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Improved prediction of runout distance for in situ highwall instability in Australian eastern coast coal mines

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Abstract

The non-homogenous and often insufficiently characterised nature of rock slopes requires mining geotechnical engineers to ensure that pit design is supported by appropriate operational controls. The consequences and near misses from recent large open pit slope failures (>500 m^3 failed volume) have driven industry bodies to further refine the delineation of wall failure runout distances.

In managing failure hazards, a standoff distance is typically determined by the prediction of potential failure mechanism, volume, and runout distance. Accurate prediction of the runout distance is critical to mine operations for safety and economic reasons.

Whilst a comprehensive dataset and research history exists for slope runout predictions in environments such as rock avalanches, landslides, and natural debris flows, similar work directly applicable to the open cut coal mining industry is in its infancy. In particular, the travel angle, or Fahrböschung angle, is a well-recognised relationship that has been used for excavated slopes but is not commonly applied to open cut coal slopes less than 100 m.

This investigation has taken the opportunity to gather and interpret new data points from historic failures to improve the accuracy of runout distance predictions. The new dataset included over 50 additional historic open cut highwall failures from eight open cut coal mines situated across the Bowen Basin and the Hunter Valley. Systematic characterisation of runout distances was based on geotechnical parameters such as in situ wall failure height, floor dip, slope angle, failure mechanism, volume of failed material, and geotechnical domain.

Through detailed analysis, this new dataset has been statistically evaluated and showed comparable results to previously published data, including the coal industry specific slope stability assessment methodology (SSAM) tool, as well as new empirical trends. Additionally, the investigation has considered initial works for a Fahrböschung angle relationship.

This database can be used as a proactive tool to inform failure run out predictions, and also to ensure learnings and data from past failure history is captured and used by the next generation of geotechnical engineers without having to experience past failures.

Keywords: *runout distance, standoff, highwall failure, coal mine, Fahrböschung angle*

1 Introduction

Whilst excavated mine slopes are designed to be geotechnically stable, there are instances where natural variability, geological uncertainty, or decision uncertainty have led to pit slope failures. A critical component of the site geotechnical engineer's role is to provide Fall of Ground hazard control to support safe and economic operations. Particularly, highwall failures have a large impact on production and greatest potential for injury due to volume of failed material and rapid failure progression when Fall of Ground risk is considered for open cut coal mines.

Whilst the number of high potential incidents related to falls of ground in Queensland mines and quarries has reportedly decreased slightly from 51 in 2018–2019 to 47 in 2019–2020 (Resources Safety and Health Queensland 2020), more progress is still required to maintain safe operations. Additionally, the aversion to voluntarily publish case histories describing pit slope failures in the mining industry has resulted in a lack of lessons learnt and quality data available. In terms of toppling failures, references in open cut coal mines are sparse, with majority of research being completed in other rockfall environments where different rheological conditions and mobility trends apply. Coupled with the current skills shortage in geotechnical engineering, these combined factors suggest that there is a risk of knowledge loss and potential to repeat past mistakes.

Controlling a highwall instability during excavation can be done through a standoff with a bund, at an engineered location based on predicted runout distance. The use of the bunded standoff is two-fold; it firstly delineates the hazardous area and secondly provides catch capacity if the wall were to fail. The prediction of the failure runout, or how far the failed material will dislodge from the wall is determined by a number of parameters including geotechnical domain, rheological model, slope height and angle, failure height, presence of structure, structural dip and angle of intersection with the highwall.

The determination of a runout distance is difficult to estimate if there is a limited amount of data that may be available in the field when a prompt response must be made. Using the data from a sufficient size database of previous rockfalls enables the development of an empirical model. This paper recognises the work done by Whittall (2009), Whittall et al. (2017a) and Whittall et al. (2017b) in determining runout distances for larger open pit failures (most with a fall height between 75 m and 400 m) where appropriate.

Whittall (2009) used a failure database to determine a Fahrböschung angle, or travel angle, which is a relationship used to predict the distance between the failure backscarp and the final resting trajectory of failed material furthest from the highwall. The respective models and constants, however, have a rheological model influenced by debris flow, liquefiable substrates, and vegetation which are not always applicable for the open cut environment. This paper details the case studies of 40 new wedge failures and 11 toppling failures recorded across BHP open cut coal mines over the past 11 years. Failure runout distance relationships have been developed for the prediction of highwall wedge failures using a similar Fahrböschung angle method to Whittall (2009). The same relationship could not be inferred for the toppling mechanism, however, the industry-leading slope stability assessment methodology (SSAM) developed by McQuillan (2019) validates mobility trends.

