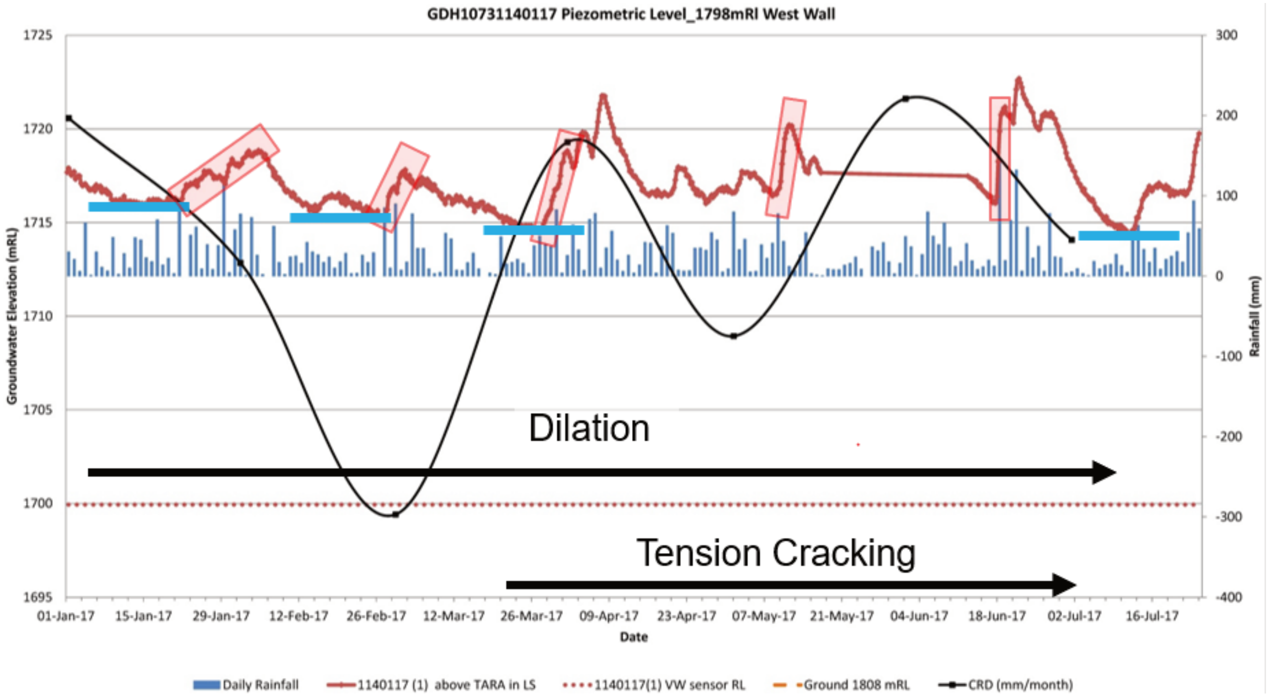


Figure 5 Piezometer response to rainfall, Block 1A. Rising groundwater levels pre-2017 not illustrated

3.5 Visual monitoring

In modern mining operations, visual monitoring is completed by both walk over inspections of accessible slopes and drone inspection, which allows inspection of previously inaccessible areas of the slope. Visual monitoring by drone has allowed huge improvements in the identification of the onset and growth of surface tension cracking by offering ‘birds eye views’ of previously inaccessible areas of the slope, which in this case represents the majority of the West Wall slope.

In the case of the West Wall, drone inspections and creation of a 3D photogrammetry model were completed weekly and/or following high rainfall events. Creation of the 3D photogrammetry model allowed accurate mapping of all tension cracking on the West Wall not covered by vegetation, and a greater view of the overall performance of the West Wall by allowing better views than offered by site look outs.

Mapped tension cracks were then illustrated in plan, which allowed a greater understanding of the evolution of pit slope deformations. This development is illustrated in Figure 6, showing mapped tension cracking in April 2017, and then again in August 2017. August 2017 includes the significant tension cracking which occurred following the high rainfall in June 2017.

