Runout analysis and mobility observations for large open pit slope failures

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Runout analysis and mobility observations for large open pit slope failures

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Abstract

Objectively forecasting the runout of a potential open pit slope failure, in addition to identifying the failure itself, is a critical component of a mine’s risk management plan. Recent losses arising from large open pit slope failures demonstrate shortcomings in current practice. A dataset of 105 pit slope failures was compiled to compare open pit runout trends against established empirical runout relationships for natural landslides. Fahrböschung angle vs. volume and Fahrböschung angle vs. slope angle relationships provide reasonable runout estimates. Open pit slopes have the advantage of removing the influence of morphological features, vegetation, and liquefiable substrates while controlling the travel path angle and roughness. In such a controlled environment, landslide mobility has a strong sensitivity to slope angle, material properties and fall height, and is only modestly sensitive to volume. A grouping of highly mobile open pit slope cases involving weathered, saturated, collapsible rock mass materials exceed expected runout distances when compared to established runout trends. This suggests mobility for these weaker rock masses is controlled by pore pressures mediating basal friction. The result is that two different runout exceedance trends are observed based on whether the unstable rock mass involves fresh, strong rocks or weathered weak rocks.

KEYWORDS: Open pit slope failure, rock slope stability, runout analysis, exclusion zones, landslide mobility
Introduction

Recent large open pit slope failures that have caused significant damage to mine infrastructure and equipment demonstrate shortcomings in current practices used to estimate landslide runout and establish exclusion zones for an impending failure (e.g. Pankow et al. 2014; Farina and Coli 2013). Objectively forecasting the zone of impact of a potential slope failure, in addition to identifying the failure itself, is a critical component of a mine’s risk management plan, yet few guidelines exist.

In the study of natural landslides empirical runout methods are commonly used to assess runout potential (e.g., Scheidegger 1973; Hsü 1975; Li 1983; Corominas 1996; Iverson et al. 1998; Fannin and Wise 2001; Hunter and Fell 2003). These methods are largely based on field observations and on the analysis of the relationship between the source volume of the landslide and the distance travelled by the debris. Empirical methods are quick, repeatable, and useful for bracketing site conditions where detailed data is limited. The utility of these methods has been recognized for open pit slope failures (Rose 2011), however, existing data sets have solely focused on natural landslide case histories and have not been validated for open pit slope failures.

This paper presents a dataset of 105 extremely rapid (>5 m/s) open pit slope failures that have been compiled, analyzed and compared against established empirical runout relationships for natural landslides. Established methods are calibrated to an open pit context and evaluated quantitatively using a cross validation procedure. A discussion of differences between open pit and natural slope runouts highlights possible limitations to the application of these models to open pit slopes, but also identifies useful trends. The absence of natural morphological features, vegetation, and liquefiable substrates in open pits, which are common on natural slopes, also provides an
opportunity to assess their influences on runout distance, lateral spreading and deposit shape through comparison of the different data sets.

**Open pit slope failure database**

A comprehensive public-domain literature search returned ninety-six open pit slope failures that included a runout component, at over fifty different mines. Anonymous sources provided another nine case histories, for a total of 105 open pit slope failures with a runout component. These case histories are presented in a supplement to this paper. Whittall (2015) presents a detailed accounting of each case. The authors infer from anecdotal evidence (the failures ran out) that the landslide motion after detachment was very rapid to extremely rapid and are analogous to Hungr et al.'s (2014) description of rock avalanches. Failures that did not runout, were <40,000 m³, or were retained by effective slope management measures (e.g., Hamel 1970; Brawner 1971; Newcomen and Martin 1988; Martin and Mehr 1993; Newcomen et al. 2003) were excluded from the dataset. Failures where material funneled into collapse features above underground workings related to block caving (e.g., Brummer et al. 2006) were also excluded.

If unspecified, volume estimates are assumed to represent in-place (i.e. un-bulked) source volumes. Where references provide both in-place and bulked failure volumes, plots use the in-place volume for consistency. Wherever possible, additional geometric estimates are taken from satellite imagery, particularly: Google Earth Pro, NASA earth observatory, UNOSAT, Geoscience Australia, ESRI, and hard copy aerial photographs.
Empirical analysis of data

Why empirical models?

Empirical runout models can be useful to perform slope risk assessments and aid decision making in an operating open pit mine. Safety and economic constraints related to personnel withdrawal, equipment, and lost production may leave little time for detailed mechanistic analyses. Treating site-specific influences holistically is appropriate when time and geological uncertainty limit the degree of precision that can be expected. Empirical methods are quick, repeatable, and useful for bracketing site conditions where detailed data are limited.

Numerical runout models (e.g. DAN3D, McDougall and Hungr 2004) are useful tools for studies that require a vulnerability estimate. For example, designing a protection structure or estimating potential damage to infrastructure require an estimate of the destructiveness of the landslide, in addition to delineating the impact area. For landslides in open pit mines, where the vulnerability of workers is near 100%, delineating the runout zone is the main objective and the added complexity of a numerical model is not needed.

