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Dealing with Rockfall Issues at Argyle Diamond Mine Open Pit Operation

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Abstract

Argyle Open Pit Operation has been dealing with potential rock fall situations for various reasons. Common reasons for this are having to work on two levels of the same cutback, and having to develop pit walls below active rill slips or landslides. The Argyle open pit operation commenced in 1985 and will continue towards 2010. Over the course of the mine life, Argyle has carried out in-pit rock fall tests in order to check the appropriateness of the initial pit slope designs and subsequently for the derivation of design parameters; coefficients of restitution, for rock fall analysis. Rock fall analyses are used to design and determine rock fall arrester or barrier sites, and rock fall arrester heights. Risks due to rock fall hazards are managed by attempting to maintain clean walls, introducing or increasing catching capacity of the berms above the lower working areas by design, or erecting barriers like windrows and bund walls. Introduction of low cohesion loose soils in the rock landing areas help reduce the rock bouncing, thereby increasing rock arrester capability. For long term rock fall arresters, consideration must be given to the requirement of subsequent cleaning with safety behind the rock fall arrester. Having to work on two levels of the same cutback invariably causes continuous rill slopes between the cut backs. This can be controlled by introducing a wide berm above the lower working area with built in rock fall arresters. In extreme situations the work on the lower level may have to be temporarily stopped or alternate activities carried out on upper and the lower levels. When it comes to cleaning up the continuous rill slope and exposing the berms, remote control Load Haul Dump (LHD) equipment can be used without endangering personnel. This activity must be built into the mine plan for effective implementation.

1 Introduction

Argyle Diamond mine is located in the East Kimberly Region of Western Australia in the Northern tropical part of Australia 2200 km Northeast of Perth. Argyle has an average annual rainfall of 800 mm. Open pit mining at Argyle started in 1985 with an annual ore production of 3.25 Mt and subsequently increased its production to 10 Mt/y (equivalent to current rate) by 1995. Argyle Diamonds consistently produced 25 to 40 million carats per year over the years to become the largest single producer of natural diamonds in the world (Deakin et al., 1994). Currently the open pit mine life is nearing completion and preparations are underway for the underground block cave operation. The underground block cave operation will commence in the early part of 2009 and the open pit operation may continue in the northern part of the pit till 2010.

The Argyle diamondiferous orebody is 2 km long and the width varies from 500 m in the north to 150 m in the south-central part, as shown in Figure 1.

2 Geology

The Argyle orebody consists of Lamproite and is located in the Halls Creek Mobile Zone, a Northeast-Southwest trending highly deformed, tectonic belt, which has undergone several episodes of deformations resulting in large scale faulting and associated folding (Boxer et al., 1990). Orebody emplacement is dated at approximately 1200 million years into Northerly dipping (30°) Proterozoic sediments. The orebody trends generally North South and dips approximately 70° to West.

The country rocks of sedimentary origin typically consist of alternating shales and quartzite, or interbedded mudstone/quartzite units. A thick band of massive quartzite, the Hensman, separates the Revolver Creek Formation in the South from the Lissadell Formation in the North as shown in Figure 1.