The evolution of the slope breakup was also mapped and documented using drone photography. Drone photos were compared following ‘slip’ movement events, to visually identify areas of slope breakup and ravelling which allowed understanding of the evolving slope behaviour and stress distributions within the slope. This evolution of failure/ravelling areas from June 2017 through to May 2019 is illustrated in Figure 7. Also evident in these photos is the vertical displacement of Block 1A compared with the surrounding rock mass.

Visual monitoring combined with tension crack mapping allows quantification of sub-stages 2, 4, 6 and 7 within the cracking and dislocation stage, all of which were observable in Block 1A from June 2017.

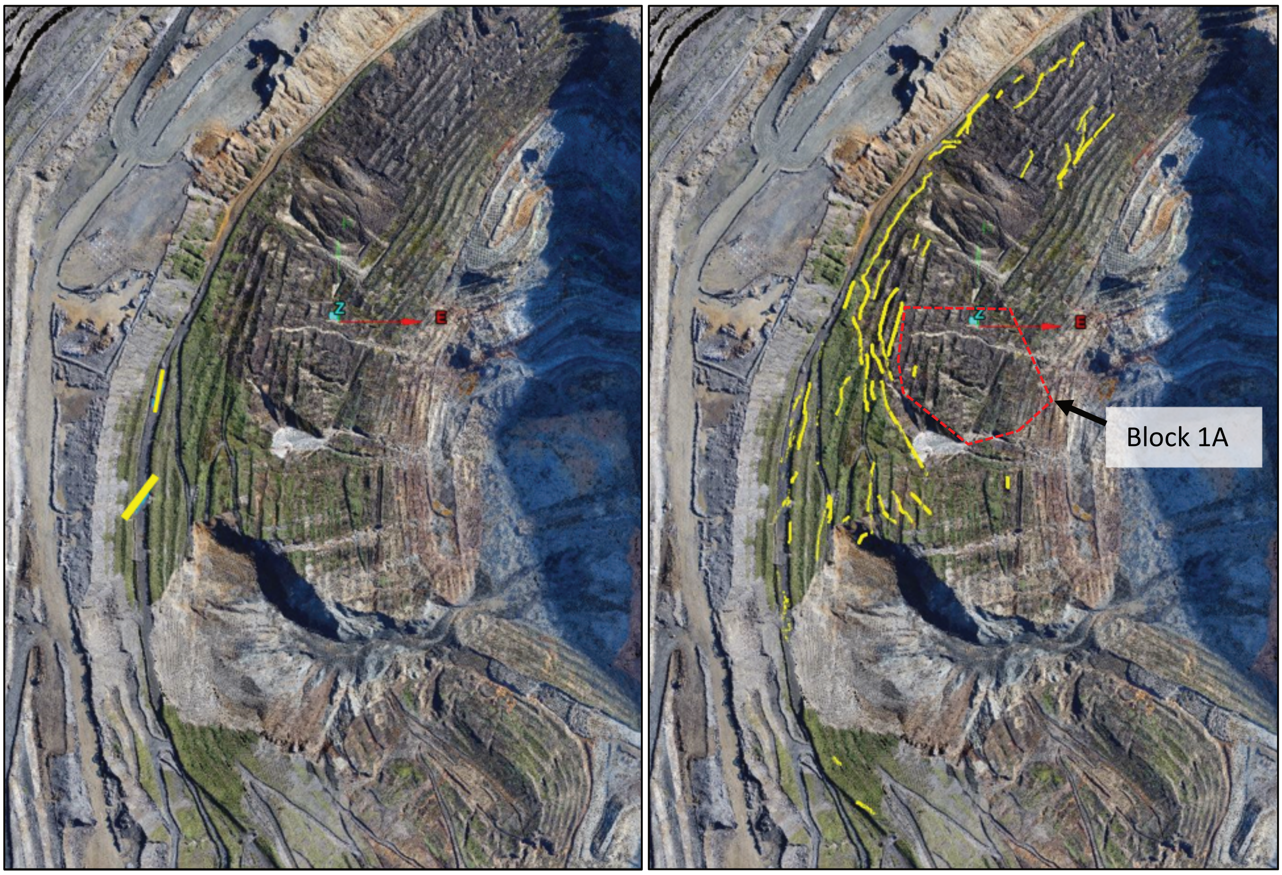
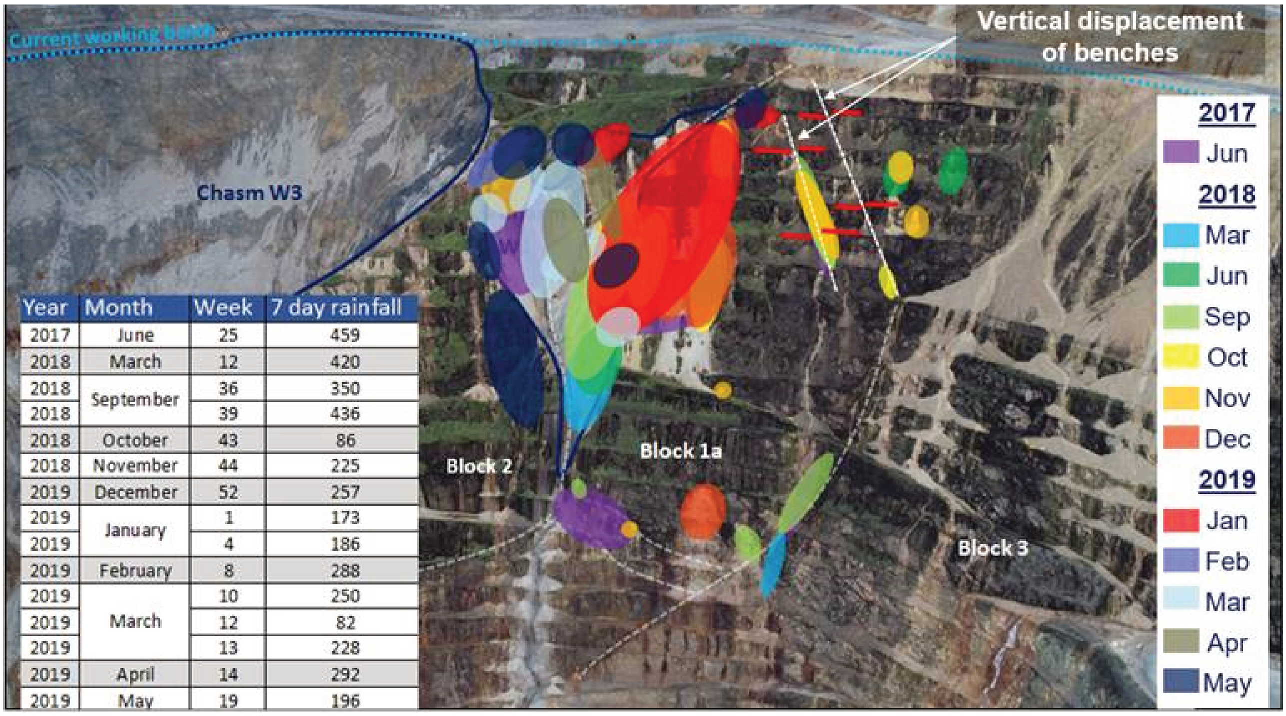