Relationships analyzed

The earliest empirical relationship for landslides was developed by Heim (1932), who proposed that the distance a landslide will travel is proportional to its volume. He equated energy lost to work done, and postulated that the effective friction coefficient of sliding motion should be equal to the ratio of vertical to horizontal displacement. His “Fahrböschung” angle related volume of failed material to the ratio of fall height (H) and horizontal runout distance (L), to graphically describe the
runout as the inclination of the line connecting the crest of the main scarp and the toe of the deposit (Figure 1).

Several authors have built on Heim’s work to incorporate the effects of path morphology and landslide type. Each empirical relationship requires an approximation of source location and travel path, however, disagreement persists on the importance of other parameters. Several established runout relationships were considered in this study using the open pit slope failure database. Full details on each relationship are reported in Whittall (2015).

Volume-based mobility relationships that were analyzed included: Fahrböschung angle (Scheidegger 1975; Li 1983; Nicoletti and Sorriso-Valvo 1991; Corominas 1996; Davidson 2011), runout length (Legros 2002), excessive travel distance (Hsü 1975; see Figure 1), excessive travel distance normalized to total runout length (Nicoletti and Sorriso-Valvo 1991), and inundation area (Li 1983; Iverson et al. 1998).

Hunter and Fell (2003) found that the Fahrböschung angle of flow slides in loose granular fills and waste dumps had almost no dependence on volume; rather, mobility is proportional to the average travel path inclination. Slope angle-based mobility relationships that were analyzed included: Fahrböschung angle (Hunter and Fell 2003), runout length, and excessive travel distance normalized to total runout length.

Other authors studying long runout natural landslides considered landslide motion as an energy balance problem (i.e. the distance a landslide will travel is proportional to the potential energy available). Potential energy-based relationships that were analyzed included: Fahrböschung angle (Howard 1973), runout length (McSaveney 1975), and inundation area (Dade and Huppert 1998).
Lastly, Staron (2008) suggested that a dimensionless mobility parameter can be derived to describe the shape and thickness of the deposit, providing a relative measure of mobility. Staron plotted runout length normalized to thickness \((L/V^{1/3})\) against inundation area normalized to volume \((A/V^{2/3})\) and found a positive correlation in log-log space.

**Relationships omitted**

Compared with natural slope conditions, an open pit has the advantage of removing morphological features, vegetation, and liquefiable substrate while controlling travel path angle and roughness. Methods developed for channeled flow (Benda and Cundy 1990; Fannin and Rollerson 1993; Zimmerman 1997), small volumes involving less than \(\sim 1,000\) m\(^3\) (Finlay et al. 1999; Rickenmann 1999), and volume balance (Cannon 1993; Fannin and Wise 2001) do not lend themselves well to a mining context because they involve factors that are irrelevant for open pit slope failures. Relationships describing the centre of mass of the source and deposit were also excluded. The position of the centre of mass is difficult to estimate and is inconsequential to equipment or workers compared with the position of the leading edge of the landslide.

Boulder rollout methods were also excluded but deserve future consideration. Literature and satellite imagery that were available for this study did not have sufficient detail to describe the boulder rollout.

**Mobility relationship comparison**

**Model uncertainty**

Validating established empirical runout models to open pit data was achieved by evaluating whether the data conforms to the constraints of the method:
• Does the empirically predicted runout length provide a reasonable match to the observed runout?
• If not, do they conservatively over predict runout or hazardously under predict runout?
• Can we integrate pit slope failure runout into a risk management plan as we can with natural landslides?

This evaluation was achieved by superimposing the open pit data on the established best-fits, comparing the datasets, plotting a best-fit regression, then quantitatively validating the relationship to obtain a prediction quality, and estimating the parameter sensitivity for each relationship.

Validation was assessed using k-fold cross validation (Stone 1974). Cases are grouped randomly into k equal-sized folds. Each fold retains a distinct subset of cases as a validation set and the remaining cases are the training set. The training-validation process is repeated k times. This method is well-suited to small datasets that cannot afford to lose data to a validation set. All cases have a role in both training and validation, and each case is used for validation only once.

Root mean square error (RMSE) and normalized index (NI) are calculated for each fold and parameter variance, as in Equations 1 and 2, respectively:

\[
RMSE = \sqrt{\frac{\sum (X_{predicted} - X_{observed})^2}{n}} \quad [1]
\]

\[
NI = \frac{X_{predicted} - X_{observed}}{X_{observed}} \times 100 \quad [2]
\]

Normalization can be positive or negative depending on whether or not the model results in over- or under-estimation of runout. A positive NI means that the mobility relationship overestimates runout, whereas a negative NI means that the mobility relationship underestimates runout. Using RMSE and NI together provides extra context for goodness of fit. For example, a
runout estimation error of 100 m may only represent an error of a few percent if the case in question involves a large, long runout landslide.

