Preliminary results of the back-analysis of 24 rock avalanche case histories

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ABSTRACT
Rock avalanches are extremely rapid, flow-like landslides that can travel unexpectedly long distances. The mechanisms that result in the excessive travel distance of these landslides are still debated and, as a result, risk analysis of rock avalanches is not routine. One promising tool that can be used to forecast rock avalanche motion is the equivalent fluid runout model Dan3D-Flex. Dan3D-Flex is semi-empirical, as the parameters that govern simulations can only be constrained through back-analysis. This work details preliminary results of the back-analysis of 24 rock avalanche case histories. Trends in the derived parameters are used to infer information about rock avalanche movement mechanisms. It was found that the character of the path material is a plausible explanation for much of the variance associated with rock avalanche mobility. Cases that overran saturated substrate were found to have higher mobility than those that overran bedrock. These results have significant implications for researchers and practitioners tasked with forecasting rock avalanche motion.

1 INTRODUCTION

Rock avalanches are extremely rapid (defined as velocities greater than 5 m/s) flows of fragmented rock that can impact people and infrastructure far from their source. As shown in Figure 1, these events initiate as large rock slope failures, before fragmenting and turning flow-like (Hungr et al., 2014).

Figure 1. Frank Slide, Alberta. This 1903 rock avalanche travelled approximately 2 km across the valley floor and claimed an estimated 70 lives.

Three recent rock avalanche events highlight the risk posed by these catastrophic landslides. The Mt. Meager rock avalanche, which occurred in 2010, travelled over 8 km, and attained velocities greater than 70 m/s. This event dammed the Lillooet river and impacted a campsite (Guthrie et al., 2012). In 2014, the West Salt Creek rock avalanche occurred in Colorado. This event initiated from a previously failed slump block and travelled over 4.6 km down a sinuous channel, reaching velocities of 40 m/s (Coe et al., 2016). In August 2017, a catastrophic rock avalanche initiated from the peak of Piz Cengalo in Switzerland. This rock avalanche travelled over 5 km and impacted the village of Bondo (https://www.swissinfo.ch/).

As demonstrated above, there is a need for methods that are able to accurately quantify the risk posed by rock avalanches. Such a risk analysis requires an assessment of the potential impact area, flow depths and velocities of a rock avalanche before it occurs (this sort of analysis will be referred to in this paper as a runout analysis (Hungr et al., 2005)). Such an analysis requires an understanding of the mechanisms that govern rock avalanche motion.

Beginning with the work of Heim (1932), many researchers have noted that rock avalanche mobility increases with increasing volume. This observation is based on plots of H/L vs. volume, as shown in Figure 2. Heim (1932) noted that, if resistance to motion is assumed to be governed by the friction angle of dry, fragmented rock, the H/L measured for a rock avalanche should be approximately 0.6. The observation that rock avalanches can have H/L values much lower than this indicates that other mechanisms must act to reduce flow resistance in rock avalanches (Hsu, 1975).

Since the work of Heim (1932), a wide variety of rock avalanche mobility mechanisms have been proposed to explain the excessive mobility problem. Some of these theories were reviewed by Legros (2002). Aaron (2017) provides a brief overview of some more recent work on this topic.

The purpose of the present work is to use a database of 24 rock avalanche case histories to test one of the theories for excessive rock avalanche mobility. This theory, first invoked by Buss & Heim (1881), and formally defined by Hungr & Evans (2004), is that rock avalanche mobility can be explained by the character of the path material.

This paper is laid out as follows. Firstly, an overview of the path material theory is provided. Then, the dataset assembled for this work, as well as the numerical model used to analyse this data, are briefly described. Finally, preliminary results and conclusions are provided.

2 PATH MATERIALS ENCOUNTERED BY ROCK AVALANCHES

One of the oldest theories of rock avalanche motion is that rock avalanche mobility is governed by the character of the path material (e.g Buss & Heim, 1881). This theory hypothesizes that shearing occurs along the base of the rock avalanche, with the shear resistance governed by the interaction of the rock avalanche material and the path material it is overriding. In particular, this theory posits that extreme runout in rock avalanches is caused by low strength path materials.

