Geotechnical considerations following a major haul road collapse Paddington Goldmine, Western Australia

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ABSTRACT: The collapse of the west wall and loss of the haul road in the Pad1 open pit at the Paddington Goldmine on 8 May 1990 had far reaching implications. Geotechnical considerations were of key importance in restarting production, designing and carrying out remedial measures and design for future west wall slopes within Pad1 and elsewhere at Paddington. Unbenched slopes have been designed as part of remedial works and mining of the nearby Pad2 deposit. As a result of the failure, research to assess the effect of artificial support is currently underway, and greater quality control of support installation has been identified as a requirement. Slope monitoring utilising a variety of techniques continues to be an integral part of mining at the site.

1.0 INTRODUCTION

Up until May 1990, the Paddington Number 1 Pit (Pad1) was the main source of ore at the Paddington Goldmine near Kalgoorlie in Western Australia. Access to Pad1 was cut on 8 May, 1990 by a major collapse of the western wall of the pit, that removed a section of the haul road.

The consequences of the collapse were far reaching and the following points were of key importance:

1. How to restart production in the short term ?
2. How to continue mining in the Pad1 pit to the final design depth of 180m ?
3. What were the implications for continued mining of the Paddington ore bodies ?

The answers to these questions required that the causes of, and the mechanisms involved in the failure were understood. This paper is based on the results of a number of studies carried out by various personnel and organisations following the collapse and provides a brief discussion of the responses required to such a major event.

2.0 BACKGROUND INFORMATION

2.1 Geology/Geotechnical Conditions - Pad1

Pad1 lies within the Bardoc Tectonic zone, within the tight NNW-SSE trending Bardoc-Broad Arrow synform which is composed of steeply dipping Archaean rocks, including the Black Flag Sediments (BFS), the Paddington Volcanic sequence and the Mount Corlac ultramafics.

The geology of Pad1, and an outline of the pit, is presented on Figure 1. The ore in Pad1 is hosted in the Paddington Volcanics, while the BFS occur in the west wall and the Mount Corlac Ultramafics occur in the east wall of the Pad1 pit. A brief summary of the geotechnical parameters for each of these units is presented in Table 1.

The area has a complex structural geological history, with at least two major phases of deformation proposed and with second order structures including shears and faulting, resulting in a complex structural geology. There is a strong N-S shear fabric in the BFS and Mount Corlac ultramafics which has developed approximately parallel to the trend of the synform and major shears, and dips steeply to the west, typically around 70^{o}. The Paddington Volcanic sequence is less sheared.

A number of other defect sets have also been defined in Pad1 including a N-S striking set with a shallow dip (<20^{o}) to the east. Defects from this set are typically discontinuous.

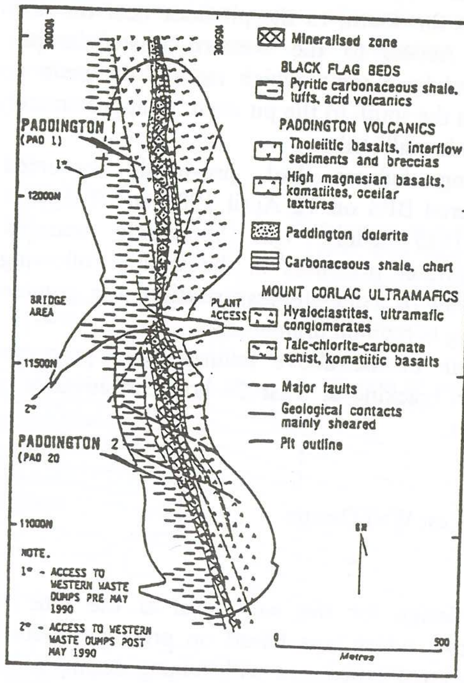

Figure 1: GENERALISED GEOLOGY OF THE PADDINGTON MINE AREA

Table 1: Summary of geotechnical properties Pad1 units

Unit	Lithology	Weathering	Strength	Rock Quality
BFS	Graphitic Shales	HW to 960mRL MW 960mRL to 940mRL, F below 940mRL	HW= R1, MW= R1 HW= R1 to R2	Very poor to poor quality due to the pervasive foliation planes
Paddington Volcanics	Basalts and dolerites, minor intercalated shales	HW to 960mRL MW 960mRL to 920mRL, F below 920mRL	HW= R1, MW= R1 to R3 F= R3 to R5	HW very poor quality, MW to F fair to good quality
Mount Corlac Ultramafics	Talc carbonate chlorite schists	HW to 940mRL local increases in depth of weathering due to shearing F below 940mRL	HW= R1, F= R2 to R3, variations due to intensity of shearing	2 acute foliation sets result in break down of the rock mass to "football" sized and shaped blocks

Note: The reader is referred to Hoek and Bray (1981) for definition of the codes used in Table 1.