Table 1 is a comparison of the mobility relationships calibrated to pit slope failures. Figure 2 is a description of the prediction quality for each mobility relationship. The box is the first and third quartile error bisected by the median error. The whisker bars contain the 5th and 95th percentile. Fahrböschung angle vs. volume and Fahrböschung angle vs. original slope angle mobility relationships provide reasonably similar prediction to the observed runout and appear to be roughly normally distributed. Single parameter relationships, those based on runout length alone, present more asymmetric error distributions with long tails.

**Parameter uncertainty**

An open pit slope has the advantage of having a well-defined geometry, deformation monitoring, and structural and geotechnical models. As such, parameter selection is less complicated than for natural landslides. While uncertainty remains regarding the rupture surface and source volume, *a priori* estimates of slope angle, crest location, material properties, and failure mechanism can be reasonably constrained. To test how sensitive the models are to their inputs, parameters were varied individually for every case over a range of up to 100% of their reported value. The RMSE and NI were then calculated for each parameter variance.

Whittall (2015) provides comparison plots of model sensitivity to volume, slope angle, and fall height, respectively. The parameter uncertainty assessment indicates:

- The single parameter relationships (i.e., \( L \) vs. \( V \), \( L_e \) vs. \( V \)) are highly sensitive to the input estimate.
• Fahrböschung angle and Le/L are only modestly dependant on volume and more sensitive to slope angle.
• Fahrböschung angle and excessive travel distance relationships have fall height in their equations and are proportionately sensitive (1:1).
• All of the remaining mobility relationships are also sensitive to fall height.

The sensitivity to fall height is expected because the travel length and drop height for an object traveling down an incline are dependant variables. Contrasting with natural landslide research, empirical models using this dataset are most sensitive to slope angle and fall height, rather than volume.

**Recommended relationships**

**Fahrböschung angle vs. volume**

The Fahrböschung angle is the simplest parameter to apply and particularly amenable to rapidly developing failure scenarios in complex ground. Figure 3 is the open pit dataset superimposed on established natural rock avalanche Fahrböschung relationships developed by Scheidegger (1975), Li (1983), and Davidson (2011). All three natural rock avalanche relationships are an assemblage of rock avalanche datasets with various geology, failure mechanisms, geomechanical properties, slope configurations, and path morphology. The holistic nature of these models captures the inherent complexity of each event. This, however, leaves significant scatter.

The landslide runout trends in Figure 3 can be seen to generally agree with the open pit data set, although it should be emphasized that the fits are plotted in log-log space. Scheidegger's (1975) and Davidson's (2011) fit reasonably capture the mean trend while Li's (1983) fit under predicts runout in a significant number of the cases.
The linear regression for the open pit data has an RMSE of 109 m and mean NI of 3.1%. Error appears normally distributed but contains tails, as can be seen in Figure 4. The outlier cases are influenced by obstructions at the opposing wall (less mobile cases) or flow-like behaviour (more mobile cases). The effect of obstruction at opposing walls and pit-bottom sumps is addressed later in the paper. Closer interrogation of the material behaviour reveals two trends based on the rock mass characteristics and slope angle, as shown in Figure 5. Li’s regression reasonably describes the less mobile trend, while Scheidegger and Davidson’s regression under predict runout for the more mobile trend. Equations 3 and 4 are best fit least squares regression lines for the two mobility trends for cases involving fresh strong rock and weathered weak rock, respectively.

\[
\frac{H}{L} = 0.559 \text{volume}^{-0.150} \quad [3]
\]

\[
\frac{H}{L} = 0.408 \text{volume}^{-0.146} \quad [4]
\]

Volume units in equations 3 and 4 are million cubic metres. Separating the data into two trends improves the correlation, with an RMSE of 48 m (0.8%) for the less mobile trend and 61 m (1.5%) for the more mobile trend. Figure 6 shows the combined error distribution for the two datasets.

**Fahrböschung angle vs. slope angle**

Hunter and Fell (2003) recognized that the runout of waste dump flow slides is sensitive to path angle and insensitive to volume. Their dataset included path confinement conditions and volume ranges similar to those seen with open pit failures ($10^3$ to $10^7$ m$^3$). Figure 7 presents a linear space Fahrböschung angle vs. original wall angle plot for the pit slope failure dataset. Note that Hunter and Fell (2003) used the angle of the topography, not the angle of the waste dump face.
Like the waste dump trend, the H/L ratio for the open pit failure dataset increases with the slope angle without the separate trends seen in the volume-dependent relationship, and fits sufficiently well to plot in linear space.

The x-axis of Figure 7 is the bench stack angle if the case was contained to one set of benches; otherwise, it is the overall slope angle.

More data is required to assess the suitability of this method for slopes steeper than 50° (\(\tan 50° \approx 1.2\)). These steeper cases illustrate an important limitation of this relationship and perhaps an additional threshold exists at 50° where mobility remains relatively constant. Goodness of fit statistics and the best-fit regression shown in Equation 5 exclude these cases.

\[
\frac{H}{L} = 0.488 \tan(\text{slope angle}) + 0.117 \tag{5}
\]

The remaining data have an RMSE of 87 m and a mean NI of 1.6% with normally distributed error (Figure 8).

