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Development of a universal open access rock avalanche case study database

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Abstract

Predicting the post-failure behavior of complex events such as rock avalanches often involves looking at past events to make inferences about potential future events. Many case studies of rock avalanches have been published, but a consistent methodology for describing these events has not been universally adopted. Furthermore, geohazard researchers and practitioners must go through many publications to find details on a sufficient number of events to make inferences on factors that may be controlling runout characteristics. An open access database has been developed that contains the digitized impact areas, descriptive attributes, and bibliographic references for a large number of events. This open access database has recently been used to develop new empirical relationships for travel distance and impacted area. Where available, information about the coarse rocky debris and mobilized sediments of the rock avalanche deposit are provided. The attributes within the database have been selected to be simple enough that they can be consistently assigned by different users and to maximize sample sizes, while still being able to separate out factors that have been demonstrated to influence rock avalanche mobility. The database is intended not only to make the existing spatial and descriptive information on these events available, but to allow for other researchers and practitioners to share data in a consistent format. By collaboratively building a universal, open access database of events, greater insights into the controls on rock avalanche mobility, including potential regional trends, may eventually be gained.

1 INTRODUCTION

Rock avalanches involve the detachment, fragmentation and subsequent flow-like motion of rock (Hungr et al., 2014). These events attain extremely rapid (> 5 m/s) velocities and are highly destructive. The hazards associated with rock avalanches are not limited to direct impacts from the fragmented rock debris; associated hazards such as air blasts (Zhuang et al., 2019), and the formation and breach of landslide dams (Ischuk, 2011; Evans et al., 2011) can also be destructive. Furthermore, substrate materials in the impact zone can be mobilized into mass flows of sediment (Abele 1997), or impacts into water can cause impulse waves (Higman et al., 2018).

The travel distance of rock avalanches tends to be greater than what is expected from a purely frictional process involving rock fragments, a phenomenon referred to as excess mobility (Hsü, 1975). There have been many theories proposed to explain the mechanisms behind the high mobility of rock avalanches. Theories include processes related to the flowing rock mass, including pore-air pressures (Shreve, 1968), acoustic fluidization (Johnson et al., 2016), frictional heating and melting (Hu et al., 2019), dynamic fragmentation (Bowman et al., 2012), and fragmentation in the presence of water (de Blasio, 2009). The effect of travel path substrate materials on enhancing mobility has been proposed by a number of authors, including saturated substrates leading to rapid undrained loading (Hungr and Evans, 2004), and glacial ice or snow, resulting in meltwater generation reducing friction (de Blasio, 2014). The lack of consensus regarding the physical causes of rock avalanche mobility and the practical limitations of describing the detailed physical state of a rock slope pre-failure have hindered the development of purely physically-based approaches to predicting rock avalanche mobility.

In most practical applications, empirical or semi-empirical methods are used to estimate the potential impacts from rock avalanches (McDougall, 2017). To support these predictions, descriptions of past events must be collected to develop statistical predictions (e.g. Mitchell et al. 2019), or to calibrate semi-empirical runout models (e.g. Aaron et al. 2019). These empirical or semi-empirical approaches require case histories of past events for their development. A selection of published rock avalanche case-history compilations is provided in Table 1. It should be noted that there are some events that are listed in multiple datasets (i.e. the global total of distinct events is less than the sum of the number of cases in each dataset).

Table 1. Selected datasets used to establish terrestrial rock avalanche travel distance relationships

Reference	Region (# of cases)	Attributes in dataset[1]
Scheiddeger (1973)	Global (33)	V, α
Hsü (1975)	Global (33)	V, α, L_e
Li (1983)	Europe (76)	V, α, L_d, A_d
Nicoletti and Sorriso-Valvo (1991)	Global (40)	V, α, H, L, W, G, T
Corominas (1996)	Global (47)	V, α, H, L, T
Legros (2002)	Global (non-volcanic) (32)	V, α, H, L
Zhan et al. (2017)	China (38)	V, α, H, L, A_s, T[2]
Strom and Abdrakhmatov (2018)	Central Asia (433)	V, α, H, L, W, A, A_d, G, T
Mitchell et al. (2019)	Canada (49)	V, H, L, A, G, T, S

Notes:

1. V = volume, α = travel (fahrböschung) angle or H/L ratio, H = fall height, L = runout distance, L_e = excessive runout distance, L_d = deposit length, W = width, A = total impact area, A_d = deposit area, A_s = source area, G = geological description, T = travel path topographic description, S = travel path substrate description

2. Topography is described with source slope angle and channel slope angle as opposed to descriptive attributes

The terminology in use to describe landslide processes in general has been largely standardized (Cruden and Varnes, 1996; Hungr et al. 2014). However, a consistent method for describing and mapping rock avalanche events has not yet emerged, as shown in Table 1, with a variety of attributes, and a variety of ways of measuring or describing those attributes, in use for the existing datasets. The continued use of the mobility attribute known as fahrböschung angle (Heim, 1932), despite its well-documented limitations (Legros, 2002), points to the power of simple, yet informative descriptions of events.