Figure 6 Tension Crack Mapping, April 2017 and August 2017 showing distribution of tension cracks after June 2017 rainfall event and location of Block 1A relevant to early tension cracking



Year	Month	Week	7 day rainfall
2017	June	25	459
2018	March	12	420
2018	September	36	350
2018		39	436
2018	October	43	86
2018	November	44	225
2019	December	52	257
2019	January	1	173
2019		4	186
2019	February	8	288
2019	March	10	250
2019		12	82
2019		13	228
2019	April	14	292
2019	May	19	196

Figure 7 Illustrated areas of failure around Block 1A, June 2017 to May 2019. Ravelling failures concentrated within and near boundary of Block 1A. Note vertical displacement of benches evident

3.6 Radar monitoring

Radar monitoring is the most effective real time displacement monitoring tool for pit slopes in the cracking and dislocation stage. Movement is detected quickly, displacement/velocity alarms can be set to warn operations of increasing rates of movement, and the operation is able to respond by evacuating machinery and personnel out of the area. Radar monitoring also delineates the exact area of slope movement, and changes within movement areas, as shown in Figures 8 and 9.

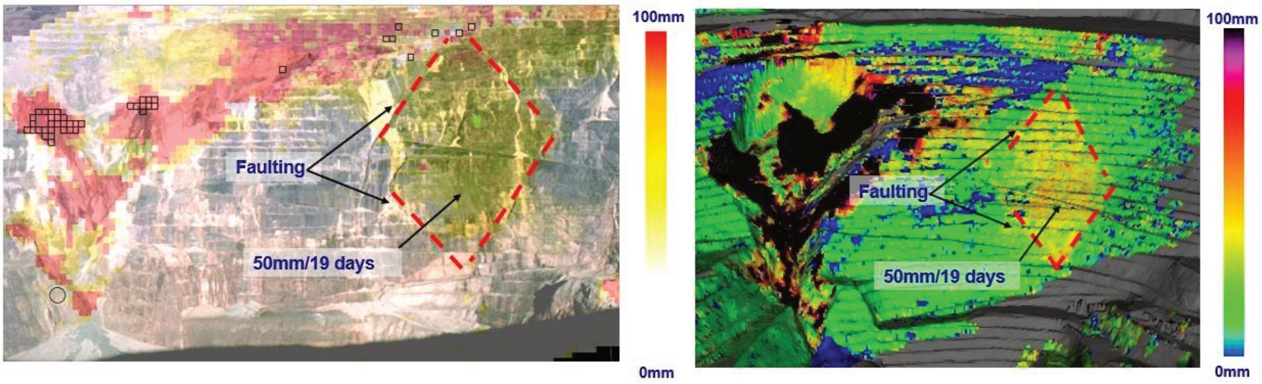


Figure 8 Radar movement, West Wall, 19 day movement for GroundProbe (left) and IDS (right) radars, early July 2018