2.2 Mining History and Status at Time of Failure

Stage I mining commenced in the Pad1 pit in 1985. At the time of the failure, Stage II mining had commenced and the Pad1 pit had been excavated to a maximum depth of around 105m in the centre of the pit and 100m along the west wall. The design depth of the Stage II pit was 180m. The west wall was slightly concave in shape with the southern half striking around 000° (due north) and the northern half striking around 20°. The main haul road ran down the west wall, from the bridge area between Pad1 and Pad2 in the south, to the pit floor near the northern end. Access to the western waste dumps was provided by a ramp which ran off the main access ramp in the south to the pit crest, at approximately the change in wall strike.
Toppling failures had previously occurred in weathered BFS on 11 April 1989 and 7 April 1990. The 1989 failure was apparently initiated by groundwater pressures in the wall. Following the 1989 failure slope depressurisation was commenced utilising horizontal drainholes.

Both of the above failures were precursed by tension cracking at least 24 hours in advance of the failures.

2.3 West Wall Design

The design for the west wall at the time of the collapse, which was based on previous geotechnical studies and experience with mining during Stage I, is summarised in Table 2 and presented in plan on Figure 2 and cross section on Figure 3.

Table 2: West wall design parameters

RL	Bench Height (m)	Face Angle (°)
1000*-980	10	45
980-960	10	60
960-920	20	65
920-820	20	70

* denotes original ground surface.

All berms were designed to be 5m in width.

Ground support was used extensively across the west wall and comprised:

980mRL-960mRL	2 rows of 2 strand birdcaged cable bolts, 12m to 20m in length, installed -5° to -15° nominal capacity 500kN, pre-tensioned to 250kN W strapping used in places.
960mRL-940mRL	4 rows of cable bolts as above with W strapping
Below 940mRL	4 rows of cable bolts with W strapping as above Walls completely covered with mesh anchored by 2.1m split sets on a 1.5m vertical by 1.0m horizontal spacing.

Slope depressurisation/dewatering was achieved utilising horizontal drainholes up to and over 100m in length. Horizontal drainholes were drilled into the wall by exploration drilling rigs at an angle of approximately +5°. Groundwater monitoring utilising simple standpipe piezometers indicated that the horizontal drainholes were successfully draining the slopes (Figure 3.)

3.0 WALL COLLAPSE, 8 MAY 1990

3.1 Description of the Failure

A major wall collapse occurred on the west wall of the Padl pit at approximately 8.35am on 8 May 1990. The failure began in the relatively fresh rock, which was intensively supported between the haul road and the pit floor and including the haul road, over a strike length of around 150m. Despite regular bench inspections, no tension cracking prior to the event was observed. Failure appeared to be initiated in the south, possibly by a small wedge or sliding failure at around 920mRL which resulted in loss of confinement in that area and overloading of the adjacent support, causing a chain reaction of cable bolt failures and rapid propagation of the failure to the north.

Less than 5 minutes after this first event, the fresh BFS above the haul road also failed by toppling, and slumping occurred in the pre-existing failed mass. Tension cracks opened up across the waste dump haul road.

The extent of the failure and the phases of the failure are outlined on Figure 2.

The first phase of the failure, which was a block flexure toppling failure, as defined by Hoek and Bray (1981), occurred independently of the April 1993 failure described in Section 2.2. The second phase of the failure was an extension of the first phase and may also have had elements of either a slide toe or slide base toppling, as defined by Hoek and Bray (1981). The second phase was triggered by the first phase, but may also have been influenced by surcharge loading.

In total, approximately 60m in vertical height of intensively supported BFS had failed due to toppling, around 30m of failed material had slumped and tension cracks had developed behind the failed material, resulting in a single rill slope from the waste dump haul road to the pit floor, with a maximum height of 90m. It is postulated that the basal surface of the failure consisted of a stepped path along the shallow dipping defect set, described in Section 2.1, failure through rock material and along foliation planes, dipping between 30^{o} to 45^{o}. The inferred position of this basal plane is shown on Figure 3.