This paper provides a set of definitions for rock avalanche impact zones, details a mapping methodology to delineate the different impact zones, and introduces an open online database to host the data in a spatially referenced format. Examples of statistical analyses using these data are also provided. The overarching goal of this work is to catalyze the development of a universal, collaborative, open access database for consistent descriptions of rock avalanche events, to facilitate future studies, improve runout prediction methods and lead to a better understanding of rock avalanche mobility.

2 ROCK AVALANCHE IMPACT ZONES

As discussed in the preceding section, there are a variety of hazards associated with rock avalanche events. Differentiating separate impact zones for an event can help to highlight the areas impacted by different processes, which may be associated with different consequences. Three impact zone definitions are provided. These definitions are meant to be appropriate for mapping events with aerial or satellite imagery, and low-resolution topographic data.

2.1 Zone 1 Impact Area

The Zone 1 impact area is the spatial area that has been impacted by coarse, rocky debris. This area extends from the source, through the transport zone to the distal extent of continuous fragmented rock debris. In cases where the rock avalanche encounters sediments, the Zone 1 impact area may include coarse debris rafted on top of the sediments (see Figure 9 in Abele, 1997). Typically, the Zone 1 impact area is all that is observable in aerial or satellite imagery for prehistoric events.

Mapping the Zone 1 impact area separately from the rest of the impact areas is meant to facilitate a direct comparison of the impact areas from modern events to prehistoric events. The statistical validity of this approach was demonstrated in Mitchell et al. (2019).

2.2 Zone 2 Impact Area

The Zone 2 impact area is the area impacted by a rapid to extremely rapid mass flow triggered by a rock avalanche impact. These mass flows may involve sediments, water, and/or snow and ice. Zone 2 impacts occur coincidently with the deposition of the Zone 1 material; essentially they are part of the same discrete event.

Our current research is focused on mass flows involving sediments. In these cases, isolated blocks of the fragmented source rock may be rafted on top or within the sediment flow. These impacts may be radial, forming a fringe of displaced sediment around the Zone 1 deposit (e.g. Matthews and McTaggart, 1978), or they may be linear, becoming confined in a channel downslope of the Zone 1 deposit (e.g. Boultbee et al., 2006). Zone 2 impacts can be rapidly obscured in imagery, and while detailed field mapping can find evidence of these impacts (e.g. Calhoun and Clague, 2018), the frequency of rock avalanche-generated mass flow occurrence is difficult to estimate.

A schematic of the Zone 1 and Zone 2 impact areas is shown in Figure 1.

