Monitoring and risk-control of large-scale toppling failures – a case study from Ok Tedi

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Abstract. This paper presents the monitoring and management of a large-scale toppling failure that was first observed in 2005 at the Ok Tedi mine. Ok Tedi is a large open-cut copper gold mine in the Western Province of Papua New Guinea and is one of the wettest mines in the world (>10 m annual rainfall). The management of large-scale failures in open-pit mines expresses geotechnical challenges in terms of balancing economical designs and safe operations. The failure located at the southern end of the West Wall was reactivated in June 2019 due to continuous mining and prolonged rainfall events. Erosion, cracking, and rock toppling associated with lateral displacements, evolved rapidly. Hence, ground control and groundwater management plans, including a Trigger Action Response Plan (TARP) and measurements to monitor movement across the wall, were implemented. This monitoring system, associated with daily visual inspections, enhanced the understanding of the necessary controls to maintain a safe mining operation. Furthermore, the water management plan was crucial in managing this failure. The successful risk-control of this large-scale toppling failure at Ok Tedi ensured continuous mining with a functional balance between economic and safety during operations.

1 Introduction

This paper presents the reactivation and successful management of a large-scale toppling failure in 2019 at the Ok Tedi mine in Papua New Guinea (PNG). Ok Tedi is a large open-cut copper and gold porphyry mine in the Western Province of PNG and, due to its reserves, it is considered as one of the largest copper-rich and gold porphyry deposits in the world [1], [2]. The mine is currently operated by Ok Tedi Mining Limited (OTML) [3]. Furthermore, the mine is subject to severe weather conditions with more than 10 m of annual rainfall and hence considered as one of the wettest mines in the world [4], [5].

The pit is about 2,000 m by 1,500 m in plan and approximately 900 m deep. The toppling failure zone presented in this paper is located towards the southern end of the West Wall in an area called Belfast; the West Wall is approximately 2,000 m long, 1,000 m wide and 500 m deep. In the past 4 years, the West Wall experienced numerous instabilities including two large-scale pit wall failures (referred to as ‘chasms’) and additionally several complex failures of varying scales across the entire extent of the West Wall. These instability zones present significant challenges in terms of mine safety and, from an economical perspective, in reaching the life-of-mine design.

2 Belfast

The Belfast area is largely mined within Darai Limestone (top), Ieru Siltstone (centre) and Monzodiorite (base), figure 1. The limestone and siltstone are separated by the weak Taranaki Thrust Zone (TTZ). In this area and through much of the West Wall, the Ieru Siltstone has undergone significant alteration and
rock mass weakening; the majority of Belfast Ieru Siltstone included in the “West Wall Weak Zone” (WWWZ), where the historic (2005-2008) and more recent (2019) toppling failures occurred.

The hydrogeology at Belfast is variable due to different permeabilities through major structures and lithological units with diversified water tables. The water table in the TTZ within the Darai Limestone is close to being hydrostatic due to perched groundwater above the low permeability TTZ, whereas the water table in the Ieru Siltstone below the TTZ is slightly less than hydrostatic. Those conditions and active mining operations triggered the previous toppling failure. Consequently, a management plan was built to successfully contain and control the failure.

The key to this effective management plan was a combination of different factors:

- TARP (Trigger Action Response Plan),
- Depressurisation holes to reduce the pore pressure,
- Radar to monitor any movement,
- Monitoring system, such as prisms and inclinometers,
- Surface water management including berms, benches, toe drains and drainage channels,
- Daily visual and drone inspections,
- Geological mapping and photogrammetry to build a structural model of the area.

![Figure 1. Rock mass model at Belfast. WWWZ and TTZ through the centre between Limestone and Siltstone. Dashed lines represent the major geological structures. Yellow lines indicate direction of historic toppling and red lines show direction of movement in 2019. Arrows indicate the direction of movement.](image)

