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Rio Tinto Iron Ore mines actual failure percentages case study

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Abstract

Rio Tinto Iron Ore (RTIO) has observed and safely managed fall of ground (FoG) events throughout the history of its open pit operations. These FoG events have been documented in a central database and recently visualised using ArcGIS. The entire dataset has been leveraged to compare the actual failed surface area to the surface area of the pits and design sectors they're located in. This dataset has revealed the actual failure percentages fall well below industry norms, with actual failure percentages ranging between 0.0 and 3.5% for the majority of design sectors. This is somewhat expected for bulk mining operations with the requirement to meet such a high volume of production, with RTIO maintaining over 300 Mt annually. However, this dataset has become an invaluable tool to flag design sectors where there is an opportunity to challenge the original design assumptions and lead to a potential re-design and pit optimisation. The dataset also shows interesting relationships for actual failure rates by mechanism, scale and geological setting. By developing this database, RTIO has developed a powerful tool and methodology for design and risk management.

Keywords: *slope stability, Probability of Failure, fall of ground, reporting, geotechnical data*

1 Introduction

Safely managing slope failures throughout the lifecycle of an open pit mine is crucial to ensure the safety of personnel and economical extraction of the orebody. Some level of failure is assumed in design and accepted in industry practice, provided that safe management practices are in place. Rio Tinto Iron Ore (RTIO) has been able to observe and safely manage slope failures throughout the lifecycle of its open pit iron ore mines in the Pilbara region of Western Australia. RTIO owns or is the primary operator of 17 open pit iron ore mines, with each mine containing multiple pits, and have procedures in place to capture and record detailed information for every fall of ground (FoG) event. This information is documented in a centralised database and provides a wealth of knowledge to investigate the slope performance of RTIO's pits and identify trends in slope failures.

This paper demonstrates the current slope performance for five of RTIO's mines, providing the percentage of failed slope area, that can be compared to RTIO's and Large Open Pit Guidelines probabilistic design acceptance criteria (DAC). This paper fills a gap in the current literature for open pit slope failures, particularly in iron ore in the Pilbara region of Western Australia, as there is limited to no papers that discuss the percentage of failed slope area, but instead focus on the back-analysis and causal factors of individual slope failures. A robust dataset of over two hundred slope events, mainly single batter, over the past 15 years is used to present statistics on the failed surface area in relation to the overall pit area. The causal factors are not discussed in detail, but includes a brief discussion on failure mechanisms and general causes.

2 Methodology

Performance of open pit slopes across five of RTIO's mines was assessed utilising RTIO's FoG database and aerial imagery. The FoG database consists of an extensive list of data entries in acQuire and FoG reports, containing detailed information on each FoG event. Information utilised in this paper from RTIO's FoG database is listed below:

- Mine, pit and location.
- Date and time.
- Failure dimensions and scale.
- Failure mode and mechanism.
- Geology.

One of the first steps in assessing the slope performance was to review the legacy dataset and identify if any gaps exist. It became clear that not all FoG events were captured in the database, particularly for batter scale. To resolve this problem and build a more complete dataset, aerial imagery and 3D mine models were utilised to identify additional FoG events not documented in the database. Any additional FoG identified, through the use of aerial imagery, was added to the database to provide a complete and comprehensive dataset of FoG events across RTIO's mines.

Utilising this complete dataset and aerial imagery in ArcGIS, the areas of failed pit slope were annotated and the slope failure area calculated for each FoG event. The slope failure area calculated is a projected two-dimensional area that contains the entire FoG event. An example of the annotated slope failures in ArcGIS is displayed in Figure 1, highlighting the areas of the pit slope that have failed, with a legend provided to distinguish between failure scale and method of identification of the slope failure. The pit displayed in Figure 1 has been operational for more than 20 years, in different stages, with the north wall structurally controlled and south wall rock mass controlled.

Figure 1 Annotated fall of ground events

The same methodology was used to calculate the overall slope area for each assessed pit. The overall slope area consists of the entire area within the pit crest, but excludes the pit floor, haul roads and locations within the pit that have been backfilled. Excluding these components from the entire area within the pit crest provides a more accurate representation of the current pit slope area where slope failure can potentially occur. An example of the annotated overall slope area is displayed in Figure 2. For selected pits, the overall slope area was divided into design sectors and annotated to assess the pit slope performance for different failure modes, structurally and rock mass controlled. Only four pits were subdomained by design sectors and these pits were generally selected based on a higher percentage of failed slope area. The design sectors are created during the design stage of each pit and subdivides the pit based on failure mechanism and material parameters, therefore it's applicable to use for this method. An example of the annotated design sectors is displayed in Figure 3, highlighting the structurally and rock mass controlled sections of the pit slope.

