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Factors impacting and controlling water erosion of rock benches and slopes

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Abstract

Rock slope faces typically comprise assemblages of benches intended to catch dislodged rock debris, channel groundwater and rainfall runoff along slope faces, and flatten overall slopes to design angles. Excavation of neat design-width benches is often not achieved as planned. If bench widths are reduced by adverse structure and/or poor blasting, or if their surfaces lack the required gradients for water flow and discharge at selected locations, runoff cascades over bench crests. If sufficient geological defects data exist, then risk of partial to entire bench height and akin berm width instabilities can be statistically quantified. These risks are often rock-type and slope-facing direction-dependent. In existing pits, such risks can also be estimated either by stereo-pair slope photography done from suitable vantage points around the pit or by drone flyover inspection of slope faces, but single- and multiple-event (i.e. progressive failure) structural, and poor blasting, failures are often difficult to distinguish and quantify. Water runoff over bench crests often occurs along major faults and zones of weak ground. Such discharge erodes geological defects to establish narrow slots that rapidly enlarge and coalesce into major V-shape chasms on slopes; with voids at some mines being 150 m along strike, 80 m deep and 300 m high, and with their debris runout exceeding 100 m. To avoid chasms, preventative measures are installed at time of bench mining. Remedial works are undertaken after some erosion occurs. The management decision to install preventative measures is dictated by site-specific experience and based on good appreciation of the safety and mining consequences if slope void development is not prevented. Reinstating bench drainage across large chasms is impossible; water needs diversion around such chasm footprints. Once established, considerable ongoing remedial effort is required to arrest or to retard the rate of chasm expansion. Stability monitoring alone does not solve the problem, but does provide safer working conditions. Examples of defect-controlled bench stability risks are presented. The stability impact of water runoff erosion is illustrated by examples from Australian and overseas mines. The general decision process, use of risk matrices, advantages, disadvantages, and the durability, difficulty and timing of water erosion preventative (geotextile on bench faces and high-density polyethylene, mesh with shotcrete in water drains) and remedial works (void rock backfill, toe buttress, gabion basket wall, pit floor bund and slope cutback) are discussed.

Keywords: *benches, blasting, adverse defects, water erosion, preventative and remedial measures*

1 Introduction

Various factors impact and control water erosion of rock benches and slopes.

Bench stability depends on its height, face angle and rock mass strength, the occurrence of adverse faults, the pattern and intensity of other defects, seismicity, blasting, groundwater, rainfall and the effectiveness of installed ground support. Rocks weather and thus strength degrades with time. Bench location (e.g. the critical area if above or below key infrastructure) in the pit and its intended design life are important. Risk of bench instability due to adverse structure can be quantified. Interim slopes typically have a short life and require less bench design attention. Benches in critical areas on final slopes need more consideration.

However, suitable-width benches with good water runoff are often not achieved as planned. Design bench widths may be reduced by adverse structure and/or poor blasting. On benches without adequate surface gradients or discharge at strong rock locations, water runoff cascades over bench crests and slope chasms may erode. These initiate along faults and weak ground, and progressively enlarge and coalesce into big chasms. Invariably, mining plans change; some initially deemed temporary slopes become permanent if proposed cutback plans are shelved. Also, due to mineral economics, there may be periods of mining inactivity and less chance for slope maintenance.

If risks of defects-defined and surface water erosion bench attrition are assessed to be unacceptably high, effective preventative measures need to be installed at the time of bench excavation or remedial works done after water erosion is initiated and before bench access is lost. Construction of narrow vehicle access ramps down the slope face may be required to regain slope face access for remedial works. Repairing disrupted bench drainage across large chasms is impossible due to settlement of any placed rockfill and ongoing debris runout. Such chasms may require slope cutback remediation, but this is expensive if there is little ore in the cutback ground to pay for it. At-risk chasms may be bunded off on the pit floor, but this sterilises ore beneath the bunded-off footprint area.

In this paper, water runoff impacts are illustrated by examples from Australia and overseas. Bench face mining options are mentioned. Kinematic, limit-equilibrium and risk-based stability analysis methods for benches with adverse geological structure are outlined. The risk-based decision process, mine manager's and geotechnical engineer's roles, advantages, disadvantages, durability, difficulty, timing of water erosion preventative (geotextile on bench faces and high-density polyethylene [HDPE], mesh with shotcrete in water drains) and remedial works, (void rock backfill, toe buttress, gabion basket wall, pit floor bund and slope cutback) and lead-times needed at remote sites for the procurement and delivery of consumables and mobilisation of specialist contractors are discussed. All three co-authors had at some stage worked at the Ok Tedi Mine in Papua New Guinea (PNG), where annual rainfall across the project area is 10–13 m. Due to this association, many cited examples are from this mine.

2 Examples of bench and slope water runoff erosion damage

Flow and discharge of surface water runoff along slope faces should be well planned. Lack or loss of water management on benches often results in their face erosion (see Figure 1). If this erosion is unabated, major, multi-bench high, chasms may progressively develop on slopes. Chasms may develop for various reasons:

- Intentional discharge of rainfall/groundwater runoff into pits deemed to be abandoned (Figure 1a) or an expedient, but perhaps poorly considered, water management option (Figure 1e) where water is discharged from a slope cutback area across a toppling failure landslide.
- Lack of opportunity for surface water channel berm maintenance and its washout during periods of temporarily suspended mining activity (Figure 1b).
- Insufficient water runoff management on slopes destined to be a cutback area at a near future date (Figures 1c, 1d and 1f).

To iterate, all chasms initiate as minor erosion features along geological defects and zones of weak ground but, if the situation continues unchecked, they may rapidly develop into seemingly unstoppable huge chasms.

(a) Intentional water discharge into disused pit, Paddington WA; Quarters Pit (June 2019)

(b) Unintentional water runoff in 8-years' halted mining, Mt Moss, QLD; Lilley Pit (Sep 2022)

(c) Hard-attempted, but insufficient water run-off control on benches; chasm debris runout onto haul road, cascading to pit floor below, 15m high benches; Ok Tedi, PNG (Oct 2014)

(d) Zoom of damage on ground-reinforced 15m high bench faces beneath pit haul road, with debris blockage of shafts to drainage tunnel; Ok Tedi, PNG; Berlin Chasm (Oct 2014)

(e) Intentional water discharge from slope cutback mining across toppling landslide area; Ok Tedi, PNG; Paris area (May 2014)

(f) Chasm debris runout onto LV down-slope ramp and pit haul road; Ok Tedi, PNG; West Wall, Berlin-Paris area (May 2014)

Figure 1 Examples of water runoff erosion problems on mine slopes

3 Mining of bench faces

Open pit blasting is a specialist subject. At many mines, external consultants are engaged to advise on this topic to achieve the most satisfactory mining outcomes in various strength rocks and geotechnical ground conditions.

A favourable blasthole layout that might be considered to mine final pit slope faces is shown in Figure 2. This layout comprises several types of holes; i.e. pre-splitting holes (red), additional shallow holes (blue), buffer row holes (green) and normal production blastholes (brown). Spacing and blast-initiation delay between each blasthole type will depend on ground conditions.