2 Methodology

2.1 Variable selection

Records of highwall failures across BHP open cut coal mines were collated into a database which included extracting the parameters required as inputs into a runout calculation. The information was separated into two datasets: wedge/planar and toppling failure mechanisms. The selection of parameters to be collected was based on enabling a Fahrböschung calculation to be produced. The structural defect properties were based on ranges in the SSAM runout prediction tool. The list of collected variables is found in Table 1.

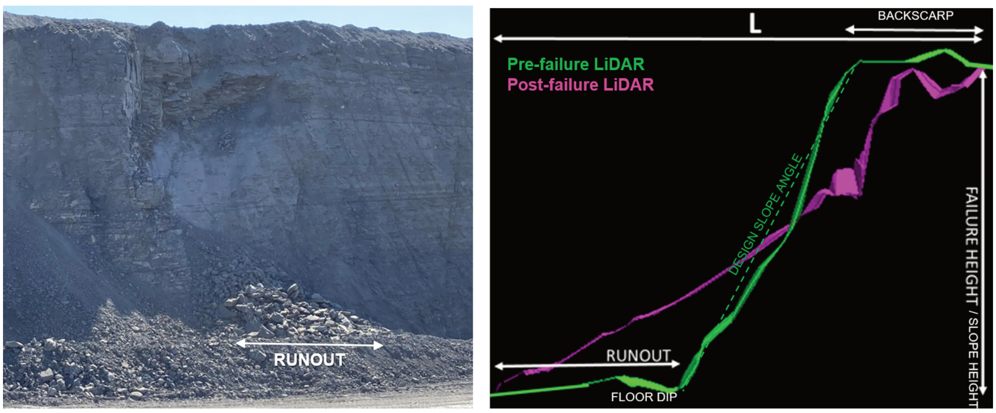
Table 1 Data parameters collected for the highwall failure database

Parameter	Unit	Details
Bench slope angle	Degrees (°)	Overall crest to toe angle, typically aligned to design angle
Bench slope height	Metres (m)	Crest to toe (dz)
Runout distance	Metres (m)	Horizontal distance from highwall toe to the final resting point of furthermost dislodged rockfall piece
Failure height	Metres (m)	Measured from toe of highwall to crest of failure (dz). This may be equal to the bench slope height
Failure volume	Cubic metres (m^3)	Assumed to be an approximate swell volume calculation after time of failure
Backscarp	Metres (m)	Measured from highwall face to furthest depth of failure into the wall
Structural dip	Degrees (°)	Range selection of 0–40°, 40–60°, 60+°
Structural angle of intersection with highwall	Degrees (°)	Range selection of 0–30°, 30–50°, 50+°
Pathway obstruction	Y/N	Whether a stopping bund was in place prior to failure
Failure mechanism	–	Wedge/planar, or toppling

2.2 Data collection

Case examples of rockfalls were identified by interrogating BHP Coal's open cut examiner reporting tool database (HazRT), finding cases as far back as 2009. All failures have occurred in fresh permian rock slopes up to 65 m located across eight open cut coal mines located in either the Bowen Basin or the Hunter Valley. Rock composition typically consists of high-strength sandstone and interbedded siltstone and mudstone, where coal seams generally dip into the highwall.

Quantitative data was collected using the available LiDAR survey scans to compare pre- and post-failure conditions (Figure 1). The Maptek Vulcan program (Maptek 2021) was used to take a worst-case cross-section to measure and collect the data variables detailed in Table 1. A total of 51 new case studies were captured into the new database: 11 toppling failures and 40 wedge/planar failures. The failure database was then subject to analysis against existing published datasets; namely the industry-leading SSAM calculator (McQuillan 2019).



(a) (b)

Figure 1 **(a) Highwall wedge failure at a BHP Coal site showing runout distance of the failure volume; (b) Cross-section measurements taken of failure database input**

3 Empirical relationship findings

3.1 Slope stability assessment methodology comparison

The first coal industry runout prediction tool, SSAM, provides an empirical relationship between slope height and failure runout distance. The linear approximation equations for runout distance predictions are (McQuillan 2019):

Wedge failure

$$Dr_{50\%} = 0.459x - 0.773 \quad (1)$$

$$Dr_{95\%} = 0.4651x + 8.9533 \quad (2)$$

Toppling failure

$$Dr_{50\%} = 1.0526x - 4.2105 \quad (3)$$

$$Dr_{75\%} = 0.9435x + 21.391 \quad (4)$$

where:

$Dr_{a\%}$ = runout distance with an '*a*' % empirical probability that the true runout will be equal or less than the predicted runout.