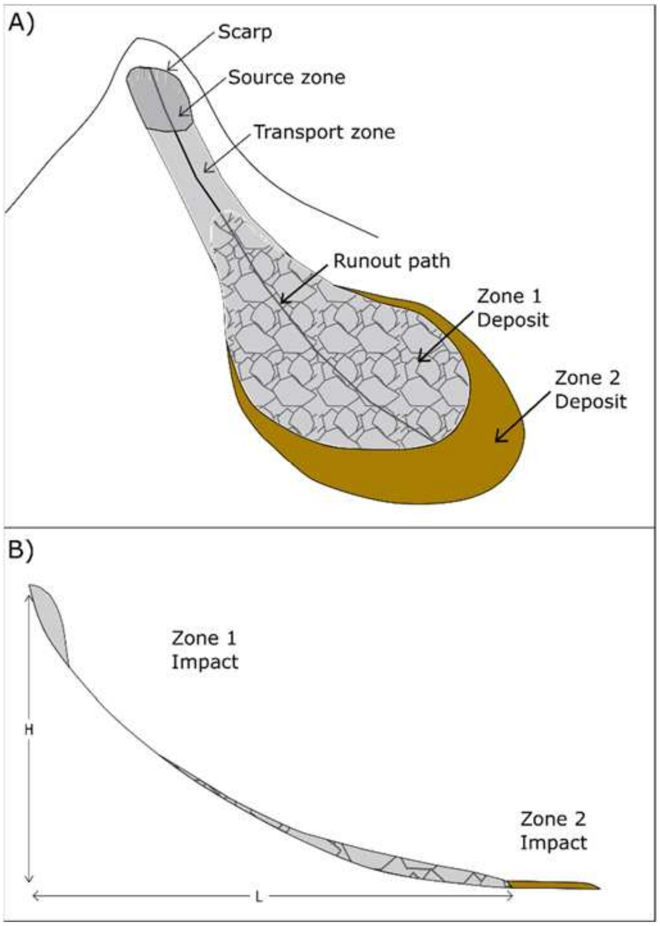


Figure 1. A) Definition sketch for Zone 1 and Zone 2 impact areas, and B) a schematic cross section showing fall height (H) and runout distance (L) along the Zone 1 runout path.

2.3 Zone 3 Impact Area

The Zone 3 impact area refers to spatial areas impacted by processes that are a direct result of the rock avalanche but are not triggered by the impact of fragmented rock debris, often separated from the Zone 1 and Zone 2 (if present) impacts in time. These impacts may include the formation of a landslide dam lake or rapid aggradation of a channel downstream of a rock avalanche, either through fluvial processes or breach of a landslide dam.

An example of a Zone 3 impact area can be seen in the satellite imagery following the Hapuku River rock avalanche that occurred as a result of the November 14, 2016 Kaikoura earthquake in New Zealand (Dellow and Massey, 2017), shown in Figure 2. A landslide dam lake is visible immediately following the event (Figure 2A), and the landslide dam was subject to seepage and erosion (Dellow and Massey, 2017). The size of the landslide dammed lake is substantially smaller in Figure 2B, however the amount of downstream deposition in the channel has increased greatly.

There are other potential impacts from rock avalanches, such as air blasts or hyperconcentrated flows that remain confined within a channel downstream of the Zone 1 and/or Zone 2 impact areas. These effects are difficult to visually identify in aerial imagery, and often leave little to no sedimentological record, and as such are not included in the zones defined here. There may be events, especially in confined terrain, where mass flows occur after the initial deposition, but are identified as Zone 2 due to limitations in the timing of available imagery.

3 EVENT MAPPING AND DESCRIPTIONS

Zone 1 impacts have been mapped for 66 distinct events, and Zone 2 impacts have been mapped for 22 events. Quantitative measurements of the deposit areas and runout distances for Zone 1 and Zone 2 impacts were digitized using Global Mapper software. Orthorectified images were obtained using historical air photos rectified using Agisoft Metashape, or using Planet satellite imagery (Planet Team, 2020), or DigitalGlobe satellite imagery. Elevation data was obtained from the ASTER GDEM v2 in all cases. Published case histories were used to validate measurements, and to check if there were discrepancies in the mapping methodology.

Qualitative descriptions of the Zone 1 and Zone 2 areas were made separately. Path topography descriptions use terminology consistent with Strom et al. (2019), and the substrate condition interpretations use terminology consistent with Aaron and McDougall (2019). A description of the source geology is provided using the criteria given in Whittall et al. (2017). These attributes were selected so that they would be relatively simple to apply when limited site data is available, either for describing events that have happened or for performing a forward analysis. We also wanted to avoid creating many small subsets of the data, but to be descriptive enough to provide meaningful distinctions between events.