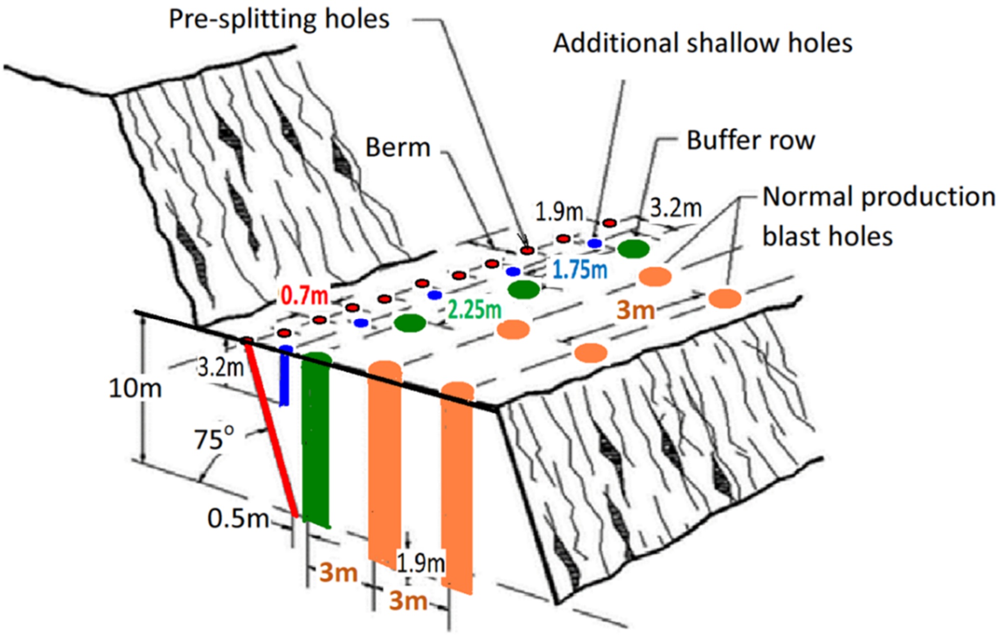


Figure 2 Example of a favourable blasthole pattern that might be used to mine final slope faces

Notwithstanding the geotechnical merits of Figure 2, the main aim of blasting is to fragment waste rock and ore to a size that improves the productivity of blasted rock digging, transportation and crushing. In addition to blasting shock energy (fragmentation), there is gas or bubble energy. The latter not only promotes fragmentation but, more importantly, creates heave and muck pile looseness to greatly assist dig rates. This venting gas, if not effectively directed away from pit walls, can escape into fissures/joints in said benches, exacerbating weaknesses and, in extreme cases, destroying bench crests due to excessive back-break.

Thus, blasting aims sometimes compete with the geotechnical aims of least damage to bench faces.

The ways of creating bench faces are listed in order of likely increasing costs:

- Excavator mining of the ground (without the need for blasting) and bench face trimming; i.e. typically in readily diggable ground on interim and final slopes (Figure 3a).
- Production blasting to improve mining productivity, with excavator trimming of bench faces; i.e. again, typically in readily diggable ground on interim and final slopes (Figure 3b).
- Production blasting only, without any special consideration near the proposed bench faces, and with excavator clean-up of still-diggable loosened rock blocks hung up on bench faces. Ideally used on interim slopes with a short design life but sometimes used on all slopes irrespective of design life (Figure 3c).
- Production blasting, but with special consideration of blasthole layouts (i.e. diameter, depth, declination and spacing), and the explosives, decking, stemming and timing sequence in the one to

three rows of blastholes nearest the proposed interim and final bench faces, to minimise blasting damage (Figure 3d).

- Trim blasting where, after the main production blast and removal of the blasted ground, a much smaller secondary blast is done; comprising one to ideally three rows of more closely spaced blastholes to fragment the remaining ground up to the proposed bench face line, with excavator clean-up of loosened ground hung up on the excavated bench face. Typically used on final slopes.
- Pre-split blasting where an airgap is created along the proposed bench face by an initial blast comprising a single row of small diameter (50–150 mm), closely spaced (1–4 m) blastholes. With the thus-created airgap in the rock mass, most vibration and gases from the main production blast do not penetrate into the rock slope behind the pre-split line. After production blasted materials are dug away, if still required, there is an excavator clean-up of loosened ground hung up on bench faces. Used on final slopes (Figures 3e and 3f), this method is widely used in Australian coal and most metal mines with excellent outcomes; much better than those shown in the paper.

With exception of the third option listed above, the rest usually yield good bench face stability outcomes. The last option is most desirable, but its use needs forward planning because pre-splitting may slow down the overall mining process if pre-split lines are not created well ahead of the ore production blasts.

Bench mining option listed in the third bullet-point results in least satisfactory bench faces (Figures 3c). The outcome is worsened where strike of geological structures is at <20° across the bench crest trend direction, as shown in Figures 4a to 4f.

The bench surface should consistently grade (say, ~5–10°) into the toe of the bench above. This will ensure that rainfall and groundwater discharge will flow along the bench instead of spilling over the bench crest and cascading uncontrollably down the slope face. In high rainfall and significant groundwater outflow situations, long-term functioning water drains are needed along toes of benches.

Ideally, drains need sufficient capacity and gradient to accommodate the anticipated water flow and to conduct it to geotechnically preferred drop points for its removal/pumping from the pit floor. In low-strength materials, required drains could be backhoe excavated. In stronger rock, trim blasts in combination with pre-splitting could be used to try to create such drains.

Trim blasthole depth above the berm of the next proposed bench below can be designed to ensure that this next berm surface grades from its crest into the slope face and also has a slight lateral gradient to allow natural flow along the bench to specific water catchment points. If necessary, excessive undulations in drain profile and gradient can be chipped out with a handheld jackhammer or mechanical rockbreaker. Alternatively, a drain could be built above the bench rock surface with its profile and gradient achieved via gravel-cobble rockfill. Irrespective of how the drain profiles are created, drain surfaces should be sealed to prevent leakage; i.e. lined with a high-density polyethylene (HDPE) liner or more robustly engineered with mesh and fibre-reinforced shotcrete.

(a) Decomposed rock; not-blasted, excavator dug ore and bench face on final slope; Simberi, PNG; Pigibo Pit (May 2016)

(b) Weathered rock; production blasted, excavator trimmed bench face on final slope Simberi, PNG; Pigibo Pit (May 2016)

(c) Near-fresh strong rock, production blasted, excavator cleaned-up bench face; West Bokaro, India, Coal Quarry C (Sep, 2010)

(d) Fresh strong rock, production blasted, fairly effective excavator clean-up of bench face; Ok Tedi, PNG, SE slope (Aug 2011)

(e) Strong FR rock, effective pre-slit bench faces; Paddington, WA; Mulgarrie Pit (Aug 2019)

(f) Strong FR rock, effective pre-split bench face; Lumwana Mine, Zambia (Jul 2010)

Figure 3 Bench faces excavated without and with pre-split blasting on mine pit slopes