X = slope height (m).

In comparison to the measured runout distances in the failure database, the results show that 80% of wedge failures have a runout distance inside the SSAM 50% prediction interval. Using a 95% confidence interval, it is reasonable to multiply the SSAM 50% prediction interval by 1.1 to predict runout distance for the conditions of the coal mines assessed (Figure 2). For toppling failures, 95% of failures have a runout distance inside the SSAM 50% prediction interval (Figure 3). Toppling data points where slope heights were less than 25 m showed inconclusive results and were excluded from the set. Therefore, the failure database provides validation of the SSAM empirical linear relationship between slope height and runout distance.

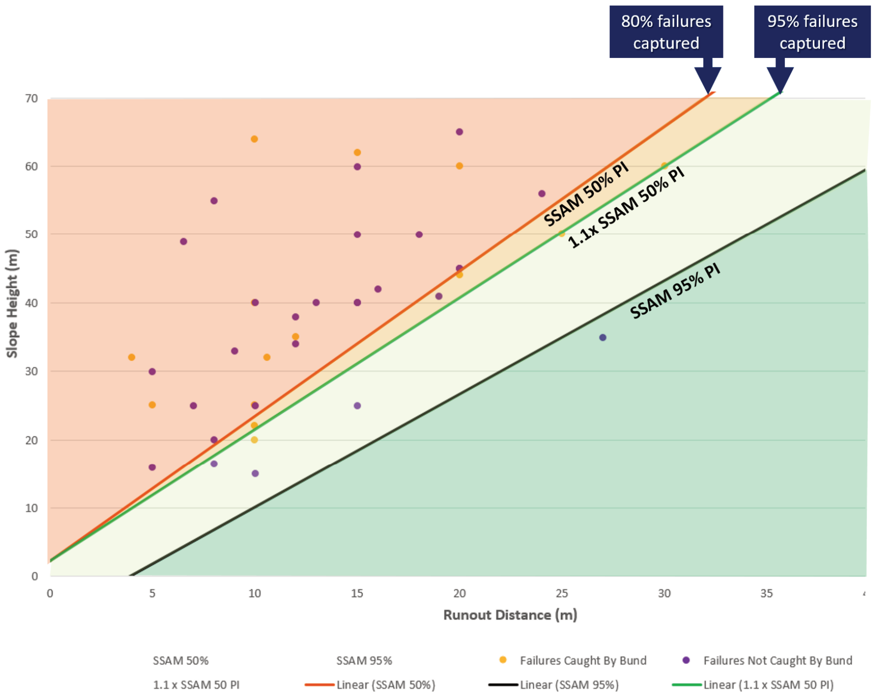


Figure 2 Wedge failure database comparison to slope stability assessment methodology (SSAM) predictions (PI = prediction interval)

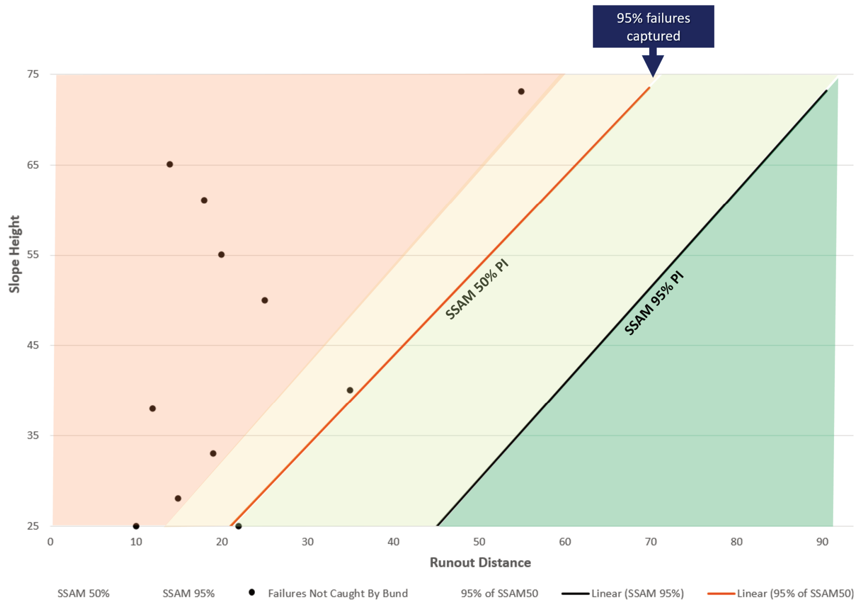


Figure 3 **Toppling failure database comparison to slope stability assessment methodology (SSAM) predictions (PI = prediction interval)**

3.2 Other empirical relationships of data variables regarding runout distance

3.2.1 Slope height and slope volume for wedge failures

The runout distances captured in the new failure database, and predictions from SSAM, clearly demonstrate the relationship between slope height and runout distance for both toppling and wedge failures.