One path material that is generally accepted to increase rock avalanche runout is glacial ice (e.g. Evans & Clague, 1988; Sosio et al., 2012). More controversial is how this theory can explain long runout for cases that do not overrun glacial ice.

As summarized in Hungr & Evans (2004), based on concepts from Sassa (1985), when rock avalanches override loose, saturated, substrates there is potential that the rock avalanche will liquefy the sediments. This would lead to extremely low shear resistance along the interface between the rock avalanche and the substrate material, resulting in long runout and high velocities. This process is schematically shown in Figure 3.

At first glance, it appears as though this theory cannot explain the volume-dependence of rock avalanche motion that is shown on Figure 2. Both small and large volume rock avalanches should have enhanced mobility due to the character of the path material. Hungr and Evans (2004) explained this by hypothesizing that, since larger volume rock avalanches spread more, they have a higher probability of overriding loose, liquefiable substrate. This appears plausible, as there is significant scatter on volume vs. H/L plots, indicating that volume alone only partially explains rock avalanche mobility.

Using a database of 24 rock avalanche case histories, we tested the following hypotheses that can be made based on the Hungr & Evans (2004) mobility theory:

1. Regardless of volume, rock avalanches that encounter loose, saturated substrate should experience relatively low basal resistance.
2. Regardless of volume, rock avalanches that do not encounter loose, saturated substrate (other potential substrates include bedrock and/or unsaturated dense sediments) should experience relatively high basal resistance.

3 METHODOLOGY

The numerical runout model Dan3D-Flex was used to test the two hypotheses detailed above. The model is described in detail by Aaron and Hungr (2016) and Aaron (2017) and is an extension of previous models described by Hungr and McDougall (2009). It combines a solid mechanics-based block model that simulates the initially-coherent motion of some rock avalanches with a fluid mechanics-based continuum model that simulates flow-like motion following fragmentation. Dan3D-Flex is classified as a semi-empirical model because the parameters that govern simulations must be calibrated through back-analysis of real landslides. These user-calibrated governing parameters include the parameters that govern the basal shear resistance and the point at which the simulation switches from solid to fluid behaviour. The latter input can be guided by an assessment of slope topography (Aaron 2017).