The failure occurred due to toppling along the pervasive foliation planes present in the BFS. Along the section of the wall that failed, the strike of the wall and the strike of the foliation planes were essentially parallel, with the foliation dipping into the wall at around 70^{o}. This combination of factors results in the ideal geometry for toppling to occur.

Other factors which were thought to contribute to the failure included:

- o subtle but significant, convex section of the wall between the 940mRL and the pit base in the centre of the failed area. This shape was caused by remedial action following the 1989 failure, which resulted in the toes of the successive benches below 940mRL being moved southward to accommodate the failure. This provided potential for foliation surfaces to daylight at either end of the convex section, hence reducing restraint against toppling.
- o It is possible that the failed mass, and even the waste dump which occurs near the north western end of the pit, provided an active surcharge to the pit slopes, which although insufficient in itself to cause major toppling failure may have caused a sufficient increase in stress levels in the lower slope to initiate minor failures.
- o Wall fretting and hence loss of confinement could potentially be caused by vibration during production blasting.

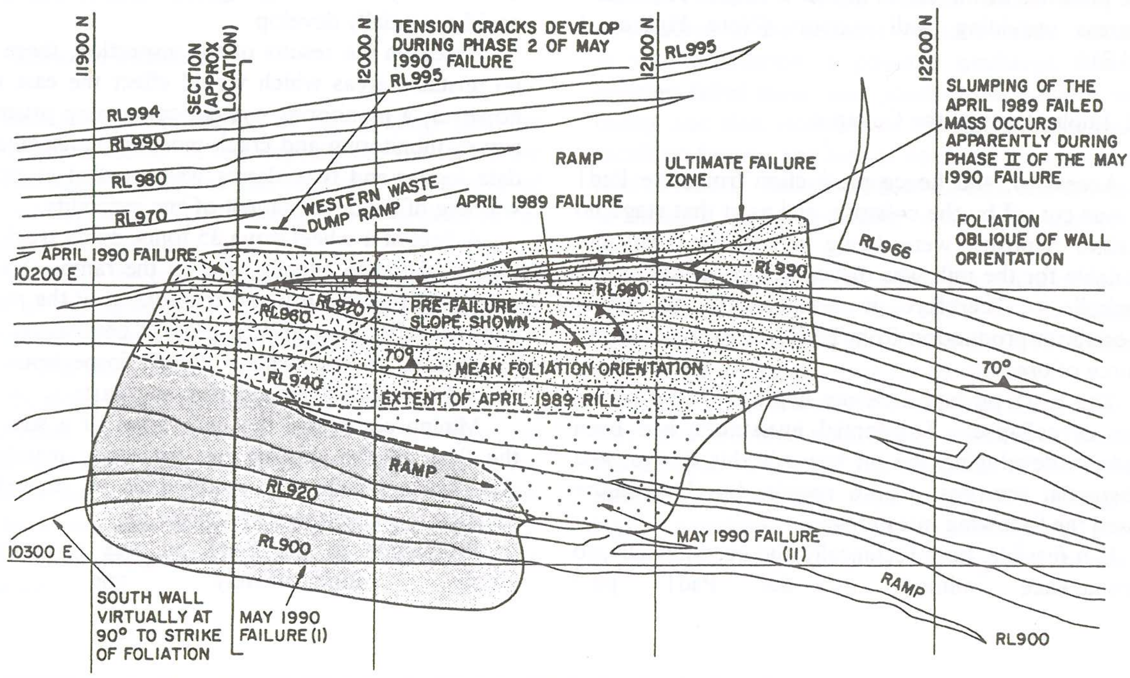

FIGURE 2. PLAN OF COLLAPSED WALL SHOWING EXTENT OF VARIOUS FAILURES

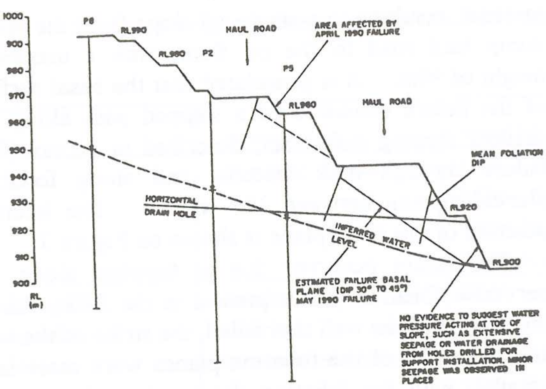

FIGURE 3. SECTION THROUGH COLLAPSED WALL PAD 1

o Tectonic stress concentrated by the presence of the open pit could be postulated to lead to wall fretting, causing general loss of confinement. An earthquake, or the build up to an earthquake could also potentially have a similar effect (an earthquake centred near Cadoux around 450km to the west of Kalgoorlie occurred at 6.40pm on the 8 May 1990).