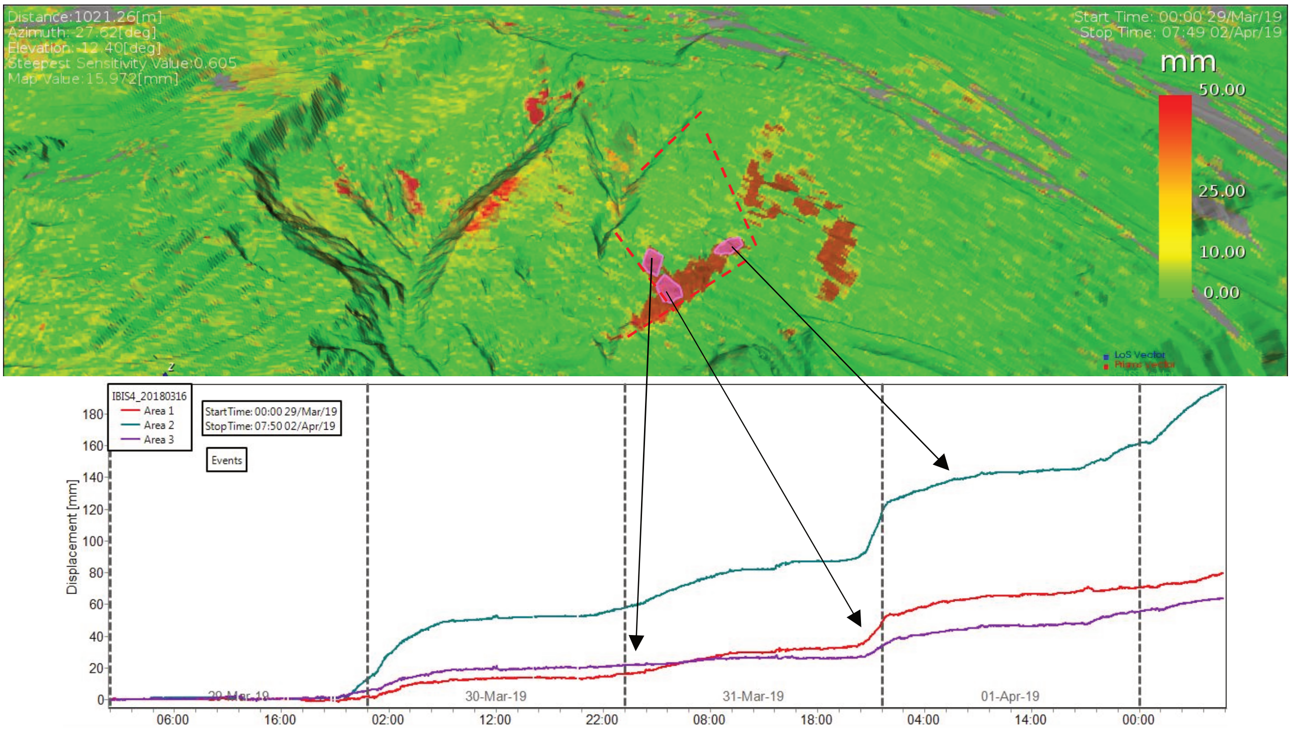


Figure 9 Radar movement, West Wall, 4 day movement for IDS radar, 29 March to 2 April 2019

Figure 8 illustrates the initial movement of the Block 1A zone following the June 2017 rainfall event. This movement was evident over a large area, picked up by both IBIS and GroundProbe radars, with the movement zone well defined by bounding geological structures.

Figures 8 and 9 show slope movement but also the evolution of the Block 1A movements, in this case the slope dislocation and breakup, sub-stage 7. Initial pre-failure movements of Block 1A involved the entire block as evident in Figure 8. Over time, as Block 1A continued to dislocate and breakup, zones of concentrated movements began to emerge, which often moved independent of each other. After the large rainfall event in March/April 2019, the lower section of Block 1A moved 200 mm over three days, while the upper section of Block 1A showed significantly less movement (Figure 9).

3.7 Prism monitoring

While radar monitoring is the most effective short-term (minutes to months) displacement monitoring for slopes in the cracking and dislocation stage, prism monitoring still provides vital long-term (months to years) information to aid in understanding pit slope movement behaviour. Figure 10 illustrates prism movement within the centre of Block 1A between March 2017 and December 2018.

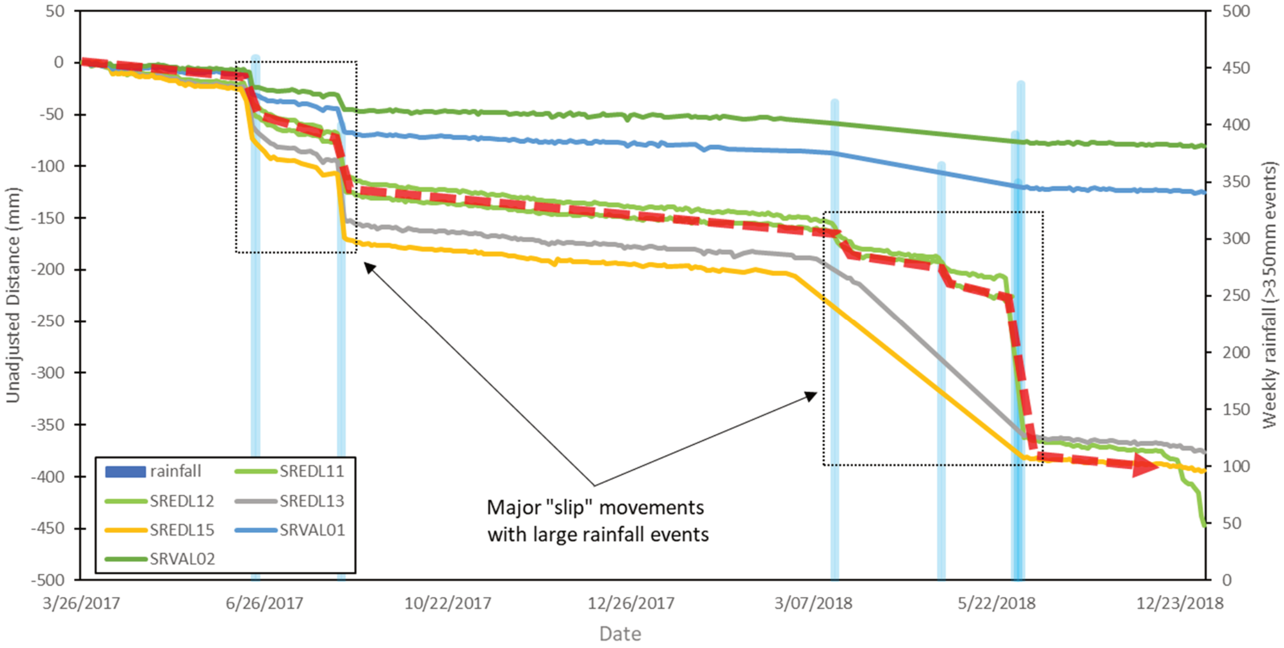


Figure 10 Block 1A prism movement, March 2017 to December 2018. Rainfall events of >350 mm/week are shown in the plot, with accelerated prism movement evident

