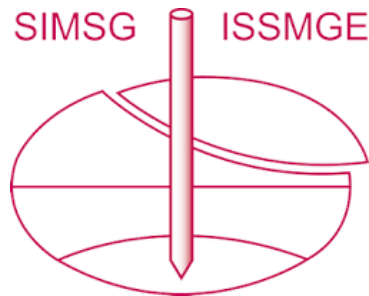


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Management of high wall failure at Dubbo Quarry, NSW

Gestion de la rupture du front de taille à la carrière de Dubbo, NSW

Jason Hellmuth

GHD Pty Ltd, Australia, jason.hellmuth@ghd.com

ABSTRACT: Management of the risk of slope instability involves not only estimation of consequences, but importantly also quantifying the potential for a failure to occur. Likelihood estimation is recognised as challenging and accordingly may be based on conservative assumptions. Recently at Dubbo Quarry, the decision was made to manage a worst-case failure of the high wall rather than quantify probability of its occurrence. The high wall of the quarry has been developed to a total height of 20 m. Tension cracks behind the crest were noted during mining of the lowest bench. These cracks appeared to be propagating over time, and a sliding plane was identified in the footwall. Due to uncertainty regarding appropriate slope stability parameters, an observational approach was taken. Controls including exclusion zones, catch berms and prism monitoring permitted mining of blasted ore below the potential failure within acceptable risk levels. During mining, an 80 m by 16 m section of the high wall slid approximately 4 m. The failed material was almost completely contained by the controls, with no injury to personnel nor damage to plant. This case history demonstrates that quantification of probability of occurrence is not always necessary to successfully manage a potential failure.

RÉSUMÉ : La gestion des risques d'instabilité des flancs implique non seulement l'estimation des conséquences, mais surtout la quantification du potentiel de défaillance. L'estimation de la probabilité est reconnue comme difficile et doit donc être basée sur des hypothèses prudentes. Récemment, à la carrière de Dubbo, la décision a été prise de gérer le pire des cas de défaillance du front plutôt que de quantifier la probabilité de son apparition. Le front de la carrière a été aménagé sur une hauteur totale de 20 m. Des fissures de tension derrière la crête ont été notées lors de l'exploitation de la banquette la plus basse. Ces fissures semblaient se propager au fur et à mesure et un plan de glissement fut identifié à la base du mur. En raison de l'incertitude concernant les paramètres appropriés à la stabilité des flancs, une approche d'observation a été adoptée. Les contrôles, y compris les zones d'exclusion, les bermes de capture et la surveillance avec prismes, ont permis l'extraction du minerai dynamité en dessous de la défaillance potentielle, à des niveaux de risque acceptables. Pendant l'exploitation, une section de 80 m sur 16 m du front a glissé d'environ 4 m. La défaillance a été presque entièrement contenue par les commandes, sans incidents pour le personnel ni dommages à l'installation. Cette étude de cas démontre que la quantification de la probabilité d'occurrence n'est pas toujours nécessaire pour gérer avec succès une défaillance potentielle.

KEYWORDS: slope instability, quarrying, observational method

1 INTRODUCTION

Typically, management of slope instability involves: identification of the failure scenario; development of an understanding of the failure mechanism and triggers; the consequences in the event of failure and, importantly, quantification of the potential for a failure to occur (Wylie and Mah, 2004).

The assessment of likelihood of realisation of the failure can be achieved by various methodologies; from estimating the likelihood of failure based on the practitioner's experience, review of historic failures and aerial photographs, characterising the frequency of failure based on field observations, to conducting slope stability analyses based on assumed or measured slope parameters to generate a factor of safety (AGS, 2007). The assumptions made regarding slope stability parameters often are conservative, as it is better to overestimate the likelihood of failure occurring. Unfortunately, this may then lead to an over-engineered stabilisation solution.

On the other hand, it is possible to directly measure slope stability parameters by conducting a site investigation and/or retrieving samples of the soil and rock mass for further laboratory testing. Rightly or wrongly, either option leads to an increase in cost and time to determine the potential for a failure to occur. This paper provides an example of the adoption of an observational approach to managing an estimated worst-case failure of the high wall within a hard rock quarry located near Dubbo, NSW.

