Forecasting open-pit slope runout distances

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Abstract

Geotechnical engineers are routinely tasked with advising suitable stand-off distances below high-risk sections of slopes in open-pit mines that are identified to have potential to deform or collapse. Accurate prediction of failed material runout can mean the difference between continuous safe mining and unwanted high-potential incidents that result in loss of production, equipment damage, injury, or loss of life. This paper updates previous empirical relationships presented by the authors for estimating the volume and runout distance of excavated slope failures, in an open-pit mine operation, using slope geometry as the primary predictor. Cases are sourced from varying slope geometries (fall heights up to 385 m, slope angles up to 80°) and a range of commodities (iron ore, coal, nickel, gold, copper, boron, and limestone), excavated in sedimentary, banded-sedimentary, epithermal, and copper-porphyry deposits, across all six inhabited continents. Analysis of these cases identified positive correlations between slope height and runout distance, and slope height and failed material volume. In general, negative correlations were identified between Fahrböschung angle and slope height, and Fahrböschung angle and failed material volume; however, significant scatter is observed in these datasets. A definitive relationship could not be derived comparing Fahrböschung angle with failed material runout. Slope angle was also found to be a poor indicator of runout. Of the parameters analysed, slope height (i.e., fall height) was found to be the simplest and best predictor of runout distance. This paper presents new charts for predicting failed material runout distance for rock slopes. Relationships are defined for structurally and rock-mass driven slope failure mechanisms at average, 75%, and 95% prediction intervals.

Keywords

rock slope failure, open-pit, failed material runout distance

Introduction

This paper updates previous empirical relationships presented by McQuillan and Bar (2020) for estimating the volume and runout distance of excavated slope failures, in an open-pit mine operation, using slope geometry as the primary predictor.

New relationships are presented for two categories:

1. Structurally driven slope-failure mechanisms (i.e., primarily driven by geological structures);
2. Rock-mass-driven slope failure mechanisms.

The presented charts are designed to provide mining operations with an additional tool to select appropriate stand-off distances, or exclusion zones, below identified geotechnical hazards that indicate potential slope failure or observed excessive deformation.

Runout predictions based on the historical performance of slopes with similar geometrical characteristics are considered valuable tools because they can be firmly linked to real-world cases. Without doubting the benefit of numerical analysis, empirical charts can be more valuable in instances where numerical predictions of failed material runout use estimates of material properties that are derived or merely adopted from literature. Further, empirical charts can be utilized in minutes or hours whilst numerical analysis may take several days, weeks, or even months.

The purpose of this study is to provide mining operations with a fast, defensible means of predicting runout distance, using slope geometry dimensions that are readily predictable, or measurable, by both technical and operational personnel. As such, a single measure of slope geometry, using slope height (i.e., fall height), is presented to predict runout distance.

Figure 1 summarizes the geometric parameters measured and analyzed in this study.

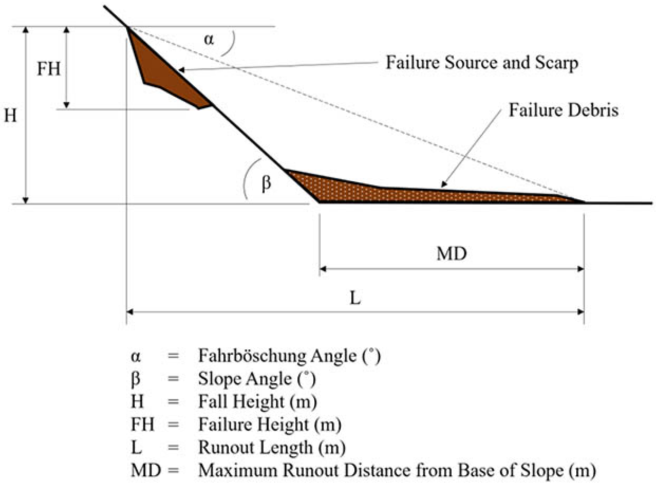

Figure 1—Nomenclature for key slope failure geometry and failed material runout parameters. Fahrböschung angle (H/L) is calculated after Heim (1932)

Database

This study is based on 549 slope cases, which is an increase of the 238 slope cases previously published by McQuillan and Bar (2020). Case studies are sourced from open-pit mines in Australia, South America, North America, Asia, Europe, and Africa, and are divided into two categories: (i) structurally driven failure mechanisms; and (ii) rock-mass failure mechanisms. Cases categorized as having a structurally driven failure mechanism include failures driven by planar, wedge, toppling, or step-path mechanisms. Cases attributed to rock-mass failure mechanisms include circular failures (42 cases) and debris flow (13 cases) descriptions.