Figure 10 illustrates that the movement behaviour of Block 1A is ‘stick-slip’, i.e. movement is cyclical, triggered by prolonged high rainfall events (initially >350 mm/7 days), with relatively short episodes of high movement caused by slip movement along structures within the rock mass. After short periods of sharp acceleration, the movement then decreases to a more linear and generally constant displacement rate. This is also evident for movement over shorter time periods as illustrated in the radar movements in Figure 9.

3.8 Rainfall monitoring

Rainfall monitoring in combination with prism, radar and visual monitoring also provides a valuable insight into the increasing sensitivity of the Block 1A slope as it continues to evolve. Figure 11 illustrates the rainfall events which triggered slope movement/failures within Block 1A between November 2016 and February 2019. This shows the movement triggering level of 7 day rainfall totals decreasing over time, indicating the slope is becoming more sensitive to rainfall as it continues to breakup, which not only decreases the rock mass strength within the slope but also results in higher pore pressure spikes following rainfall as more surface cracking opens up.

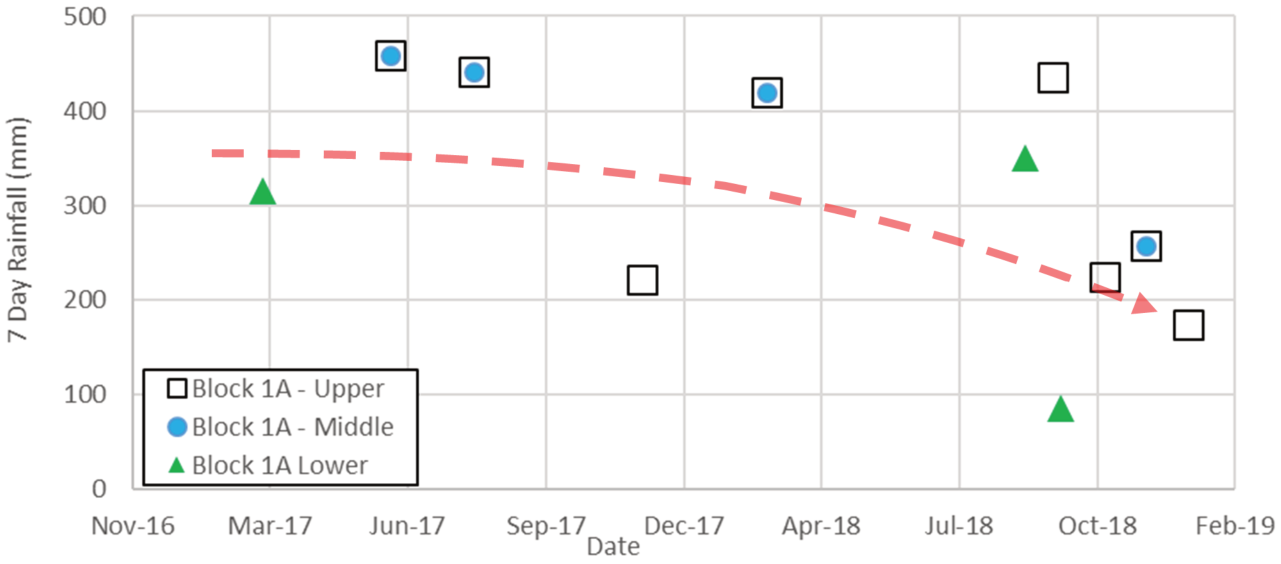


Figure 11 **Rainfall Events triggering movement, Block 1A, showing decreasing total required to trigger slope movement over time**

3.9 Collapse and post failure deformations

To ensure the potential risk of slope failure is adequately managed, the maximum potential post failure deformations need to be quantified. While slope failures of similar scale to Block 1A have occurred in mining environments before and could be used as comparable runout benchmarks, there is little precedent for such failures falling directly onto deep and saturated debris material in the mining industry. Such a failure could potentially cause liquefaction of the debris material resulting inflow and extensive runout of the material up the East Wall and potentially through the slot towards Harvey Creek to the south.