Assuming that most wedge and toppling failures are structurally controlled, a greater slope height inherently means a greater volume of failed material should also be expected where defects are of the same orientation (Figure 4). Failure relationships found in the new database have been compared to another published dataset for excavated coal mine slopes found in McQuillan (2019). Wedge failure data has shown conclusive results of an empirical power trend existing when data from both sources is collated.

The power trend relationship in Figure 4 shows approximate failure volumes that can be expected. The relationship between slope height and runout distance is shown in Figure 5. Data suggests that 82% of combined data points observe a relationship where runout distance is less than or equal to half the slope height.

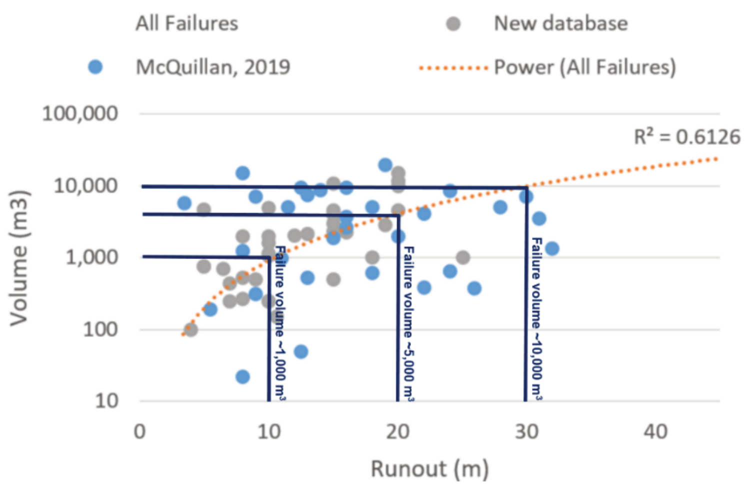


Figure 4 **Relationship between wedge failure volume (m^3) and runout distance from the new failure database and data in (McQuillan 2019)**

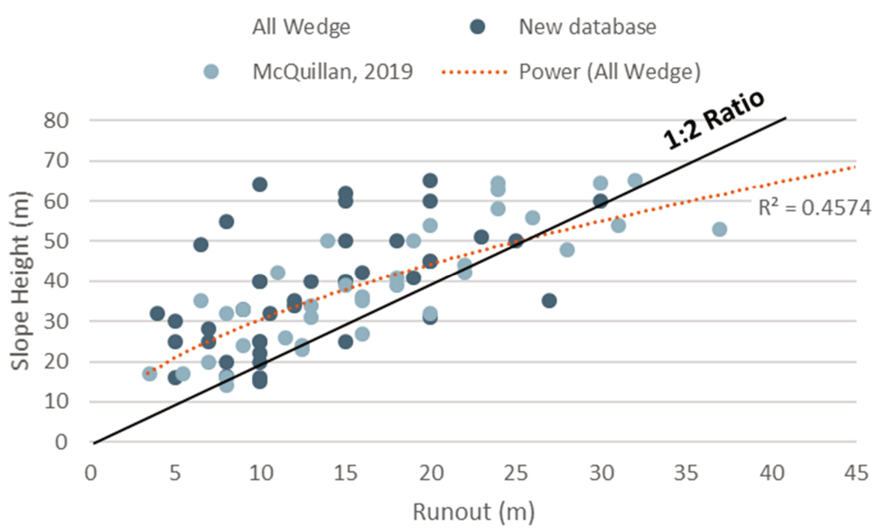


Figure 5 Relationship between wedge failure slope height (m) to runout distance (m) from the new failure dataset and McQuillan (2019)

3.2.2 Lateral spread

Lateral spread is the ratio between in situ failure cavity width and failed material spread width (Figure 6). The new database results show that for wedge failures, a mean lateral spread of 1.55 times the failure width can be expected. A median lateral spread of 1.54 times the failure width was demonstrated. A maximum lateral spread of 2.2 times the failure width was calculated (Figure 7). For toppling failures, the results are inconclusive as accurate measurements for these criteria could only be attained for three case studies. However, a maximum lateral spread of two-times the failure width was calculated. The findings are commensurate with the results detailed in McQuillan (2019) where 90% of failed slope cases were calculated to have lateral spreads of less than or equal to 2.2.

