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Framework to predict open pit mine failure runout

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Abstract

This paper focuses on the development of a framework implemented by Rio Tinto Iron Ore to systematically document 185 instances of slope failures in open pit mining operations located in the Pilbara region of Western Australia. With mining activities extending to deeper levels within intricate geological formations, often below the water table, the frequency and potential lethality of slope failures have escalated. While prevailing guidelines and industry standards recognise a Probability of Failure (PoF) of up to 30% for controlled benches in open pits, with no personnel at risk, the immediate attention following a fall of ground (FoG) is typically directed towards operational risk management and rehabilitation.

Regrettably, the essential information pertaining to a FoG is frequently collected after the slope failure has undergone rehabilitation and operations have resumed, resulting in a delay in comprehending the underlying instability. This paper aims to rectify this issue by furnishing engineering personnel with a consistent and exhaustive dataset comprising FoG incidents. This dataset encompasses meticulous and comprehensive details including the circumstances surrounding each slope failure.

The paper introduces novel empirical relationships enabling the estimation of the runout distance for slope failures in open pit iron ore mining. These relationships consider several factors including slope height and angle, rock mass conditions, geological setting, the failure mechanism and the volume of failed material. By integrating this information into geotechnical design and risk management, engineers can formulate runout predictions through failure back-analysis and calibration of PoF and material strength assumptions.

The proposed data-driven approach aims to support geotechnical engineers and engineering geologists during both the design review and operational phases of mining projects. By adopting this framework, engineers can access a comprehensive dataset of FoG incidents, thereby facilitating calibrated geotechnical design and risk management practices. Ultimately, this strategy will enhance the safety and productivity of open pit mining operations.

Keywords: *slope stability, slope failure, runout distance, fall of ground, reporting, geotechnical data*

1 Introduction

The mining industry has experienced remarkable growth, largely driven by the increasing global demand for various minerals and the ongoing pursuit of more efficient extraction techniques (Read & Stacey 2009). A notable development in this regard has been the proliferation of open pit mining operations. These operations, despite their substantial contributions to economic development, carry substantial risks, including the considerable hazard of open pit wall failures (Bar et al. 2022; Bar & Barton 2018). Unforeseen events like these can greatly endanger operational safety, environmental integrity and economic viability. As a result there is an urgent need for predictive models to accurately forecast these failures, thereby enabling mining engineers to manage the attendant risks effectively (Bar et al. 2020).

Past research has been completed that attempts to predict mining failure runout (McQuillan 2020; Whittall et al. 2020, 2017a, 2017b). Whittall et al. (2020) assessed 167 open pit case studies from gold, boron, copper and coal mines. These case studies ranged in height from 50 to 500 m, with a slope angle from less than 20 to 65°. Similarly, McQuillan & Bar (2020) studied 311 failed slope cases from open cut coal mines in Australia and Canada. The failed slopes ranged in height from 6.5 to 63 m, with slope angles from 60 to 75°. Both studies highlighted the complexity of predicting slope failures due to varying failure mechanisms and geological conditions.

While significant strides have been made in risk management across the global mining industry, wall failures pose a complex issue due to the intricate interplay of geological, geotechnical and operational factors (Bar & Barton 2018). This complexity necessitates the development of sophisticated predictive models (Bar & McQuillan 2021). Therefore this paper aims to underscore the importance of capturing accurate data related to these factors. In doing so it proposes a simple relationship to estimate the potential runout of material in a Pilbara iron ore open pit wall failure.

Traditional methods of predicting wall failure consequences have often fallen short, largely due to the challenges associated with capturing and processing a diverse array of data (Finlay et al. 1999; Hungr 1995; Mitchell et al. 2018; Zou et al. 2017). This paper seeks to bridge this knowledge gap by analysing key factors contributing to the estimate of the Pilbara iron ore open pit wall failure runout, such as fall height, failure mode and slope scale.

By providing a framework based on numerous input factors to predict runout, this study strives to offer a foundation for informed decision-making in mining operations. The ultimate objective is to safeguard human lives, protect the environment and ensure economic sustainability in the industry. Furthermore, given the limited literature focusing specifically on open pit slope failure runout, especially on more frequent, lower magnitude events such as batter-scale failures, this study fills an essential gap. Leveraging an extensive dataset of 144 case studies from various open pit iron ore mines, this paper introduces relationships that use fall height as a predictor to estimate the runout distance of a Pilbara iron ore open pit slope failure. The proposed approach serves as an estimation method for practitioners to assess appropriate stand-off distances or exclusion zones until further control measures can be implemented, thereby significantly enhancing the process of risk management in open pit mining.