Groundwater pressure was not considered to be related with the failure. (Note Figure 3).

The lack of precursors to the failure such as tension cracking or ravelling were attributed to any tension cracking on the haul road being obscured by continued trafficking during production, and the intensive support in place. The rapid nature of the failure was also attributed to the intensive support, which essentially resulted in an extremely brittle system which was overloaded by failure of a key block.

Failure did not continue to the south because the west wall merges with the south wall in that area. To the north of the failed area the strike of the wall swings 20° to the east, thus obliquely cross cutting foliation, resulting in lower potential for toppling. The presence of the basalt in that area also provides a buttress providing wall support (Note Figures 1 and 2).

3.2 Implications of the Collapse

Access to, and hence production from, the Pad1 pit was cut off by the collapse, and as at that stage no satellite deposits were being mined the only ore available for the mill was that which remained on the stockpile. Therefore it was critical to either re-establish production from Pad1, or to find another source of ore.

The Pad1 pit had a design depth of 180m at the time of collapse. Substantial investment had been made in developing the pit towards this design, and substantial reserves of ore remained. The failure raised the following questions:

1. Is it feasible, both technically and economically, to recommence mining in the Pad1 pit?
2. How could mining be restarted quickly to continue to supply feed to the mill?
3. What remedial measurers were required in the failed area and what changes were required to the wall design below the current pit base to ensure that further failures did not occur?

The inability of the reinforcement to prevent the failure raised the following questions:

1. Was the reinforcement being installed correctly?
2. What is the length of time that the reinforcement can realistically be expected to be effective given the corrosive nature of the conditions at the site?
3. Should the use of reinforcement be considered for future mining at the site?

The Paddington 2 deposit (Pad2) which is located immediately to the south of Pad1 (Figure 1), was being investigated for a possible pit to 190m depth. The whole of the west wall of the Pad2 pit would be in BFS. The Pad1 failure raised doubts as to whether it would be viable to mine the Pad2 deposit by open cut mining techniques.

The failure occurred rapidly, with no warning. Future mining would require a system to provide early warning of such failures.

4.0 RESTARTING PRODUCTION

Following the west wall failure access to the base of the Pad1 pit was restricted to a single lane ramp on the east wall, which consisted of highly sheared ultramafic materials. Although the ramp had previously been restricted to 4WD use it was decided to use it in its current condition to provide access to the pit to restart production.

Prior to recommencing production the east wall, and particularly the walls in the vicinity of the east ramp, were carefully inspected/mapped for evidence of instability and to highlight areas where instability could potentially develop.

Based on the results of the inspection, there were no unstable areas which would effect the east ramp, however, a monitoring system comprising prisms for survey monitoring and crack monitors connected to a data logger and two alarms was installed to provide warning of the development of any instability.

A fleet of 6 wheel drive 35 tonne dump trucks was mobilised to the site for use on the ramp. Spotters were placed at the top and the bottom of the ramp to control traffic flow and to provide continuous visual monitoring of the walls. Bench inspections were carried out twice daily and after any blasts.

Mining comprised the excavation of a sub pit in the floor of the existing pit, extracting mainly ore. Any waste which was required to be moved was dumped in the northern end of the pit.

Production in the Pad1 pit was re-established within approximately one week.

5.0 IMPLICATIONS FOR CONTINUED MINING OF PAD1

5.1 Failure Analyses

Following the failure, a detailed geotechnical/structural geological model of the west wall was prepared and a variety of stability analyses were carried out by various organisations in an attempt to realistically model the behaviour of the failed slope, and thus to provide a tool for analysis and design of remedial measures and design of the pit below 900mRL. It was recognised that each method utilised had inherent limitations when analysing a complex failure such as that which had occurred. The results of each method were considered individually, and in conjunction with the results of the other analyses, observations of the failure occurring and the final failed mass.