Cases were sourced from varying open-pit slope geometries excavated across a range of commodities, as outlined in Table I. Cases are derived from the authors' practical experience and in collaboration with several operating mines. The case studies grouped in the Other (undisclosed) category in Table I are those published by Whittall (2015). As is evident from the data, structurally driven failures account for 90% of slope failures in open-pit mines. Rock-mass-driven failures in open-pit rock slopes are, in comparison, quite rare, accounting for only 10% of the reference database. Circular failure modes account for less than 8% of open-pit slope failures in the database.

Case-study fall heights range from 3 m to 385 m, exhibit slope angles from 19° to 80°, and include linear, convex, and concave slope profiles, excavated in sedimentary, banded-sedimentary, and sulfide-intrusion deposits, across all six inhabited continents.

Table I

Distribution of case-study slope cases by commodity

Commodity	Structurally driven	Rock-mass-driven
Iron ore	99	18
Coal	34	0
Nickel	161	9
Gold	97	6
Copper	49	1
Other (undisclosed)	54	21
Total	494	55

Individual rock or block-fall failures were excluded from this study as these are considered a different failure mechanism and so different runout (or rollout) behaviour would be observed. For predicting the primary impact and total runout distances of rock falls (i.e., individual rocks falling, rolling, or sliding down a face) in quarries and mines, refer to studies by Robotham et al., (1995), Gkouvailas (2014), Ferrari et al., (2015), and Saroglou and Bar (2017).

Only slope failures with unobstructed runout profiles were included in the study. Failed cases with notes of obstructed or bund (windrow)-impeded runout profiles were excluded because they were assumed to obscure the dataset with conservative measurements of actual runout distance.

For all cases, complete measurements of fall height (H) and maximum horizontal runout distance from the base of the slope (MD) were recorded, as defined in Figure 1. Total slope height, slope angle, and estimated failed material volume (V) are available for most cases and were analysed where measurements were available.

Data analysis

Analysis of the measured parameters illustrated in Figure 1 identified the following relationships, for both structurally driven failure mechanisms and rock-mass-driven failure mechanisms:

i. Runout distance increases with increasing fall height (i.e., there is a positive correlation between MD and H), as seen in Figure 2. A distinct linear trend is observed for rock-mass-driven failure mechanisms. This finding is consistent with results reported by Corominas (1996) and McQuillan and Bar (2020). This observation conforms to gravitational potential energy (PE) laws, Equation [1], where the greater the fall height, the greater is the potential energy:

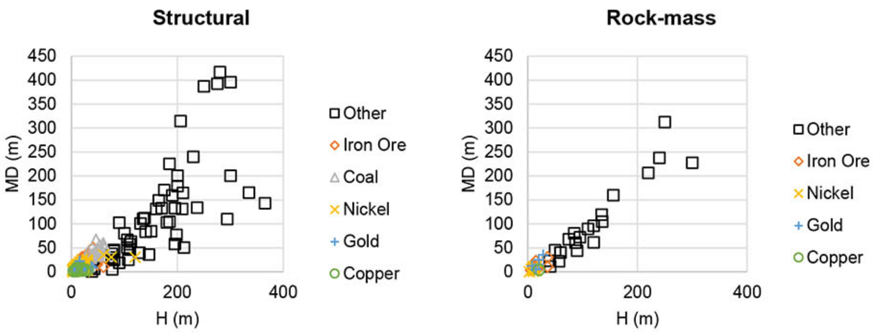

Figure 2—Maximum runout distance (MD) as a function of fall height (H). Left: Structural failure mechanism (494 cases). Right: Rock-mass failure mechanism (55 cases)