This relationship has a similar model uncertainty to its volume counterpart but much lower parameter uncertainty. This model provides a useful check for geometrically complex landslides where volume is difficult to estimate and pit walls are inclined less than 50°. The user needs to decide on the relevant wall angle: the bench stack angle if the source and deposit are likely to be contained on the same bench stack, or the overall angle if the travel path is likely to overrun ramps and reach the pit floor. A mechanistic explanation H/L increasing with slope angle is presented later in this paper.
**Inundation area vs. volume**

Estimating a two-dimensional deposit area is a useful addition to locating the distal toe of the deposit. Established inundation area relationships (Li 1983; Iverson et al. 1998) have used datasets of various landslide classifications to compare both reach and spread of landslides. The maximum inundation area of an *average flow* can be reasonably described in log-log space as $A = cV^{2/3}$. Griswold and Iverson (2008) compared lahar, debris flow, and rock avalanche cases to show planimetric shape is scale invariant, but different landslide types require unique values of the coefficient $c$. Figure 9 is the open pit data plotted with Li (1983) and Griswold and Iverson’s (2008) regressions.

Open pit landslides show the same self-similar deposit shape (slope=2/3), but with a less mobile y-intercept ($c=6$). Inundation area was only available in 47 (45%) of the cases compiled in the database because it is rarely reported in the literature and high resolution satellite imagery is only recently available. The RMSE and mean NI for this index is $4.6 \times 10^4 \text{ m}^2$ and 10.1%, respectively, uniformly distributed with outliers (Figure 10).

Predictable error, albeit large, is still useful. Inundation area combined with other mobility relationships is useful to map a hazard back from the estimated deposit toe. This relationship is recommended to complement a runout distance model to create a hazard map. It may also be useful to assess the degree of spreading when the landslide is obstructed by an opposing wall.

**Performance of empirical runout relationships**

Researchers of natural landslides have searched for trends in natural landslide behaviour and explanations for exceptional cases. They can be grouped into endogenic (within the system) or exogenic (outside the system) influences (Alexander 1993). Endogenic influences are properties of
the landslide: its size, the nature of the materials, failure mechanism, fall height, and travel path angle. Exogenic influences are properties of the environment: liquefiable substrate, confinement or obstruction, triggering event, and surface water or glaciers along the travel path. An open pit has the advantage, relative to natural landslides, of controlling most exogenic influences. As such, the dataset presented here is a well constrained subset of landslides with known external influences. This provides an opportunity to ask: Which parameters have the most influence on landslide mobility if external influences like material entrainment are removed or controlled?

**Slope angle**

The separate trends in the Fahrböschung angle vs. volume plot have a clear dependence on original slope angle, as shown in Figure 11. This plot shows that steeper slopes having smaller failures and shorter runout distances. The typical constant slope angle of a pit wall, relative to natural landscapes and flat pit bottoms, is likely the cause. Abrupt path angle changes are an obstruction to the travel path and consume energy. Equation 6 is the sliding resistance (T) to a frictional sliding block.

\[ T = \rho h (g \cos \alpha + a_c) \tan \varphi_b \]  

[6]

When the sliding path is curved, bed-normal stress is a function of centripetal acceleration \((a_c)\), shown in Equation 7, which in turn is a function of velocity \((v)\) and radius of curvature \((R)\).

\[ a_c = \frac{v^2}{R} \]  

[7]

A shallower slope creates a larger radius (Figure 12), decreasing the centripetal acceleration, and therefore presents less basal resistance or energy consumption. The same effect
occurs with lateral spreading (McDougall and Hungr 2004). If everything else is equal, steeper slopes produce shorter runout lengths and less spread.

**Volume**

Most researchers studying natural landslide mobility agree that volume has an influence on runout. However the volume of pit slope failures is a narrow subset of the natural landslide spectrum, biased towards the lower volume end. The usefulness of established volume-dependent relationships must be tempered by this contextual difference.

Figure 13 shows the Fahrböschung angle minus the slope angle, as defined in the inset, versus volume for the open pit failure cases. This is not a mobility relationship; it is a comparison of the relative parameter sensitivity. Subtracting the tangent of the slope angle from $H/L$ is an attempt to remove the influence of slope angle in Figure 11. The resulting horizontal trend infers that $H/L$ is less sensitive to volume than slope angle, and mobility of this dataset is only modestly dependent on volume. This is consistent with the parameter sensitivity analysis presented in Whittall (2015).