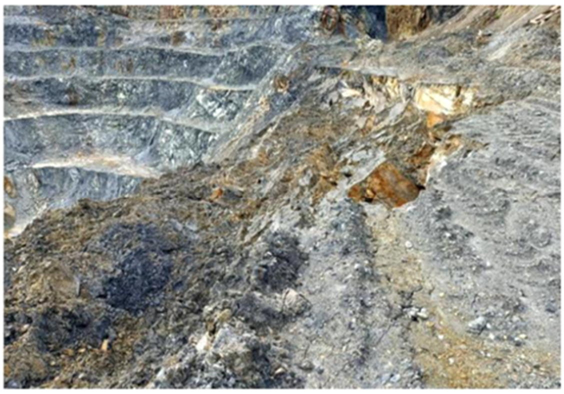
(a) Igneous intrusive rocks, Ok Tedi, PNG, Taranaki NE slope (2003)

(b) Igneous intrusive rocks, Ok Tedi, PNG, Taranaki NE slope (2003)

(c) Igneous intrusive rocks; Ok Tedi, PNG, Moscow SE slope (2008)

(d) Igneous intrusive rocks; Ok Tedi, PNG Moscow SE slope (2008)

(e) significant backbreak from blasting induced gas-jacking along bedding planes; Pueblo Viejo, Dominican Republic, N slope (2021)



(f) Same as (e), plus unmanaged surface water flow inducing toppling instability (Pueblo Viejo, Dominican Republic, SW slope (2021)

Figure 4 Bench width attrition by production blasts due to adverse defect orientations

4 Impact of mining plan changes on established slopes

Mining plans may change as the three-dimensional (3 D) orebody layouts and their grades are better defined by investigations and if ore prices fluctuate. Some planned slope cutbacks may be shelved, resulting in initially considered temporary slopes becoming final slopes. Depending on remaining mine life, existing slope stability condition and future dewatering needs, some areas of redesignated final slopes may need to be accessed and remediated. Temporary slope faces may simply be created by production blasting with adequate short-term catch-bench berm widths, but may be unsuitable for long-term catchment function. If a major temporary slope is redesignated as final, access is often needed to remove the already accumulated rockfall debris to improve the benches' future rockfall capacity, repair any already damaged surface water drains, backfill already created significant water erosion voids with rock and to install horizontal drainage flow bores for slope dewatering. In temporary slopes, groundwater drainage bores are typically omitted because future cutbacks destroy such installations or make initially installed bores too short for their long-term dewatering needs.

Risk matrix in Section 5 was developed with a 2012 date for end of Ok Tedi's mine life, but mining is still ongoing in 2023 and is expected to continue till 2030+. Also, in 2008–2013, three underground mines behind current slopes were considered; hence, slope water erosion was the least of anticipated concerns as existing slopes would experience subsidence. Existing drains and ground-reinforced areas would perish due to this ground movement around block caves and stopes. Both open pit and underground options were being evaluated in parallel. Underground plans were shelved in 2013 and efforts refocused on-slope cutbacks and waste rock dumps up to 650 m high. West Wall cutback removed the upper perimeter drain before a contingency drain was established, and the volume of surface water runoff cascading on slopes below the cutback footprint increased.

5 Risk matrix for quantification of water erosion

Risk matrices are standard decision tools for all types of activities on mine sites. They comprise a table that cross-plots the likelihood of occurrence in five rows rated as rare (E), unlikely (D), moderate (C), likely (B) and almost certain (A) against the consequences in five columns rated insignificant (1), minor (2), moderate (3), major (4) and catastrophic (5). Many, but functionally similar, versions of risk matrix tables are used.

Little et al. (1998, 2000) interpreted high risk (MW4) for uncontrolled surface water erosion of Ok Tedi pit slopes (Figure 5). The likelihood of occurrence was rated as 'almost certain' and the consequence was rated as 'moderate'. This risk assessment reflects a typical rock condition scenario. This last comment is important because for purpose of 1996–2000 pit slope stability analyses, 36 geotechnical domains – most with two to three different slope-facing directions – were distinguished. Hence risks differed around the pit. Also, when this assessment was done, Ok Tedi pit slopes were 350–450 m high, structural data at 450–900 m depths was entirely based on orientated core drilling, difference existed between mapping and drilling data, and data was sparse in some existing pit domains and below its then pit bottom, especially for intensely fractured rock types (e.g. Taranaki, Parrot's Beak and Basal Thrust Fault Zones, some types of skarns, most siltstones and all mudstones). Some geotechnical models needed to be extrapolated over 400–500 m distances.

When the 50–70 m thick Parrot's Beak Thrust Fault was exposed on the west wall in 2010–2013, its stability and erosion risks were deemed high. This area was reinforced with cable bolts, mesh and shotcrete beneath the pit haul road due to the vital importance of this infrastructure.

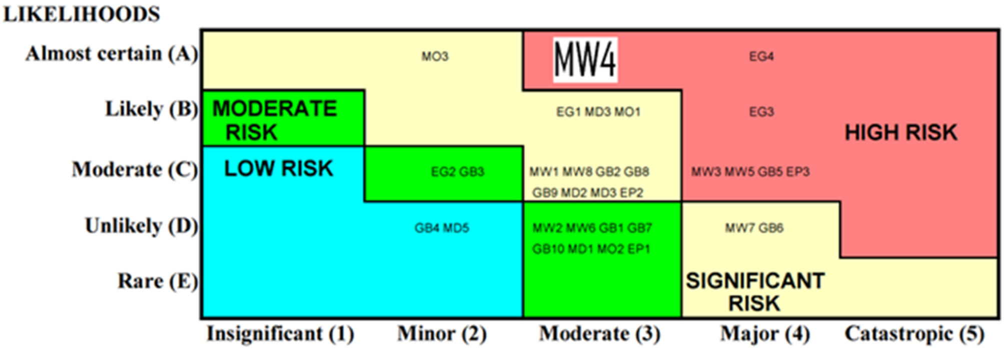


Figure 5 Risk matrix for surface water erosion of Ok Tedi pit slopes (MW4) (Little et al. 1998, 2000)

With respect to surface water rock erosion, some contributing components can be quantified. For example, there might be a 10–20% risk that the entire bench berm width might be lost in some rock types due to circular or wedge failure, as per Section 6 below. Other contributing components/considerations are conditional, interdependent, and changeable with time and different mining plans, and are thus not easily quantified. For example, if one or both pit perimeter surface drains malfunction (e.g. they are blocked by landslide debris), additional surface water runoff will cascade down slope faces and the bench drain will not cope with the extra water flow. But prediction of perimeter drain problems is not easily quantified. Also, if bench voids are not fixed in a timely manner or washed-out surface drains are not promptly repaired, progressively larger areas of slope face become affected. Likewise, changes in mining plans (as discussed in Section 4) alter what best strategies need to be adopted.

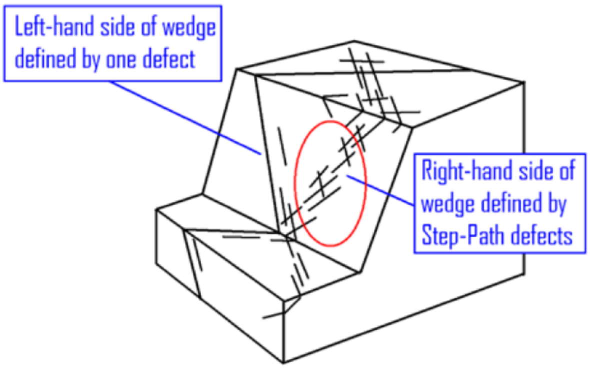
6 Risk of bench failure due to adverse geological defects

Risk of bench failure by slip-circle and planar and wedge sliding along geological defects can be quantified.