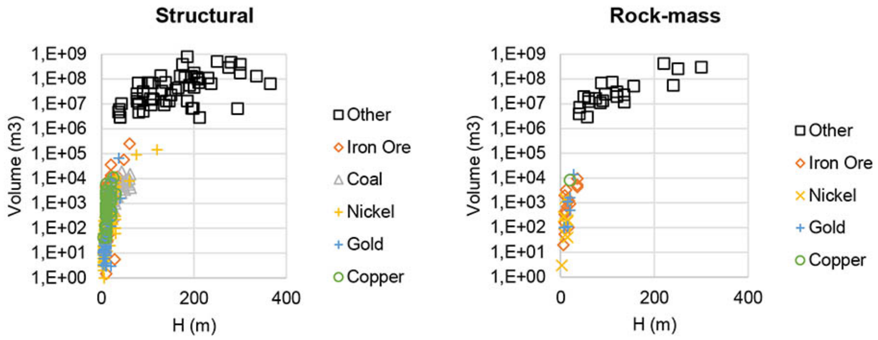

Figure 3—Failed material volume (V) as a function of fall height (H). Left: Structural failure mechanism (480 cases). Right: Rock-mass failure mechanism (44 cases)

$$PE = mgh, \quad [1]$$

where m is mass, g is acceleration due to gravity, and h is height.

As material starts to move down a slope, the potential energy converts to kinetic energy (KE) (Equation [2]). The increased potential energy on a higher slope results in higher kinetic energy as the material accelerates, which is observed in longer runout distances in this study.

$$KE = 0.5mv^2, \quad [2]$$

where v is velocity.

ii. Failed material volume increases with increasing fall height (i.e., there is a positive correlation between V and H), per Figure 3. This finding is consistent with prior results of McQuillan and Bar (2020), and reflects the positive volumetric relationship between slope height and rock mass volume (i.e., the larger the slope (i.e., fall height), the greater the volume of material that exists to run out of the slope face).

iii. Fahrböschung angle generally decreases with increasing runout (i.e., there is a negative correlation between α and MD), as indicated in Figure 4. There is significant scatter in this relationship for slope heights less than 100 m for structural-driven failure mechanisms, and for slopes heights less than 50 m for rock-mass-driven failure mechanisms. Fahrböschung angle is therefore not considered a reliable predictor of runout distance for open-pit mine excavated slope failures.

iv. Larger failed material volumes are observed with smaller Fahrböschung angles, (i.e., there is a negative correlation between V and α), as observed in Figure 5. There is generally significant scatter in this relationship for $20° < \alpha < 70°$, indicating Fahrböschung angle to be an unreliable predictor of runout distance.

v. There is no discernible correlation between MD and slope angle, as indicated in Figure 6. This finding confirms the

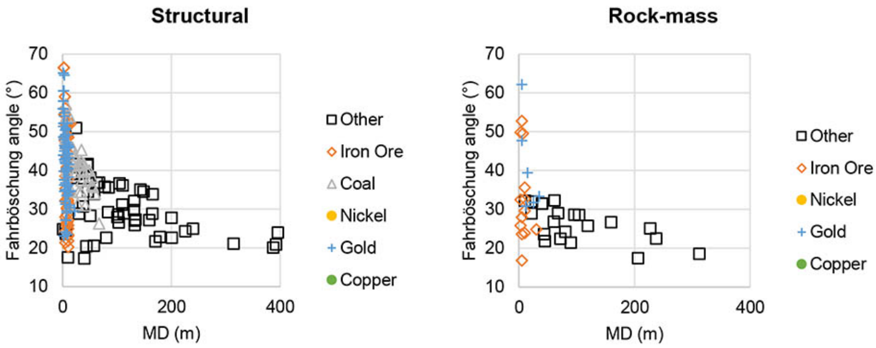

Figure 4—Fahrböschung angle as a function of maximum runout distance (MD). Left: Structural failure mechanism (243 cases). Right: Rock-mass mechanism (40 cases)