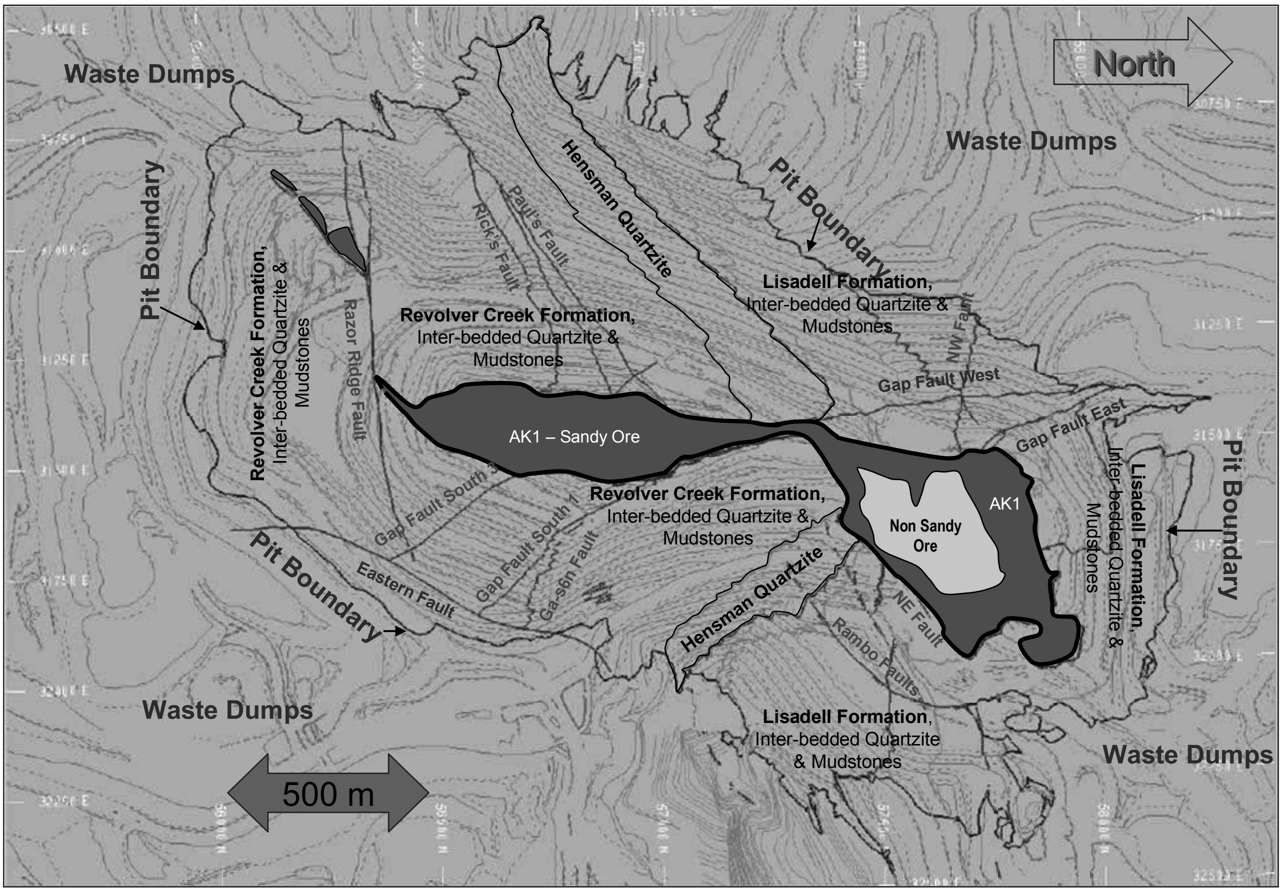

Figure 1 Surface geology map at Argyle

3 Geotechnical Conditions

The mine waste rocks consist of bedded quartzites and mudstones.

3.1 Geotechnical properties of quartzite

The quartzites are medium to coarse grained, with colour varying from cream to grey to pink to red-brown rocks consisting of quartz with minor hematite. The quartzites are silicified, hematised and are highly abrasive. Quartzites in the Revolver Creek Formation are characteristically interbedded with mudstones in contrast to massive quartzites of the Hensman Sandstone. Geotechnical properties of quartzites are shown in Table 1.

Faults within the quartzites are typically zones of brecciation and closely spaced joints. Prominent joints are parallel to, and normal to, bedding. Furthermore, on the west wall a prominent set of continuous joints strikes about N20°E (sub-parallel to orebody) and dips approximately 80°E. These form slabs sub-parallel to the batter faces in the pit. On the East wall there is a prominent set of joints striking about N30°W and dipping approximately 60°W, sub-parallel to Gap Fault (McMahon Associates, 1999). The attitudes of prominent joint sets are taken into account in determining batter angles on slopes.