Methods utilised in the analyses included limit equilibrium analyses using the techniques described by Hoek and Bray (1981), FLAC (Fast Lagrangian Analysis of Continua) analysis, Block analysis using the kinematic data and the program TBLOCKS and UDEC (Universal Distinct Element Code) modelling. Limitations which applied to the various modelling techniques included accurately determining the rock material parameters required, inclusion of the effects of the various discontinuity sets present in the rock mass and realistic modelling of the support which had been installed.

The results of the analyses indicated that the slope appeared to be stable when the full capacity of the installed reinforcement is included. If a notch, indicative of a localised wedge or slide failure is included at the toe of the slope this would appear to be enough to initiate failure. Simple kinematic analyses and block analyses indicated that such small scale failures could occur.

5.2 Remedial Measures

Based on consideration of the geology and the geotechnical model of the deposit, the results of the various stability analyses and economic assessment of the viability of continued mining, it was decided to re-establish production in Pad1.

Access to the base of the pit was regained by a cut back of the failed area. The design of the cut back comprised unbenched slopes separated by the haul road. The slope above the haul road was cut at 35^{o} and the slope below the haul road was cut at 38^{o}.

Access to the western waste dumps was re-established via a ramp cut from the bridge area at the southern end of the pit, to the west. Waste from the cut back was also dumped in a previously mined out area of the bridge, resulting in very short haulage distances.

5.3 West Wall Redesign

Design of the west wall below the 900mRL was based on the past performance of the west wall, the geological model for the deposit, the results of the stability analyses outlined above and consideration of the extent of the deposit. Based on these factors, it was decided to continue mining to 840mRL. In favour of continued mining was the presence of the Paddington Volcanics which were located in the lower part of the slope, essentially acting as a buttress for the less competent BFS.

Wall development comprised 10m high benches cut at 60^{o} with 5m wide berms. The use of extensive support was continued in the BFS however strict quality control procedures including the use of better, and more, centralisers to hold the cable bolts off the base of the hole and implementation of a grouting and tensioning specification were introduced.

The pit was successfully mined to 840mRL and investigations of the extent of ore below the pit base are currently underway.

6.0 CONCLUSIONS AND IMPLICATIONS FOR FUTURE MINING IN THE AREA

A number of methods were utilised to analyse the stability of the west wall of the Pad1 pit which collapsed on 8 May, 1993. One of the conclusions to be drawn from these analyses was that stability analysis of such a failure is difficult to carry out with any degree of confidence. Limitations to the analysis included accurately determining the rock material properties required, inclusion of the effects of the various discontinuity sets present in the rock mass and realistically including the effects of the extensive support measures which had been installed in the various models. Other factors which may have contributed to the collapse included subtle variations in wall orientation, a possible surcharge from the existing failed mass, and possibly the western waste dump, and blast vibration or tectonic stresses causing localised fretting and loss of confinement which could lead to failure. Including these aspects into any model is difficult, as is providing them with the correct weighting.

The collapse occurred where the strike of the wall was exactly parallel to the strike of the foliation. Where possible, future pit walls within BFS should be designed to obliquely cross cut the foliation.

As noted previously the existing failed materials may have provided a surcharge which contributed to the collapse. Design of the west wall of the Pad2 pit included a continuous slope cut at 38^{o} through the highly weathered materials, to attempt to prevent failures in that zone, thus limiting any surcharge.

The pit wall that collapsed was intensively supported. Whilst the analyses indicated that if the support was acting at full capacity, the slope would be stable, the fact that failure occurred brings into question exactly what effect support was and is having.

Research is currently being carried out to more accurately define the effectiveness of artificial support, and the length of time that support will be effective. Strict quality control is required to ensure that support is being installed in such a way that it is possible for it to reach full capacity.

No precursors of the 8 May, 1993 collapse were observed, despite routine monitoring being carried out. This is attributed to the very stiff nature of the system because of the extensive support in place.

Monitoring of extensively supported slopes should include borehole extensometers and detailed survey networks as well as regular bench inspections and crack monitoring. Borehole extensometers and survey monitoring aid in providing advance warning of large scale movements as stress builds within a slope.

7.0 REFERENCES

Hock, E. & Bray, J. (1981): Rock Slope Engineering (Revised Third Edition). The Institute of Mining & Metallurgy, London.

8.0 ACKNOWLEDGMENTS

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