Figure 2 Annotated overall slope area

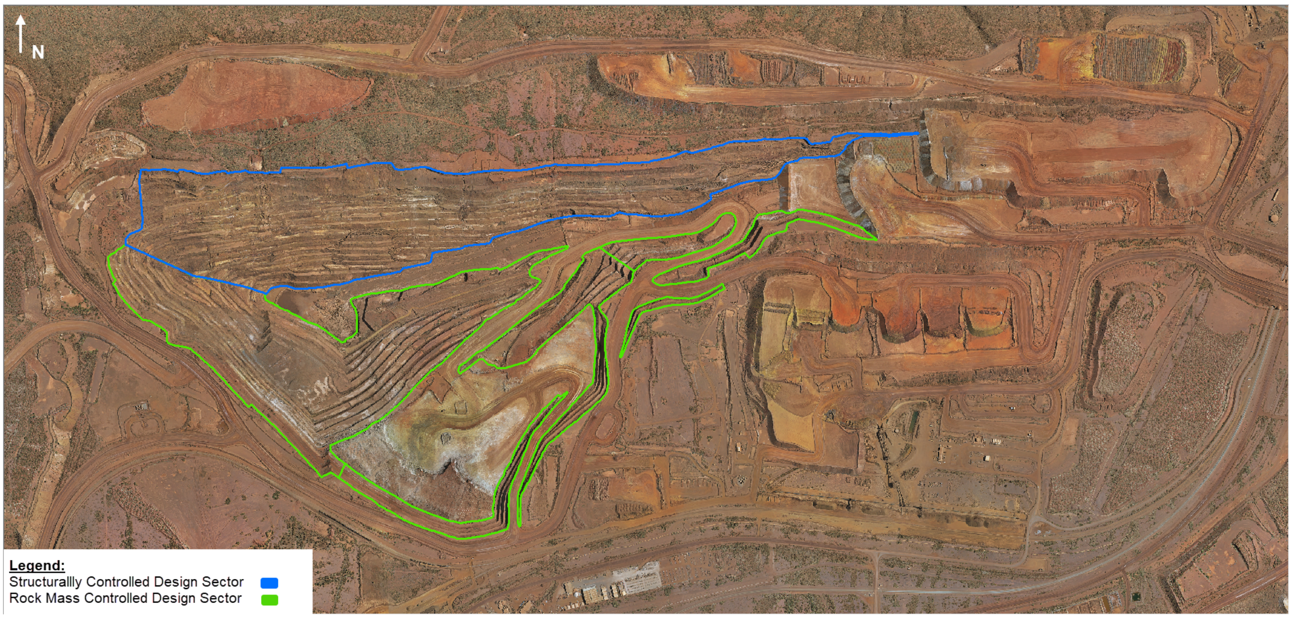

Figure 3 Annotated failure mode area

The percentage of failed slope area was calculated for each of the 29 pits assessed in this paper. The percentage of failed slope area was calculated by adding the failure area of all FoG events for each failure scale, within the same pit, and dividing it by the current as-built overall slope area of the pit. This method is completed for single batter, multi batter, inter-ramp and overall slope scale failures. This process was replicated for the pits that were subdomained based on failure mode, utilising design sectors instead of overall pits, to calculate the percentage of failed slope area for each design sector and failure scale. The percentage of failed slope area calculated through this methodology is time-dependant and provides an insight into the slope performance at the time of assessment, with no indication on the slope performance as mining progresses until closure.

To assess the slope performance for each of the pits and design sectors, the percentage of failed slope area was compared to RTIO's probabilistic DAC, displayed in Table 1. RTIO's DAC aligns with industry guidelines and is based on the acceptance criteria in *Guidelines for open pit slope design* (Read & Stacey 2009). It is noted that the Probability of Failure (PoF) captures the percentage of failure surfaces below a Factor of Safety (FoS) of one (Rocscience n.d.), not the percentage of failed slope area as measured in this paper. Although the failure area and PoF are not a direct comparison, the probabilistic DAC is used as a proxy to benchmark the slope performance against. This methodology aligns with RTIO's interpretation of the probabilistic DAC and RTIO are content for any given pit to have up to the PoF in actual percentage of failed slope area for each failure scale. The percentage of failed slope area wasn't compared to the design PoF results due to limited data for legacy pits and RTIO's current design methodology, generally, only performs probabilistic assessments for batter scale scenarios.