3.2 Geotechnical properties of mudstones

The mudstone term in this paper is used collectively to include all fine grained sedimentary rocks including shale, claystone, siltstone and very fine grained sandstones with clay or silt matrix. Within the mudstone units, the mudstones are up to 43 m thick with minor interbedded quartzites. Mudstones also occur as thin interbeds in the quartzite units.

Mudstones are mostly fissile although some thickly bedded strata do occur. The fissile mudstones typically breakdown to angular fragments a few centimetres across, when struck by a hammer. Geotechnical properties of mudstones are shown in Table 1.

The majority of joints in fissile mudstones make angles of about 30° to the bedding. In the more thickly bedded units the prominent joints are approximately parallel to, or normal to, the bedding. The joint sets described as prominent in quartzites also occur in the mudstones (McMahon Associates, 1999).

3.3 Geotechnical properties of the lamproite ore

Lamproite is an olivine bearing ultramafic igneous rock which, at Argyle, bears diamonds. Within the volcanic vent, the Lamproite, in the form of volcanic ash, became mixed, in part, with quartz sand to form 'sandy tuff' (AK1- Sandy Ore). Where such mixture did not occur the rock is referred to as 'non-sandy tuff' (Non Sandy Ore). Lamproite magma which remained liquid formed dykes and intrusions of rock referred to as Magmatic Lamproite (McMahon Associates, 1999). Geotechnical properties of Lamproite Ore are shown in Table 1.

Table 1 Geotechnical properties of rock units at Argyle Mine

Rock Type		UCS (MPa)	Young's Modulus (GPa)	Poisson's Ratio	Dry Density (t/m^3)	Moisture Content (%)
Quartzite	Mean	80	64	0.18	2.58	0.22
	Min	5.4	10.5	0.08	2.44	0.00
	Max	295	123	0.32	2.72	0.60
Mudstone	Mean	26.5	27	0.25	2.73	0.8
	Min	1.0	10	0.11	2.56	0.1
	Max	89	52	0.45	2.97	2.0
Lamproitic Sandy Tuff (ST)	Mean	67	43	0.19	2.69	0.63
	Min	10.1	15.8	0.05	2.56	0.30
	Max	187	110	0.35	2.88	1.1
Lamproitic Non-Sandy Tuff (NST)	Mean	75	38	0.27	2.69	1.0
	Min	9	19	0.22	2.62	0.5
	Max	132	79	0.31	2.74	1.1

3.4 Geotechnical properties of the orebody contact zone

The orebody contact zone average about 15 m wide and consists of highly sheared and fractured mixtures of wall rocks and Lamproite. They contain sheared mudstones and lamproite with intense chloritic alteration and shiny sheared surfaces. Quartzites are mostly brecciated (McMahon Associates, 1999).

4 Slope Design Criteria

Slopes at Argyle are generally designed for kinematic stability. The inter ramp slope angle (IRSA) generally varies from 23.5 to 55° as shown in Figure 2. In most of the waste rocks batters are cut at 70°. The batter angle in West wall Sandy Ore and Non-Sandy Ore is 55° to improve batter scale stability. Batters in the East wall Sandy Ore are developed at 70°. Batter angles are generally governed by the preferred orientation of joints. The pit is subdivided into a variety of geotechnical domains where the rock mass within each domain is generally similar. Typically one set of slope geometry parameters (IRSA, batter / berm configurations) are provided for each domain. A set of slope geometry parameters may have a variety of different IRSA's for different wall orientations in that domain. Batter angles and Berm widths vary depending on the geotechnical domain to achieve suitable IRSA whilst maintaining catching capacity on the berms as shown in Table 2.

The berm widths were initially selected as the minimum width along which a dozer could work and maintain the berms by removing loose rocks and chaining the batters below (McMahon Associates, 1999).