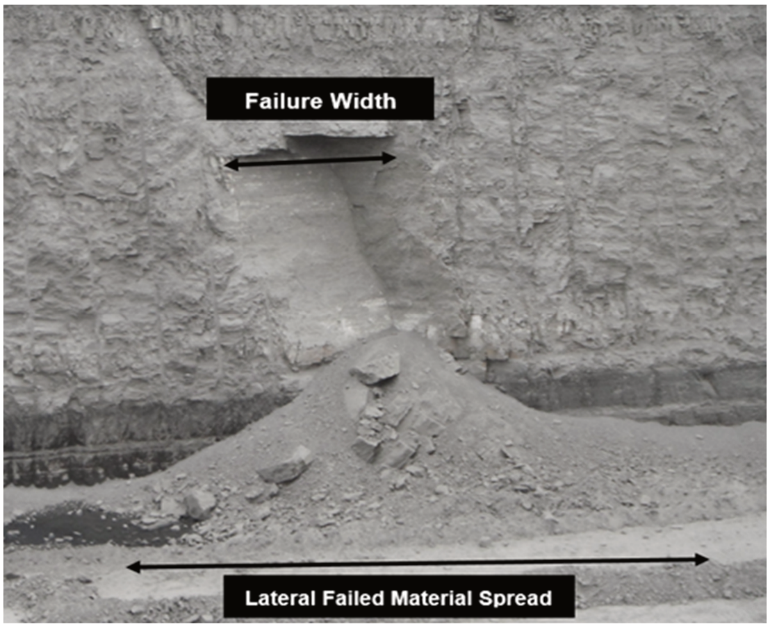


Figure 6 Example of lateral spread calculation method

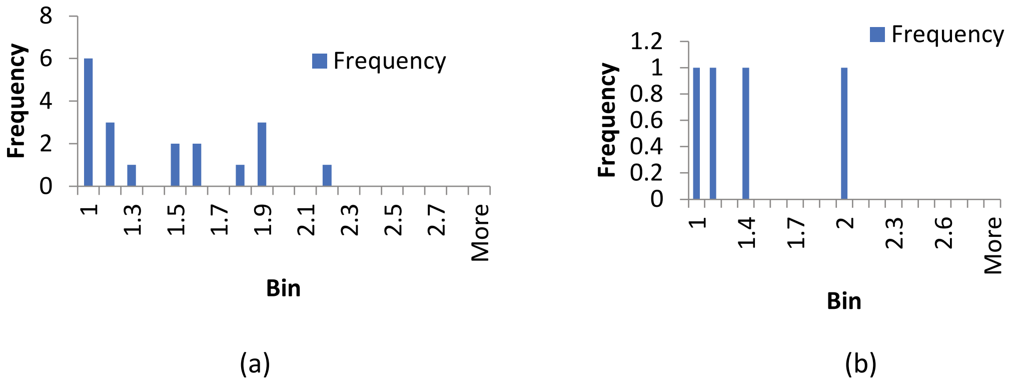


Figure 7 (a) Lateral spread factor histogram for wedge failures from the new database; (b) Lateral spread factor histogram for toppling failures from the new database

3.2.3 Structural orientation

All 51 case studies failed on at least one structural defect. For wedge/planar failures, all of these defects failed where the structural dip was greater than 40°and 64% had an angle of intersection of less than 30°. Where wedge/planar failures contained two structural defects, 69% of cases had at least one defect with a dip greater than 60° and 50% had a combination of one angle of intersection less than 30° and one angle of intersection greater than 50°. These results are reasonable and reflect the higher risk ranges in SSAM prediction analyses.

For toppling failures, only three cases contained two structural defects. 90% of cases contained a structural defect with a dip greater than 60° and an angle of intersection less than 30°.

3.3 Improved prediction of toppling runout distances

In toppling failures, joint spacing and persistence means that different slope height to block thickness ratios exist. This changes the forward displacement experienced by the overturning rock columns, which makes it difficult to define a runout distance prediction standard for all toppling failures; especially considering that there may be unknown structures present behind the wall.

A common industry practice is to assume a 1:1 ratio of slope height to runout distance (Figure 8). This conservative approach is appropriate for toppling failures, which are the highest severity failure mode based on increased velocity, faster acceleration, and larger failure volume. The new failure database confirms the appropriate use of this technique, supported by data in McQuillan (2019).