Table 1 RTIO geotechnical slope design acceptance criteria

Criteria		Factor of Safety		Probability of Failure	
		Risk category		Risk category	
Scale	Infrastructure	High	Mod–low	High	Mod–low
Single batter (<20 m)	NA	1.2	1.1	25%	30%
Double batter (≥20 m)	NA	1.2	1.1	10%	15%
Inter-ramp	None	1.2	1.2	10%	15%
Inter-ramp	Long-term ramp	1.3	1.3	10%	10%
Overall slope	None	1.3	1.2	5%	5%
Overall slope	Long-term ramp	1.3	1.3	5%	5%
Overall/inter-ramp (slope)	Fixed (critical) infrastructure	1.5	1.5	1–3%	3–5%

The methodology used to assess the performance of open pit slopes and measure the percentage of failed overall slope area for each pit and design sector, is based on multiple assumptions used to collect additional FoG events not initially in RTIO's FoG database. The assumptions used in the methodology are listed below:

- All inter-ramp and overall slope scale FoG events can be identified for the current as-built pit slopes from the FoG database and aerial imagery. If inter-ramp or overall slope scale FoG events have been remediated, a scarp will be visible in the as-built pit slope.
- FoG events located in areas of the pit slope that have been cutback or backfilled are excluded from the assessment. Only slope failures in the current as-built pit slopes are included.
- Batter scale FoG events during the batter pulling process are not included in this assessment due to the difficulty to identify the FoG and confirm the conformance to design at the time of failure. The intention of this paper is to only assess the slope performance of the intended designs.
- Batter scale FoG events that have been remediated and haven't been reported are excluded from this assessment. This is due to the difficulty to distinguish if the scarp in the batter face is due to batter pulling practices (i.e. removing potential instabilities prior to failure) or from a FoG event that has been remediated.
- The methodology doesn't exclude pit slopes that are not geotechnically constrained (i.e. constrained by the orebody or mining practices). These slopes may influence the inter-ramp and overall slope scale results as generally they have a higher FoS and lower PoF.

- Rilling and degradation of batters due to weathering and water erosion have not been considered as FoG events.

3 Results

Identification and measurement of open pit slope failures using the methodology and data outlined in Section 2 was applied to 29 pits across five of RTIO's mines. The percentage of failed slope area was calculated for each pit individually and the percentage of failed overall slope area for each mine is summarised in Table 2.

Table 2 Percentage of failed overall slope area

Mine	Single batter	Multi batter	Inter-ramp	Overall slope	Total
Mine A	0.24%	0.04%	0.30%	0.00%	0.58%
Mine B	0.40%	0.05%	1.72%	0.00%	2.17%
Mine C	0.10%	0.00%	0.00%	0.00%	0.10%
Mine D	0.17%	0.19%	0.01%	0.00%	0.37%
Mine E	0.10%	0.07%	0.20%	0.00%	0.37%
Total	0.18%	0.09%	0.39%	0.00%	0.66%

RTIO's FoG database contains information on the failure mode, mechanism, scale and date of slope failures, providing an insight into the occurrence, location, scale and mode of the slope failures across RTIO's Pilbara Operations. This data is presented in the following figures, with a timeline of the failures across the five mines in Figure 4, timeline of failures by failure scale in Figure 5, timeline of failures by failure mode in Figure 6 and breakdown of failure modes by failure scale in Figure 7. It is noted that the majority of failures identified through aerial imagery aren't included in Figures 4, 5 and 6 due to insufficient information on the failure date.

