Temporal analysis of 4D rockfall activity and patterns of erosion from automated hourly-resolution laser scanning monitoring

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Overview

Rock slope failures are hazardous erosional events that result from a range of processes, including both direct environmental forcing and progressive rock fracture. In this study, we present a novel 4D dataset compromising three years of continuous laser scanner monitoring based on hourly change detection of the cliff-face topography undertaken on a vertical cliff (Whitby, North Yorkshire, UK). We developed a computational workflow to automatically process a total of 20,098 collected scans to undertake automatic pairwise change detection measurements. We used our data to examine in detail the evolution and timing of rock slope failure and how this is manifest as short- and long-term rates of material loss and cliff retreat. We found that the average rate of cliff retreat over a three-year monitoring period is ~11 mm y^{-1}. Periods of higher erosional activity (~140 – 300 mm y^{-1} within five day internals) punctuate periods of slower erosion (~2.5 – 9.3 mm y^{-1}), where the rate of volume loss during slower erosion is controlled by small-magnitude rock slope failures. Our research characterizes the retreat rates at both high resolution and long-term monitoring, and holds implications for the understanding of the drivers of rock slope erosion.

Background

Monitoring of rock slopes can yield fundamental insights into erosion rates, rockfall hazards, landform and landscape evolution, the processes that control rock slope failures and how these may be modified by a changing climate. Recent monitoring studies have measured erosion using hourly to monthly LiDAR surveys over months to several years (e.g., Rosser et al., 2005; Rosser et al., 2007; Lim et al., 2010; Rosser et al., 2013; Barlow et al., 2012; Williams et al., 2018). These studies have provided quantitative understanding erosion dynamics, but they are limited by the frequency of data collection and the duration of the monitoring campaigns (Rosser et al., 2017). In particular, this limits our understanding of the magnitude and frequency of rockfall events and, in turn, our understanding of the driving mechanisms. To address this, we developed a computational workflow to efficiently process a large volume of LiDAR scans (2017 – 2019) acquired at 1 h intervals at East cliff of Whitby, North Yorkshire, UK (Figure 1).

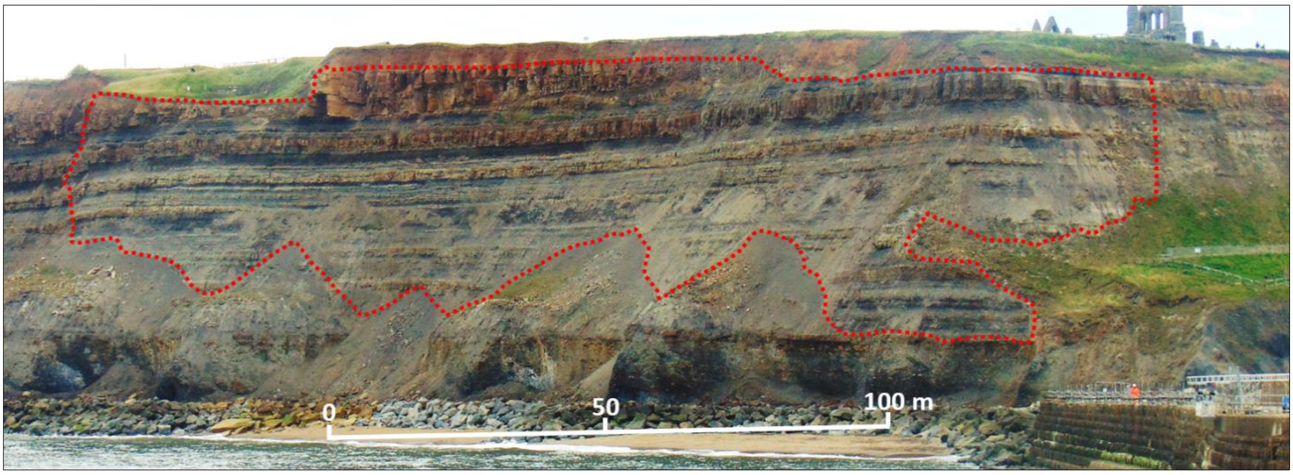

Figure 1. Study site - East cliff of Whitby, North Yorkshire, UK. The dotted red line delimits the area of research (~ 5,500 m^2). Areas not included within this area, such as the topsoil and debris/talus units, were removed from analysis (photograph © Ignacio Ibarra).