It can be asserted that steeper walls often contain higher quality rock and that higher quality rock may minimize the failure volume. The increase in slope angle that opposes mobility may be counterbalanced by the volume induced reduction in mobility. In fact there is a strong covariance of original slope angle and source volume for pit slope failures (Whittall 2015), both contribute to the momentum of the landslide. However, a steep wall angle does not infer a small failure volume. In this dataset, $H/L$ has an inverse relationship with volume but it appears less influential than slope angle because of the narrow range of source volumes, compared to natural landslides.
Fall height

Several researchers (Hsü 1975; Davies 1982; Legros 2002) point to fall height as simply contributing to data scatter. Although its role is clear in a mathematical energy balance, it is less so for proxies like the Fahrböschung angle. Legros and others show that a plot of runout length vs. volume gives a better correlation and suggest that natural landslides rapidly dissipate the kinetic energy gained during initial fall and “forget” the initial fall height (Legros 2002).

Figure 14 shows a similar plot with the open pit data. Several smaller volume cases (e.g., 97, 105) that behaved as expected have become outliers, which is conspicuous. The RMSE is 116 m and mean NI is 13%, with scatter close to 400 m for the low volume cases. Figure 15 is the lognormal distribution of the error showing a general under prediction.

Corominas (1996) used a comparison of fall height to horizontal travel length to show that, if two identical failures occur from different fall heights, the one with the larger drop will travel farthest. Figure 16 is a similar plot derived from the open pit data that clearly shows that fall height has an influence on runout length. The difference between open pit and natural landslide mobility dependence on fall height may be the same abrupt change in slope angle discussed above, enhanced by the lack of liquefiable substrate. A natural landscape typically has a gradual transition from mountain side to a gently inclined overburden-rich valley floor. The landslide may entrain and rapidly load the valley substrate, producing an undrained condition and contributing to a large increase in L while only modestly increasing H (Hungr and Evans 2004). These natural valley conditions are not available in an open pit.
Spread

Considering Li’s (1983) trends in Figure 3 and Figure 9, established runout relationships appear to over predict the planimetric deposit area of pit slope failures but under predict the location of the distal deposit toe. The mechanisms that control runout length and spread appear to act differently in an open pit.

There are two common deposit shapes. Figure 17 depicts deposit width measurements taken at 0%, 10%, 25%, 50%, 75%, 90% and 100% of the deposit length, normalized to deposit length to provide an aspect ratio. The first shape (black) is a wide talus cone sitting at its angle of repose. Typically, these talus deposits form an apron hung on or below the source. A more prevalent shape (red) is a long, thin deposit where the width is similar to the source width. Figure 18 is a comparison of the degree of spreading, the ratio of mean source and deposit areas, versus volume symbolized by broad material categories. The spread is generally centralized around 1, indicating that $\text{Area}_{\text{deposit}} \sim \text{Area}_{\text{source}}$ and that this data does not show significant spread. For context, Abele (1974) found that natural rock avalanches in the Alps spread between ratios of 1 and 10 depending on material type, and that spread decreased with volume.

Staron’s (2008) dimensionless inundation area to runout length relationship is another useful comparison of deposit aspect. Deposits in the bottom left corner of the graph include those that neither ran far nor covered a large area, creating a thick, less-mobile deposit. Cases in the top right corner ran far and spread to form a thin veneer. Figure 19 is the open pit data fit to Staron’s (2008) model with natural landslide cases to show his intended observation. There is no discernable trend in the open pit data and it tends to cluster to a small range. Data clustering at $x=6$ is encouraging for the $A=6V^{2/3}$ relationship developed earlier. A useful by-product is that the data is
concentrated around the lower left corner of the plot, indicating thicker deposits with similar aspect ratios but distinctly different behaviour than natural landslides.

Figure 20 is a cumulative frequency plot of inundation area normalized to volume. Normalization is required because the open pit dataset only spans the lower volume range of the natural landslides. The open pit and natural landslide datasets occupy different ranges of spread values; the open pit data plots farthest left and sub-vertically. This result indicates that they spread less per unit volume than natural landslides and that there is not significant variety in deposit shapes. The verticality of the open pit data makes it impossible to make statistical comparisons. Nonetheless, qualitatively, Figure 20 shows that open pit failures spread less than natural landslides and into more predictable shapes.

A logical explanation for less spread in this dataset is that a pit bottom has finite available space to spread. An obstruction by the opposing wall or water will cause thickening of the deposit, rather than spread, reducing the inundation area and perhaps channeling material into a longer runout. Most cases in the dataset, however, were not obstructed.

Theoretically, spread in landslides without path constrictions is controlled by normal and transverse shear stress and the internal and basal shear resistance of the landslide (McDougall and Hungr 2004). A physical justification for the lower inundation area but longer reach of this dataset is the travel path inclination and lack of liquefiable substrate; the same mechanism as above. A pit wall transitions abruptly to a flat, rough floor composed of materials of a similar strength. This expends centrifugal force and limits the spread of the landslide. There may also be high longitudinal pressures that develop through the abrupt slope transition. As such, the landslide may deposit thicker, or the tip may travel farther with less spread.
Material properties

The separate trends in the Fahrböschung angle vs. volume relationship are partly a consequence of different material properties. Heim's (1932) original Fahrböschung angle proposition was an energy balance, where the average friction coefficient is equal to the ratio of vertical and horizontal displacement. It does not attempt to describe the path or dynamics of the flow. It is not surprising that materials with different frictional characteristics have different mobility.