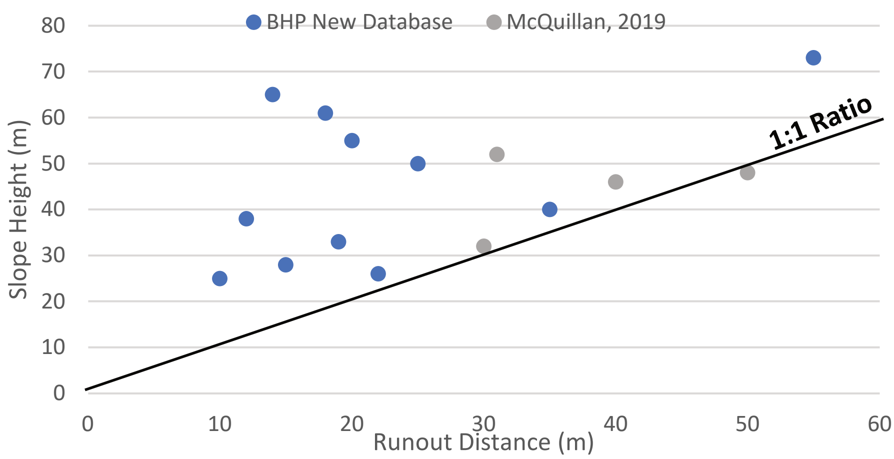


Figure 8 Relationship of slope height (m) to runout distance (m) for toppling failures, showing the 1:1 ratio linear trend

4 Improved prediction of wedge failure runout distances

4.1 Development of Fahrböschung angle for wedge failures

Using back-analysis of case studies in the new failure database, a Fahrböschung angle can be translated for artificially excavated open cut coal mines. The parameters required for the back-analysis are detailed below in Figure 9. Back-analysis of the failure database determined a Fahrböschung angle, (θ_F), of 43° exists for open cut coal highwalls (≤65 m high) where conditions are similar to the study region strata. A mean angle of 42.7° and a median angle of 43.8° was calculated (Figure 10).

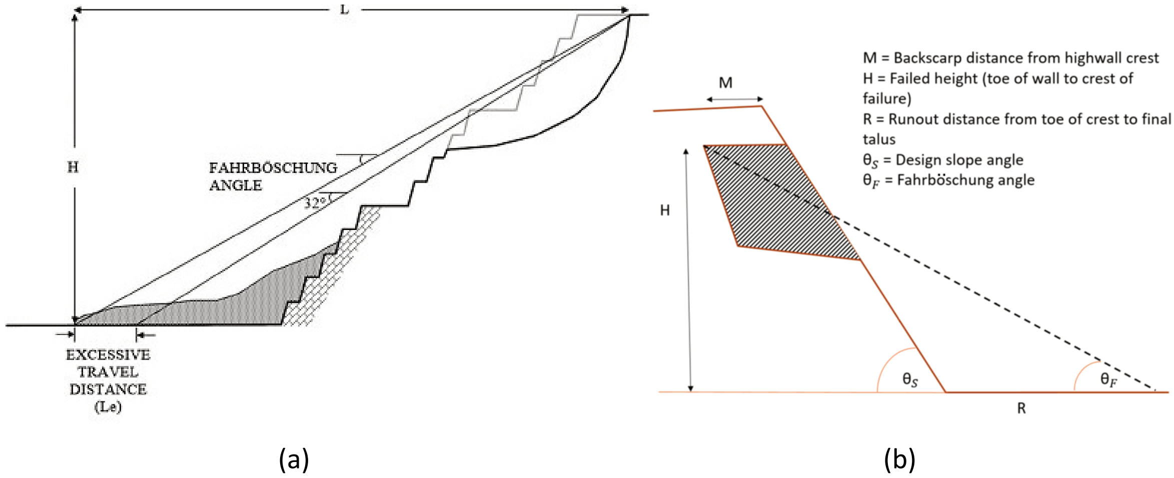


Figure 9 (a) Diagram of Fahrböschung angle used in Whittall (2009); (b) Design parameters used in the determination of the Fahrböschung angle for coal mines for the new database

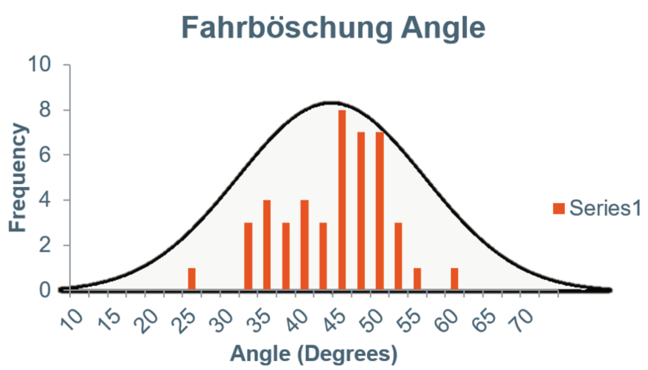


Figure 10 Determination of Fahrböschung angle from the new failure database

As the backscarp distance into the crest is dependent on daylighting structure angle or plunge angle, low geological confidence or understanding may hinder these from being known prior to potential failure. In order to make the relationship applicable in the absence of a backscarp distance measurement, a theoretical backscarp approximation can be used (Figure 11). Using the failure backscarp predictions allows trigonometry to predict runout distance for a given slope, where the only input parameters required are failure height and slope angle.