1.1 Geological setting

Dubbo Quarry is a basalt quarry to the south-west of Dubbo, in the Central Plains region approximately 300 km north-west of

Sydney, NSW. The quarry is located within a Tertiary alkali basalt (Tb), and adjacent to Jurassic Purlawaugh Formation lithic quartz sandstone (Ju), both overlain by Quaternary alluvial sediments (Qa) (Raymond, Warren and Hendersen, 2000). It is postulated that the basalt was deposited as lava flow into a previous river channel. This basalt appears to be composed of two stages: a vuggy and sometimes ropy, altered basalt; and a more competent, fine-grained basalt that is the main ore targeted by the quarrying activities. The altered basalt is directly adjacent to the lithic sandstone, and a chilled margin may be observed at the contact. The quarry is operated by Holcim Australia and provides crushed basalt product as road base and engineered fill. The general location of the site and the underlying geological setting is presented in Figure 1.

The eastern high wall of the quarry has been developed as two benches. The first bench was approximately 8 to 12 m in height and was blasted in mid-2018. Mining was completed in two production shots; first the northern half and then the southern half of the quarry. The second bench, approximately 8 m in height and 15 m wide, was then blasted in November 2018. The high wall design also included a 3 to 5 metre wide, mid-height catch berm at the level of the second bench. This second bench was blasted in a single production shot and mining began at the southern end of the quarry. This second bench was expected to be the final cut along this eastern high wall, as a consequence of reaching the limit of the target resource. A typical section through the eastern high wall is presented in Figure 2.

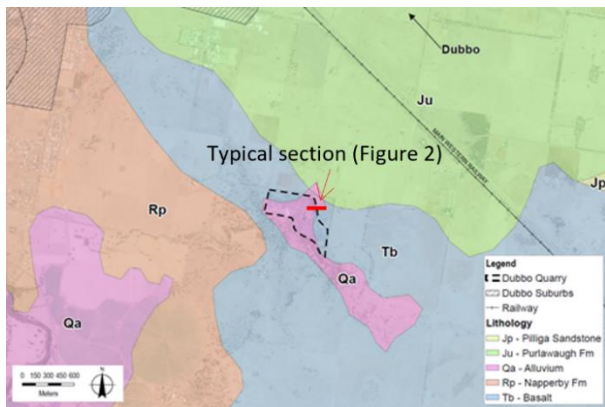


Figure 1. General location and geological setting of Dubbo Quarry, adapted from Raymond, Warren and Henderson (2000).

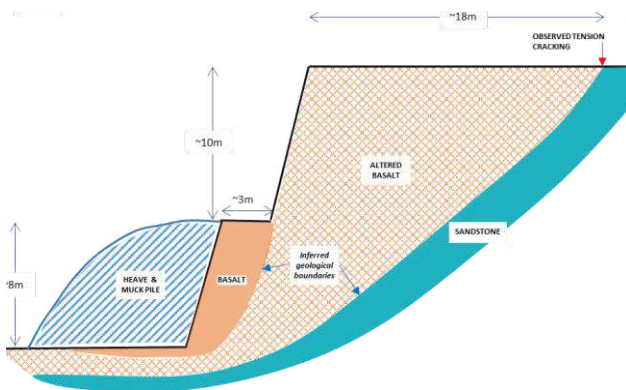


Figure 2. Typical section through the eastern high wall.

1.2 Development of the high wall failure

During mining of the second bench, in December 2018, cracks were noted by the pit supervisor as forming approximately 18 m behind the crest of the eastern high wall, within both soil and the bound asphalt pavement of the quarry access road (which was situated behind the high wall). These cracks were observed approximately a month after production blasting, though were not noted immediately following the blasting or during mining of the first bench, nor the blasting of the second bench. It was thus surmised by mining personnel that these cracks were probably due to a large-scale circular or planar failure of the upper part of the high wall, likely coincident with the contact with the Purlawaugh Formation sandstone.

In response, the quarry manager diverted traffic to a new access road, further back from the high wall, and set up a geodetic prism monitoring regime adjacent to the line of cracking. Locations of prisms are generally shown in Figure 3. Mining of the blasted material was also prohibited in vicinity of the area beneath the cracks. Geotechnical advice was then sought regarding slope instability assessment and ground conditions behind the high wall.

1.3 Engineering geological mapping

Engineering geological mapping was undertaken on site, and included identification of stratigraphic units (Table 1) and observations of potential failure mechanisms. The author observed that cracking appeared to be up to 20 mm wide and up to 600 mm deep. Cracks extended into nearby windrows. The cracks were generally observed to be between 5 and 18 metres behind the crest. When observed from the quarry floor, the eastern high wall appeared to be composed of the altered basalt with some lenses of competent basalt visible in the face. In the area where the cracks with the largest displacement were

observed at the crest, the high wall face directly beneath appeared to be composed entirely of altered basalt.

