COASTAL ROAD ASSET MANAGEMENT: DEALING WITH UNCERTAINTY USING QUANTITATIVE EROSION MONITORING AND MODELLING

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Abstract

The A183 is an essential transportation link in the northeast UK that joins coastal areas from South Shields to Sunderland. The route runs through the hinterland of Marsden Bay and concerns have been raised about the proximity of the road to the eroding cliff line. The Shoreline Management Plan (Lane and Guthrie, 2007) sets out the overarching management policy in the area and, based on the analyses of historic map data, uses projected coastal cliff retreat rates of 0.1 – 0.2 m a^{-1}, although more recent investigations have suggested the rates may be nearer 0.04 – 0.1 m a^{-1}. Quantitative data on the true rates and nature of cliff erosion are scarce and asset management decisions typically use the higher rate of 0.2 m a^{-1} when considering the potential impact on road operations and lifespan in order to account for uncertainty and future sea-level rise; which is additionally used to accelerate the predicted rates of retreat. Consequently, an enhanced high order estimate of cliff erosion rates has restricted the serviceability of the A183 to within 20 – 50 years, and there are three areas (pinch points) of particular concern where the close proximity of the cliff line threatens the safe operation of the road. This approach and the data it uses suggest that significant and potentially costly decisions may soon be required to ensure the viability of this vital transport corridor.

Set against the context of assumed high cliff erosion rates, and further predicted increases to this metric, this work presents the results of a re-evaluation of existing map and aerial imagery data that highlights the typically high uncertainty associated with historic map data. The errors often exceed the changes being detected in rock cliffs, producing contradictory results and variability in processing and interpretation that restricts the reliability of the data used in current policy decisions. Using a significance-based analysis, questions are raised about how appropriate it is to reduce a three-dimensional recession process down to a single linear retreat. To provide a more appropriate and accurate assessment of the erosion occurring here we present

the results of a monitoring approach of the Marsden Bay site using three-dimensional survey analyses to improve understanding of cliff failures at the site and ultimately to aid policy decisions.

Coastal road

The site is defined here as the 1540 m coastal stretch from the velvet beds in the north to the A183 cliff top car park in the south, situated between the Tyne and Wear rivers. It contains many coastal features including beaches of various types, shore platforms and cliffs cut into Magnesian Limestone of Permian age (formed *c*. 250 million years ago) that provide classic examples of cliff and stack development in this rock type. The largest such feature is Marsden Rock (Figure 1); the remnant of a former headland. This 40 m wide stack has a well-documented recent history and has, along with the adjacent grotto, provided a sustained focus for visitors since the late 1700's. The site draws high numbers of people to the foreshore area in front of the cliffs, which potentially exposes them to rock fall hazards. Two recently commissioned boreholes collected runs for geotechnical testing and have demonstrated that the cliff forming materials are generally weak and highly susceptible to fragmentation during the coring and collection process. The macro-structure of the cliff is also highly disturbed, with evidence of dissolution, weathering and collapse. An inclinometer and a vibrating wire piezometer have been installed in the bores to capture deep seated movement and surficial ground water fluctuations respectively as part of a longer term monitoring programme.