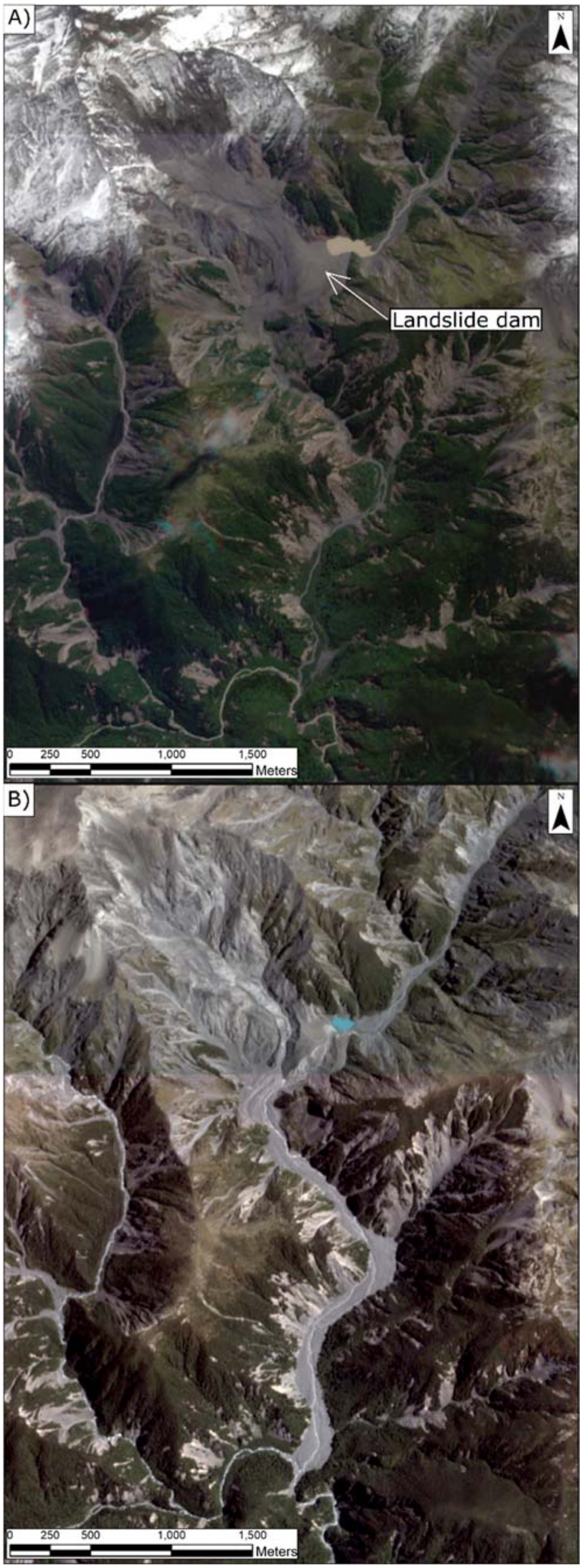


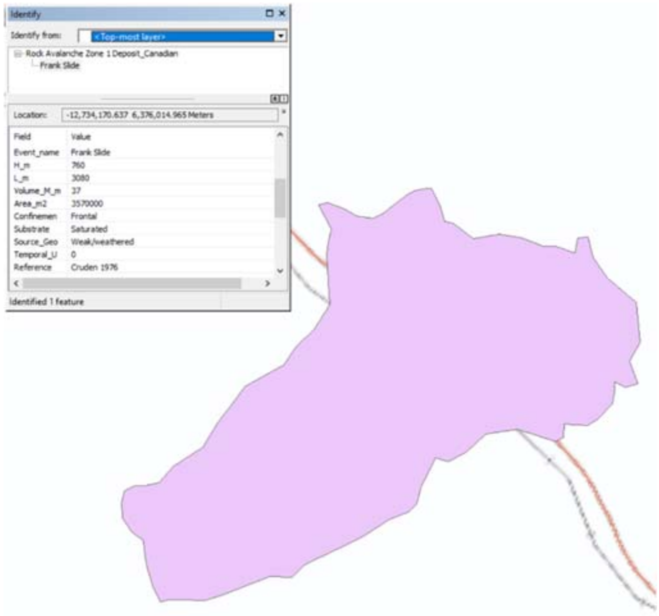
Figure 2. A) Hapuku River Landslide dam, satellite image from November 17, 2016, and B) satellite image from January 4, 2019. Imagery courtesy Planet Inc. (Planet Team, 2020).

Additional details on the mapping and descriptive methodology are given in Mitchell et al. (2019).

4 OPEN ACCESS DATABASE

We would like to facilitate the easy exchange of knowledge and avoid unnecessary duplication of work and/or allow for other researchers to attempt to replicate or challenge our results. Towards that goal, the Zone 1 impact mapping, descriptions, and compiled references for events in the Canadian Cordillera region have been made publicly accessible online (Mitchell, 2019a). The data is hosted on the DesignSafe-CI website, which uses cloud storage and computing for data storage, visualization, and research workflows (Rathje et al., 2017).

The data posted includes shapefiles that show the mapped extents of the 49 Zone 1 impacts from the Canadian Cordillera region (Mitchell et al., 2019). A database file is linked to the shapefiles so that by querying an impact area polygon, the quantitative measurements, descriptive attributes and bibliographic reference associated with that specific event will come up. The spatial data is accompanied by a read-me file that provides the definitions for the attributes used in the shapefiles, and the complete reference list for the dataset. An example of the data linked to a mapped deposit (Frank Slide) in ArcGIS is shown in Figure 3.



Location: -12,734,170.637 6,376,014.965 Meters

Field	Value
Event_name	Frank Slide
H_m	760
L_m	3080
Volume_M_m	37
Area_m2	3570000
Confinemen	Frontal
Substrate	Saturated
Source_Geo	Weak/weathered
Temporal_U	0
Reference	Cruden 1976

Identified 1 feature

Figure 3. Example of a digitized rock avalanche and the attributes of this event. Other attributes not shown include metadata related to the mapping projection.