2 Method

The dataset used in this study comprises 144 documented failed slope cases from more than a dozen open pit iron ore mines in Australia (Figure 1). The data encompasses various failure mechanisms including structural, rock mass and complex. Among these, 41 cases are of multi-batter FoGs and 103 are cases of single-batter FoGs, with planar failure being a predominant factor in both categories.

Each of these cases provides measurements of key parameters including the Fahrböschung angle (used to describe the angle of the slope from the crest of the pit wall to the toe of loose material), slope angle, failure volume, runout from the crest, runout from the toe and fall height from the crest. These metrics provide detailed insight into the conditions and characteristics of each failure event. Other factors including geology, groundwater, weathering intensity and rock mass strength were not included in this geometric assessment and may contribute to material runout lying outside of the expected distances. Furthermore, the failure heights of the studied slope cases range from 1–120 m, with runout distances spanning from 1–40 m and overall slope angles of between 10 and 80 degrees. This extensive variability in parameters ensures a comprehensive understanding of the failure mechanisms across a wide range of geological scenarios including structural, rock mass and complex.

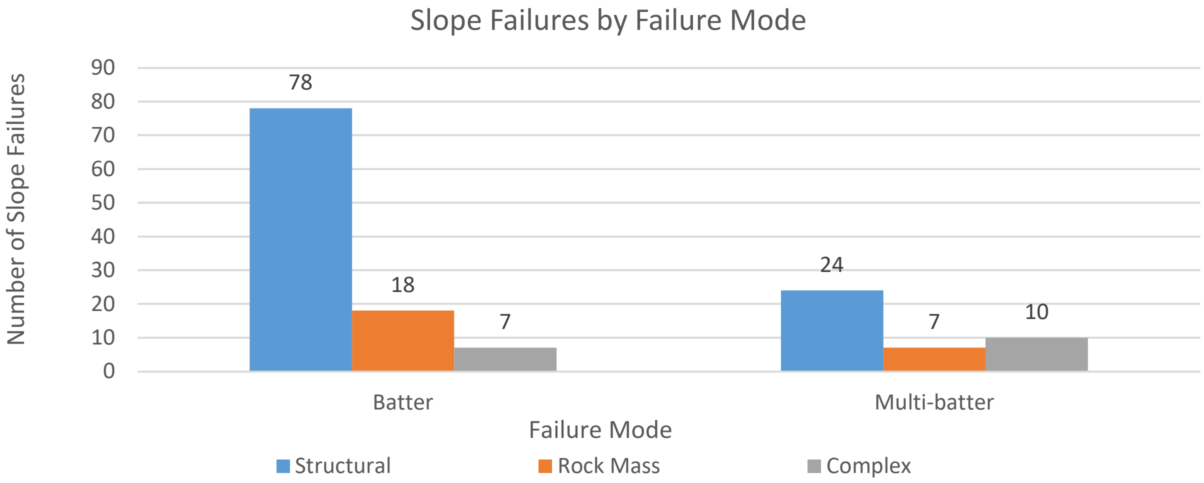

Figure 1 Description of the 144 failed open pit iron ore mine slopes investigated in this study separated by failure mode (structural, rock mass or complex) and failure scale (single batter or multi-batter)

A detailed schematic diagram (Figure 2) accompanying the dataset provides the nomenclature used to describe various geometrical aspects of the slopes and the primary mass of failed material runout parameters. This graphical representation serves to further elucidate the concepts and terminologies referenced throughout the data.