In this dataset, geology and rock mass characteristics are generally well known. The less mobile trend contains failures in fresh, strong rocks that is described well by Li’s (1983) regression. These rocks failed as dry, frictional materials. The volume increase resulting from dilation and bulking as the rock slope fails and passes from intact rock to debris reduces the ability of pore pressures to increase within the sliding mass (Hung and Evans 2004). Combined with the lack of liquefiable substrate, the basal friction angle is not significantly mediated by pore pressure. Deposits appear granular and sit at approximately 37°.

A more mobile Fahrböschung angle vs. volume trend is observed for weathered, clay rich rocks and poorly cemented sedimentary rocks. These materials are often characterized using soil constitutive models. A hypothesis for the difference in behaviour compared with fresh, strong rocks is that these materials have a collapsible structure, creating undrained strength conditions when sheared. Hunter and Fell (2003) and Locat and Leroueil (1997) provide natural landslide precedents for different runout behaviour in dilative versus contractive materials.

Many of the literature sources of the open pit failure cases note a significant precipitation event, high or perched water tables, and/or deficiencies in surface water management as
contributing to the failures. Forty-seven of the cases (including all but two of the most mobile cases) assign a precipitation event as the failure trigger, despite pit depressurization measures being in place. Detailed pore pressure data is not available; however, reduced effective stresses in response to elevated pore pressures in the pit walls seem likely given these anecdotes.

**Poorly cemented granular materials**

Poorly cemented sedimentary rocks often have high porosities, either due to the depositional environment (e.g., Boron, cases 13 to 24), alteration (e.g., Gold Quarry, case 38), or mining disturbance (e.g., Grasberg, case 47). Minor amounts of cohesion are suggested as holding together a disorganized *house of cards* clay-rich structure with void space available for contraction. Hutchinson (2002) and Sassa (2000) proposed that such materials crush and contract in shear, generating excess pore pressure at the rupture surface. When saturated, granular contracting materials subjected to shear at a high strain rate behave undrained, even if initially in a drained condition (Ladd 1991).

Sassa (2000) demonstrated the role of pore pressure in shearing granular materials and coined the term *sliding surface liquefaction*. A loose granular material forced to shear will want to contract. This effect is enhanced if the rock has cohesion to lose. If the rock is saturated, as many of the triggering events imply, the volume change cannot occur and pore pressures increase. In turn, effective stress and basal resistance decrease.

**Clay-bearing fault zones**

Sheared discontinuities, and their infill, have a shear strength at or near their residual values. Any cohesion that existed from previous over-consolidation will be destroyed during
shearing. In the case of joint infill, Barton (1974) showed that infilling is expected to act in a
normally consolidated state.

**Weathered materials**

Saprolite and other residual soils are generally more heterogeneous than sedimentary soils
and do not have a stress history. These weathered materials are not composed of individually
deposited discrete particles, but rather a degradation of a previously intact block. The void ratio to
effective stress plot, and normal- versus over-consolidated states, are not applicable to residual
soils. Rather, Wesley (2010) showed disturbing or remoulding residual soils causes them to
disintegrate and contract, much the same as Sassa’s (2000) grain crushing experiment.

**Pore pressure dissipation in clay-rich materials**

Iverson (1997) showed that there is a negative correlation between the rate of pore
pressure dissipation \(t_{\text{diff}}\) and compressibility and permeability of the material (Equation 7). He
showed that clay-rich materials with excess pore pressures dissipate their pore pressure orders of
magnitude slower than dilative materials, leaving interstitial fluid available to mediate the basal
friction:

\[
\tau_{\text{diff}} = \frac{Y^2 \mu}{kE} \tag{7}
\]

where \(Y\) is a normalizing length term, \(\mu\) is the viscosity of the fluid, \(k\) is the permeability of the
material, and \(E\) is the stiffness modulus.

Either from the addition of total stress (through redistribution and concentration of
stresses during pit excavation) or by decreasing effective stresses (precipitation triggers), clay-rich
materials forced to rapidly shear will behave in an undrained manner. Large natural landslides show this effect where fluidization occurs from a relatively small volume of water initially present in the failing mass (Legros 2002). The initial failure mass may also load the travel path, increasing the pore pressure and decreasing the shear resistance. Rapid undrained loading is a common long runout mechanism in natural debris avalanches (Hungr and Evans 2004).

This mechanism does not dismiss the possibility of other site-specific influences on runout. A unique combination of material and slope properties are, however, difficult to estimate in an emergency and may lead to misguided deterministic use of these empirical relationships. Pore pressure mediating basal friction provides a reasonable holistic explanation for long runout landslides and can be identified using parameters practitioners can map.