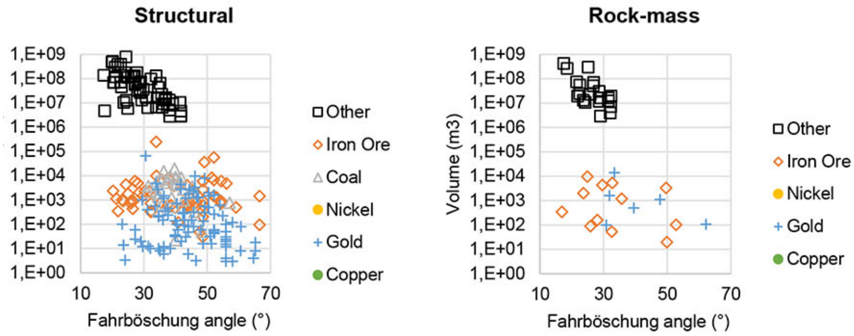

Figure 5— Failed material volume (V) as a function of Fahrböschung angle. Left: Structural failure mechanism (243 cases). Right: Rock-mass failure mechanism (40 cases)

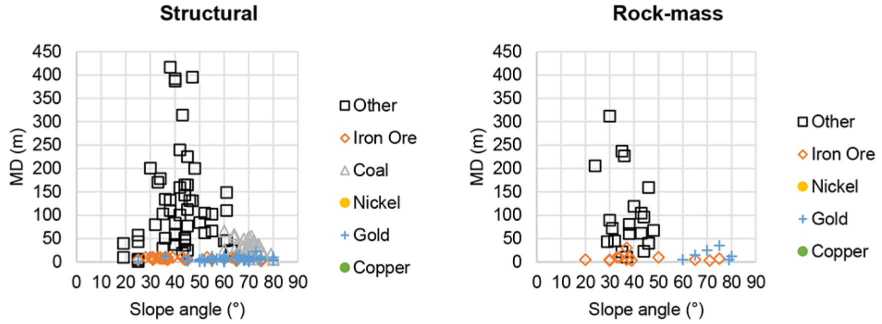

Figure 6— Maximum runout distance (MD) as a function of slope angle. Left: Structural failure mechanism (243 cases). Right Rock-mass failure mechanism (39 cases)

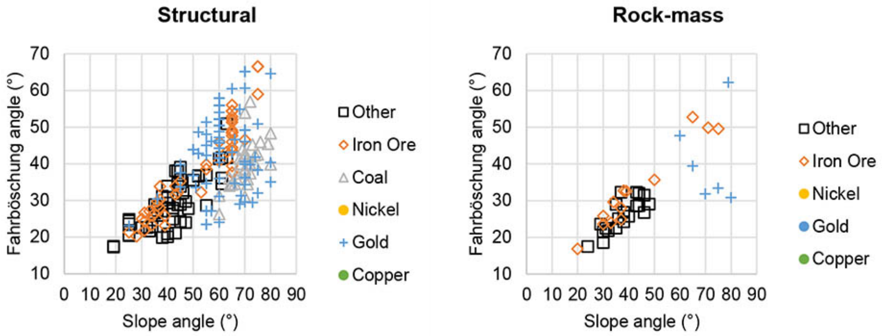

Figure 7— Fahrböschung angle as a function of slope angle. Left: Structural failure mechanism (243 cases). Right: Rock-mass failure mechanism (40 cases)

results of McQuillan and Bar (2020), and shows that slope angle is not a reliable predictor of runout distance. Slope angle was previously identified to have little influence on excavated single-bench slope stability (McQuillan et al., 2018); instead, structure orientation (dip and dip direction) relative to slope orientation have a greater influence on slope stability. However, slope angles have been directly related to total rollout distances for individual rock falls (Bar et al., 2016; Saroglou and Bar, 2017).

vi. Fahrböschung angle generally increases with slope angle (i.e., there is a positive correlation between α and slope angle), as per Figure 7. However, there is wide scatter in the data at increasing slope angles.

Predictive equations

Where fall height (H) was determined to provide a reasonable, readily predicted (or measured) variable to estimate runout distance (MD), predictive equations were developed to assist mining operations with geotechnical risk management.