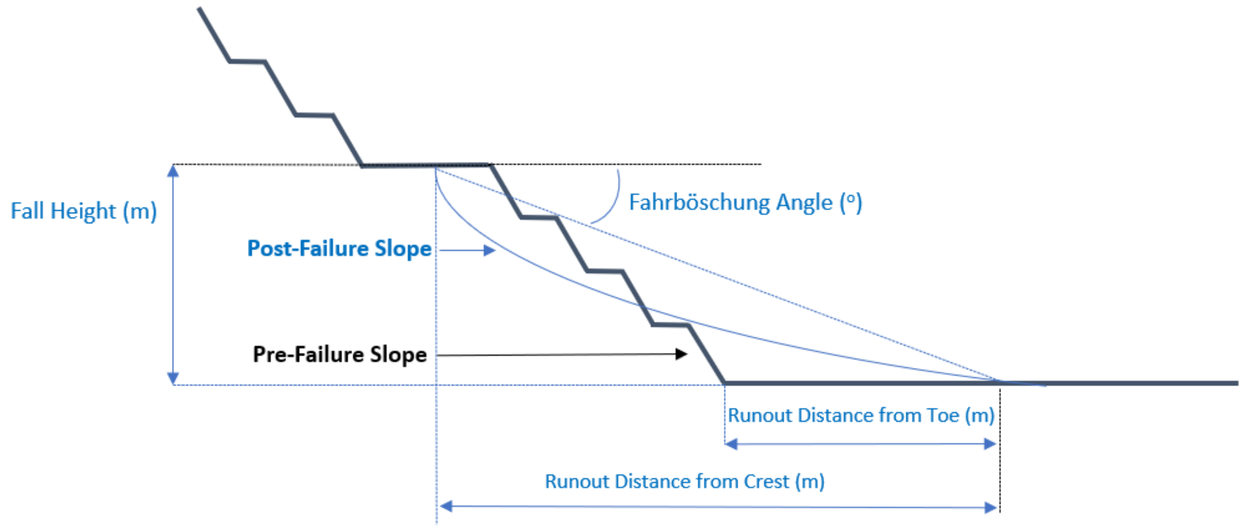

Figure 2 The slope failure parameters collected for the 144 failed open pit iron ore mine slopes

In this study the methodology entailed conducting evaluations to explore potential correlations among a set of predefined parameters. These parameters included: (a) a comparison between the fall height and runout distance from the crest, with this approach juxtaposed against the work of Whittall et al. (2020); (b) an assessment of the correlation between the fall height and the runout from the toe, a comparison drawn against the findings of McQuillan & Bar (2020) and Whittall (2019); (c) the relationship between the Fahrböschung angle and the slope angle, a key metric used in assessing landslide risk (Corominas 1996); and (d) the association between the Fahrböschung angle and the volume of the failure. Each of these parameters was presented for failure mode and failure scale, and was evaluated in a systematic manner aiming to enhance the accuracy of our predictive models for open pit slope failures.

3 Results

Measurements extracted from the FoGs were analysed to identify useful trends for application in geotechnical hazard identification and risk mitigation. Identified trends included: (i) a strong correlation between fall height and the runout distance from the crest by failure mode; (ii) a positive correlation between fall height and the runout distance from the crest by failure scale; and (iii) a moderate correlation between fall height and the runout from the toe for complex and multi-batter failure modes and scales, respectively. Finally, from the analysis, no correlation between fall height/runout distance and slope angle or failure volume was observed. These relationships are discussed further in the following sections.

3.1 Fall height and runout distance from the crest

The analysis of fall height in relation to maximum runout distance from the crest, when segregated by failure mode and failure scale (Figures 3 and 4), revealed a robust correlation. This finding is consistent with previous research conducted by Corominas (1996) which demonstrated that failures originating from higher heights exhibit greater travel distances. Specifically, if two identical failures occur from different heights, the one with a larger drop will travel a greater distance. This observation can be attributed to the influence of potential energy, wherein the distance travelled by the failed material is directly proportional to the available potential energy, predominantly dictated by the slope height (Corominas 1996; McQuillan & Bar 2020).

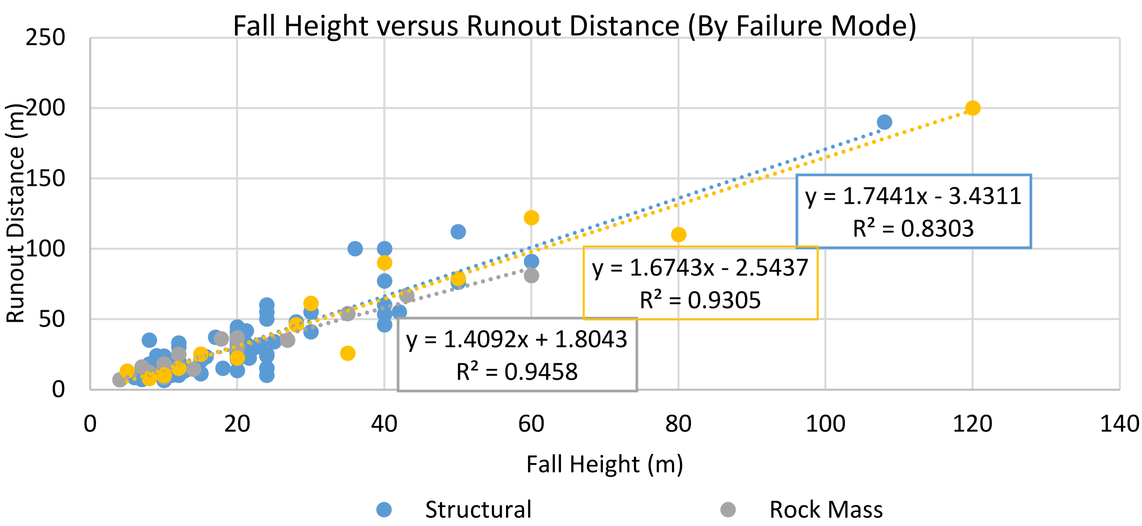

Figure 3 Relationship between fall height and runout distance from the crest respective of the failure mode from 144 failed slope cases in open pit iron ore mines, where R^2 is the coefficient of determination between the actual and predicted values