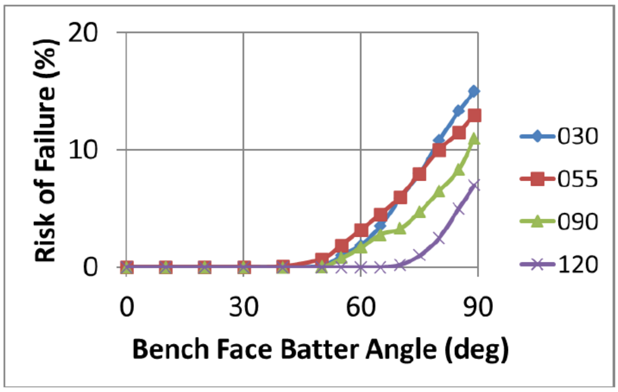
In the first instance, a kinematic stability analysis is often used. Based on stereographic projection plots, the chance of potential wedges sliding from benches is estimated for each designated slope-facing direction, face angle, wedge geometry tightness, sliding direction and friction angle being considered. More sophisticated limiting-equilibrium analyses (LEA) are then done. These additionally consider statistical variability in friction angle and cohesion for each defect set, defining the sliding block's base, groundwater, rock density and earthquake loading.

The underlying logic of kinematic analysis using stereographic projections has significant limitations, in particular by assuming that all defect sets are infinitely persistent, have equal shear strength and occur everywhere within the rock mass. As a result, such analyses often overestimate bench failure risks. The same applies to LEA used to assess simple wedge geometries. Without defect length data, partial and full bench height/berm width failures cannot be adequately considered. Defect set occurrences may be <100%. For example, if a defect set only occurs at <50% of rock mass locations, then this set's members are absent in the remaining >50% of the rock mass. If a 50% occurrence model applies for each of the two defect sets defining a tetrahedral wedge, risks of wedge sliding derived via stereographic projection kinematic and LEA probabilistic methods need to be reduced twice by a 0.5 factor, with actual risk being 0.25 (i.e. a three-quarters reduction) of pre-adjusted failure risks (Baczynski 2016).

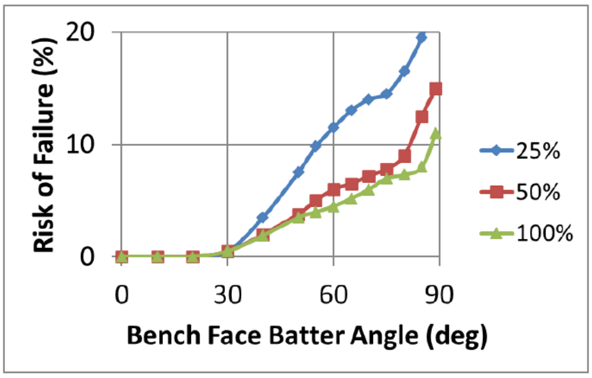
If one wishes to know how much of a bench height and its berm width are likely to fail, then defect length is important. In many rock masses, the majority (90–95%) of defects are often shorter than a typical 15 m high bench, but a full bench height failure might still develop by shearing along zones of coaligned shorter defects and through intact rock bridges between them (Figure 6a). Consideration of defect zones is a step-path method (SPM) approach (Baczynski 2023). Most times, zones of short defects are stronger than similar length individual defects. Thus, an SPM approach often reduces estimated bench failure risks. Figure 6(b to d) are examples of bench stability failure risks estimated in Little et al. (1999). Risks vary, with rock type, slope-facing direction, and relative proportions of bench height and berm width being considered. Risk that failure will impact one-quarter of bench height or berm width is much higher than the risk of losing the entire bench height or width.



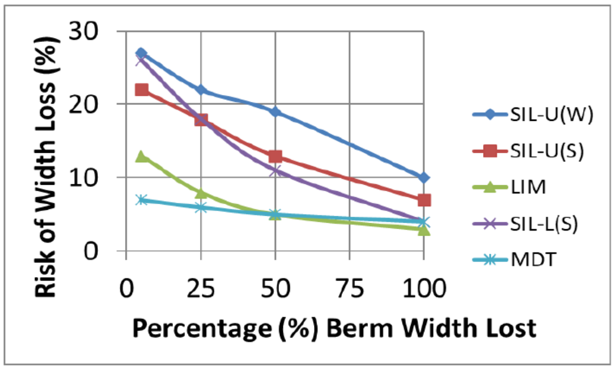
(a) Example of Step-Path Method (SPM) use for rock wedge sliding (Baczynski, 2023)



(b) Risk-impact of bench facing direction and face angle for Ok Tedi Berlin Limestone



(c) Percent (%) of 15m bench height lost in Ok Tedi NE slope siltstone due to wedge-sliding



(d) Percent (%) of 8m berm width lost on benches with 65° batter angles in various rock types

Figure 6 Bench wedge sliding failure risks for Ok Tedi pit (based on data in Little et al. 1999)

The above discussion, and examples in Figure 6, demonstrate that structurally controlled bench failures can be quantified, but the analyst needs to statistically consider all geotechnical factors likely to impact risks and not just use a simple stereographic projection kinematic stability approach. Figure 6b shows that with a 30° slope-facing direction for Ok Tedi Berlin Limestone, risk of wedge sliding bench failure is negligible for bench batter angles <45° but increases to ~15% for vertical faces. Figure 6c shows that bench wedge sliding failure for Ok Tedi New York siltstone is negligible for batter angles <30° but increases to >20% for near-vertical bench faces. For 15 m high benches with 65° batters in various Ok Tedi Moscow area rock types, Figure 6d shows that the risk of losing 25% of berm width is 6–22%, 50% berm loss is 5–19% and entire berm loss is 3–10%.

In simple terms, Figure 6d shows that, on average, every 100 m of bench length was expected to have a 3–10 m cumulative length section where bench berm had totally failed by wedge sliding and a 5–20 m section where half the berm width is lost. This outcome highlights the challenges in water drainage along the mine's benches.

Figure 6d also indicates that even without bench water erosion consideration, some Ok Tedi rock types are more prone to structurally controlled failure. In the plotted results, Ok Tedi ieru siltstone [SIL-U(W), SIL-U(S) and SIL-L(S)] have a higher failure risk than darai limestone (LIM)or monzodiorite (MTD) intrusive rocks.

While the results in Figure 6 are based on data gathered via conventional geotechnical slope face mapping, similar data can also be collected via stereographic-pair photography of slope faces from suitable vantage points around the pit perimeter or via the now fine-tuned drone photogrammetry flyover technology (e.g. Nguyen et al. 2023). However, all photographic methods have limitations. These include the inability to determine defect orientations if there is little or no breakout on defects to expose their surfaces or to assess infill type, small-scale surface roughness and uniaxial compressive strength of the wall rock immediately adjacent to defects. Perhaps there also seems to be a trend in drone flyover mapping literature to focus on longer defects and hence resulting stereographic projection plots seem to contain less data. Thus, defect set orientation and other attribute statistics may be developed on a less-than-ideal amount of data.