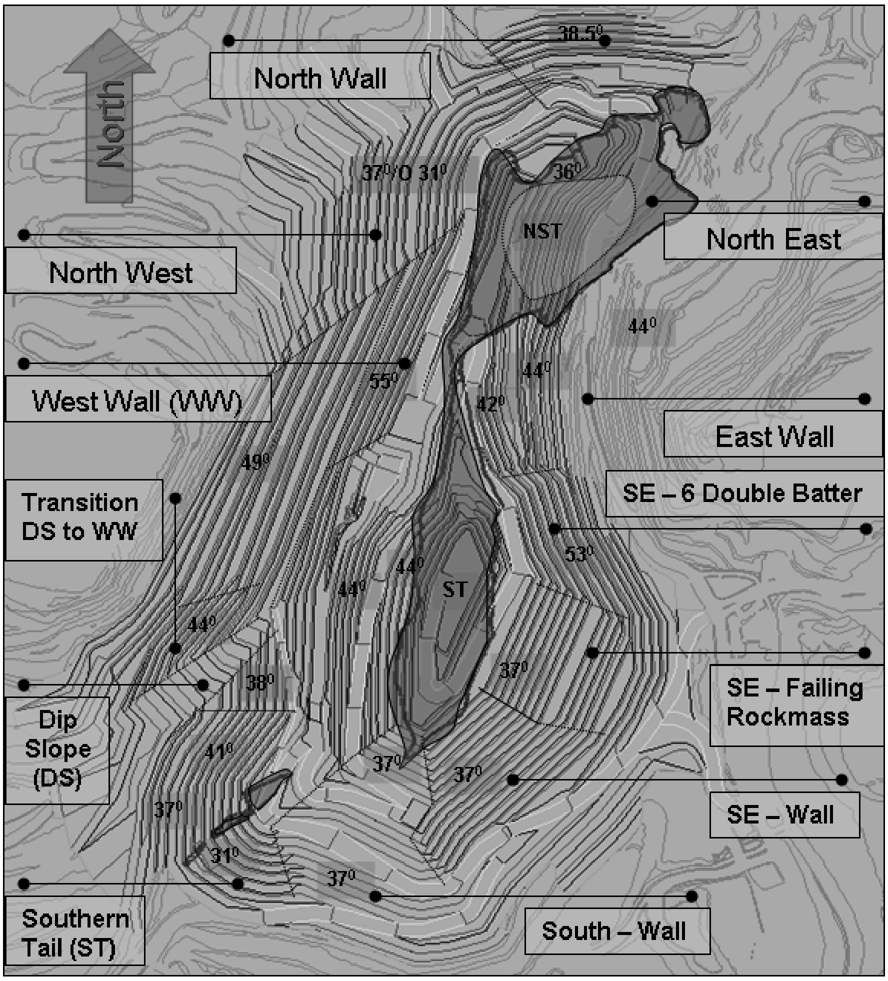

Figure 2 Slope design parameters at Argyle open pit

Most benches remain accessible for some time. When the batters and berms remain intact it is easier to get equipment [dozers/excavators] to clean up the berms to improve debris catching capacity. However, due to deterioration of batters in mudstones, especially when interacting with adversely oriented joints and fault structures, the berm widths are reduced by rilling and berm collapses. When this happens the berms become largely inaccessible to walkers and to equipment for clean up.