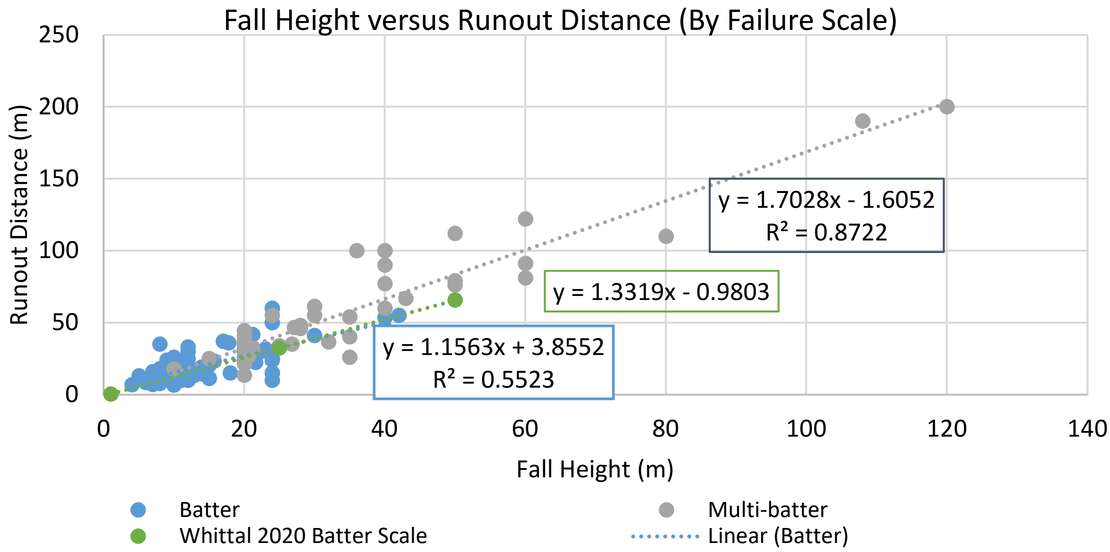

Figure 4 Relationship between fall height and runout distance from the crest respective of failure scale from 144 failed slope cases in open pit iron ore mines, where R^2 is the coefficient of determination between the actual and predicted values

Utilising linear regression analysis, the relationships between fall height and runout distance from the crest (Figures 3 and 4) were defined. The resulting linear regression models enabled the estimation of runout distance based on the input fall height value. The strong relationships observed between fall height and runout distance, when examined in the context of failure mode, emphasise the necessity of comprehending the underlying geomechanical failure mechanisms to accurately predict runout distance. These findings highlight the importance of a thorough understanding of potential failure modes in developing reliable runout distance predictions. The relationship observed for multi-batter failure scale in Figure 4 aligns favourably with the findings reported by Whittall et al. (2020) regarding batter-scale failures. This correspondence strengthens the reliability and applicability of the presented results, further supporting their practical significance.

The predicted failure runout distances from the crest that were derived from this study hold practical implications for geotechnical engineers and engineering geologists. Specifically, these estimates can assist in determining suitable stand-off or exclusion zones at the base of unstable or failing slope sections. By minimising the risk of harm to individuals and equipment operating within the pit, these predictions contribute to enhanced safety measures and informed decision-making within the field of geotechnical engineering.

3.2 Fall height and the runout from the toe

Upon analysing the relationship between fall height and maximum runout distance from the toe when divided by failure mode and failure scale (Figures 5 and 6), it was observed that the correlation was not as strong compared to that from the crest. The linear regression models depicted in Figures 5 and 6 were employed to estimate failure runout from the toe across varying fall heights. The estimated relationships displayed moderate correspondence, specifically for multi-batter failure in terms of failure scale and complex failure for failure mode. Nevertheless, the weak associations observed between fall height and runout distance from the toe did not align with the confidence thresholds proposed by McQuillan & Bar (2020). This discrepancy suggests that runout distance from the toe may not be the most suitable parameter for accurately calibrating runout distance for an open pit iron ore pit slope.