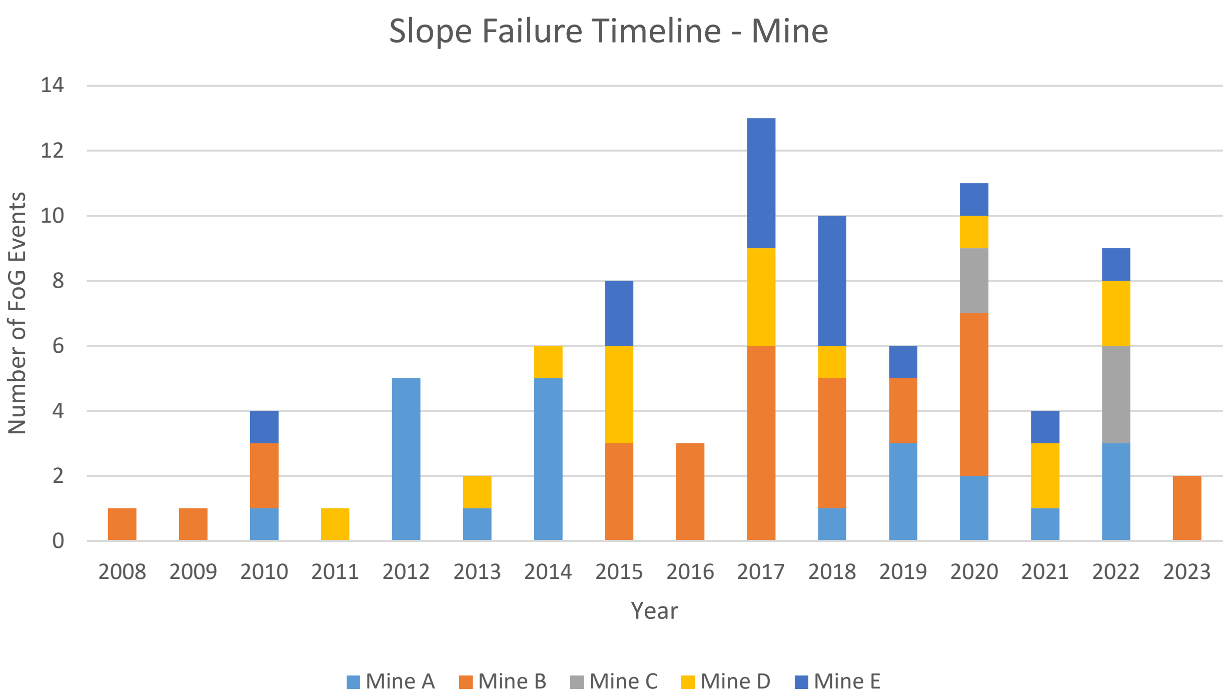

Figure 4 Recorded slope failure timeline by mine

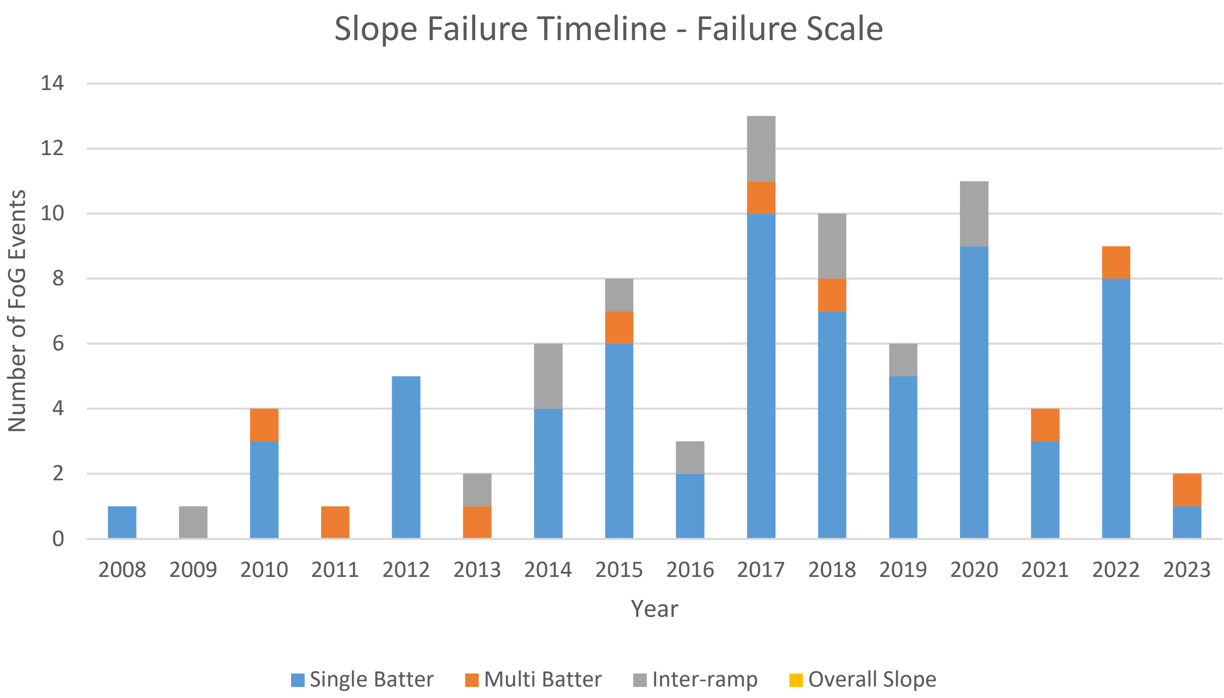

Figure 5 Recorded slope failure timeline by failure scale

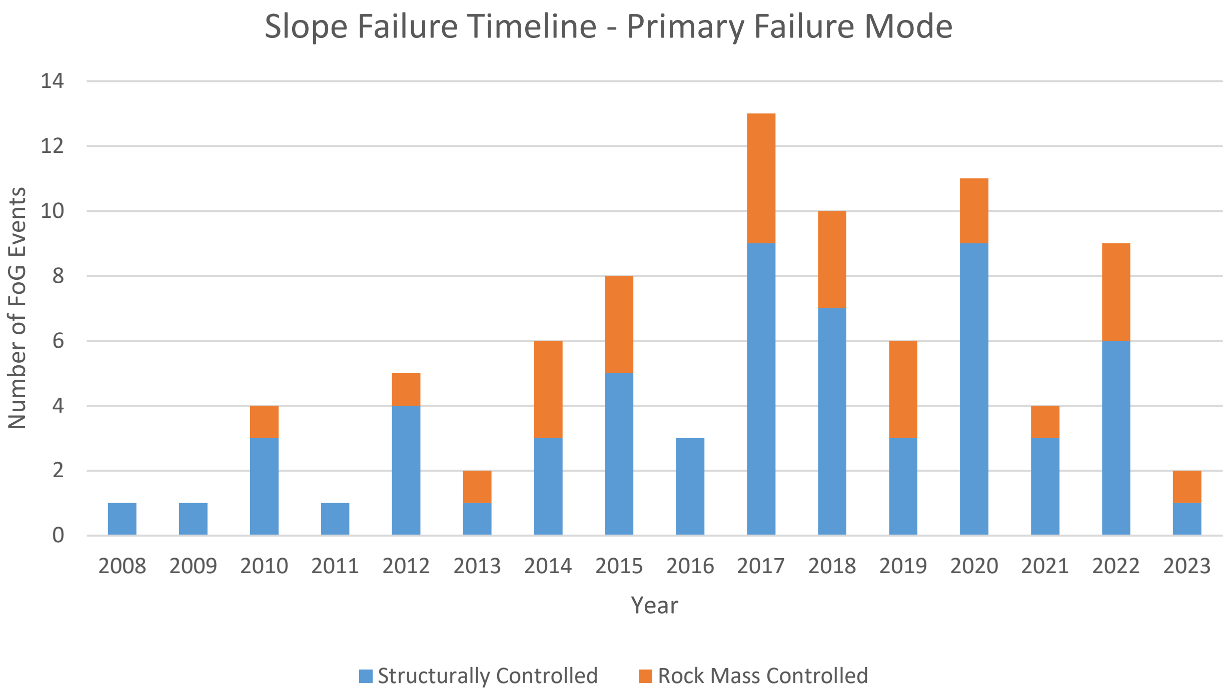

Figure 6 Recorded slope failure timeline by primary failure mode

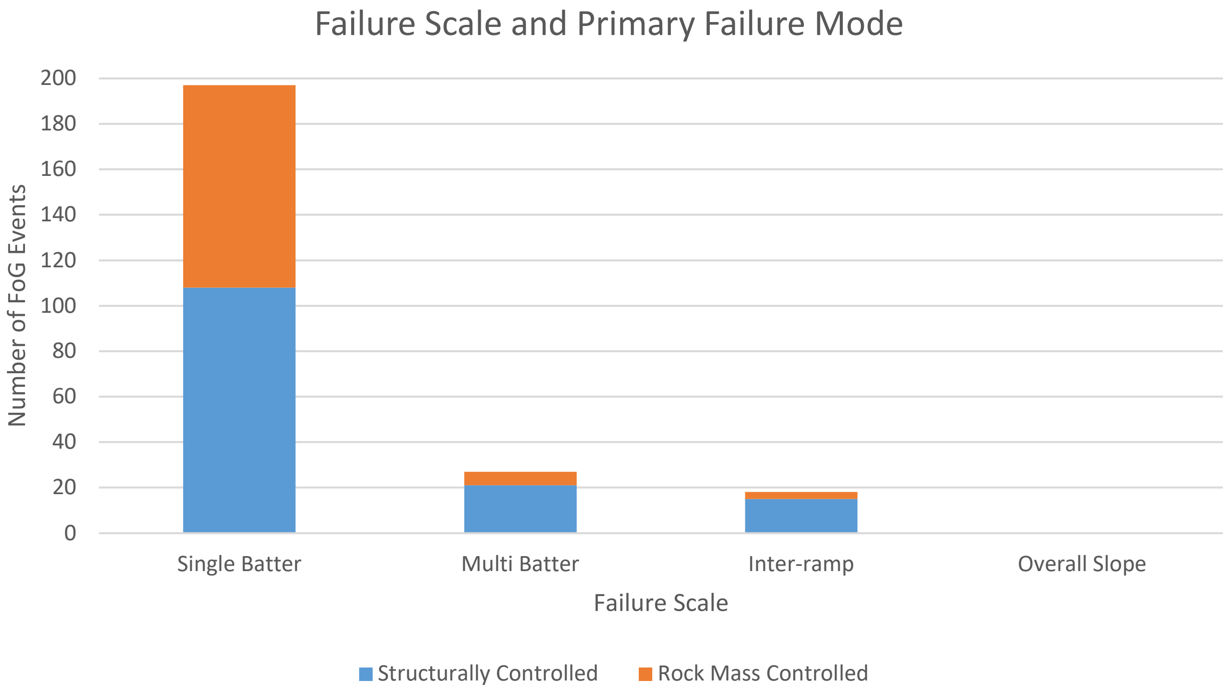

Figure 7 Slope failure scale by primary failure mode

Initial assessment of the results reveals the percentage of failed overall slope area for all 29 pits assessed are within RTIO's probabilistic DAC, presented in Table 1, for all failure scales. The breakdown of slope failures by the primary failure mode in Figures 6 and 7, indicates a higher percentage of structurally controlled failures for multi batter and inter-ramp scale slope failures. Further investigation was completed to assess the slope performance of structurally and rock mass controlled pit slopes and quantify if individually these slopes meet RTIO's probabilistic DAC. To calculate the percentage of failed slope area for