Table 1. Summary of stratigraphic units as observed on site.

Stratigraphic Unit	Description
Alkali basalt (Tb)	Fine grained alkali basalt with some tholeiite, basanite, nephelinite, limburgite, and trachyte as part of the undifferentiated Tertiary Cainozoic units.
Altered basalt (Tb)	This is an altered, friable basalt and represents the chilled margin between the lava flow and its contact with the lithic sandstone within existing channels.
Sandstone (Ju)	Fine to medium grained lithic quartz sandstone with ferruginised red siltstone, ironstone, minor coal ironstone. This Jurassic Purlawaugh Formation is part of the Surat Basin of the Great Australian Basin.

The altered basalt was orthogonally jointed, with some persistent defects being noted within the face, generally dipping at 30 to 40° to the west (i.e. dipping out of the face). Joint planes were observed to be generally clean, smooth to rough, planar and closed. Groundwater seepage was not observed on the face of the high wall. The standing groundwater level appeared to be roughly level with the floor of the quarry, based on observations of ponding water. A small dam is located to the east, which captured run-off from a small creek. At the time of the inspection, this dam was dry, as was the creek.

A shear plane or similar was noted within the face of the eastern high wall, apparently striking perpendicular to the trend of cracking. It may be that the creek is related to this structure, however it did not appear to be a contributing factor to the development of a failure plane within the high wall.

Rainfall did appear to have an influence on the development and propagation of the cracking at the crest, as well as the development of the failure. The Bureau of Meteorology recorded observations of monthly rainfall in December 2018 of 34.4 mm, and in January 2019 of 64.4 mm (BOM, 2019). These rainfall events appear to precede movement of the prisms, as shown on the graph below (Figure 4). Also of particular note were daily rainfall observations on January 21 of 39.4 mm and January 23 of 16.6 mm. Annual mean rainfall in Dubbo is recorded as 552.8 mm (BOM, 2019).

2 MANAGEMENT STRATEGIES

The failure mechanism was postulated to be the development of a sliding plane at the interface between the lithic sandstone (footwall), and the altered basalt (hanging wall). However, the failure surface did not appear to daylight within the face. In addition, the geometry and engineering characteristics of the failure were not known.

As the potential high wall failure was restricting access to blasted product, which was scheduled to be mined, a management strategy was required to allow access at the toe of the eastern high wall. Based on the uncertainty regarding geotechnical parameters for slope stability analysis, in concert with the Quarry Manager an observational approach was developed, which introduced controls to mitigate the 'worst-case' failure of the eastern high wall, and how it might affect the elements at risk, which included the access road above, which was excluded to pedestrians and vehicles by means of earth bunds and signage, and plant and personnel below, who would be involved in day-to-day operational quarrying activities.

In this instance, the worst-case failure adopted was a rotational failure approximately 18 m wide (i.e. distance from the crest of the rear-most cracks) and 10 m high. The height was based on the approximate height of the upper bench in this area, as the lower bench, which featured a 3 to 5 m wide catch berm, was still to be mined and therefore had blasted material sitting at the toe. The catch berm and blasted material were expected to act as a ‘weighted berm’ supporting the toe of a deeper rotational failure. It was also expected that the failed material would start to support the toe of the sliding plane as it piled up, and therefore the full volume of the worst-case failure would not fall onto the quarry floor.

As discussed in Section 3, a prism monitoring regime was established at the first signs of cracking. Nine prisms and three backsights were set up in total. The general location of the prism monitoring setup is shown in Figure 3. The prisms were surveyed regularly, with the current Easting, Northing and height above datum (in metres) recorded. The data gathered were then plotted against time for each prism. This resulted in a series of graphs which displayed absolute movement over time and could provide an indication of acceleration in any particular direction.

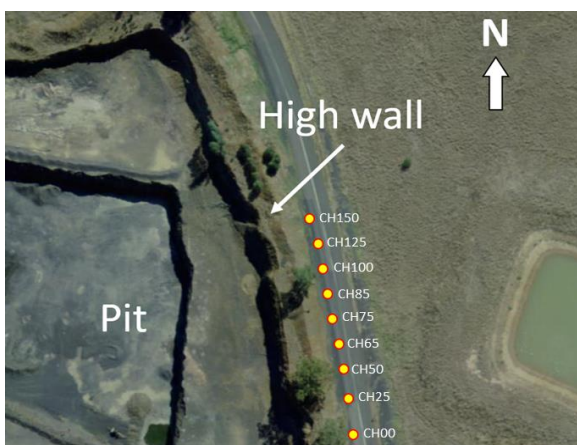


Figure 3. General arrangement of prisms on the eastern high wall.