On the West wall an IRSA of 49° is achieved by introducing double batters with alternating 10 and 20 m berms. The double batters are supported by cablebolts and W-strapping, with rock-link mesh and enviro-mesh in weak mudstones. In certain quartzite zones, rock-link mesh is draped to minimise rockfalls. To minimise toppling failures in quartzites, cablebolts have been used as a crest row in conjunction with W-strapping. Weepholes are drilled up to 40 m length at the toe, to minimise water pressure build-up on the large persistent joint planes that run parallel or sub-parallel to the pit wall batters. Past experience revealed that hydraulic jacking on such joint structures dilates the joints over short periods of time, increasing the risk of toppling failures. This can happen in areas above the water table due to transient water pressure build-up during rain periods. When quartzite is underlain by weak mudstone, due to deterioration and subsequent erosion of this mudstone the quartzite beds get undercut and increase rockfall hazards. In this situation, application of spray-on membrane material, Tunnel-Guard, on mudstones minimise its exposure to the elements, sun, wind and rain, thus minimising deterioration of the weak mudstones. This way minimising natural removal of the underlying mudstones prevents formation of quartzite overhangs with its subsequent deterioration leading to rockfalls.

Table 2 Slope design parameters

Zone	IRSA (°)	Batter angle (°)	Batter height (m)	Berm width (m)	Overall slope angle (°)
North Wall	38.5	70	15	13.4	-
North East	36	70	15	15.2	-
East Wall	44	70	15	10.1	-
SE 6 Double Batters	53	70	30	11.7	-
SE Failing Rock Mass	37	70	15	14.5	33
SE Wall	37	70	15	14.5	-
South Wall (Undercut Bedding Area)	37	70	15	17	31
Southern Tail (ST)	31	70	15	14.5	-
Transition: ST to Dip Slope	37	70	15	14.5	-
	41	70	15	11.8	-
	38	70	15	13.7	-
Dip Slope (DS) (Remediated old Wedge Failure)	23.5	28.5 (bedding dip)	30	13.9	-
Transition: DS to WW	44	70	15	10.1	-
West Wall (WW)	49	70	30	Alternating 10 and 20	-
West Wall Lower Zone	55	70	30	10.1	-
North West	37	70	15	14.5	31

5 Rockfalls

Over the operational life of the Argyle open pit operation, there has been a number of minor rockfall incidents recorded. Most resulted in mere observations and some minor equipment damage. However, one serious incident has occurred due to a rockfall. In this incident, one engineer was seriously injured while working on blast monitoring equipment under a double batter. The same rockfall also seriously damaged a vehicle. On this occasion rocks from Lissadell Quartzite formation was involved. Another rockfall incident occurred outside the pit in the Northwest bore-field at close proximity to a waste dump seriously damaged the power supply unit to the water bore pumps. On this occasion a quartzite boulder rolled down the waste dump slope landed on a rock ledge at the toe region of the dump disintegrating the boulder and the resulting rock particles at high speed caused extensive damage to the equipment.

Geomechanics personnel at Argyle open pit operation, urge all stakeholders of the operation to consider rockfall as a serious issue. In order to minimise rockfall-related issues, the approach is to address the means of controlling the rockfall incidents from planning, implementation and contingency stages (Gunasekera, 2005). During the planning stage considerable effort goes into providing adequate controls to minimise rockfall hazards. This includes targeting potential rockfall areas and proposing controls by means of adequate catch berms, soft landing provisions and bunds. In the next few years mining at the bottom of the Argyle open pit will be associated with working in close proximity to the existing slope instabilities. In order to ensure safe mining at lower levels, adequate controls need to be in place when considering future design evaluations, such as provision of adequate catching capacities along with windrows or install meshing to control rockfalls. During design implementation, the daily geotechnical effort is focused on the operational safety of personnel and equipment based on the day to day observations and results of pit slope monitoring results. Furthermore, regular communications on the slope behaviour in response to mining or adverse weather conditions, as well as educating the workforce on slope hazard awareness, help to enhance the knowledge of the workforce on rock slope related hazards. As a result of this increased awareness considerable numbers of rockfall or slope stability-related incidents get reported. Such prompt reporting allows the geotechnical personnel to take appropriate action to control the situation. Annual risk reviews on the pit designs highlight the business risks associated with achieving annual targets. This helps management to set realistic production targets.