each failure mode, the overall pit area was subdivided into design sectors for four selected pits as described in the methodology in Section 2. The results for the percentage of failed slope area based on primary failure mode is displayed in Table 3 for structurally controlled pit slopes and Table 4 for rock mass controlled pit slopes.

Table 3 Percentages of failed slope area by primary failure mode – structurally controlled

Mine	Single batter	Multi batter	Inter-ramp	Overall slope	Total
Mine A	0.28%	0.00%	0.00%	0.00%	0.28%
Mine B	0.87%	0.00%	8.73%	0.00%	9.60%
Mine D	0.18%	0.31%	0.00%	0.00%	0.50%
Total	0.36%	0.20%	2.11%	0.00%	2.67%

Table 4 Percentages of failed slope area by primary failure mode – rock mass controlled

Mine	Single batter	Multi batter	Inter-ramp	Overall slope	Total
Mine A	0.69%	0.00%	2.75%	0.00%	3.43%
Mine B	0.06%	0.00%	0.00%	0.00%	0.06%
Mine D	0.02%	0.12%	0.00%	0.00%	0.14%
Total	0.10%	0.07%	0.29%	0.00%	0.47%

The 29 pits assessed in this paper consists of two iron ore formations, Brockman and Marra Mamba formation. To investigate the slope performance of these two iron ore formations, the pits were separated by formation, with the results for Formation A displayed in Table 5 and Formation B in Table 6. The frequency of slope failures by iron ore formation and scale is presented visually in Figure 8. It is noted that 18 of the pits assessed consists of Formation A and the remaining 11 pits Formation B, with a ratio of overall slope area of Formation A and Formation B of 45:55.

Table 5 Percentages of failed slope area by formation – Formation A

Mine	Single batter	Multi batter	Inter-ramp	Overall slope	Total
Mine A	0.24%	0.04%	0.30%	0.00%	0.58%
Mine D	0.18%	0.20%	0.01%	0.00%	0.39%
Total	0.21%	0.14%	0.12%	0.00%	0.47%

Table 6 Percentages of failed slope area by formation – Formation B

Mine	Single batter	Multi batter	Inter-ramp	Overall slope	Total
Mine B	0.40%	0.05%	1.72%	0.00%	2.17%
Mine C	0.10%	0.00%	0.00%	0.00%	0.10%
Mine D	0.06%	0.00%	0.00%	0.00%	0.06%
Mine E	0.10%	0.07%	0.20%	0.00%	0.36%
Total	0.18%	0.05%	0.60%	0.00%	0.84%