Acceleration of movement is often an indication of incipient failure, with the classic example being Chuquicamata mine as described in Wylie and Mah (2004). This formed part of the observational approach adopted for the management of the failure (Watton and Fowler, 2019). Prism survey intervals increased in frequency from fortnightly to twice weekly during the monitoring programme, and surveying was undertaken at the same time each day, early in the morning, to reduce the influence of ambient temperature on the recorded position. Following this, a Trigger and Response Plan (TARP) was developed by the quarry operator.

Five of the nine prisms displayed a significant displacement to the west, which accelerated over time. A smaller magnitude of movement was also noted downwards for these prisms. The recorded total movements from some select prisms are presented in Figure 4, where acceleration towards the west (in blue) can be clearly seen.

As noted above, on January 21 and 23 the recorded daily rainfall was 39.4 mm and 16.6 mm, respectively (or 56 mm over approximately 72 hours). This correlates to apparent acceleration of prism movement. In response to the acceleration to the west seen around 24 January, more frequent prism monitoring was undertaken, becoming daily for a short period of time. The consequences of the acceleration (i.e. likelihood of failure) were discussed as part of morning pre-shift safety talks.

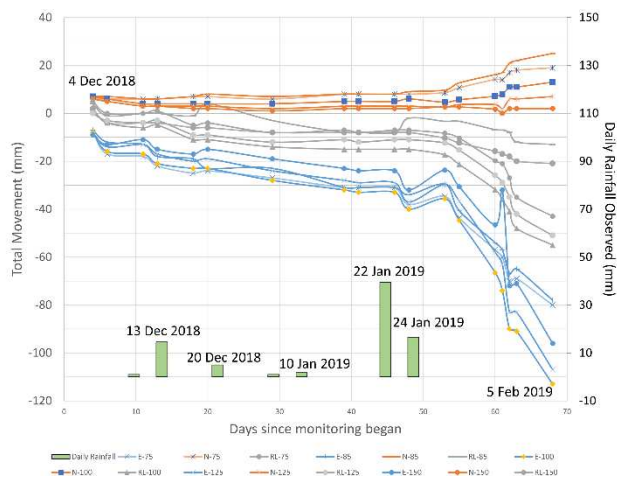


Figure 4. Recorded total movements for the five prisms which experienced the greatest magnitude of movement. Orange lines represent movement relative to Northing, blue lines relative to Easting, and grey lines relative to RL. Daily rainfall (mm) is displayed in green on the secondary axis.

Part of the management of the worst-case failure was the implementation of a 20 m wide exclusion zone extending into the quarry, in the area of prism monitoring. This was instituted to prevent personnel from being present at the crest of the slope in the event of failure. An exclusion zone was also to be set-up at the toe of the eastern high wall for 12 hours following blasting within the quarry, or for 24 hours after a rain event of 10 mm or four hours duration, based on observations of the apparent influence of rainfall.

Note that during rainfall, activities in the pit generally ceased as the rain affected the manoeuvrability of the haul tracks. In either event, a visual assessment of the high wall was also to be undertaken before lifting the exclusion zone at the toe. As noted above, a total exclusion zone was created on the access road behind the crest.

The mining sequence and final high wall geometry were also modified to manage the predicted consequence of a worst-case failure under the TARP. Specifically, a 3 m width of blasted material was selected to be left against the 3 to 5 m wide catch berm to allow for extra stand-off from the upper bench. The remaining blasted material outside of this selected zone was then used to create a bench for the excavator to sit upon.

Following this creation of a bench, the excavator mined the remaining blasted material by reaching towards the high wall and excavating the material from outside the stand-off area, thus creating a catch trench between the high wall and the excavator (Figure 5). Mining otherwise progressed as normal, though the mining direction was always from the catch trench back towards the open edge of the blasted material. This mining campaign was expected to take approximately three weeks.