A literature review was completed on natural landslide events within valley settings where the landslide failed onto alluvial material and up the adjacent slope. Empirical evidence from such failures suggests a maximum possible debris run up distance on the adjacent slope/pit wall of half the slope failure height. With this in mind, the minimum evacuation boundary in the event of possible Block 1A collapse was set at the same relative level of mid-way up Block 1A for the surrounding pit areas.

3.10 Recent improvements in slope performance

Recent slope monitoring shows a significantly improvement in the slope stability situation of Block 1A since approximately mid-2019, directly as a result of the successful slope modifications implemented immediately after elevated pit slope movements were identified in June 2017. The unloading cutback and improvements to surface water drainage in particular (discussed in Section 2.2 and 2.3 respectfully), have resulted in the following slope performance improvements since June 2019:

- No small-scale failures or rilling of the slope within Block 1A.
- No significant 'slip' movement events.
- Decrease in movement rates, with radar monitoring indicating linear movement approximately <0.01/day.

While it may be too soon to predict if Block 1A will progress to collapse in the future, the stability situation has undoubtedly improved since June 2019 when the monitoring data indicated Block 1A collapse was highly likely. The slope modifications and slope management system have been so successful in reducing the likelihood and impact of a collapse of Block 1A, that the decision has been made to halt advancing the unloading cutback and recommence mining within the Centre Pit.

3.11 Block 1A slope behaviour summary

Careful and considered collation and interpretation of multiple slope monitoring sources has shown that Block 1A has exhibited all signs of the cracking and dislocation stage, and has done since approximately late 2017. This, along with the increasing sensitivity of the slope to lower rainfall totals, indicated that in mid-2019, the slope was close to collapse. Since mid-2019, the stability situation of Block 1A and the wider West Wall has improved due to unloading and surface water drainage improvements, and while collapse cannot be ruled out, monitoring data suggests it is now unlikely.

The behaviour of the slope throughout 2017 to 2019 can be summarised as:

- Block 1A is complex zone showing instability, with movement dominantly structurally controlled with a component of shear through weak rock mass.
- The movement trend is typical ‘stick-slip’ or cyclical movement, with the ‘stick’ being constant linear movement or relatively low rates, between short duration episodes of ‘slip’ movement along geological structures of up to 60 mm/day.
- The episodes of ‘slip’ movement have almost always been triggered by high rainfall events.
- Initially, these were rainfall events totalling more than 400 mm over 7 days. Over time, the rainfall totals triggering movement have been decreasing, with totals as low as 83 mm/7 days.
- This indicates the slope is becoming increasingly sensitive to rainfall and potentially closer to collapse.
- Block 1A then separated into smaller blocks which are moving independent of each other (though no doubt influenced by movement of others).
- To date, slope movement has not been triggered by other factors such as mining or blasting, however this may change as the cutback begins blasting and mining closer to Block 1A.
- Recent reductions in slope movement and surface breakup indicate large-scale collapse is now unlikely.

4 Risk management

To allow safe mining of the West Wall cutback to continue above the failure areas showing advanced stages of cracking and dislocation, a significant risk management system was implemented. This system is set out in a West Wall specific Ground Control Management Plan (WW GCMP), which documents the technical, operational and administrative requirements for the geotechnical management of the West Wall. The WW GCMP is the primary geotechnical risk management tool for the West Wall and is based on active management and ongoing review of a multilayered combination of multiple slope monitoring systems.

The scope of the WW GCMP comprises:

1. A summary of the geotechnical conditions along the West Wall, which is updated progressively as conditions evolve or change.
2. A description of the GCMP management strategy.
3. A description of roles and responsibilities.
4. Procedures for geotechnical slope management including:
    a. Operational geotechnical procedures and reporting.
    b. Escalation procedures.
    c. Key monitoring and trigger action response plans (TARPs).
5. Outline methods to effectively communicate the WW GCMP to the workforce.

