USING A PATTERN-BASED APPROACH TO PROVIDE A FIRST-ORDER ESTIMATE OF FAILURE POTENTIAL ACROSS A ROCK SLOPE

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EXTENDED ABSTRACT

Rockfalls are a significant agent of geomorphic change (Dussauge et al., 2003) and present a hazard to people and infrastructure located below unstable cliffs. Determining where rockfalls are likely to occur is of high importance when considering how to manage and mitigate against rockfall hazards (Matasci et al., 2017). Areas with the potential for rockfalls to occur can be identified by analysis of structural, geological, and environmental characteristics of a rock slope (Krautblatter and Moore, 2014; Messenzehl et al., 2016). However, evaluating the potential for rockfalls is often limited by understanding of the underlying processes driving failure, and does not provide any indication of timing. Furthermore, this approach fails to consider the role of surface topography and the interaction of failures (Whadcoat et al., 2017). Advances in the monitoring of slopes via tools such as LiDAR and photogrammetry, have provided data that has allowed rockfalls to be observed at a higher spatial and temporal resolution. This work has revealed apparent patterns in rockfall distribution, such as the clustering and sequencing of events (Stock et al., 2012; Rosser et al., 2013), suggesting the importance of small-scale, connected processes for determining the timing and location of subsequent failures, yet these tools are not accounted for in current approaches to rock slope assessment and modelling.

Pattern-based analysis is a widely used tool in environmental research and has become a well-established approach to understanding complex relationships within the landscape. Here we propose that adopting a pattern-based analysis offers a new approach to assessing rockfall distribution. By analysing the distribution of rockfalls events across a slope, the spatiotemporal patterns observed in rockfalls can be quantified, and the findings used to develop a series of rules that govern the system behaviour, and subsequently can be used to assess rockfall likelihood across a slope. This approach is summarized in Figure 1.

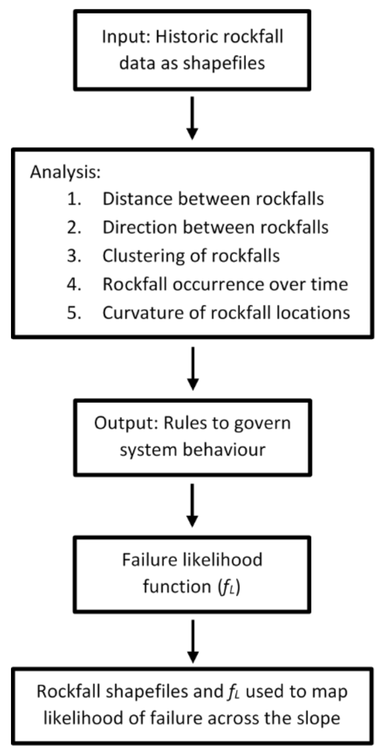

Figure 1: Workflow to apply failure likelihood mapping to a rock slope

Qualitative analysis of rockfalls in a two-year dataset of coastal cliffs in North Yorkshire, U.K. (Whadcoat et al., 2017) highlighted five factors as potentially governing the rockfall distribution: the distance and direction between rockfalls; clustering of rockfalls; the time of year; and the slope curvature (see 'Analysis' in Fig. 1). The results of quantitative analysis of these factors in the U.K. dataset can be summarized as follows:

(i) Distance and direction: During one year, rockfalls occur contiguous to 75% of existing rockfall scars. Of the contiguous rockfalls, 62% occur above and alongside the existing rockfall scars.

(ii) Clustering: Using a modified Ripley's K analysis (Tonini et al., 2013) shows that rockfalls are not randomly distributed but cluster significantly around existing rockfall scars at all timescales. Rockfalls cluster most significantly at distances of 2 m, suggesting a critical distance-value for clustering of rockfalls over time for this environment.

(iii) Time of year: Spatially averaged erosion displays periods of acceleration between November and January. During this time, the largest rockfalls occurred and the rockfall count was above average.

(iv): Slope curvature: When using local slope curvature, calculated at a 0.1 m^2 resolution, we observe a higher proportion of rockfalls on convex areas of the slope compared to flat or concave areas. There is also a positive correlation between slope convexity and rockfall depth.