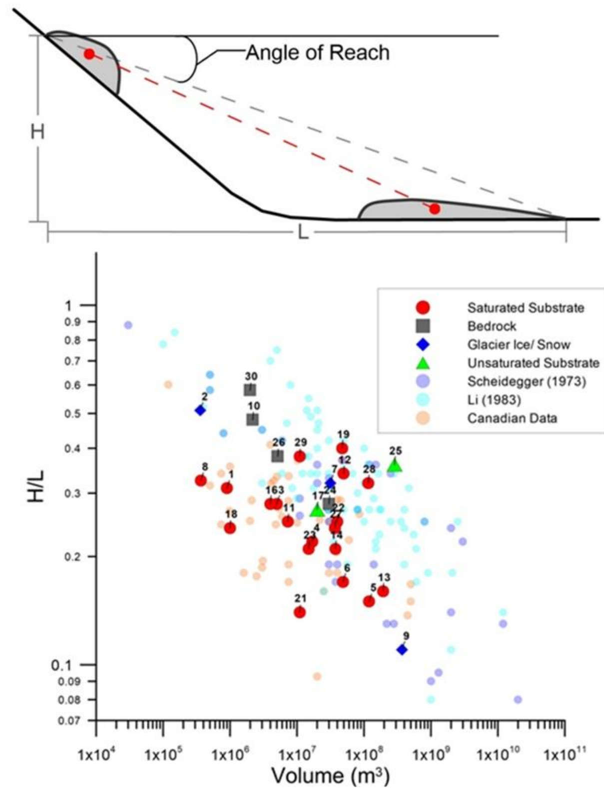

Figure 2. Top: Explanation of H/L ratio. Bottom: Volume vs. H/L of cases in the database of rock avalanche case histories. For comparison, H/L data collected by Scheidegger (1973), Li (1983) and an unpublished database of Canadian rock avalanches (Brideau, M.A, BGC Engineering, unpublished data) are shown. Labels: 1. Zymoetz, 2. Crammont, 3. Six des Eaux Froides, 4. Huascaran, 5. Kolka, 6. Mt. Meager, 7. Mt. Steele, 8. Nomash River, 9. Sherman Glacier, 10. Thurweiser, 11. McAuley Creek, 12. Val Pola, 13. Avalanche Lake, 14. Goldau, 15. Mystery Creek, 16. Turnoff Creek, 17. Madison Canyon, 18. Chisca, 19. Hope, 20. Pandemonium Creek, 21. West Salt Creek, 22. Frank, 23. Guinsaugon, 24. Bingham Canyon, 25. Sentinel, 26. Daubensee, 27. Rinderhorn, 28. Rautispitz, 29. Platten, 30. Chehalis. References for each case history are provided in Aaron (2017).

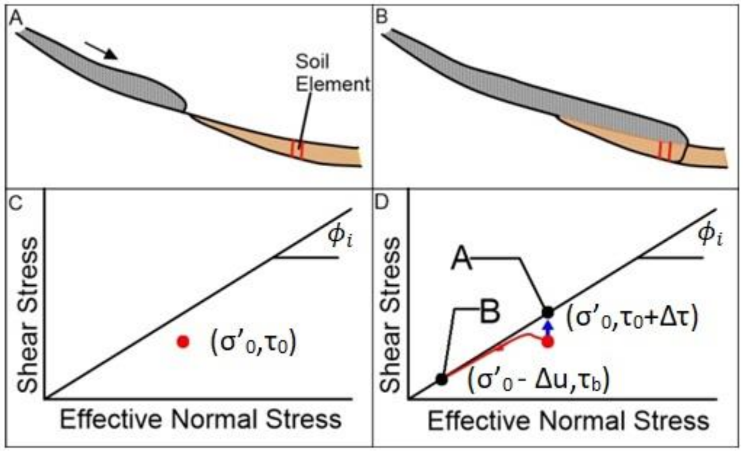

Figure 3. Schematic of the undrained loading process described by Sassa & Wang (2005). Panels C and D show the shear and normal stresses acting on the saturated and cohesionless soil element highlighted in panels A and B. Before being overridden, panel C shows that the soil element (red dot in C and D) is stable. When the soil element is overridden (B and D), both the shear and normal stresses acting on the element increase. If drainage is restricted but no contraction occurs, shear stress increases until the column fails, while effective normal stress remains constant (panel B point A). If the overridden mass is loose and liquefiable, then shear stress will decrease to a very low value. ϕi is the internal friction angle of the path material. Figure from Aaron (2017).

When back-analysing the case histories in the database, we parameterized the basal rheological model based on the path material. We used a frictional rheology in the source zone, where the rock avalanche typically moved along a structural feature, with a switch to the two-parameter Voellmy rheology when the rock avalanche encountered sediments covering the path. An overview of these rheologies is provided by (Hungr & McDougall, 2009). The strength parameters back-analysed in the source zone are often lower than those required for a limit-equilibrium stability analysis. The reduction in strength is likely due to extreme polishing of the planar rupture surface due to shearing under high normal stresses, combined with sudden, brittle failure due to breakage of rock bridges. We make the simplifying assumption that this strength loss is instantaneous.

Model calibration was performed using the calibration methodology detailed in Aaron (2017). This calibration methodology accounts for the following issues commonly encountered in trial-and-error calibration:

- Best-fit parameter combinations are often non-unique.
- Back-analysis can be time consuming if performed using trial-and-error calibration.
- Model results are often subjectively interpreted, so different users could determine different best-fit parameters for the same case.
- Calibration often does not explore the entire parameter space, so there is no guarantee that the best-fit parameters have been obtained.