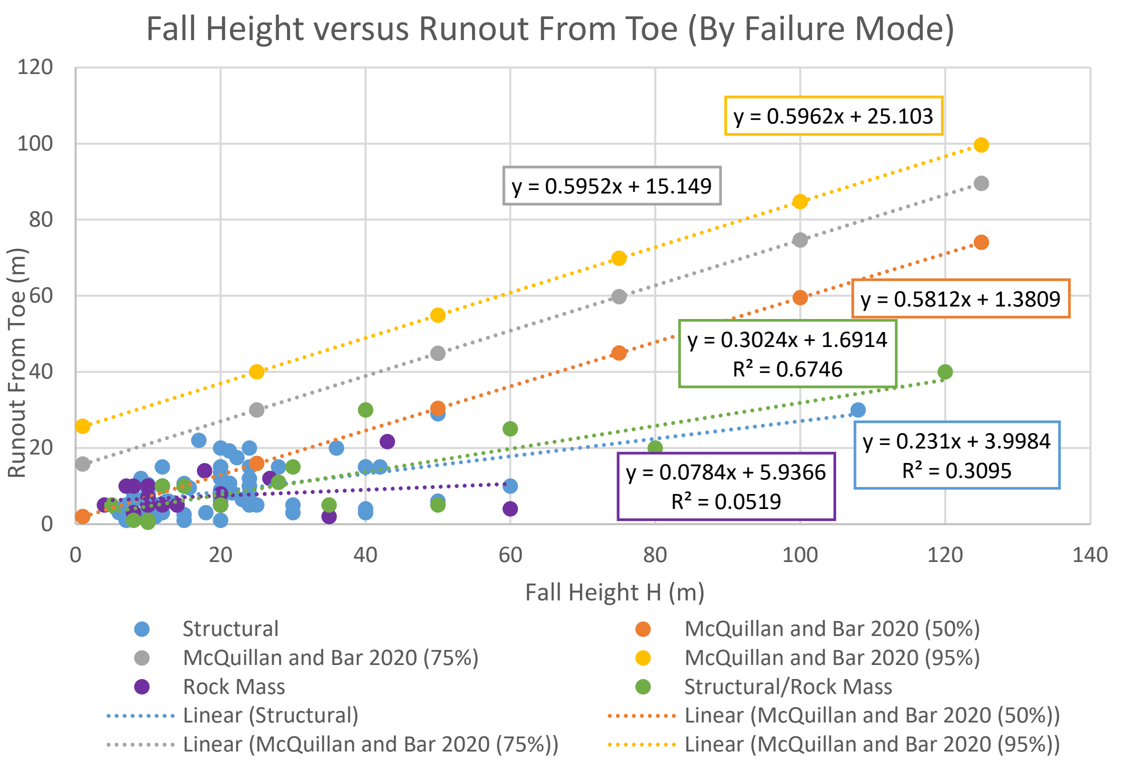

Figure 5 Relationship between fall height and runout distance from the crest respective of failure mode from 144 failed slope cases in open pit iron ore mines, where R^2 is the coefficient of determination between the actual and predicted values