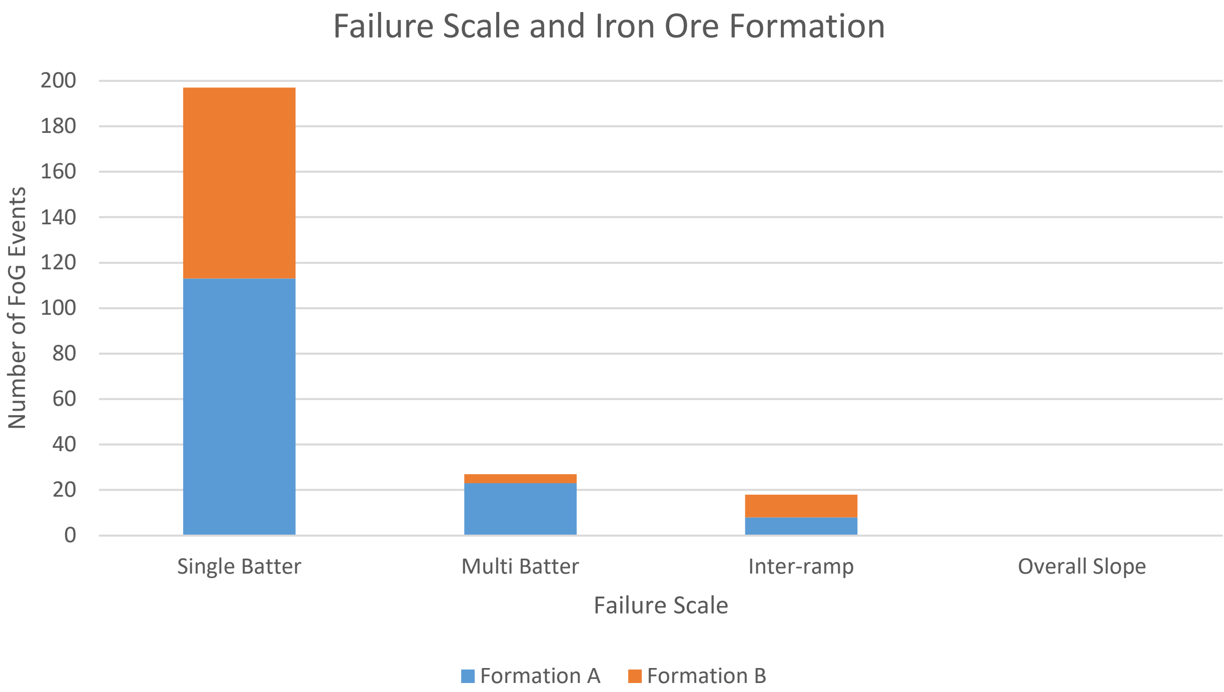

Figure 8 Slope failure scale by iron ore formation

4 Discussion

RTIO's FoG database provides an insight into slope failures across its open pit iron ore mines in the Pilbara region of Western Australia. This paper utilises a portion of the FoG database to investigate slope failures for the five mines assessed, with the database containing 15 years of information on FoG events. The data indicates over this time frame, on average, 14 single batter, two multi batter and one inter-ramp failure per year, with no overall slope scale failures. Figures 4, 5 and 6 show an increase in the occurrence of slope failures in the second half of the data, which aligns with a higher volume of material mined and improved reporting procedures. It is noted that Figures 4, 5 and 6 do not include all the FoG events for the five mines due to insufficient information on failure dates for FoG events identified through aerial imagery.

The results presented in Table 2 indicates the percentage of failed overall slope area for the five RTIO mines assessed are well within RTIO's probabilistic DAC, outlined in Table 1, for all failure scales at the time of assessment. Although the PoF and failure areas are not a direct comparison as discussed in Section 2, it is viewed that the failed slope area can be compared to RTIO's probabilistic DAC as a proxy to indicate the performance of the current pit slopes. These results are somewhat expected for bulk mining operations in which geotechnical parameters are often not the primary constraint of the design. However, these findings establish a strong foundation to comfortably pursue steeper slope designs as appropriate to the overall mine plan and strategy.