The calibration methodology presented by Aaron (2017) uses quantitative fitness metrics to assess the quality of a simulation. These metrics can account for a variety of simulation constraints, including impact area, velocity and deposit distribution. For each case history calibrated using this methodology, a wide range of parameter combinations are evaluated. This approach promotes the exploration of the entire parameter space and improves the chances of achieving the best possible fitness to all available back-analysis constraints.

To assess the fitness of a simulation, we compared simulation results to field estimates of impact area, deposit distribution and velocity (where available). All cases had an estimate of the impact area, and most had a subjective assessment of deposit distribution. Velocity estimates were available for five cases.

Based on the two hypotheses above, we expected that, regardless of volume, cases that overran saturated substrate have lower back-analysed resistance than those that overran bedrock and/or unsaturated substrate material.

4 DATA

The database of rock avalanche case histories analysed in the present work contains 24 case histories. The volume of the cases in the database spans three orders of magnitude from $1x10^5$ m^3 to $4x10^8$ m^3; however, most cases in the database are between $1x10^7$ m^3 and $1x10^8$ m^3. A description of the cases, as well as details of each back-analysis, are presented in Aaron (2017).

Figure 2 shows the volume vs. H/L relationship for the cases in the rock avalanche database. The cases span a wide range of mobility, from the 'expected' value for dry fragmented debris of 0.6 (Hsu, 1975) to 0.1, corresponding with the extremely mobile Sherman Glacier rock avalanche (McSaveney, 1978). Most cases in the database likely overran saturated substrate, as indicated in Figure 2; however, cases that overran bedrock, glaciers and unsaturated sediments were also analysed.

5 RESULTS

A plot of volume vs. source zone friction angle is shown in Figure 4. The source zone friction angle was constrained through observations of the deposit distribution. If all the material was observed to vacate the source zone then a low friction angle was back-analysed, and if some material deposited in the source zone then a higher friction angle was back-analysed.

Figure 5 shows the best fit zones of the path material for cases that overran sediments, coloured by event volume. These zones represent the regions of the parameter space with the highest probability of containing the best-fit parameter values. Due to parameter non-uniqueness, only a best fit zone could be determined for many of these cases. Figure 6 shows the best fit parameter zones for the cases that encountered sediments and/or snow along the path. Figure 7 shows the best fit friction angles for cases that overran bedrock as the path material.

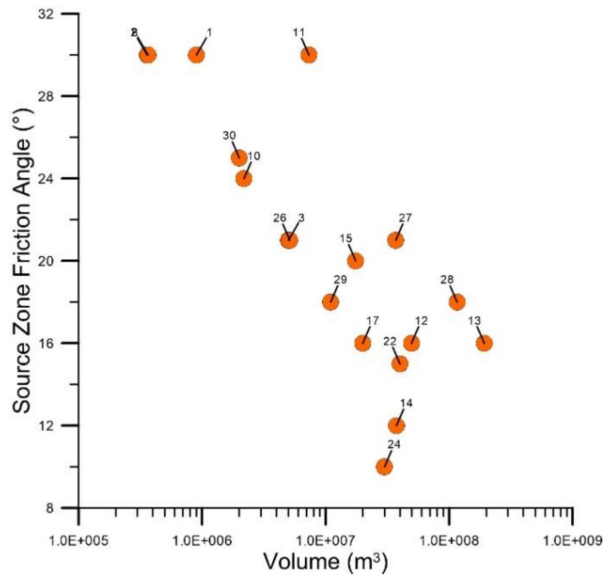

Figure 4. Back-analysed friction angles in the source zone. These values are constrained by observations of the deposit distribution. See Figure 2 for case names that correspond to the case numbers. Figure from Aaron (2017)