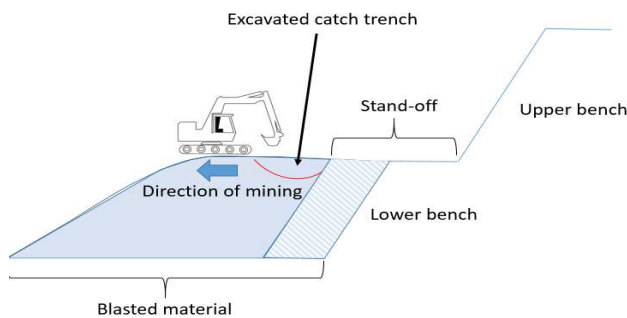


Figure 5. Cartoon of mining sequence of blasted material at toe of failure.

3 DISCUSSION

3.1 Outcomes

In February 2019 the eastern high wall failure slid down approximately four metres and outwards by approximately 3 metres (Figure 6). The area of failure was roughly 80 m in length, and up to 20 m in width, located between prisms #75 and 175. The prisms within this area (#85, 100, 125 and 150) had recorded the greatest movement to the west during the period of monitoring and had also shown an acceleration in westerly movement in the 10 days beforehand. The failure occurred almost immediately after a rain event of 12.2 mm on 8 February, and soon after the above-mentioned rain events in January.

The failure spanned the full width of the former quarry access road (which had been closed to vehicles after the first signs of failure). The back scarp of the failure did not reveal the lithic sandstone of the footwall, but observations of the failed material supported the theory that it was due to rotational failure through the altered basalt, initiated at the sandstone-altered basalt contact (Figure 2). At this stage, nearly two-thirds of the accessible blasted material had been recovered.

The failed material was almost entirely captured by the extra stand-off and catch trench, with the exception of the southern end of the failure where a small amount of material associated with a slight overhang in the face fell onto the quarry floor. There was no interaction between fallen material and personnel or plant.

This represents a successful outcome in which the majority of blasted material was extracted for processing and sale, without placing personnel or plant in harm's way. It is possible that, if probabilistic analysis had been undertaken, the volume of material retrieved safely before the failure would be far less unless similar controls would be undertaken. In addition, it is likely that attempts to stabilise the worst case failure through slope treatment (such as ground anchors) would have put personnel at risk and may not have been cost-effective. Plans are currently underway to access the failure from above and continue extraction, again by adopting an observational approach.



Figure 6. The eastern high wall following occurrence of the failure. The deep shadow to the right of the picture is the high wall into the pit, and the deep shadow to the left is the back scarp of the failure. The grey material in the middle of the photograph is the asphalt of the now inaccessible access road.

3.2 Applicability to civil geotechnical engineering

This case study demonstrates an occasion where successful management of a potential high wall failure was achieved without quantifying the likelihood or factor of safety against failure. In addition, by not requiring a site investigation, there was no need for a drill rig to access the hanging wall side of the tension cracks.

Although this management strategy was undertaken in a mining/quarrying context (where it has been successfully employed in the past, such as Macqueen, Salas and Hutchison,

2013 and Watton and Fowler, 2019), and it is recognised that mining operations are typically much more 'dynamic' than is feasible in civil projects, it is also feasible to apply a similar approach in civil geotechnical engineering. An example could be where an embankment in the rail corridor has shown signs of potential failure. As geotechnical investigations in the rail corridor can be expensive and carry risk, best value might be achieved by designing a stabilisation treatment to support the worst-case failure.

This approach does have its limitations, and the economic benefits of designing for the worst-case consequence versus conducting slope stability analyses and/or site investigations should be considered – generally for where an initial semi-quantitative risk estimation would indicate an unacceptable risk, and where the ability to collect numerical data to inform a risk analysis or slope stability analysis would be marginal. However, such an approach could provide real value to the client, both in terms of potential reduction in cost, and also in potential reduction in harm to personnel or plant to perform site investigations.

The benefits of using prism monitoring to observe and anticipate failure also has benefits to the civil geotechnical space, such as where residential or commercial properties have been developed within decommissioned quarries, as has occurred within metropolitan Sydney. This type of point monitoring, alone or combined with other methods such as laser scanning, radar or photogrammetry, is a powerful tool for risk management in an environment where access or budget constraints do not allow for site investigations and extensive slope stabilisation treatment (Macqueen, Salas and Hutchison, 2013).

4 CONCLUSIONS

A high wall failure was identified within an active hard rock quarry. The decision as made to plan for a "worst case" scenario and manage risk accordingly using observational methods and engineered controls. The occurrence of the failure was controlled well with no harm to personnel or damage to plant and allowed quarry operations to continue. The management approach and monitoring methodology could have applications in civil geotechnical situations, as well.

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