If several bench failure modes are possible, e.g. say planar, tetrahedral and active-passive wedge or circular slip, then the following multi-mode failure mode equation (Baczynski 2016) needs to be used to assess the likelihood that a bench might fail by just one of the several possible different failure modes:

$$PF = P1 + (1 – P1)\,P2 + [1 – P1 – (1 – P1)\,P2]\,P3 + \{(1 – P1 – (1 – P1)\,P2 – [1 – P1 – (1 – P1)\,P2]\,P3\}\,P4 + etc \quad (1)$$

where:

PF = combined Probability of Failure.

P1 = Probability of Failure by mode 1 (say, circular).

P2 = Probability of Failure by mode 2 (say, planar sliding).

P3 = Probability of Failure by mode 3 (say, tetrahedral wedge sliding).

P4 = Probability of Failure by mode 4 (say, toppling).

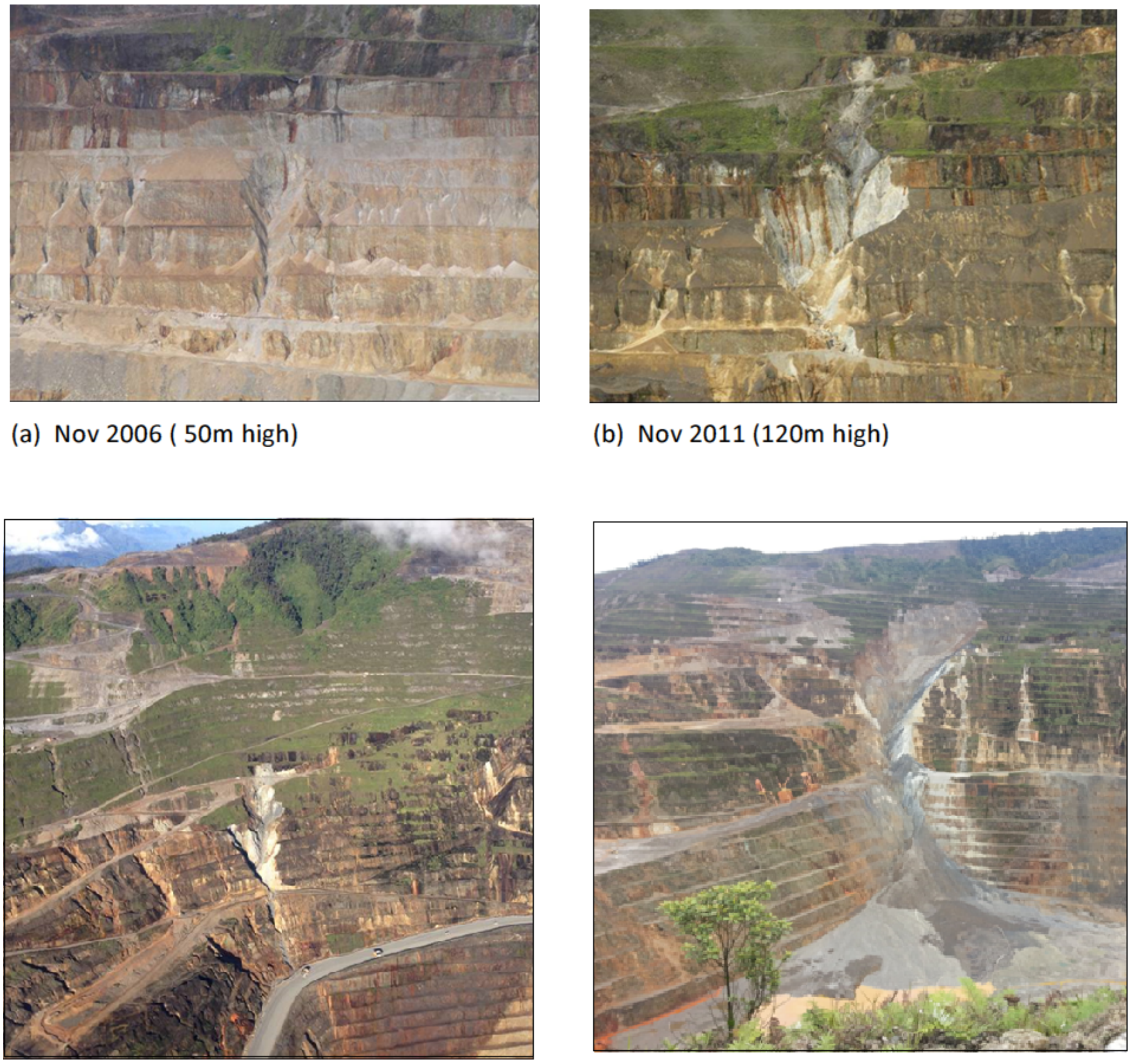
The underlying logic of this equation is that if a bench at particular location has already failed by one failure mode then it is impossible for this same area to fail again by another mode. Without this equation, the cumulative sum of individual failure mode risks may exceed 100%, and failure risks are much over-estimated.

7 Definition of preventative and remedial measures and timeline

Two old phrases perhaps sum up water erosion impacts on-slope benches: ‘A stitch in time saves nine’ and ‘From a small acorn, a big oak grows’.

The former phrase aptly describes the effort involved in preventative versus remedial measures; the latter reflects on how a minor water-eroded notch on the bench face, if not fixed in a timely manner, eventually grows into a huge chasm. Preventative stability measures are installed as the respective benches are being mined and before any surface water runoff erosion had initiated. Remedial stability measures are installed at some time after benches had been mined and water erosion problems had started to impact safety and/or production in-pit workings. Figure 7 aptly demonstrates the general truth of the two old phrases cited above.

The timeline for chasm expansion without remedial measures is likely exponential, especially in weak ground and high rainfall situations. Chasm W3 shown in Figure 7 was first noticed in late 2004, when a cross slope light vehicle (LV) access ramp was being constructed. In its early stages, this chasm was repairable. Various options were discussed and recommended to reinforce this void’s surface when it was still only two to three benches high, but none were agreed on or pursued. By 2009–2010, the chasm was 90 m high and considerable remedial effort was now being made to arrest further erosion of its crest and V-notch toe. Figure 7c shows that in December 2013, the chasm’s toe was at the level of the LV cross slope ramp. By early February 2014, the chasm’s toe had cut through the LV ramp to about 40 m below it. Prompt major repair action was urged. Use of pit mining equipment was needed to backfill the chasm’s toe back above LV ramp level, but this task was not pursued. By May–June 2014, the chasm’s toe had reached the pit haul road, regularly inundating it with huge volumes of debris (as shown in Figures 1c, d and f). Figure 7d attests that the chasm’s expansion accelerated in 2014 until, by mid-2015, it was 450 m high (i.e. the same as a 150-storey high-rise building) and had destroyed the haul road.