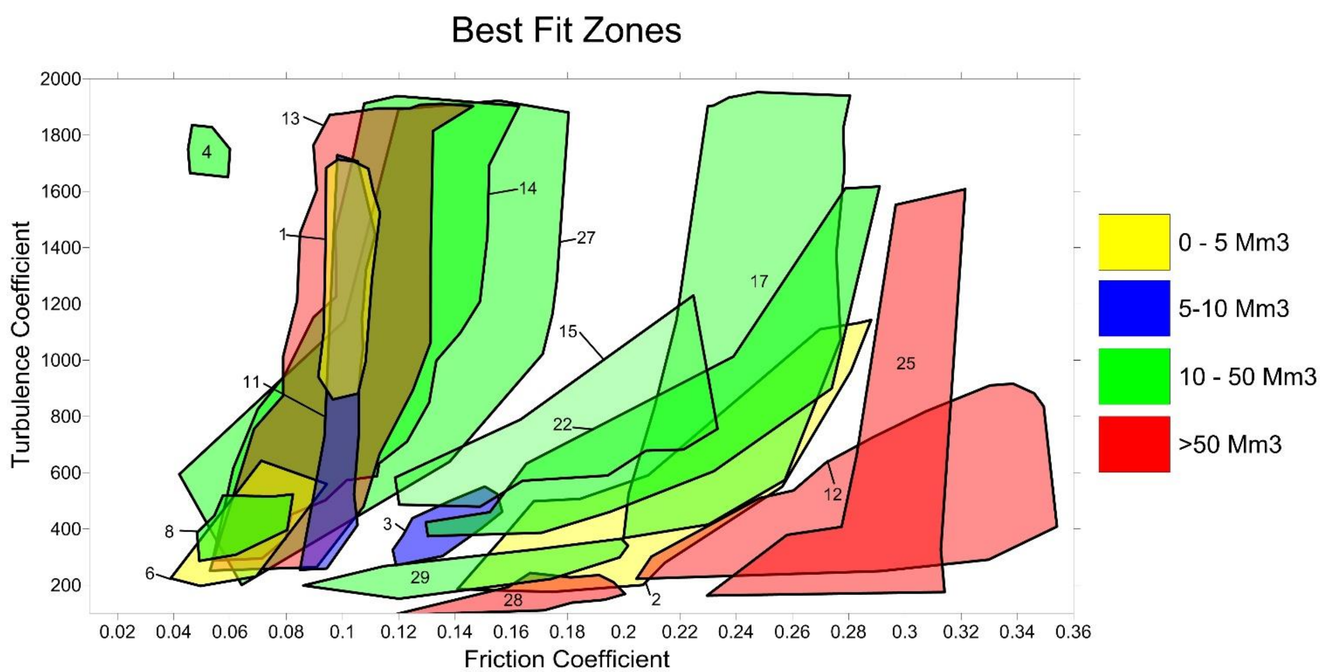

Figure 5. Best fit path material parameter zones for each of the cases analysed with the Voellmy rheology. Each polygon represents one case. The case names corresponding to the case numbers can be found in the caption of Figure 2. Figure from Aaron (2017).