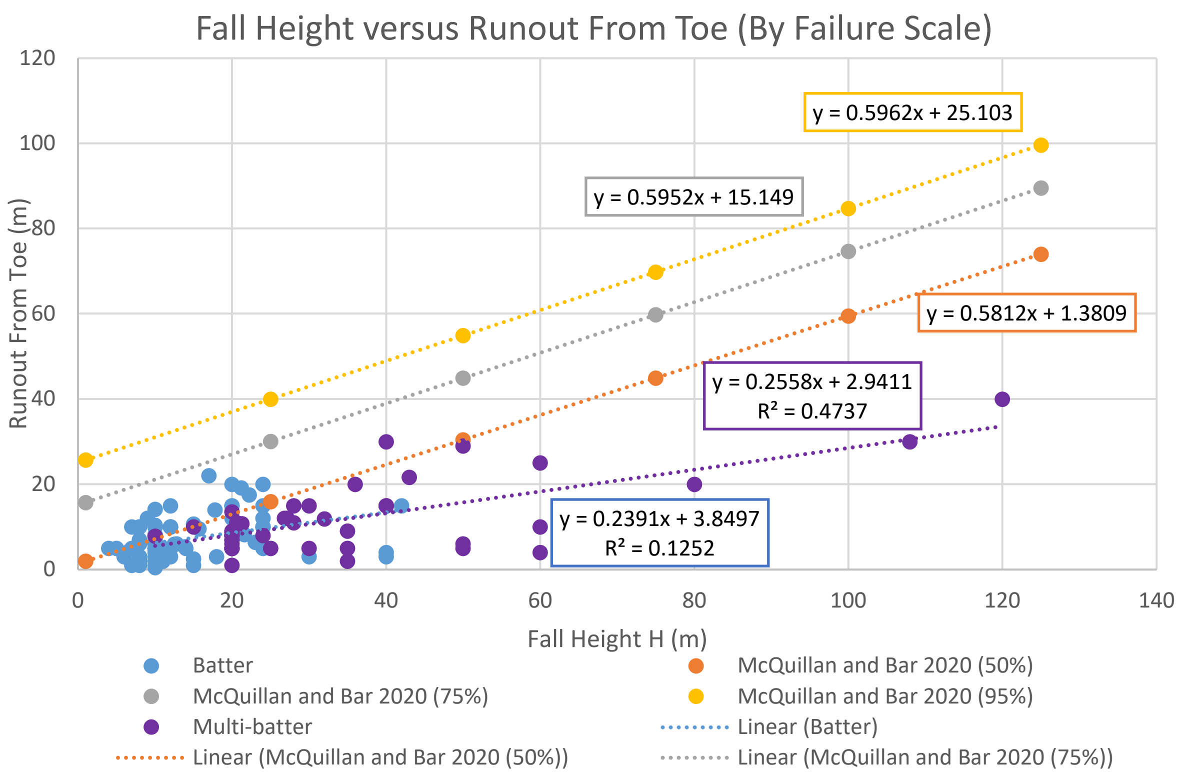

Figure 6 Relationship between fall height and runout distance from the crest respective of failure scale from 144 failed slope cases in open pit iron ore mines, where R^2 is the coefficient of determination between the actual and predicted values

3.3 Fall height/runout distance

The investigation into the correlation between the ratio of the fall height to runout distance and slope angle (Figures 7 and 8) as well as failure volume (Figures 9 and 10) revealed no meaningful associations, even when considering the breakdown by failure modes and failure scales. These findings are consistent with the research conducted by McQuillan & Barr (2020), who reported a lack of correlation between the Fahrböschung angle and slope angle in their analysis of 311 failed slopes. Conversely, Whittall et al. (2017b) proposed that the Fahrböschung angle versus volume and Fahrböschung angle versus slope angle relationships could provide reasonable estimates of runout from a dataset encompassing 105 failed slope cases. Furthermore, it is worth noting that the Fahrböschung angle did show significance when examined in relation to landslides (McDougall et al. 2012).

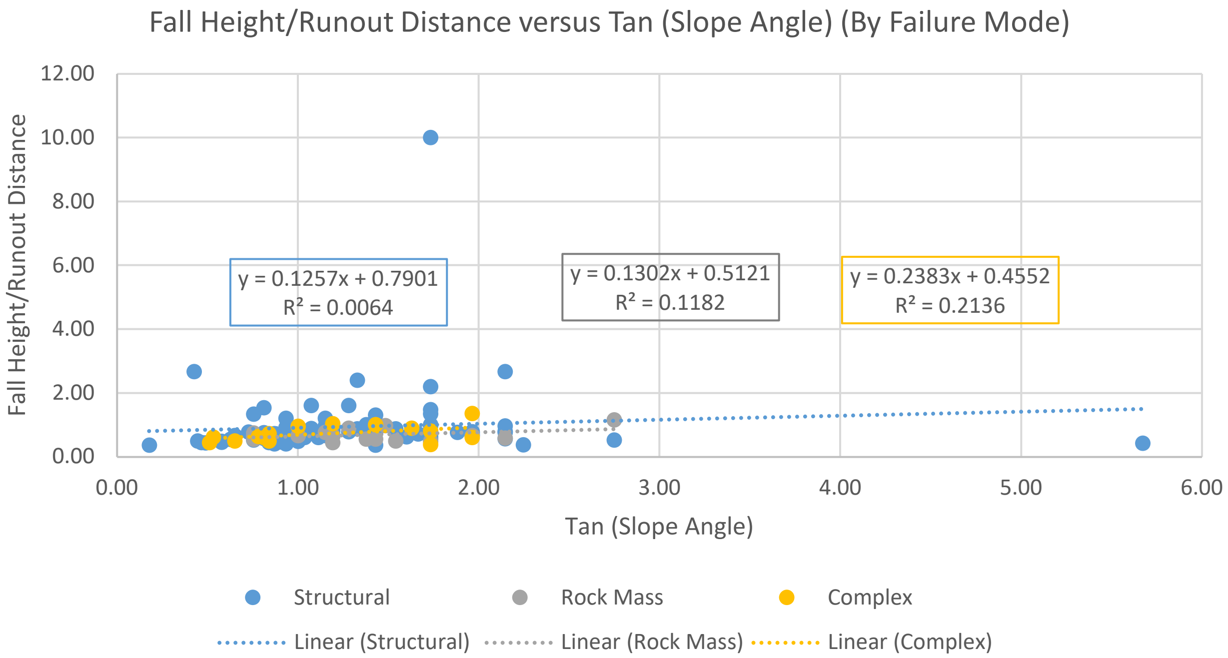

Figure 7 Relationship between fall height/runout distance versus slope angle respective of failure mode from 144 failed slope cases in open pit iron ore mines, where R^2 is the coefficient of determination between the actual and predicted values