Table II summarizes the predictive equations developed for failed material runout distance, using fall height as the prediction variable. Predictive equations are presented for: (i) slope heights less than 100 m, representing typical inter-ramp slope geometries; and (ii) all slope heights in the database. Figure 8 and Figure 9 present these datasets graphically.

Linear regression was applied to the dataset to calculate the average runout distance of each dataset. Prediction intervals of 75%

Table II

Predictive equations for estimating failure material runout distance using slope height, H

	Runout estimation by prediction interval		
Scenario	MD_{LR}	$MD_{75\%}$	$MD_{95\%}$
Structural-driven failure mechanisms with H < 100 m	0.61H - 0.14	0.61H + 8.53	0.62H + 14.65
Structural-driven failure mechanisms with H < 350 m	0.79H - 3.4	0.79H + 25.17	0.8H + 45.33
Rock-mass-driven failure mechanisms with H < 100 m	0.72H - 1.77	0.73H + 8.35	0.75H + 15.73
Rock-mass-driven failure mechanisms with H < 350 m	0.94H - 7.86	0.95H + 13.2	0.95H + 28.45

and 95% were calculated using linear regression and the Student's t-distribution (Preston 2000), given by Equations [3] and [4], respectively. The prediction interval is a useful measure of reliability for the prediction of an observation: in this case, runout distance. Prediction intervals of 75% and 95% provide mining operations with conservative estimates of runout distances, and an arguably more-effective (lower risk) stand-off distance.

$$\text{Prediction interval } \% = \hat{y}_0 \pm t_{crit} \times \text{SE}, \qquad [3]$$

where $\hat{y}_0$ is the forecast value derived from linear regression, t_{crit} is the two-tailed inverse of Student's t-distribution, and SE is the standard error of the data, given by:

$$\text{SE} = S_{yx}\sqrt{1+\frac{1}{n}+\frac{(x_0-\bar{x})^2}{ss_x}}, \qquad [4]$$

where S_{yx} is standard error of the predicted y-value for each x in a regression, n is number of degrees of freedom, $\bar{x}$ is the mean, and SS_x is the sum of squares of deviation of data points from their sample mean.

Limitations

These empirical relationships are proposed to supplement currently available slope-stability and runout assessment methods and tools. It is not intended, nor advised, that these relationships entirely replace numerical simulations.

Where there is appreciable scatter in the charts, runout predictions should not be specified as a deterministic value, but rather quoted as a range based on the distributions of measurements in the reference database. Smaller stand-off distances than the average distance interpreted from the charts may be justified with additional controls, rather than using the stand-off zone as an exclusive control.

This study only compared two variables of slope failure to readily predict runout distance. It is recognized that excavated slope failures have complex failure mechanisms that often include multiple driving factors (i.e., slope geometry, rock mass condition, structure orientation, surface condition, water, and degree of weathering) (McQuillan et al., 2018). Furthermore, downslope (floor dip) angle will likely influence runout distance (Hunter and Fell 2003). The scatter observed in the datasets presented in this paper is assumed to be attributed to the various slope conditions included in the case-study database. Tighter correlations in the datasets should be investigated to further define relationships between pre-failure slope conditions and runout. Such multiple-variable comparisons were not completed as part of this study, where the purpose was to rapidly identify data-driven predictors of runout using slope geometry as the primary predictor.

This study contains failures that occurred at single-bench to overall excavated slope scales from open-pit mines. The reference database includes cases with minimum slope heights (fall heights) of 3 m: it is not recommended that the predictive equations be used to estimate runout for slope heights less than 3 m.

The influence of pit floor inclination on runout distance was not included in this study, nor the dimensions and capacity of hard barriers to contain failed material. These are important parameters that also need to be considered in any estimate of runout distance and implementation of exclusion zones below high-risk potential failures.

For runout predictions specifically developed for single-bench failures in coal mines, refer to studies by McQuillan et al. (2018) and Nairn et al. (2021).