3 Overview of pit slope failures
Sullivan [6] identified that pit slope failures typically have four stages of movement:

1. Viscoplastic response,
2. Creep,
3. Cracking and dislocation, followed by
4. Collapse or failure.

Therefore, it is crucial to monitor each slope as it is mined, to identify any early signs of potential instability. This allows mining operations to strategize and carry out any mitigating measures to stabilise the slope, even at stage 3 of the slope failure. Mitigation measures may range from depressurisation holes for pore pressure reduction to surface water management, or modifications to the slope, such as...
unloading, toe buttressing or redesign. If these mitigation measures are initiated at an early stage, later stages of pit slope failure might be avoided. Most open pit slope monitoring systems focus on stage 3 and 4, as these stages are considered as the safety and economic risks to the mining operation [4]. The first two stages of a pit slope failure are slow-moving processes and can continue contemporaneous to mining without impacting the safety [4], whereas stage 3 is a clear indicator of a developing slope failure and potential risk to safety [7]. Tension cracks may develop due to sliding movements along discontinuities in the rock mass or due to the redistribution of stresses caused by the removal of support in the rock mass forming the slope. Furthermore, the presence of tension cracks enhances the permeability of rock masses and supports the introduction of surface water run-off into the slope [7], which may contribute to the slope instability.

Successful management of failure zones requires the understanding of the mechanisms to adequately assess the behaviour and potential deformation of the area. For the case study site, geotechnical monitoring instruments, such as prisms, radar, inclinometers, and vibrating wire piezometers (VWPs), were immediately employed to monitor the deformation. The understanding of the geotechnical model and deformation mechanism allowed for the implementation of a TARP.

3.1 Toppling Failure: Historic Toppling Instability

A toppling failure describes a mechanical mode of structurally controlled instabilities where, sets of steeply, into the face dipping discontinuities, form blocks. Toppling occurs if sliding movements along these steeply inclined sets cause an offset in the centre of gravity of the block outside of their base, and thus develop a critical overturning movement [7]. In open pit mining, mining at the toe of the slope, and thus increasing depth, may enhance the development of toppling failures [8]. Figure 2 illustrates the different stages of toppling failures in open pit mining due to continuous mining at the toe of the slope.

Figure 2. Different stages of toppling failure for slopes ([8] after [9]).

The historic toppling failure at Belfast was first observed in 2005 and described by Baczynski et al. [4] (please refer to Blaczynski et al. [4] for more details on the structural control and analysis of the failure). The toppling failure was initially confined to a single bench in the weak Ieru Siltstone below the TTZ. In this area, the defects within the Ieru Siltstone and Darai Limestone dip pre-dominantly 45-85° into the slope (NNW) and thus control the development of a toppling failure. Due to mining activities at the toe of the slope, the failure zone initially progressed downwards into the Monzodiorite, then subsequently developed into the Darai Limestone. In response to the enhanced movement, the upper
benches of the slope were mined down to unload the instability [4]. This practice has also been successful in managing a large-scale ‘chasm’ failure along the West Wall [2].

In June 2019, the toppling failure was reactivated due to mining at the toe of the slope, prolonged rainfall events and poor surface drainage control. Tension cracks developed across the slope and benches, accompanied by enhanced erosion and rilling along those cracks and surrounding rock mass.

4 Management of monitoring system

4.1 Overview
In June 2019, at the early stage the reactivation of the toppling failure (figure 3, figure 4), a TARP was created to monitor the instability zone and ensure safe mining at the toe of the slope. The TARP considered the geological and geotechnical characteristics of the slope and subsequent response of the rock mass to mining, as well as current weather conditions, and included displacement and rainfall triggers for the radar, prisms, extensometers, and weather monitoring stations. While automated trigger levels were selected and continuously revised to adapt to changing conditions, a critical aspect of the management plan included the manual activation of alert levels by the geotechnical monitoring team, if adverse conditions developed in areas, which were not picked up by the monitoring system (e.g., rock fall events).

Figure 3. Deformation along Belfast: (a) location of the deformation and failed slip and (b) closer view of the tension cracks location observed on the 27th of June 2019.

Figure 4. Tension cracks dilation at Belfast. (a) large crack running sub-parallel to the drainage channel with vertical displacement and (b) dilated cracks over road
4.2 Groundwater management

At Belfast, the reactivation of the failure was triggered by rainfall events, which led to an increase in groundwater level and pore pressure. If the slope begins to dilate, the process is likely to occur along tension cracks, since these cracks provide a direct path for surface water to infiltrate into the rock mass. Depending on the frequency of tension cracks, the permeability of the rock mass may be enhanced and therefore the infiltration rate of surface water significantly increased. Intensive and continuous rainfall events have shown to lead to higher infiltration rates, as occurred at the beginning of the toppling reactivation, at the end of June, and on the 23rd of July and on the 7th of October 2019 (figure 5a). Once surface cracking begins, the pore pressure response and slope dilation increases with each consecutive high rainfall event, unless changes to surface water management, depressurisation measures, or slope modifications are carried out.