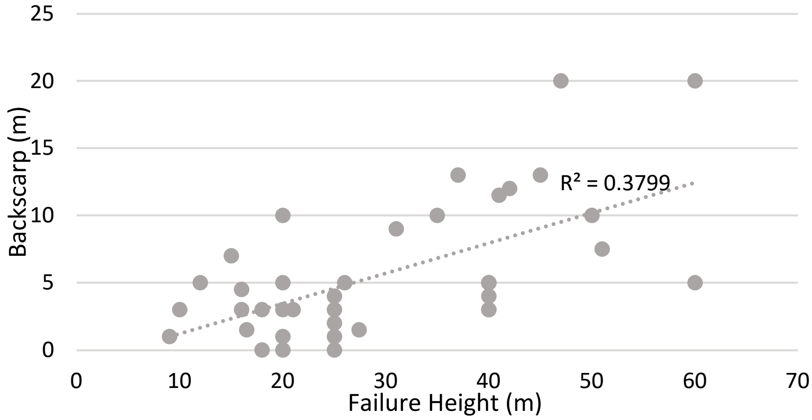


Figure 11 Relationship between backscarp distance and failure height

The applicability of the theoretical relationship has been tested by using the developed Fahrböschung angle and theoretical backscarp where runout distances were calculated for the case studies (Figure 11). The mean and median prediction were within 6% of the actual measured runout (Figure 12 and Figure 13). The results demonstrate a solid approximation of runout prediction in the absence of higher confidence data.

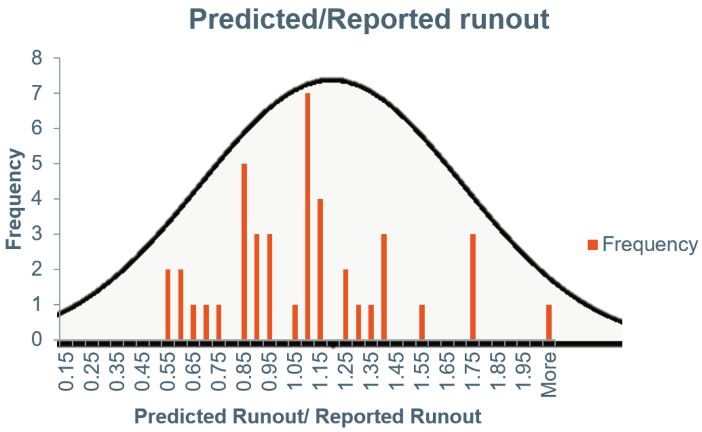


Figure 12 Predicted runout distance using theoretical Fahrböschung angle/reported runout distance in the failure database