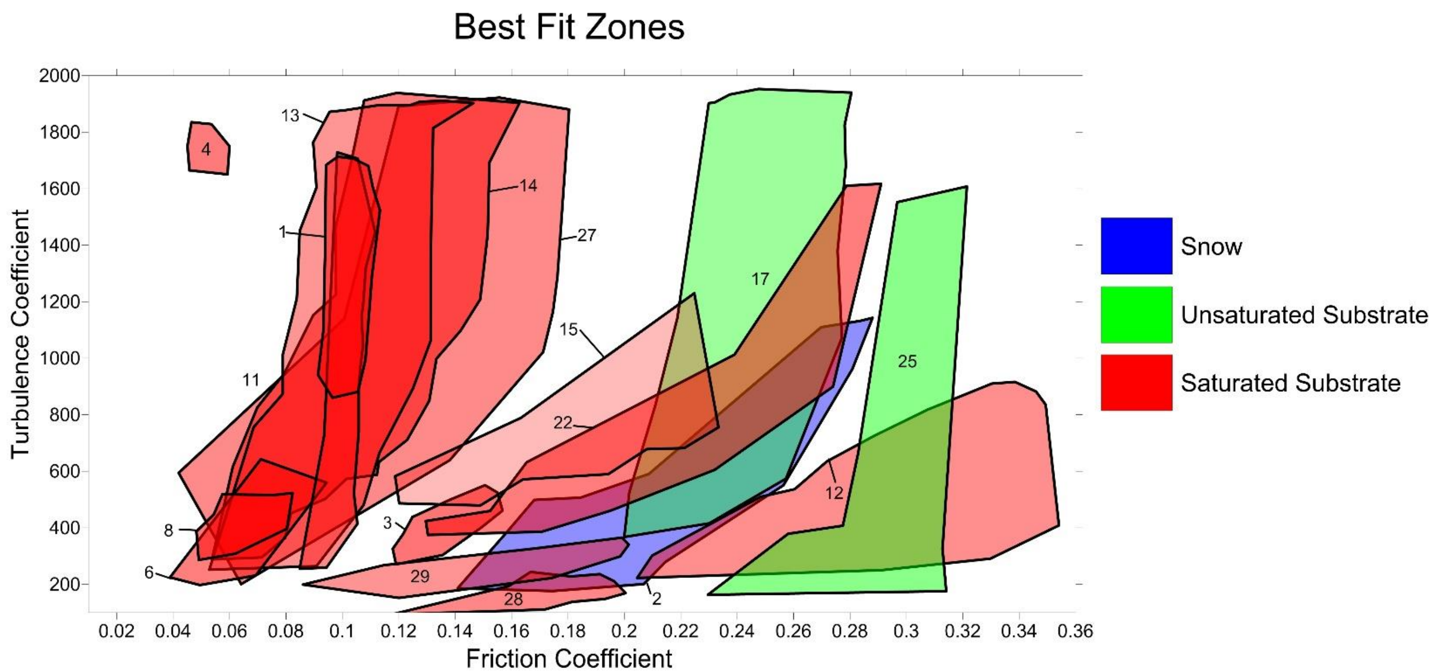

Figure 6. Best fit Voellmy parameters colored by path material, whre each polygon represents one case. Case names can be found in the caption of Figure 2. Figure from Aaron (2017).

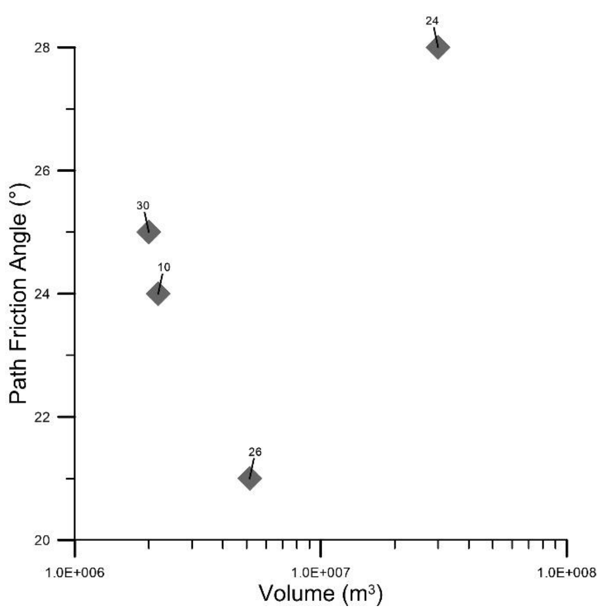

Figure 7. Best fit friction angles for cases that overran bedrock. Each point represents one case. Case names can be found in the caption of Figure 2. Figure from Aaron (2017).

6 DISCUSSION

For the majority of cases, good results were obtained using a frictional rheology in the source zone and then a change in resistance parameters and/or rheology for the path materials, over-ridden downslope of the source area. Figure 4 indicates that the source zone friction angle for the cases that were analysed is volume-dependent. This suggests that some mechanism is required to significantly reduce the basal resistance along the rupture surface. Many of the rupture surfaces of the large volume rock avalanches develop along continuous planar features. One factor that may significantly reduce the strength along a continuous planar feature is extreme polishing and removal of asperities, which leads to a reduction of the friction angle to the "ultimate value", as proposed by Cruden & Krahn (1978). This mechanism would be volume-dependent, as higher volume cases would have higher normal stresses along the planar feature, which would increase polishing and removal of asperities.