5.1 Rockfall tests

Since its inception, a total of three sets of rockfall tests have been carried out at Argyle:

- Rockfall test Series 1: Dames & Moore, September 1990.
- Rockfall test Series 2: BFP Consultants Pty Ltd, September 1999.
- Rockfall test Series 3: Argyle Diamonds Ltd, July 2005.

In all cases representative slope sections were selected and Hensman Quartzite boulders were used in the tests to reflect the worst condition one can expect in the pit as far as the rockfalls are concerned. The rock blocks selected for the tests were roughly equant (having all axes of the same length) in shape and of different dimensions. The blocks were numbered and the dimensions recorded. The blocks were gently pushed over the edge of the selected berm crest. A video record was made of the falling rocks and the trajectories later sketched from this on to slope profiles.

The motions at various stages of the trajectories were classified as follows:

- *Sliding (S):* The rock maintained sliding contact with the batter or berm.
- *Rolling (R):* The rock rolled so that contact of edge, face, or corner was maintained most of the time.
- *Bouncing (B):* The rock bounced so that the rock was in the air most of the time.
- *Translational Falling (T):* The rock fell without rotation.
- *Rotational Falling (F):* The rock rotated as it fell.

5.1.1 Series 1 - rockfall test (Dames and Moore, 1990)

This work was carried out as part of the ongoing geotechnical investigation into finding an optimum slope design. A series of rockfall tests were carried out to observe the trajectories of rocks of various sizes from the edge of a berm. The intention was to make a subjective judgement as to whether the blocks would have been stopped by different berm widths; 10, 15 and 20 m berms, with a 1 m deep, 2 m wide ditch at the toe and a 1 to 1.5 m high windrow. The subjective judgement was that all rocks would have been stopped by a 20 m berm with windrow. Based on the observations, whether or not a block stayed on the first berm is not related to the size of the block. With respect to the blocks that stayed on the berm, the distance from the toe of the batter to the final position of the block was only vaguely related to weight.

The conclusions of the Series 1, rockfall tests were:

- The behaviour of the rocks was independent of their weight. This conclusion agrees with the work of Richie (1963).
- Approximately 50% of the rocks pushed over the side were retained on the first berm which was 10 to 14 m wide.
- The behaviour of rocks after initial impact on the batter or berm depended on the surface condition at the point of impact. If the rock landed on an irregularity (i.e. if the batter or the berm formed with irregularities or with a rough finish or with protrusions on the batters) then it tended to develop a rotational motion. The subsequent trajectory caused it to bounce over the next crest. Rocks that did not hit an irregularity tended to remain on the berm.

5.1.2 Series 2 - rockfall test (BFP, 1999)

The Series 2 - rockfall tests were commissioned to evaluate the risks of rocks from the upper cutback, reaching the working level down below, based on the known pit geometry and geology. This also takes into account the actions taken by the mine to reduce the risk (namely placing loose rock or rill on specific berms).

From 1985 to 1997 Argyle open pit had gone through mining of slices 1 to 4. While mining the slice 4 in mid 1996, its continuation was threatened by the development of a 26 Mt large wedge failure on the West wall. In order to stabilise the failure, the slice 4 design had to be changed, incorporating a buttress of ore, 500 m long and 120 m wide, from 230 mRL to 140 mRL (base of the pit at the time). The stabilisation process of the active-passive wedge system, involved installation of six diamond cored borehole drains, each 600 m long with slotted casing to full depth, routing surface drainage to divert water away from the wedge area. Ultimately, a 45 m thick surcharge had to be placed on top of the buttress, to contain the uplifting of the passive wedge in the buttress.

In order to remove the unstable wedge and to mine the open pit mine deeper, Argyle opted for a 250 m push back on the West wall, called Cutback 1 (CB1), from 560 mRL down. When the CB1 reached 470mRL, the mining of ore was still being undertaken at the toe of the wall at 140 mRL. In order to meet the production targets prior to wet season, it was required to progress CB1 at the same time that ore mining proceeds at the base of the pit. However, this introduced a significant safety issue if rocks dislodged from crest of the cutback were able to fall, roll and/or bounce on to the lower working level.