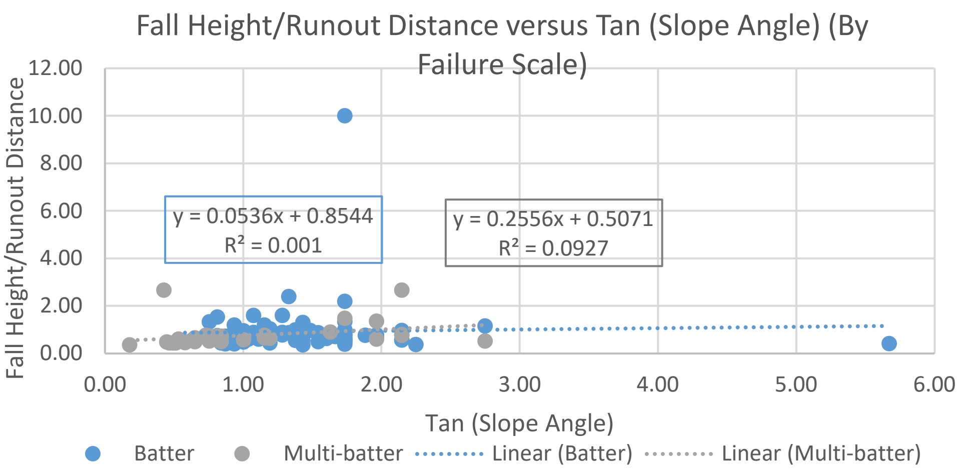

Figure 8 Relationship between fall height/runout distance versus slope angle respective of failure scale from 144 failed slope cases in open pit iron ore mines, where R^2 is the coefficient of determination between the actual and predicted values

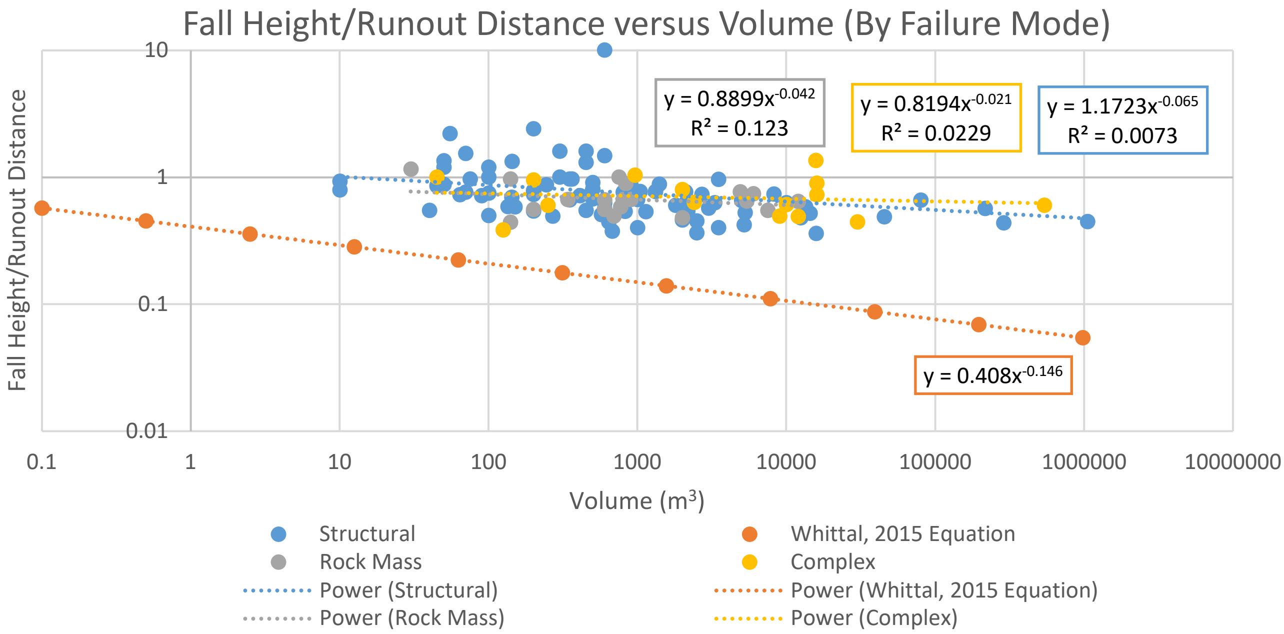

Figure 9 Relationship between fall height/runout distance versus failure volume respective of failure mode from 144 failed slope cases in open pit iron ore mines, where R^2 is the coefficient of determination between the actual and predicted values