As shown in Figure 5, the shear strengths back-analysed for the path do not have a clear volume-dependence. Figure 6 and Figure 7 show that the character of the path material is a plausible explanation for the variance in the shear resistance experienced by the moving rock avalanche once it has vacated the source zone. Figure 6 shows that, independent of volume, the cases that overran saturated substrate experienced relatively low resistance to motion, with best fit friction coefficients as low as 0.05. These cases span a range of volumes from 0.2 Mm^3 to 200 Mm^3. Two of the least mobile case histories in the database, Sentinel and Madison Canyon, overran sediments; however, it is likely that these sediments were unsaturated because both cases are located in arid regions (Hadley, 1978; Castleton et al., 2016; Wolter et al., 2016). Additionally, Hadley (1978) showed that there was no precipitation in the six weeks leading up to the Madison Canyon event. Thus, it is likely that these cases were relatively immobile because they overran unsaturated substrate materials.

The velocity-dependent term in the Voellmy rheology has the potential to introduce some volume-dependence in the basal resistance. This is because larger volume cases tend to have greater flow depths than smaller volume cases, but for a given velocity, the velocity-dependent term is constant. Therefore, thicker flows have a greater difference between driving and resisting stresses. Figure 5 shows that, for a given volume class, basal resistance appears to be independent of volume. Therefore, it is not expected that the volume-dependence implicit in the Voellmy rheology is masking a volume-dependent effect in the back-analysed basal resistance parameters.

One case that appears to disagree with this overall trend is Val Pola (Case 12 on Figure 6). The best fit basal resistance parameters back-analysed for the path material in this case are closer to those analysed for the two cases that likely overran unsaturated substrate. It failed after a period of extremely heavy rainfall, so it is likely that the ground was saturated. Further research is required to better understand why this case history was not more mobile.

Figure 7 shows that the cases that overran bedrock all experienced relatively high resistance to motion, regardless of volume (friction coefficients ranging from 0.38 to 0.53). Based on this result, the back-analysed strengths along the path appear to be poorly explained by a volume-dependent movement mechanism; however, they are consistent with those that would be hypothesized based on the character of the path material.

7 CONCLUSIONS

The results described above suggest that rock avalanche mobility is not solely governed by a mechanism that is universal and volume-dependent. The scatter on plots of H/L (e.g. Figure 2) already indicates this; however, the present study shows that the character of the path material is a possible explanation for this scatter. The present work cannot definitively rule out the possibility that multiple mechanisms are simultaneously acting to reduce basal resistance; however, no other explanations in addition to the shear characteristics of the path material are needed to explain the bulk characteristics of the analysed rock avalanches. These results show that consideration of path material is crucial in understanding and predicting rock avalanche motion. However, the back-analysis of the Val Pola case history, as well as the scatter on Figure 6, indicate that further research is needed to better understand rock avalanche interaction with sediments.

The only universal, volume-dependent mechanism needed to explain the shear strength distribution back-analysed for the 24 case histories presented here is a volume-dependent mechanism that can reduce the strength in the source zone. Extreme polishing along planar features in the source zone is one potential volume-dependent mechanism that can explain the back-analysed strengths. As described above, Hungr & Evans (2004) hypothesized that larger volume rock avalanches cover more spatial area, so are more likely to encounter weak substrate materials. This mobility mechanism, modified to account for possible volume-dependent resistance in the source zone, appears to be a plausible explanation for rock avalanche mobility.

These results have important implications to the forecasting of rock avalanche motion when using a calibration-based runout model. Such forecasts are parameterized based on successful back-analyses. To do this, a modeller must be able to select which previously successful back-analyses are similar to the case of interest, which requires an understanding of rock avalanche movement mechanisms. The results presented here appear to show that this choice can be made based on the expected path materials. These results also show that there is significant scatter in the back-analysed parameters, meaning that forecasts should be performed in a probabilistic framework.

8 ACKNOWLEDGEMENTS

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