5.1.2.1 Rockfall analysis

The initial horizontal and vertical velocity of a dislodged rock governs the trajectory of a rockfall. At Argyle, these movements could be conveyed to the rock in the following ways:

- Pushed over the edge by mechanical equipment (typical horizontal velocity would be 0.6 to 1 m/sec.
- Gravity (affects the vertical velocity).
- Fly rock from blast.
- Erosion due to wind and/or rain.

In these analyses, it has been assumed that the mechanical equipment has conveyed the initial destabilising force, and that the initial velocity is horizontal.

The input data for the rockfall analysis is as follows:

- For each rock type or surface, three parameters have to be defined. These are the coefficient of normal restitution (Rn), the coefficient of tangential restitution (Rt) and the friction angle (ø) on the rock surface that would resist any sliding motion by the falling rock.
- The coefficients of restitution relate to the attenuation properties of the rock surface. Typically the Rn is lower than the Rt. The Rn is related to the rebound of a rock hitting the surface, and is the ‘elastic response’ to the rebound. If the impact surface was horizontal and the rock was falling vertically, then the amount of rebound/original height would equate to the Rn.
- In a similar way, Rt relates to the elastic response of the rock to the glancing blow. It is apparent that in hard rock surfaces very little attenuation would occur. In gravel, the attenuation would be significant.
- Angular momentum is conveyed to the rock on impact. If a rock has considerable angular momentum prior to impact, it can increase significantly afterwards. This can be observed when rocks appear to kick after impact and fly greater distances.
- The ø is applied to rocks that are in a rolling mode, and is most applicable for slopes that are less than 45°.

5.1.2.2 Model calibration

The results from the Series 1 rockfall tests in 1990 were made available for this study. The results comprised a trace of the rock fall transcribed onto a composite cross section of the study site.

The back analysed parameters for the first trial were as follows:

Rn = 0.52

Rt = 0.8

Ø = 30°

The main criterion used for the calibration was the percentage of rocks retained on the 14 m wide berm.

The back analysed parameters for the second trial were as follows:

Rn = 0.35

Rt = 0.5

Ø = 20°

Compilation of the results provided the following parameters for Hensman Quartzites:

Rn = 0.44 (SD = 0.13)

Rt = 0.65 (SD = 0.21)

Ø = 20° (SD = 2°)

SD = standard deviation

The simulations give a reasonable summary of rocks contained on the berm, compared with the actual tests. The trajectories in the simulation appear to exaggerate the actual response. This can be due to not knowing the condition of the berms (i.e. presence of loose rock, roughness of the batters etc.) that would have accounted for the changed response.

5.1.2.3 Design parameters

Based on the calibration results, the design parameters for rock units (mean/SD) have been derived to be used in rockfall analyses as shown in Table 3.

Table 3 Rockfall design parameters derived from Series 1 & 2 Rockfall Tests

Rock Unit	Rn /SD	Rt/SD	Ø°/SD
Quartzites	0.44/0.13	0.65/0.21	25/2
Mudstones	0.5/0.1	0.6/0.2	30/2

The conclusions based on the Series 2 tests, indicated that rockfall could produce a safety hazard for personnel and equipment working in the base of the pit, if the two activities take place at the same time. Most risk occurs in the northern part of the pit and warrants further investigation.

The placement of rill on berms was interpreted to have a significant effect on reducing the effect of rockfall, and hence increasing the safety of the working level. If further tests are to be carried out, particular attention should be paid to:

- The nature of the rock being rolled.
- The condition of the surface on which the rock lands.
- The debris or back fill on the slope.

5.1.3 Series 3 - Rockfall test (Ross, 2005)

The latest rockfall tests were carried out to verify the results obtained by Series 2 rockfall tests. A total of 17 boulders from the East wall (180 m high) and 14 boulders from the West wall on the Northern end of the pit were released in this rockfall trial.