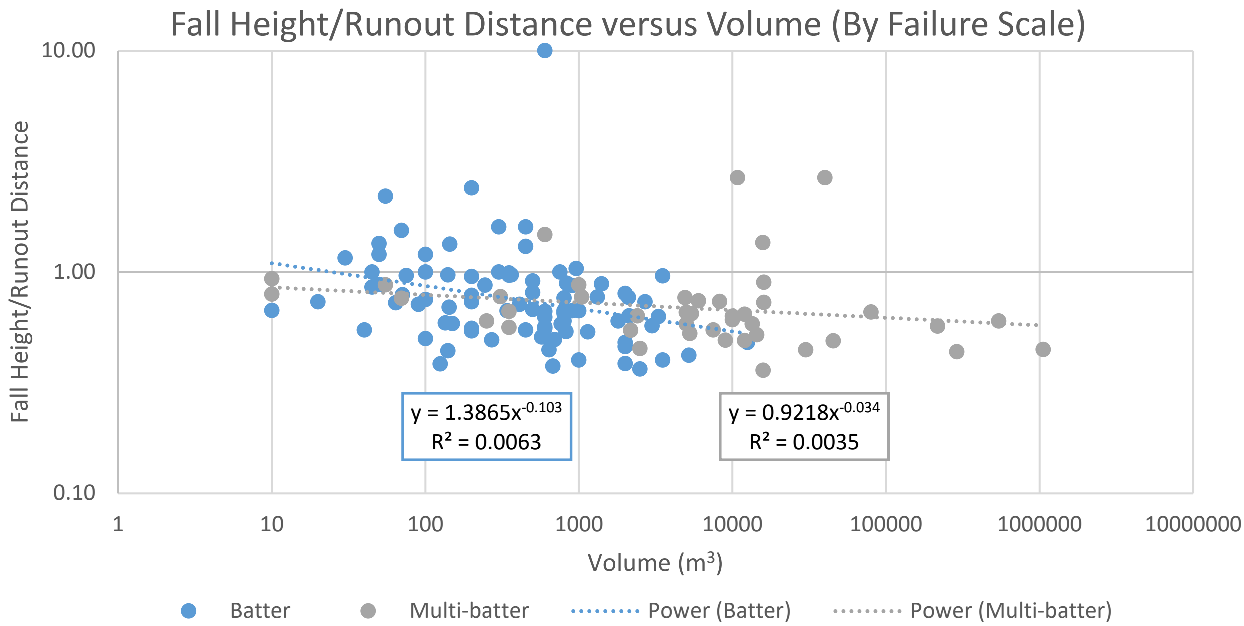

Figure 10 Relationship between fall height/runout distance versus failure volume respective of failure scale from 144 failed slope cases in open pit iron ore mines, where R^2 is the coefficient of determination between the actual and predicted values

4 Discussion

The relationship between runout distance and fall height was explored in this study, specifically comparing runout distance from the crest with runout distance from the toe. The findings demonstrated that the relationship between runout distance and fall height was strongest when considering runout distance from the crest, with the linear relationships presented in Figures 3 and 4 providing a valuable addition to existing slope stability and runout assessment methods and tools (Bar & McQuillan 2021; Whittall et al. 2017b).

It is important to note that the runout prediction equations should not be interpreted as deterministic values but rather as estimates based on the distribution of measurements in the reference database. Moreover, the analysis is based on the runout of the main failed mass, and individual debris may run out beyond the limits predicted by the models. These equations serve as a useful tool for estimating runout distance but they should not replace the comprehensive numerical modelling and inspection processes. While the empirical equations presented in this study contribute to runout prediction, they should be used in conjunction with other tools and methods to ensure comprehensive slope stability assessment. The combination of empirical approaches and numerical modelling, along with regular inspections and monitoring, provide a more robust and reliable framework for slope risk management in open pit mining operations.

5 Conclusion

Calibrated predictive models are essential for effectively managing the significant risks associated with open pit wall failures, which can have detrimental impacts on safety, the environment and economic viability. This study contributes to the development of such models by presenting empirical relationships between fall height and runout distance from the crest which demonstrate a strong correlation, supporting their utility in estimating runout distance. However, weaker associations were observed between fall height and runout distance from the toe, suggesting that this parameter may not be as effective for calibrating runout distance when considering the Pilbara iron ore pit slope dataset. Furthermore, the lack of significant correlations between the Fahrböschung angle and other parameters underscores the challenges associated with predicting runout distances of open pit slope failures. By providing a comprehensive framework based on multiple input variables, this study offers a valuable tool for informed decision-making in mining operations. The integration of empirical relationships with numerical modelling and regular pit inspections enhances the accuracy of slope stability assessments and risk management. It is important to note that the empirical equations should be treated as estimates rather than deterministic values, and they should be used in conjunction with other tools and methods. Overall, this research contributes to the ongoing efforts to safeguard lives and ensure the sustainability of mining operations.

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