Two management plans have been actively carried out as soon as the instability at Belfast began. First, a series of depressurisation holes were drilled along the toe of Belfast to reduce the pore pressure within the rock mass (figure 5b). This depressurisation campaign successfully reduced the pore pressure...
as the data from the VWPs showed in figure 5a. Second, a surface water management plan was implemented, including the maintenance of existing toe drains, to control and re-direct most of the surface water towards the south away from the instability zone (figure 6). Three VWPs were installed across Belfast. The head levels on these VWPs are sensitive to rainfall, with high rainfall events correlating to delayed, broad head level peaks since installation. The three periods of major displacements at Belfast are indicated by red circles in figure 5 (a). The data shows an increase in head level of 5m to 6m following high rainfall events between 23rd-26th June, on 23rd of July and on 7th of October. Even though water infiltrated the rock mass prior to the toppling movement, the re-activation and development of new tension cracks increased the infiltration rate.

**Figure 6.** (a) Redirection of surface water with construction of new drains and patching, and repairment of existing drainage channels, (b) example of new drainage channel.

4.3 Radar monitoring
Radar monitoring is one of the most effective monitoring tools deployed during stage 3 and 4 of pit slope failures. Movement is monitored in real time, and displacement/velocity alarms can be set up to trigger warning signals as movement rates increase. The exact area of slope movement occurred can be highlighted by the radar (e.g., figure 7) and enables the operation to respond accordingly by evacuating any machinery or personnel [2].

4.4 Prisms monitoring
Although slopes radar monitoring in the cracking and dislocation stage is the most efficient short-term (minutes to months) displacement monitoring, prism monitoring also offers critical long-term (months to years) information to assist in understanding the actions of pit slope movement. Figure 8 shows the prism displacement in the toppling zone from January 2018 to November 2019. Until April 2019, before the re-activation of the instability zone, the prism data showed linear movement at a constant pace.
Figure 7. (a) IBIS radar showing the exact location of the instability. (b) and (c) displacement velocity charts showing instability events (23/07/2019 and 6-7/10/2019).

Figure 8. Prisms chart displacement from January 2018 to October 2019.

4.5 Inclinometer monitoring
An inclinometer, installed in 2018 in a borehole located in the middle of the instability, was used to quantify the subsurface horizontal deformation and the depth of the failure, figure 9. A reverse shear at
~36 m depth, where a displacement of ~350 mm was recorded between April and early July 2019, suggested a toppling mechanism.

![Figure 9. (a) Location of inclinometer GDH1109 with axis directions. (b) Cumulative displacement on axis A: red dashed line indicates the depth of the reverse shearing.](image)

4.6 Visual Monitoring
Visual monitoring was accomplished by walk-over or drone inspections and completed multiple times per week and/or following high rainfall events. Drone photos are particularly helpful in areas where personnel are excluded for safety and impracticability reasons. Drone monitoring was also employed for photo-interpretative mapping and for the creation of a photogrammetric three-dimensional model.

The photo-interpretative mapping and the photogrammetry model were used for structural mapping of areas which were not covered by vegetation and compared with observations of geological structures and monitoring observations. This allowed for a larger view of the instability area at a mine scale and was successful in maintaining a constant high level of monitoring and management.

5 Conclusion
The management of the pit slope instability at Belfast was successfully achieved by a combination of comprehensive monitoring systems, including the use of radars, prisms, inclinometers, VWPs, and daily inspections, as well as the successful implementation of a surface water management plan comprising the drilling of depressurisation holes, and the installation and maintenance of drainage channels.

Recent slope monitoring data showed that this re-activated toppling failure was positively mitigated. This was achieved due to a comprehensive understanding of the geological and structural conditions of the mine, a good understanding of this failure mechanism and the behaviour of this type of failure generally, and a timely and appropriate response from the mine to initiate the proper controls. The successful management ensured continuous mining at a functional balance between economic value and safety during operations. However, the area continuously requires close monitoring and consistent assessment to identify any signs of instabilities so that further mitigation can be employed.

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