Methods

Our dataset is comprised of 20,098 scans acquired at 1 h intervals and an average point spacing of 0.08 – 0.10 m. We used a Riegl VZ-1000 terrestrial laser scanner to collect the data between January 2017 and December 2020. The scanner was installed inside a lighthouse provided with constant power supply, allowing the scanning of the slope from a fixed position and at a constant rate of point cloud acquisition. To process large archives of 3D point cloud data, we developed a new computational workflow that included key filtering and quality-control steps. Change detection between sequential (hourly) scans was conducted using the M3C2 algorithm (Lague et al., 2013). We also developed a workflow to automatically calculate volumes of failures, from which the rates of erosion were estimated. The results are presented using 4D time-series of the cliff-face retreat rate, which were calculated over five-day periods (pentads) of total volume loss (mm y^{-1}), permitting more straightforward examination of the emergent patterns of erosion from our dataset**.** We calculated net cumulative retreat (mm) from cumulative volume loss detected across the monitored area. We then quantified the average retreat rate throughout the three-year monitoring period**,** expressed in mm y^{-1}. We also considered variability in the magnitude and frequency of retreat rate through time; we isolated periods of more gradual erosion from those characterized by higher rates and calculated the retreat rate during these periods (Figure 2).

Results

We observed a total retreat of ~33 mm by the end of December 2019 (Figure 2). The annual retreat observed in each year was similar, but it was slightly higher in 2017 (~13 mm) compared with the retreat observed in 2018 and 2019 (both ~10 mm). The average retreat rate between January 2017 and December 2020 was 11 mm y^{-1}, suggesting a relatively high rate of volume loss of the examined cliff face to other observed rates. We observed prolonged periods of gradual cliff erosion, showing near-constant rates of volume loss between 2.5 and 4.6 mm y^{-1}; these rates were quasi-constant over continuous periods lasting between 124 and 264 days. These periods of gradual cliff retreat resulted from the dominance of incremental and ongoing low volume failures. However, shorter periods of erosion characterized by elevated rates of the erosion were also identified; these lasted from 25 to 65 days, during which where the average retreat rate ranged between 7.3 and 9.3 mm y^1 and were characterized by generally larger failure events.

By examining the retreat rate calculated within pentads, we observed high variability in the shorter-term erosion rate, which varied between ~0 mm y^{-1} during periods of minimum volume loss to a maximum rate of ~300 mm y^{-1}, which was driven, for example, by two peaks of rock-mass loss of ~23.0 ± 5 m^3 that occurred in summer 2017 and in winter 2019. In 2017 and 2018, an additional four episodes of high retreat rate were also detected throughout winter, spring and summer (140 – 185 mm y^1), while in 2019 the higher retreat rates were detected in winter and autumn. Also, the retreat rates during these periods of higher erosional activity generated marked differences compared to the long-term cumulative retreat curve (Figure 2).