Annotation of slope failures in ArcGIS displays a concentration of slope failures in sections of the pit slopes, with FoG events not evenly distributed throughout the entire pit. This is displayed in Figure 1 above, with a higher percentage of failed overall slope area on the north wall, aligning with the structurally controlled section of the pit slope. Further assessment was completed to investigate the distribution of slope failures throughout the pit, with selected pits subdivided by design sector, providing a more comprehensive insight into the slope performance of structurally and rock mass controlled pit slopes. Tables 3 and 4 presents the results for structurally and rock mass controlled pit slopes and indicates a higher percentage of failed slope area in structurally controlled pit slopes. Although there is a higher percentage of failed slope area in structurally controlled pit slopes, both failure modes are within RTIO's probabilistic DAC. Aligning with the higher percentage of slope failures in structurally controlled pit slopes, Figure 7 indicates that a larger portion of multi batter and inter-ramp scale slope failures are structurally controlled. RTIO's FoG database captures causal factors of the reported FoG events, with a large portion of inter-ramp scale failures due to daylighting shale bands resulting in a planar sliding failure mechanism (structurally controlled) and a smaller portion of inter-ramp scale failures due to localised weaker rock mass resulting in circular and slumping failure mechanisms (rock mass controlled). It is noted that a smaller dataset was used to investigate the slope performance based on primary failure mode and further analysis should be performed to improve the accuracy and confidence of these results.

The probabilistic DAC allows for a higher PoF for single batter compared to inter-ramp and overall slope scale slope failures. The percentage of failed overall slope area in Table 2 indicates a larger percentage of failed overall slope area for inter-ramp scale compared to single and multi batter scale. Although a smaller percentage of failed overall slope area for single and multi batter scale failures, these two failure scales occur more frequently, as displayed in Figures 5 and 7, and indicates the dimensions of these failures are generally significantly smaller than inter-ramp scale failures. These results align with the risk assessments completed for each pit, with batter scale failures typically having a higher likelihood of failure compared to inter-ramp and overall slope scale failures. The percentage of failed overall slope for batter scale failures are potentially being underestimated due to two reasons. Firstly, it appears that a smaller percentage of batter scale failures are reported and an increased difficulty in accurately identifying unreported batter scale failures, that have been remediated, using aerial imagery. Secondly, the methodology used to calculate the percentage of slope failures potentially underestimates the percentage of batter scale failures due to the overall slope area, which includes the berms, is used instead of an area that only captures the batter area. Only using the batter area would be more representative of the area that can experience batter scale failure, as typically, batter scale failures do not break a significant distance beyond the crest.

RTIO operates in two different iron ore formations in the Pilbara region of Western Australia, Brockman and Marra Mamba. The slope performance was assessed for these two formations separately to identify if the performance of current pit slopes is significantly different between these formations, with results presented in Tables 5 and 6 and Figure 8. A total of 29 pits were assessed, compromising of 18 pits with Formation A and 11 pits with Formation B and the overall slope area ratio between Formation A and Formation B is 45:55. The results indicates that Formation B pits have a higher total percentage of failed slope area than Formation A pits. Separating the slope failures by failure scale indicates that batter scale failures are similar for both formations, with a slightly higher percentage of multi batter failures in Formation A. For inter-ramp scale failures, Formation B pits exhibit a larger percentage of failed slope area.

The overall results indicates that generally the current pit designs across the five RTIO mines assessed are conservative with the percentage of failed slope area significantly below RTIO's probabilistic DAC. Specifically, rock mass controlled pit slopes display an even lower percentage of failed slope area. This information indicates an opportunity to challenge the current design processes by using a large dataset to reconcile slope performance and potentially add value to the business by steepening pit slopes on a larger scale.

5 Conclusion

The methodology adopted in this report and RTIO's FoG database provides valuable information on current as-built pit slope performance and the ability to reconcile slope performance against the pit designs. The slope performance evaluation is supported with accurate FoG data captured by site geotechnical engineers managing the slope failures and slope failures identified through aerial imagery. The slope failures identified through aerial imagery are subjective to judgement, knowledge of pits and aerial imagery quality. Notwithstanding the above and inherent limitations of the analysis, the current as-built pit slopes assessed in this paper meets RTIO's probabilistic DAC and the results provide a starting point to review the design process with the view to optimise.

The data presented in this paper demonstrates the importance of RTIO's FoG database, which enables a strong feedback loop between the design process and slope performance. This information is now being used to inform design and risk tolerance decisions. This dataset also challenges current design paradigms and establishes a platform for increased slope optimisation.

Now that a comprehensive database has been established, it sets up further work to investigate holistic causal factors, time windows versus mining activity, geologic setting, design methodologies etc. Developing and strengthening data sets like this, which are founded by actual performance, is a crucial step of the overall design process. Utilisation of this FoG database is expected to yield many valuable insights and provide a basis for optimisation of design inputs and processes.

Acknowledgement

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