Having developed these methods for the U.K. coastal cliff site, the methods are now being applied to a dataset from The Barrier near Garibaldi Lake (BC, Canada), where a monthly terrestrial laser scanning campaign began in July 2017. The rockfalls identified at The Barrier between August and November 2017 are shown in Figure 2. Based on this preliminary data, rockfalls are observed primarily on the upper portion of the steep rock slope (top half of Fig 2) and the talus slope below. Over three months, rockfalls occurred within 1 m of more than 50% of existing rockfall scars (Figure 3b). Over

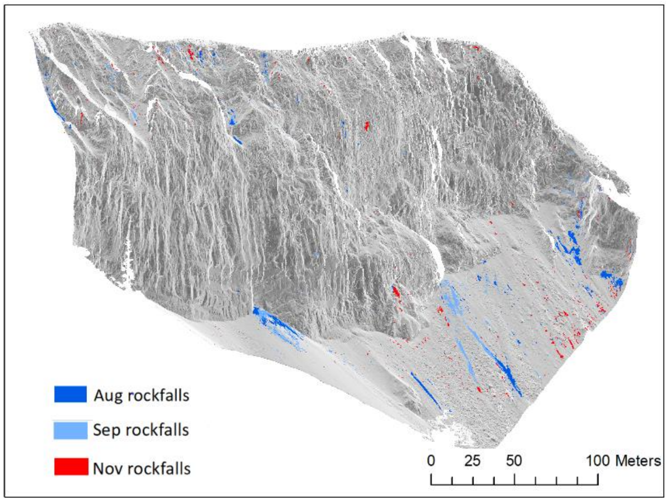

Figure 2: Rockfall shapefiles, coloured by the month in which they occur, representing areas of erosion that occurred between July 5th and August 9th ('Aug rockfalls'); Aug 9th and September 13th ('Sep rockfalls'); Sepr 13th and November 1st ('Nov rockfalls'). Shapefiles overlaid on a slope DEM from August 9th.

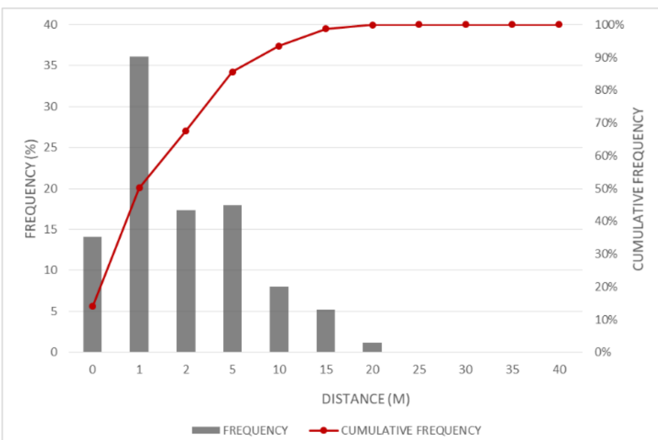

Figure 3: Histograms displaying the range of distance values from existing rockfall scars to the nearest subsequent rockfall over three months (from August to November)

the same time, rockfalls occurred contiguous to 14% of existing rockfall scars. The direction between existing rockfalls scars and subsequent failures is primarily upward and outward, with 64% of rockfalls occurring above or alongside existing rockfall scars.

These results from both study sites are being used to develop a series of rules that govern the system behaviour (see 'Output' in Fig. 1). By combining these rules, we aim to develop a failure likelihood function (f_L) (Fig. 1), which can be applied to discrete areas across a rock slope in order to evaluate the likelihood of failure. Results of the application of f_L to both study sites will be compared to subsequent monitoring data in order to validate f_L. Identifying such quantitative and reproducible methods for the analysis of rockfall distribution will allow comparison of rockfall activity at different sites and is an important step in developing and informing process representation in models.

Rockfall hazard assessments are often focused at a regional scale or at the block-specific scale, with a research gap between these methods, as highlighted by Matasci et al. (2017). The analysis of spatiotemporal patterns presented here provides an approach for assessment of rockfall likelihood at the slope scale, thus addressing this research gap. Observations of rockfalls in this study and elsewhere are indicative of a progressive failure mechanism, postulated to be driven by stress transfer (Stock et al., 2012). Quantifying the spatial and temporal length scales over which the progressive failure mechanisms are observed, allows estimation of the likelihood of failure in a way that accounts for interaction, such as stress transfer, between rockfalls. This approach also provides information that can be used to refine and develop rockfall models, which currently do not account for interaction between failures. In addition to providing information for rockfall models, the ability to map the likelihood of failure across a rock slope could assist in both event forecasting, such as identifying areas for short-term high resolution monitoring, and in post-event mitigation efforts, such as the area that should be scaled following a rockfall event.

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