5 EMPIRICAL MOBILITY ESTIMATES

The data currently available online was used to develop empirical relationships for the Zone 1 runout distance and mean path width (defined as the ratio of the total impact area divided by the runout distance) (Mitchell et al., 2019). Linear regression was used to find relationships between the variables, which were then used to estimate exceedance probabilities for predictive analysis. The application of this method is to evaluate ranges of probabilities of a rock avalanche travelling past given points along a path. An inverse analysis has also been implemented where a volume is found that results in a specified probability of travel exceedance (Mitchell et al., 2019). This approach has been implemented into an open source computer tool, called Probabilistic Runout Estimator – Rock Avalanche (PRE-RA) (Mitchell, 2019b). Similar methods are currently being studied to develop stochastic empirical predictions of Zone 2 impacts.

6 DISCUSSION

A set of definitions for different rock avalanche impact zones is presented with the objective of having these definitions applicable to mapping using aerial imagery. The three impact zones focus on the surface expression of the deposits or impacts, but are also related to the primary processes that result in their creation. Considering the distinction between the impact zones could lead to greater consistency in the measured impact areas and runout lengths. However, it must be recognized that the quality of the mapping is going to be dependent on the resolution and quality of imagery availability, the availability of high-resolution topography (e.g. bare-earth lidar DEMs), and the interpretations of the person who is doing the mapping. Another important aspect of having a high-quality description of an event is performing detailed field mapping of the event, which can provide detail and insights not available in aerial or satellite imagery. An advantage of having mapping data open access is that it allows other researchers and landslide practitioners to cross-check the mapping used in subsequent empirical analysis.

Another challenge with consistently mapping and describing rock avalanche deposits is temporal changes in deposits. To confidently map Zone 2 impacts, data from soon after the event is required, as the finer material in this zone tends to revegetate more rapidly, and the finer deposits are more susceptible to erosion than coarse fragmented rock in Zone 1. The time dependence of some effects of rock avalanches are explicitly addressed in the definition of Zone 3 impacts, however, this presents a new set of challenges, where multiple high-quality observations are required to describe the impacts. For example, a rock avalanche could result in a landslide dam that creates a lake upstream of the deposit (one impact area), which could lead to a dam breach that causes downstream flooding (a second impact area). Over a longer time period, downstream aggradation of material eroded from the deposit could increase flooding hazards or create maintenance issues for infrastructure such as culverts and bridges. The availability of daily satellite imagery (e.g. Planet, 2020) provides interesting opportunities to explore these time dependent processes by examining time series of imagery. Development of repeatable methods for mapping and describing Zone 3 impacts is another area for further development. Simple descriptors for landslide-dammed lakes were included in the central Asian database presented by Strom and Abdrakhmatov (2018), which could be expanded upon to include descriptions of areas effected by landslide dam breaches and aggradation.

Describing rock avalanches using simple, yet descriptive attributes in a consistent manner presents opportunities for future research and improvement in the state of practice around rock avalanche hazard and risk management. There were many factors that did not show a strong association with runout distance or mean path width in the analyses detailed in Mitchell et al. (2019), however, additional data may allow for stronger associations to be found. There are also opportunities to make advances in semi-empirical numerical modelling by relating the descriptive attributes to calibrated model parameters (Aaron and McDougall, 2019). Systematically examining a universal, global database of rock avalanche events could also reveal trends that could shed more light on the fundamental mechanisms leading to the high mobility of rock avalanches.

7 CONCLUSION

Having a consistent set of terms to describe the impact areas from rock avalanches is desirable for trying to build a robust, global database of event case histories. Three impact area zones have been defined, and a simple set of attributes to describe events has been developed. Empirical analysis of this data has been used to make stochastic predictions of runout distance and impact area. Further research is underway to refine these predictions and incorporate the data into semi-empirical numerical modelling.

We have made a collection of rock avalanche impact area maps and event descriptions freely available online. By doing this, we hope to promote collaboration in compiling more case histories that can be used for empirical or theoretical analyses of rock avalanche motion. Any researchers interested in contributing to this database are encouraged to contact the authors. Getting data from many geographic and climatic regions could illuminate regional or other trends within the data. It would also be beneficial to collect data on large slope deformations that do not transform into extremely rapid rock avalanches to help better define the probability that a rock avalanche occurs. This probability is a major source of uncertainty in hazard and risk assessments, and is a very important area for future research.

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