**Distinguishing mobility trends**

Figure 21 is a design chart to choose the appropriate mobility category (for use with Figure 5) using intact strength (ISRM 1978), weathering grade (ISRM 1978), porosity, and disturbance. Here, shear strength and porosity are used as key indicator properties for dilative versus contractive behaviour. The user should apply the properties of the worst 10% of the rock mass.

**Travel path obstruction**

Obstruction or deflection at the opposing pit wall can introduce curvature to the travel path or bulking of the deposit toe. Nineteen (18%) of the pit slope failures ran to the opposing wall or a constructed berm. In the case of a runout length prediction exceeding the available linear distance across the pit floor, an area vs. volume prediction is useful to estimate the degree of spread at the opposing wall.
Six (6%) of the pit slope failures ran into water. These are classified as unobstructed in Whittall (2015) because the water bodies are typically shallow sumps or ponding at the pit bottom. The authors acknowledge impact with a water body will expend momentum and have an effect on mobility. Given the shallow depth, limited areal extent, and stagnancy of these sumps and ponds, the effect is likely minor compared to natural landslides impacting lakes and rivers.

Channeling at corners or along ramps may change the flow shape of pit slope failures, however, not to the extent that valleys or gullies in natural landscapes would. Nonetheless, narrowing the data to more homogeneous obstruction populations can be a useful exercise to further identify the cause of the separate trends in Figure 5. Figure 22 compares the open pit dataset with Corominas’ (1996) regressions for rockfall/rock avalanche with path obstruction.

The inverse relation between Fahrböschung angle and volume remains regardless of path attribute. An inflection appears at 1,000,000 m$^3$ where the data follows Corominas’ (1996) deflected regression line more closely. This change may indicate a change in the mechanism of motion where the mass becomes flow-like, as postulated for natural landslides (Hsü 1975; Davidson 2011). The runout of obstructed landslides is shorter than non-obstructed landslides, however, these cases still fall within the scatter of the data and do not stratify themselves into a separate trend.

**Failure mechanism**

The failure mechanisms of the pit slope failure cases did not significantly influence mobility because the data is a narrow subset of possible landslide types. Finlay et al. (1999) and Hunter and Fell (2003) also found that narrowing the context to small debris flows and mine waste dumps, respectively, removed the variety of mechanisms and limited its effect.
Figure 23 is the Fahrböschung angle vs. volume relationship symbolized by failure mechanism. The eight toppling failures in this dataset are less mobile than the general trends in Figure 5 but within the scatter of the other cases. Seventeen of the highly mobile cases were planar failures in poorly cemented sandstones. It is difficult to determine whether the planar failure mechanism in these cases had a greater influence than the inherent low material strength and collapsible structure. The other eleven (of twenty-eight) planar failures occurred in stronger and less porous materials and did not show exceptional mobility characteristics. Rotational and debris slides plot in the more mobile end of the scatter, which suggests that material characteristics (dilative versus contractive) have a larger effect on mobility than structural control and kinematics.

**Piecemeal and successive failures**

Eighteen (17%) of the pit slope failures involved at least two distinct events. The toppling failure at Hogarth (case 49), for example, detached from the wall in a piecemeal fashion, resulting in a short runout. Experiences from the 1991 Randa rockslide (Eberhardt et al. 2004) demonstrate that simple empirical runout models using the total cumulative volume can over predict mobility in such cases. A continuous series of low volume failures will likely produce a short runout.

Conversely, remobilized debris from previous failures can be more mobile than the original landslide. Colluvium left with a loose, disorganized structure may readily collapse in shear and behave in an undrained manner. The 2005 La Conchita landslide (Jibson 2005), for example, remobilized colluvium left by a 1995 event. Despite being much smaller in volume, the 2005 event exceeded runout expectations and overtopped protection structures designed based on experiences from the first landslide.
Often rockfall and bench-scale failures are precursors for a larger event. Exclusion zones should be based on the cumulative volume regardless of how piecemeal a failure may appear. Runout estimates for pit slopes in colluvium should use the more mobile (Trend 2) mobility relationship.

**Influences on landslide mobility**

Prominent theories for surprisingly long runout landslides include: interstitial fluids (Iverson 1997; Wang and Sassa 2003), air entrapment (Shreve 1968), mechanical fluidization reducing basal friction (Heim 1932; McSaveney 1978; Davies 1982; Campbell 1989); air (Kent 1966) or acoustic (Melosh 1979) fluidization reducing internal friction; and dynamic fragmentation (Davies and McSaveney 2002).