(a) Nov 2006 (50m high)

(b) Nov 2011 (120m high)

(c) Dec 2013 (180m high)

(d) Jun 2015 (450m high)

Figure 7 Progressive expansion of chasm W3 on the west wall at Ok Tedi Mine between 2006 and 2015

8 Geotechnical engineer's and mine manager's roles

Preventative bench design is project experience based. It requires a comprehensive pre-mining geotechnical appreciation of likely poor ground condition locations, regular geotechnical inspection of benches during their excavation, and management's full support and approval for work to be done. This support includes a sufficient budget, equipment, manpower resources and realistic time-windows of work opportunity (i.e. often involving a disruption to nearby mining activity) to successfully accomplish the intended measures.

For various reasons, many mines have a high turnover of senior staff. Loss of long-term experienced staff is unfortunate; it results in poor appreciation of the past effort required for good design outcomes. The key purpose of mining is to make a profit; hence there is an understandable focus on ore production. With less appreciation of how seemingly minor water erosion issues may rapidly escalate to become major problematic chasms, short-term incumbent managers are often hesitant to spend money, time and preventative effort to address potential future situations that may or may not necessarily arise or not be as serious as anticipated. Admittedly, such hesitation may be at least partly due to less-than-effective communication on this issue; although without good convincing photographic proof (such as in Figure 7) there is often little evidence to show what the slope conditions might have looked like before the voids had developed and what remedial effort is now needed to meaningfully slow the expansion of chasms.

Likewise, remedial bench repairs are done if absolutely required for long-term mining objectives and safety. Even then, there is a reluctance to devote much effort, apart from barricading off at-risk areas, if issues don't immediately impact current production, sterilise high-value ore and are only likely to become serious at some later date. While the above comment sounds cynical, the fact is that without management's full support and allocation of adequate resources, long-term lasting remedial measures are rarely started and only become a high priority if the situation is already impacting or likely to soon impact ore production, safety and/or future mining plans. By then it may be impractical to undertake meaningful remedial works due to limited access to problem sites. Ultimately, all troublesome slope areas may be addressed by slope cutbacks, provided that the new benches on the new pit slope face do not repeat the same design flaws of those that existed on the earlier pre-cutback slope face.

9 Preventative options

Commonly used preventative water erosion control measures are shown in Figures 8 and 9.

To realistically consider preventative options, management needs to have a convinced appreciation of how geotechnical conditions will likely impact their slopes and benches. They also need reassurance that without these upfront measures, ensuing problems will escalate to impact the safety of personnel and mine equipment, seriously disrupt their ore production and will be several-fold more difficult and costly to fix than timely preventative measures. There are short, intermediate and long-term mining plans on most projects. Plans change with time, metal prices and the influx of new management. Risks for all types of activities are typically assessed in terms of simple matrices that consider the likelihood of event occurrence and the severity of resulting consequence. The main purpose of preventative options is to eliminate or at least meaningfully reduce the likelihood of the occurrence and, hence, minimise the severity of consequences (prevent loss of life; minimise equipment damage, disruption to production and loss of access to ore; and adequately budget for remedial works if problems do develop).

The key issue is that, apart from well-known major fault/shear locations, even without poor blasting damage considerations, general pre-mining rock mass conditions tend to be statistically variable around the mine area. Not all geological defect sets occur at all locations throughout the rock mass, and the orientation, length and intensity of geological defects are often rock type-dependent (see Figure 6d). Some slope-facing directions (see Figure 6b) are inherently more prone to instability than other directions. Thus, a suite of bench failure/water drain flow disruption risk matrices is required for the entire pit, along with a risk threshold level agreed by senior management beyond which preventative ground control measures are automatically installed at specific adverse ground locations. During the initial stages of mining projects, the structural pattern is mostly based on orientated core logging and/or other downhole imaging/geophysical mapping techniques. As slopes are excavated, initial models are improved by slope face mapping data.

Actual rock mass conditions in slope locations initially designated for preventative ground control measures must be confirmed by ongoing geotechnical inspections and systematic mapping of bench faces as soon as the faces are exposed. This task is required to ensure that anticipated adverse ground conditions do actually exist and that the preventative measures effort is not being wasted if encountered ground is actually better than predicted.

The range of often-used preventative water erosion control measures comprises:

- Water drains to ensure that water drains along bench toes are functional (i.e. engineered with survey-controlled gradients, able to long-term conduct the anticipated volume of flow of runoff water – both rainfall and groundwater from flow bores, to agreed and adequately engineered drop points either down into the pit workings or to designated on-slope catchment sumps for its pumping out from the open pit footprint area.

- Bench face cover (i.e. geotextile cloth placed over bench faces in soft erodible ground is also a good preventative erosion control measure; Figure 8b).

(a) Black HDPE lined bench berm, erosion on unlined berms, Ok Tedi, PNG (Sep 2003)

(b) Geotextile cloth covered face of access ramp to toe of Edinburgh Chasm (Jan 2008)

(c) Work-in-progress; meshed, 10-strand, 100t tensioned cable anchored, fibre-reinforced shotcrete sprayed bench face beneath mine office and in-pit crusher (May 2006)

(d) Final-Slope in Photo (c); bench face beneath mine office and crusher; 1-2m thick thrust fault zone at 10-20m below reinforced slope (Feb 2007)

(e) Mesh, cable-dowels (before fibre-reinforced shotcrete) beneath mine access road in 60-80m thick thrust fault zone; Ok Tedi, PNG; Paris-Berlin SW slope (Apr 2012)

(f) Vertical crest piles, cable-dowels and mesh sprayed with fibre-reinforced shotcrete beneath mine access road located in the 60-80m thick thrust fault zone (Nov 2011)

Figure 8 Ok Tedi, PNG: long-term bench face preventative/remedial measures beneath infrastructure

(a) Down-slope light-vehicle (LV) access ramp; Berlin-Paris area, West Wall (Aug 2009)

(b) HDPE lined, rockfill-shaped, water drain, Berlin area, West Wall (Mar 2005)

(c) Mesh and fibre-reinforced shotcrete drain; in-drain mini flow arrest dams, downslope LV access ramp, Berlin, West Wall (May 2010)

(d) Construction of cast in-situ concrete culvert open drains along downslope LV access ramp; Berlin area, West Wall (June 2011)

(e) Chasm crest reinforced with shear piles, mesh and fibre-reinforced shotcrete; Berlin Chasm, West Wall (Sep 2012)

(f) Chasm's V-notch toe buttressed with left-over concrete sleepers from mine's 4km long drainage tunnel, Berlin Chasm (May 2010)

Figure 9 Ok Tedi, PNG: preventative and remedial control measures for rainfall and groundwater runoff

- Bench top cover (i.e. use of high-density polyethylene (HDPE) liner on bench berms; Figure 8a).
- Water drains lined with HDPE (Figure 9b), fibre-reinforced shotcrete (Figure 9c), the latter with steel mesh if required; placement of angular cobble rockfill blankets to protect the HDPE from ultraviolet damage and rockfall impact holes, and to slow water flow in drains; and lining drains with rock-filled gabion mattresses (this latter method was not used on the authors' mining projects).
- HDPE water pipes (0.5–0.7 m diameter), buried concrete culverts, cast in situ open concrete drains (Figure 9d).
- Ground supporting by various means bench faces in poor ground in proximity of long-term required infrastructure (i.e. tensioned cable anchors, not-tensioned cable dowels, old drill rods, etc. steel mesh, fibre-reinforced shotcrete, rock-filled gabion baskets (Figures 8c to 8f).
- Reinforced-earth walls (e.g. the mid-grey coloured, metal-plate faced, areas shown in Figure 8d at both ends of the pale-grey shotcrete reinforced top bench; where rockfill was placed to widen the area for mine infrastructure (i.e. in this instance, the haul road around the in-pit ore crusher).
- Bench crests may also be reinforced with steel piles (purpose-purchased I-beams, or re-use of old drill rods, shovel cables etc.), and old haul truck and LV tyres.