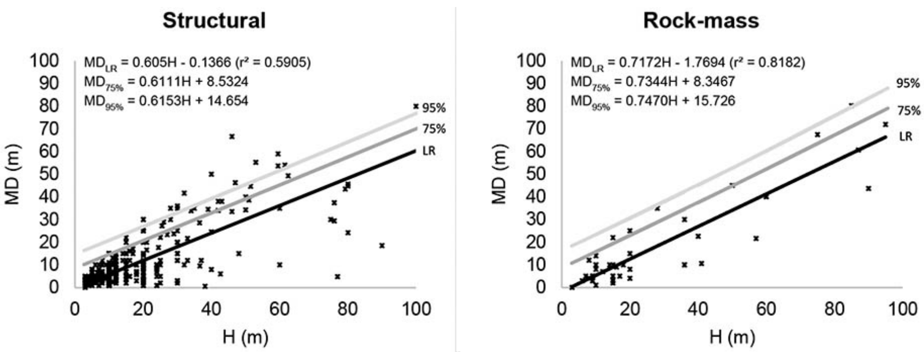

Figure 8—Maximum runout distance (MD) predictions for slope heights (H) less than 100 m. Left: Structural failure mechanism (453 cases). Right: Rock-mass failure mechanism (45 cases)

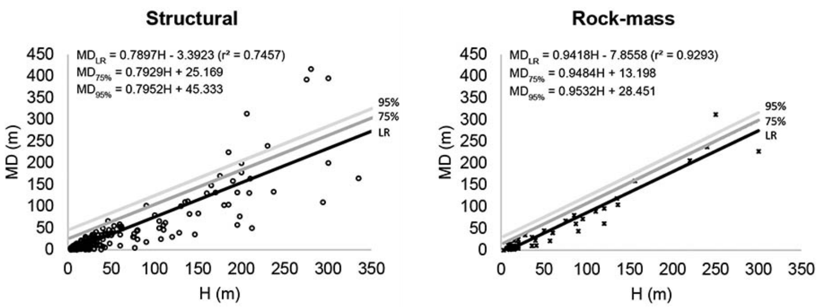

Figure 9— Maximum runout distance (MD) predictions for slope heights (H) less than 350 m. Left: Structural failure mechanism (494 cases). Right: Rock-mass failure mechanism (55 cases)

Conclusion

Accurate prediction of runout distance is critical to managing geotechnical risks in an open-pit operation. Predictive charts and equations are proposed to assist geotechnical engineers and mining operations in estimating runout distance below sections of excavated slopes that are identified to have the potential to deform or collapse. The predictive equations are only applicable to excavated slopes.

Predictive equations are based on analysis of 549 failed slope cases from iron ore, coal, nickel, gold, copper, boron, and limestone operations, excavated in sedimentary, banded-sedimentary, epithermal, and copper-porphyry deposits, across all six inhabited continents. Cases include slopes up to 385 m in height and 80° in slope angle.

Analysis of these cases identified positive correlations between slope height and runout distance, and slope height and failed material volume. Analyzed cases showed that Fahrböschung angle, which is often applied in empirical relationships, along with volume, to predict runout distance (Nairn et al., 2021; Ahn, 2023), is generally negatively correlated to slope height and failed material volume (i.e., greater volumes are observed with smaller Fahrböschung angles). However, this is a general trend only and significant scatter is observed in datasets comparing Fahrböschung angle to volume, as well as other slope parameters, including slope angle and slope height. No definitive relationship was derived comparing Fahrböschung angle with failed material runout. Slope angle was also found to be a poor indicator of runout.

Of the parameters analyzed, slope height (i.e., fall height, H) was found to be the simplest and best predictor of runout distance. The use of a single predictor of fall height provides a rapid means of estimating appropriate stand-off distances until additional control measures, such as radar monitoring (including appropriate evacuation protocols) and slope remediation, can be implemented. The use of catchment bunds is considered an additional layer of defence against failure runouts.

The relationships and predictive equations are proposed to supplement existing slope-stability and runout assessment methods, which include numerical modelling. Where scatter is observed in the dataset, any runout estimate should be quoted as a range based on the distributions of measurements in the reference dataset, not quoted as a single value. Runout predictions should be used in parallel with a suite of other controls, such as instrumentation monitoring and hard barriers.

Statements and declarations

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Both authors contributed to the development and writing of this paper.

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