On the 180 m high Northeast wall (380 mRL to 200 mRL) rill slope, 44% of boulders travelled and stopped within 30 m of the crest, another 44% made it to the toe and were retained by the windrow, 6% stopped on mid-slope and the remaining 6% impacted beyond windrow at the toe area. About 82% of boulders reached the destination intact, and 18% of boulders broke up in transit.

On the 165 m high Northwest wall, the IRSA of 49° (395 mRL to 230 mRL) consists of intact berms with alternating widths of 10 and 20 m separated by 70°, 30 m high batters. Of the rocks released from 395 mRL, none were contained on the 10 m berm at 365 mRL, 21% were contained on 20 m wide berm at 335 mRL, 7% were contained on the 10 m wide berm at 305 mRL, 36% were contained on the 20 m wide berm at 275 mRL, 7% were contained on 10 m wide berm at 245 mRL, and 29% landed on the 80 m wide bench at 230 mRL. Of all the boulders released on the West wall, 57% broke up in transit and 43% reached their destination intact.

The observations revealed that there is no relationship between the boulder size and the travel distance.

Based on the Series 3 rockfall test results, the design parameters for rock units (mean/SD) have been derived to be used in future rockfall analyses as shown on Table 4.

Table 4 Rockfall design parameters based on series three rockfall tests

Rock Unit	Rn/SD	Rt/SD	Ø°/SD
Quartzites	0.38/0.1	0.95/0.1	30/2
Bench*	0.35/0.1	0.6/0.1	30/2
Rill	0.2/0.05	0.84/0.05	18/2

* Inferred

6 Discussion and Conclusions

In order to evaluate the risk due to rockfalls, ROCFALL (Rocscience, 2004) proprietary software is used extensively at Argyle. The design parameters derived from the rockfall tests are used in calculations. This process helps to design controls against the potential rockfall hazards.

Controls to minimise rockfall hazards can be:

- Use of hard controls, such as placement of windrows, bund-walls, ditches, and soft landing pads with loose gravel spreads. Use of rock fences has not been encouraged in the mine due to underground block cave requirements, plus logistics reasons.
- Another hard control is to improve the catching capacity on the benches, by cleaning the berms full of rill between the working levels of the cutbacks. Dozer/Excavators are generally utilised for this purpose. However, when it is not safe to do so, remote control LHD machines will be used.
- When the effectiveness of the hard controls are diminished or not practical to ensure safety of personnel or equipment, soft controls such as procedural controls are used effectively (Gillespie, 2006 – internal report).

Limitations of rockfall analysis (Ross, 2006):

- Does not model large boulders travelling further than small boulders.
- Does not model large boulders splitting or initiating small boulders at very high horizontal velocities.
- Contradiction between rockfall distributions during field test for clean rock, and rockfall distributions observed in reality.

- Some adopted parameters not based on site-specific field test results, e.g. Bench parameters.
- Slope roughness – photogrammetry suggests that even presplit 70° batter slopes can have roughness variation from 47 to 83° (by presplit blasting design crests and toes achieved, however due to rock un-homogeneity and the quality of the wall-scaling effort can still give rise to local irregularities). This is very much greater than typically assumed in rockfall analyses.
- Depending on the simulated source of the rockfall (seeders) different results can be obtained (e.g. point vs. line seeder vs. location seeder).
- With simulations using 1000 rocks, results are not 100% repeatable. Run the same simulation two or three times and the result is usually slightly different.
- Analysis typically performed for 1000 rocks – 'rogue' rocks can travel further than suggested by the analyses, partly as a result of the low number simulated and also the limitations described above. Rogues are a particular issue when the frequency of rockfall is very high e.g. during blasting, chaining, edge mining or rain.
- Rocks can travel greater distances than predicted by the analyses. Exposure to this problem increases as the rockfall initiation frequency increases.

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