6. Outline requirements for reviewing/auditing the WW GCMP.
7. Outline the document control.
8. Set out plans and documents pertinent to the WW GCMP.

One important aspect of the successful management of the West Wall is the collation of data from the above slope monitoring systems along with other relevant observations into a comprehensive weekly report issued by the West Wall Geotechnical Engineer. The West Wall Weekly Report (WWWR) is delivered to the mine General Manager, Manager Mine Projects, OTML Geotechnical Department, OTML Planning Department, OTML West Wall Operations, and Pells Sullivan Meynink (PSM) Geotechnical Advisors. The monitoring reported in the WWWR, and required for geotechnical slope management of the West Wall is a combination of:

1. Recording the physical deformations as they occur, comprising:
    a. Visual inspection and photographic record.
    b. Drone surveys to cover the less accessible parts of the West Wall including mining activities and failure areas.
    c. Ongoing survey of cracks, cavities and sinkholes.
2. Recording mining activities, containing:
    a. Map illustrating recent blasting.
    b. Map illustrating recent mining and cutback progress.
3. Evaluating monitoring trends, both short and long-term, in borehole and environmental data, comprising:
    a. Rainfall monitoring to provide daily rainfalls and weekly cumulative rainfall.
    b. Vibrating wire piezometer – plot of each piezometer with daily rainfall, for previous three months and since piezometer installation.
    c. Inclinometer deformations.
4. Evaluating time series monitoring data, comprising:
    a. IBIS radar: 7 and 28 day.
    b. GroundProbe radar.
    c. Prism monitoring: previous three months, Since 1st January 2016, 2017, 2018 (short and long-term).
    d. Tension crack monitoring.

As movement is triggered by rainfall events, the real time monitoring for rainfall and radar formulate the trigger inputs into a West Wall specific TARP. This TARP area covers all mining activities along the West Wall crest, Centre Pit (below West Wall) and all other areas deemed at possible risk of large-scale collapse. The TARP includes rainfall and movement triggers based on back analyses of previous movement cycles, as well as appropriate controls for mining within these areas. This system has resulted in successful mining of the entire west wall cutback and surrounding areas without a single incident or near miss related to pit slope stability since the WW GCMP was implemented in 2017.

5 Conclusion

The West Wall at Ok Tedi mine includes very large zones of brecciated and poor rock mass, with numerous major geological structures which have caused widespread instability triggered primarily by large rainfall events. Block 1A started showing significant signs of instability and by late 2017 illustrated all signs of the cracking and dislocation stage, indicating the slope was potentially heading towards the next stage of pit slope collapse. Successful management of the pit slope movements has been achieved by utilisation of a comprehensive slope monitoring system, detailed and regular data interpretation and analyses, and a priority on slope remediation in the form of an unloading cutback and surface water drainage improvements. Recent slope monitoring indicates that the previously likely collapse of Block 1A has been successfully mitigated.

Acknowledgement

The authors thank Ok Tedi Mining Ltd for permission to publish and acknowledge the significant contribution of Tim Sullivan of PSM for his continued mentoring and guidance throughout the project.

References

Ok Tedi Mining Limited 2019, Ok Tedi Mining Limited, Tabubil, viewed 10 November 2019, https://oktedi.com/who-we-are/about-us-overview/

Sullivan, TD 1993, 'Understanding pit slope movements', *Proceedings of the Australian Conference on Geotechnical Instrumentation and Monitoring in Open Pit and Underground Mining*, Kalgoorlie, Australia, pp. 435–445.

Sullivan, TD 2007, 'Hydromechanical coupling and pit slope movements', *Proceedings of the 2007 International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering*, *Slope Stability 2007,* Australian Centre for Geomechanics, Perth.

Van Dongen, M, Wienberg, RF, Tomkins, AG, Armstrong, RA & Woodhead, JD 2010, 'Recycling of Proterozoic crust in Pliestocene juvenile magma and rapid formation of the Ok Tedi porphyry Cu-Au deposit, Papua New Guinea', *Lithos*, vol. 114, no. 3–4, pp. 282–292.