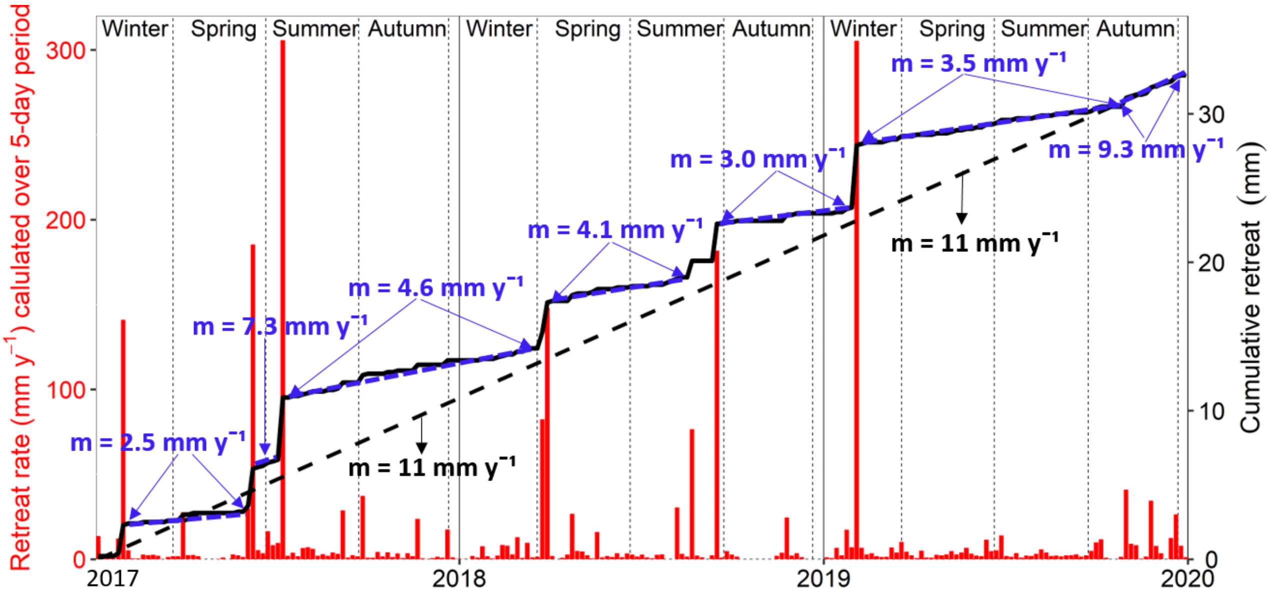

Figure 2. Evolution of the retreat rate (mm y^{-1}) calculated over five- day periods, and cumulative retreat (mm) between January 2017 and December 2019.The black dashed line shows the average rate between these two dates. Non-dashed black line shows the long-term cumulative retreat curve. The dashed blue lines/arrows indicate rates of gradual erosion. Approximate boundaries between seasons are shown using dashed vertical lines.

Conclusions and implications

Using a new workflow for automatization of large datasets of 3D point clouds have permitted us to quantify and assess slope failures of brittle rocks, where, for the first time, coastal retreat rates of UK from hourly resolution change detections over three years of constant measurements are presented. The observed retreat rates, measured at a temporal resolution that has not previously seen, are important indicators of the progressive evolution of coastal slopes made by brittle rocks, being also a surface indication of underlying processes inducing the fracturing, deformation, and final detachment of brittle rock-masses. We are exploring these processes in ongoing work.

Reference list

Barlow, J., M. Lim, N. Rosser, D. Petley, M. Brain, E. Norman, and M. Geer. 2012. Modeling Cliff Erosion Using Negative Power Law Scaling of Rockfalls. Geomorphology, 139–140: 416–424.

Lague D., Brodu N., Leroux J. 2013. Accurate 3D comparison of complex topography with terrestrial laser scanner: application to the Rangitikei canyon (N-Z). Journal of Photogrammetry and Remote Sensing, 82,10 - 26.

Lim, M., Rosser, N.J., Allison, R.J., Petley, D.N., 2010. Erosional processes in the hard rock coastal cliffs at Staithes, North Yorkshire. Geomorphology 114, 12–21.

Rosser, N. J., Petley, D. N., Lim, M., Dunning, S. A., & Allison, R. J. 2005. Terrestrial laser scanning for monitoring the process of hard rock coastal cliff erosion. Quarterly Journal of Engineering Geology and Hydrogeology, 38(4), 363–375.

Rosser, N.J., Lim, M., Petley, D.N., Dunning, S.A. & Allison, R. 2007. Patterns of precursory rockfall prior to slope failure. Journal of Geophysical Research : Earth Surface, 112, F04014.

Rosser, N.J., Brain, M.J., Petley, D.N., Lim, M. & Norman, E.C. 2013. Coastline retreat via progressive failure of rocky coastal cliffs. Geology, 41, 939 - 942.

Rosser, N.J., Williams, J. G., Brain, M.J., Hardy, R. J. 2017. Insights into progressive rockfall failure from 4D scanning. Progressive rock failure conference, Monte Verità, 5–9 June, 27-28.

Williams, J. G., Rosser, N. J., Hardy, R. J., Brain, M. J., & Afana, A. A. 2018. Optimising 4-D surface change detection: an approach for capturing rockfall magnitude–frequency. Earth Surface Dynamics, 6(1), 101–119.