Where pit slopes are excavated through major, thick, fault/shear zones in proximity of long-term required infrastructure (e.g. pit access ramps/haul roads, mine offices, mill facilities, in-pit crushers, conveyors etc.), such weak ground needs to be reinforced with tensioned cable anchors, non-tensioned cable dowels, mesh and suitably thick (say, >50 mm) fibre-reinforced shotcrete.

To avoid water pressure build-up behind shotcrete-sprayed bench faces and their cracking/flacking failure, short water pressure-relief weep holes (e.g. 50 mm diameter, 4–5 m deep) are required on 3–5 m centres over the entire shotcrete-sprayed bench face surface and groundwater depressurisation flow bores (say, 50–100 mm diameter and >30 m deep) at perhaps 10–20 m centres installed 1–2 m above each bench toe.

10 Remedial options

Remedial options are often limited by poor to non-existent access to at-risk problem locations on slopes. Most remedial options are the same as the preventative options.

There are, however, remedial-specific options which include:

- Barricading off pit floor area below the at-risk slope to prevent debris runout into active work areas (but this prevents access to ore reserves beneath the footprint of the barricaded-off area).
- Constructing vehicular access to at-risk areas i.e. down slope face LV ramps (Figure 9a). This access is necessary to try to arrest the progressive erosion expansion of chasms and to remediate any other flaws in the slope design (e.g. restore catch-bench function at locations overtopped by rockfall debris, restore and/or enlarge the network of groundwater horizontal flow bores and/or slope displacement monitoring survey prisms).
- Barricading/buttressing the toe of V-notch chasms to lessen the volume of runout debris and to slow the chasm toe's downwards migration towards the pit floor. If hard rock boulder-size rockfill is not available, any durable materials can be used to construct the buttress (as shown in Figure 9f). Ensuring that the chasm toe is long-term accessible to repair buttress washouts promptly after these occur.
- Managing and preventing, or at least limiting, the volume of water runoff entry into chasm voids; diverting slope face water runoff around the chasm footprint area.
- If practical and if durable rockfill is available, backfilling the erosion void.

- Reinforcing the perimeter of the chasm's crest with shear piles, mesh and fibre-reinforced shotcrete to halt or at least to impede the void's rate of enlargement (Figure 9e).
- Slope cutback.

With slope face access regained, small (i.e. for example, one to two benches high) chasms may be fully filled with rock-filled gabion baskets. However, it is a slow and fairly costly option to implement. If, after a gabion wall is constructed, surface water runoff cannot be successfully managed, it will continue to flow into the gabion-filled void; and, ultimately it will erode the void's sidewalls, leading to total failure of the gabion wall.

Backfilling with rockfill is a good strategy that is widely used in civil and mining engineering for stabilisation of landslides and thus-created slope voids if suitably sized durable rock materials exist or can be quarried nearby. In the early-1980s during Ok Tedi Mine construction, 1–3 m diameter natural boulders were drilled and grouted eye-bolts installed for ease of handling and placement in some bridge abutments. However, in general, scarce durable boulder-size waste is generated during production mining at Ok Tedi. Most large rock blocks are ore but suitably sized boulders could have been purpose-quarried in limestone and intrusive rock types at some locations. While quarrying and stockpiling of non-ore boulders was suggested on countless occasions, mine management failed to be convinced that it was a worthwhile exercise and it never happened. Admittedly, boulders still needed to be of a manageable size to allow their transportation along generally LV cross slope access ramps. The recurring need for durable boulders frustrated the geotechnical team to the extent that they even started pouring their own concrete boulders, but costs were high and the scale of this endeavour much too small to achieve a long-term meaningful outcome. Concrete boulders were also prone to acid mine water corrosion and hence only had a somewhat limited life.

Due to the lack of suitable boulder rockfill, bases of V-notch chasms were backfilled with whatever durable materials could be sourced onsite to arrest the downwards progress of chasms towards the pit's haul road. Materials included surplus concrete sleepers cast for the Ok Tedi drainage tunnel (see Figure 9f), old steel and PVC pipes, segments of steel girders and arches left over from early mine construction days, and old haul truck tyres. Use of old shipping containers with cemented rockfill and chain/cable interconnection was also considered; this strategy was partly successful in arresting riverbank erosion, but transportation of shipping containers and mobile crane gear for their use at void locations needed some widening of the already built LV access ramps. As a result, the shipping container option was not adopted.

11 Ongoing maintenance

No preventative or remedial works last forever; they all have a finite life.

Adequate provision is needed for regular inspection of the completed works and for ongoing maintenance repairs of damaged areas as soon as problems are noted. In recent years, pit slope inspections are aided by drone flyovers, although a walkover is still often needed to gain a better appreciation of what needs doing.

There is little merit in having sufficient special/capital budget funds for installing the preventative/remedial measures but then not allocating adequate recurring funding for maintenance repairs. This is an ongoing task. HDPE liners become brittle and crack after periods of sunlight exposure. Shotcrete-lined drains are subject to acid mine water corrosion. Both HDPE-lined and shotcrete-sprayed drains may be punctured by rockfalls from the bench face above (Figure 10a). Shotcrete is cracked by ground displacements (Figure 10b). With such damage, much of the drains water flow occurs beneath the drain's lining; eroding and creating voids in the ground beneath the lined drain. Significant-size rockfalls block drains and this debris must be cleared to re-establish drain's intended function. Buried drainage pipes may likewise be blocked by rockfall debris washed into them; such blockage must be promptly cleared. Integrity of buried and above-ground pipe joins is also damaged by ground displacements.

(a) Rockfall punctured and acid water corroded, meshed and shotcrete-sprayed drain, Berlin, West Wall (May 2014)

(b) Ground displacement-induced cracking and acid mine water corrosion of shotcrete-sprayed drains; Berlin, West Wall (May 2010)

Figure 10 Ok Tedi, PNG: recurring damage to meshed and fibre-reinforced water drains on benches

12 Forward planning and the timely procurement of consumables

In all mines, sufficient consumables and other resources need to exist as and when they are needed. In remote mine locations, consumables need to be purchased and transported to site well ahead of the time they might be needed.