Studying landslide mobility in an open pit removes topographic confinement (gullies, valleys) and liquefiable substrate (soil, surface water, ice). The remaining long runout mechanisms, if they exist, should still be operating. When we limit both the endogenic and exogenic influences, mobility has a strong sensitivity to slope angle, material characteristics, and fall height, and is only modestly sensitive to volume. Even when unobstructed, the exceptional spread seen in many natural landslides does not appear to exist in an open pit (Figure 20). The highly mobile cases occurred on shallow slopes (Figure 7 and Figure 11) composed of saturated, collapsible materials (Trend 2 in Figure 5). This result implies that mobility is controlled by pore pressure mediating basal friction (Abele 1974; Iverson 1997; Wang and Sassa 2003), and the much more impressive spread and fluidity seen in natural landslides is related to the conditions not present in open pits, i.e., rapid loading of a liquefiable substrate (Hungr and Evans 2004) and topographic channelization.
Conclusions

Fahrböschung angle vs. volume and Fahrböschung angle vs. slope angle relationships calibrated to open pit slope failures provide reasonable runout estimates and are useful for creating exclusion zones. An inundation area vs. volume relationship can be a useful complement to provide estimates of the zone of impact relative to the expected toe location. These relationships are sensitive to slope angle, the nature of the material, and fall height, and only modestly sensitive to volume.

Open pit landslides appear to deposit predictably-shaped debris aprons that either hang below the source in a 37° talus cone or flow into a continuous pile, thinning away from the source. Compared to natural landslides, they form thicker, more predictably-shaped deposits with less lateral spread. Set in a probabilistic framework, the empirical relationships presented in this paper can be used to objectively define exclusion zones and integrate runout into a mine’s emergency response plan.

Database extension

This study relied on published failure descriptions written from an operations and slope stability perspective. Only a few of the publications from which the data was extracted explicitly discuss runout. Building a dataset with greater diversity is desirable but likely only possible with access to a broader experience base. The authors would like to extend an invitation for others to share their case histories and pit slope runout experience. Confidentiality can be maintained by omitting reference to location or source of the data, if necessary. Correspondence to this effect can be made via email to Mr. John Whittall jwhittall@bgcengineering.ca.
Acknowledgments

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Pit slope dataset references


<table>
<thead>
<tr>
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<th>Site</th>
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Notes:

Schematic definition of the Fahrböschung angle and excessive travel distance

Figure 1

154x98mm (124 x 124 DPI)
Prediction quality of runout relationships calibrated to open pit landslides

Figure 2

173x200mm (124 x 124 DPI)
Open pit data with Scheidegger (1975), Li (1983), and Davidson (2011) best fit Fahrböschung angle vs. volume regressions

Figure 3

172x171mm (124 x 124 DPI)
Error distribution for Fahrböschung angle vs. volume mobility relationship
Figure 4
153x137mm (124 x 124 DPI)
Open pit data with Fahrböschung angle vs. volume relationship. Two separate mobility trends emerge based on rock mass characteristics.

Figure 5
172x171mm (124 x 124 DPI)
Error distribution for stratified Fahrböschung angle vs. volume mobility relationship

Figure 6

153x135mm (124 x 124 DPI)
Open pit data with Fahrböschung angle vs. slope angle mobility relationship

Figure 7

https://mc06.manuscriptcentral.com/cgj-pubs
Error distribution for Fahrböschung angle vs. slope angle mobility relationship

Figure 8

https://mc06.manuscriptcentral.com/cgj-pubs
Open pit data with inundation area vs. volume mobility relationship

Figure 9

171x166mm (124 x 124 DPI)
Error distribution for inundation area vs. volume mobility relationship

Figure 10

158x139mm (124 x 124 DPI)
Fahrböschung angle vs. volume mobility relationship symbolized by slope angle
Figure 11
170x171mm (124 x 124 DPI)
Exaggerated schematic of slope angle’s effect on centripetal acceleration

Figure 12

174x62mm (124 x 124 DPI)
Open pit data with Fahrböschung angle normalized to slope angle. Note there is no relationship with volume when normalized to original slope angle.

Figure 13
175x170mm (124 x 124 DPI)
Open pit data with runout length vs. volume mobility relationship

Figure 14

174x174mm (124 x 124 DPI)
Distribution of error for runout length vs. volume mobility relationship

Figure 15

158x135mm (124 x 124 DPI)
Comparison of open pit failure fall height to runout length

Figure 16

174x174mm (124 x 124 DPI)
Map of deposit aspect observations

Figure 17

167x170mm (96 x 96 DPI)
Degree of spreading in open pit slope failures

Figure 18

201x199mm (124 x 124 DPI)
Open pit data with dimensionless mobility relationship

Figure 19

181x136mm (124 x 124 DPI)
Comparison of open pit failure and natural rock avalanche deposit spreads

Figure 20

173x170mm (124 x 124 DPI)
Rock mass characteristics mobility trends matrix for use with Figure 5

Figure 21

101x95mm (144 x 144 DPI)
Open pit data compared to Corominas (1996) path obstruction Fahrböschung angle vs. volume mobility relationship
Figure 22
170x171mm (124 x 124 DPI)
Fahrböschung angle vs. volume relationship symbolized by failure mechanism
Figure 23
170x171mm (124 x 124 DPI)
Table 1. Mobility relationship comparison, where A is the planimetric inundation area, V is the source volume, $\alpha$ is the original wall angle, and H, L and Le are defined in Figure 1

<table>
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<th>Input</th>
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<th>Error distribution</th>
<th>Parameter sensitivity (%)</th>
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Volume