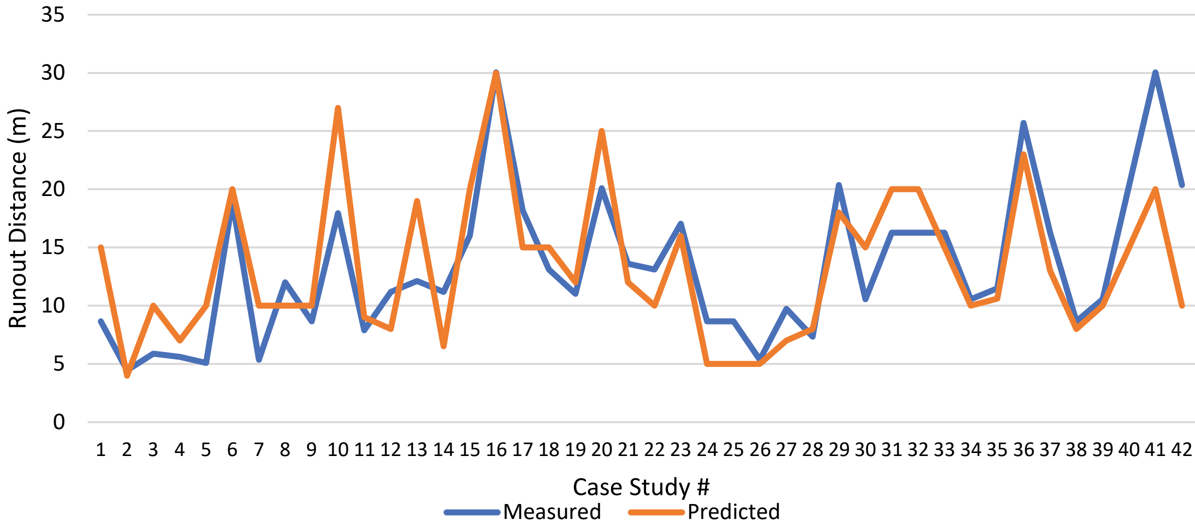


Figure 13 Comparison of measured runout distance and predicted runout distance using theoretical Fahrböschung model

5 Further work

This work lends itself to development of a design chart. A design chart with probability indexes will provide rapid response to minimise interruption to production. Additionally, optimisation of highwall failure management will occur when a bunded standoff placement can be optimised to contain the failed volume within a confidence interval and remove mine workers from an at-risk zone.

A cross-sectional analysis can be used to determine a justified bund location, which also assists in designing the mine plan and bench widths for strategic forecasting. The cross-sectional analysis can include assumptions of swell factor, bund height, and allowable material percentage to be captured, which can then be translated into a worst-case two-dimensional 'area' to be contained by a bund at a specific location (Figure 14).

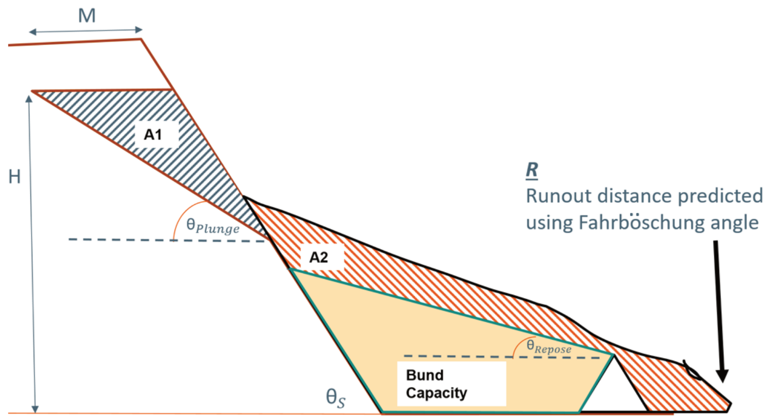


Figure 14 Tributary example of cross-sectional analysis of worst-case failure 'area'

This investigation has not explicitly considered the rotation of rock blocks or comminution during dislodgement. Engineers should consider the propulsion of inter-collisions between rocks that may pose more rotation propagation due to structure or material characterisation. Additionally, whilst a transient porewater pressure may be present in the wall, the runout predictions have not considered the additional impacts of water saturated conditions. The predictions should be considered for dry conditions only, and additional analysis where environmental factors may induce larger runouts, as rockfall runout can be significantly larger under water saturated conditions than dry conditions (Okada 2013). The SSAM calculator is one example of a tool that considered different ranges of seepage conditions into the analysis.

Additionally, the runout predictions have been projected from the toe of the wall. Future work could consider differentiation for case studies where failures daylight out of the wall at a higher elevation.

Further improvements to the theoretical prediction of the backscarp distance could help progress the runout prediction using the Fahrböschung angle. The reader is reminded of the approximate nature of the prediction and where better geological confidence exists, the actual predicted backscarp can be used.

6 Conclusion

Determining the runout distance for a slope where signs of instability have been identified is imperative to mine operations for safety and economic reasons.

This paper has shown that empirical back-analysis can be useful to approximate characteristics of the wall that influence the runout distance. For quick in-field approximation, the following trends may be applicable:

Wedge failure:

$$D_r \approx 0.5x \tag{5}$$

Toppling failure:

$$D_r \approx x \tag{6}$$

where:

D_r = runout distance (m).

X = slope height (m).

However, it should not replace more rigorous analysis methods where data permits. The empirical framework discussed in this paper should be supported by a ground control management plan and a good understanding of the geology and structure in the walls of the mine to understand high risk areas and potential failure mechanisms.

Additionally, industry members should continue to capture failure data variables, particularly those listed in Table 1, to improve the reliability of the empirical database. This is especially important for toppling mechanisms where the understanding of this behavioural mode is underappreciated.

Acknowledgements

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Additionally, the authors thank the BHP Coal open cut examiners for reporting these failures in their database. They have provided the ability to interrogate well-documented case studies and precise data collection for solid findings to be confirmed.

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