Lead-time in this forward planning depends on location (i.e. within Australia or overseas), the remoteness of the mining operation, its accessibility by various types of transport, and the need for paperwork, clearance and customs' inspections in foreign countries. Some less-bulky, less-heavy and urgently-needed consumable items may be quickly flown to sites, but this was very costly. However, in the Ok Tedi Mine situation, most items had a less costly (per kg) but significantly slower journey to site. Some items were sourced outside Australia (e.g. in Southeast Asia, USA, Europe) and initially shipped to Brisbane. These items went through Australian importation and customs' clearances, were reloaded onto ships bound for PNG and shipped to Dairu at the mouth of the Fly River in Western Province, PNG, then reloaded onto a river-navigating fleet of barges, sailed 650–700 km up the meandering river to Port Kiunga, cleared PNG importation/customs' inspections, off-loaded onto a fleet of trucks and transported 155 km along very rugged terrain with a ridge-hugging, winding, unsealed road to the mine's township of Tabubil, and then eventually driven to the mine site. The road trip was often frustrated by landslides along it. In case of especially heavy loads (e.g. a tunnel boring machine for the pit's drainage tunnel), the gear was disassembled at the start of the port-to-mine journey and reassembled at the proposed tunnel portal. The up-river transportation option for shipment of consumables mostly required a lead-time of 6 to 12 months, and sometimes longer.

If specialist external contractors or consultants were required to assist Ok Tedi Mine with installation of preventative and remedial ground control measures, obtaining PNG government approval to use non-PNG national staff and securing the required single- or multiple-entry visas involved time (e.g. 2–5 months).

13 Ground control monitoring

Progressive expansion of large chasms and associated debris discharge from them required an ongoing and considerable ground control monitoring effort (Bar et al. 2014). The following monitoring methods were used at the Ok Tedi Mine in PNG during 2003–2014:

- Computerised, radio-reporting, tipping bucket rain-gauge network that recorded the intensity and cumulative rainfall, with mining operations halting in proximity of chasms toes/within the perimeter of past debris runout fans when the threshold rainfall intensity (20 mm/hour) was exceeded.

- Daily to twice-daily drive and walkover geotechnical inspections.
- Basic, robust, manually-read ground displacement measuring tools – wire extensometers and line-of-sight star picket lines along chasm crests.
- Computerised, radio-reporting, survey prism network (although only useful in daytime and relatively clear weather). Critical alarm-activating displacements were experience-based at the mine.
- Computerised, radio-reporting, slope stability radar network using both real and synthetic aperture radar systems – useful 24/7 in all visibility and weather conditions, but sometimes not operating due to maintenance and repairs (Bar et al. 2016).
- Regular four- to six-weekly helicopter flyover inspection of pit slopes, with a focus on known at-risk areas and detailed photography of all slopes.

At present, drones instead of helicopters tend to be used for Ok Tedi pit slope inspections. Drones are much less costly than helicopters to operate, can be used more frequently and are an excellent slope inspection tool.

Notwithstanding what monitoring gear is deployed, the success of monitoring is often related to the experience of the geotechnical person looking at the raw data as it is received. In various Ok Tedi pit areas, alarms were activated and mining halted when displacements exceeded 50–150 mm per day but adopted thresholds are site-specific; each instability has its own threshold. Data that is collected but not promptly interpreted for its geotechnical implications is wasted effort.

14 Personnel efforts and equipment availability

Most mines operate with lean resources of personnel, equipment and consumables.

Hence, if project-specific contractors with their own equipment are not engaged, preventative and remedial works are done by the mine’s existing workforce. This additional workload is usually undertaken in parallel with the team members’ other duties; hence progress is slower and disrupts nearby mining activity for longer periods than if external contractors were used.

Timely availability of equipment (e.g. small trucks, bulldozers, backhoe excavators and shotcrete spraying gear, and the delivery of consumable to slope worksites, etc) is often a competitive exercise, especially if adverse weather (rain, fog) is normal and other mine projects (e.g. road maintenance) require the same pieces of equipment during the brief windows of more favourable weather.

15 Conclusion

If water flow along slope benches is likely to be significant, an effective water management plan is needed, especially if the rock mass is prone to water erosion.

Adversely-orientated defects coupled with some blasting practices damage bench faces and reduce berm widths.

A quantifiable risk exists of slip-circle and defects-defined wedge failures; this risk often varies with bench face angle, berm width, rock type and slope-facing direction. Other risks often need to be estimated/judged and are less easy to quantify, and these latter risks may vary with time as mine plans change.

If potentially adverse ground conditions are recognised at the time of bench mining there is an opportunity to preventatively reinforce the ground or to excavate out the at-risk wedges and to reinstate the thus-created void with durable rockfill, or to reinforce the dislodged block’s void surface with mesh and shotcrete to prevent its future expansion. If justified, early preventative action will avoid a more difficult remedial task at some later date. Many water erosion voids tend to initiate along major faults or other zones of weak, shattered or soft ground. These at-risk areas may often be easily identified by experienced geotechnical personnel and may be preventatively meshed and shotcrete-sprayed, with sufficient numbers of shallow weep holes and suitably deeper horizontal groundwater flow bores installed to avoid the risk of pressure build-up behind the sprayed faces. Without such water pressure relief, shotcrete facing will likely crack-up and progressively flake off.

The impact of uncontrolled water runoff erosion on rock slopes is illustrated by examples from several mines. Existing short-term climate patterns (e.g. El Nino and La Nina, with 1–2+ years duration) or the predicted longer-term changes resulting in higher rainfall may exacerbate water issues in some regions.

Erosion may also be a problem in lower-rainfall environments and occurs for reasons such as the intentional water discharge down slopes into pits deemed to be abandoned, lack of slope maintenance opportunity in extended periods of mine shutdown, the inadequate initial design of water flow drains, and/or the insufficient number and durability of discharge points along benches.

A range of preventative and remedial options are described and shown. In the co-authors' collective experience, preventative measures such as draping bench faces in weak ground in geotextile fabric, covering berms in similar ground with HDPE liner, making drains well engineered and their surfaces protected to prevent leakage and ensure long-term function, installing a sufficient number of horizontal dewatering flow bores with the depth necessary to achieve appropriate drawdown for final slope stability, and limiting water erosion from the outset, can reduce the need for subsequent remedial work. Remedial measures are often hindered by the lack of access to slope problem areas. An LV down slope access ramp may need to be constructed. With access restored, various flaws may be remediated. These include the repair of water drains, backfilling of small voids, reinforcement of the crests and toes of big chasms, redirection of water flow around chasm footprints, repair and expansion of stability monitoring network (e.g. survey prisms) and drilling of extra horizontal groundwater flow bores if required.

Preventative and remedial measures do not last forever: regular inspection and timely maintenance repairs are necessary to retain their intended function. Delayed maintenance may result in unrepairable situations.

With major chasms on pit slopes, real-time automated monitoring of rainfall and the survey/radar of at-risk slopes are essential, with alarms triggered and mining halted before site-specific threshold rainfall intensities, ground displacements and/or chasm debris discharge reach experience-based exceedance.

Management's full support and timely allocation of adequate resources to do the work are essential. Convincing management to install preventative measures in the first place and then to successfully obtain ongoing maintenance funds and resources are sometimes diplomatic challenges if there are no 'obvious' problems on the slope face. Short-term logic that 'if it's not broken, then don't try to fix it' is common, but this stance usually softens with the increasing length of manager's time on water erosion prone mine sites.

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Many geotechnical mine projects are team efforts. The co-authors thank the numerous site personnel, consultants and contractors who contributed to ensuring that rainfall and groundwater runoff is successfully managed along slope benches. Example photos are only intended to show the worldwide types of bench issues, difficulties and challenges, and are not in any way meant to belittle the dedicated efforts by management to achieve successful outcomes at the respective mines.

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