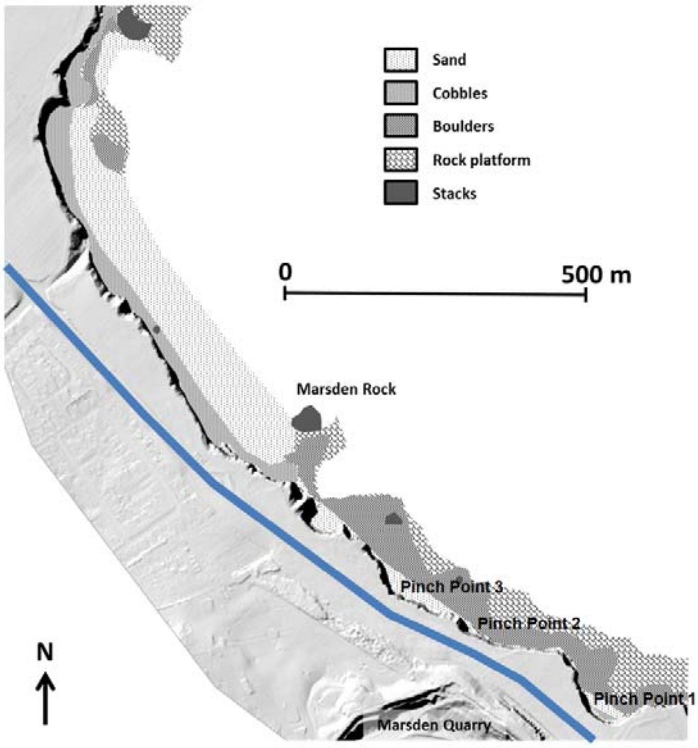

Figure 1: A topographic render of Marsden Bay area (lidar data), overlain with littoral zone classifications. The route of the A183 coastal road is highlighted in blue and the key pinch point areas of concern are annotated.

Historic map analysis

Historic and recent past cliff line mapping data form the basis of most rates of cliff retreat established for the Shoreline Management Plan (Lane and Guthrie, 2007) and subsequent policy decisions. These data form a long-term context for cliff behaviour and are often combined with worst case scenario sea-level rise (i.e. accounting for eustatic change and an increase in storm incidence) using the following equation (after Leatherman, 1991):

$$\text{Future recession rate} = \frac{\text{Historical cliff recession rate x future sea level rise}}{\text{Historical sea level rise}}$$

At the time of writing, the Shoreline Management Plan uses a predicted sea-level rise of 5 mm a^{-1} (Defra Guidelines are generally 4 mm a^{-1} for the northeast and then account has been made for predictions in increased storminess). This approach assumes sea-level is the dominant and sole control on cliff recession and that the historical cliff recession rate is accurate; assumptions acknowledged by the Shoreline Management Plan that needs to work with limited data to cover broad areas (Lane and Guthrie, 2007). Based on a 0.2 m a^{-1} retreat rate, established by historical mapping, the current policy timeframes predict a 4 m retreat in the next 20 years and then, using a factor of two to allow for predicted sea-level rise, a 20 m retreat over the next 50 years, increasing (by a factor of 2.5, again to allow for sea-level rise) to 50 m in the next 100 years. This upper bound has been used to identify the threat to the A183 coast road at three pinch point areas within the next 20 years.

Cliff line mapping of Marsden Bay has been undertaken using historic map sources and aerial photography encompassing a total period of 120 years (1896-2016). Cliff line extents were manually digitized in ESRI® ArcMap™ (v.10.0) software for each data source. Cliff line polyline vertices were densified to a regular interval of 1 m using the ET GeoWizards© plug-in, and converted to point format. To calculate the total change in the position of the cliff line for successive differencing epochs (e.g. 1985-1915, 1915-1942, etc.) the two-dimensional direct distance from a given cliff line point to its closest neighbouring point in the successive dataset was calculated. It should be noted that the mapping data and the year of production has been defined according to information provided by Edina Digimap and in some instances a range of years is given. Therefore, errors may exist in the rate calculations, but given the small size of the study area it is assumed that the whole site was surveyed at the same time and hence relative changes should be preserved. In order to account for the mapping inaccuracies and georeferencing errors (Crowell *et al*., 1991), a number of known ground control points (GCP) using clearly identifiable features were recorded. The vector distances between the control points and their corresponding location in the previous datasets have been used to establish the standard deviation of registration errors. A buffer corresponding in width to this error metric provides an envelope of positional uncertainty for each survey period. Only data where cliff line recession exceeded this error bound have been considered significant (Figure 2). This approach removed between 29.3 – 99.1% of the original cliff line from the analyses. The upper bound is attributed to the 1999 historical aerial photograph, which is poorly georeferenced, removing most of the cliff line from the analyses. Consequently, caution should be exercised when extrapolating and interpreting derived rates of cliff line retreat.

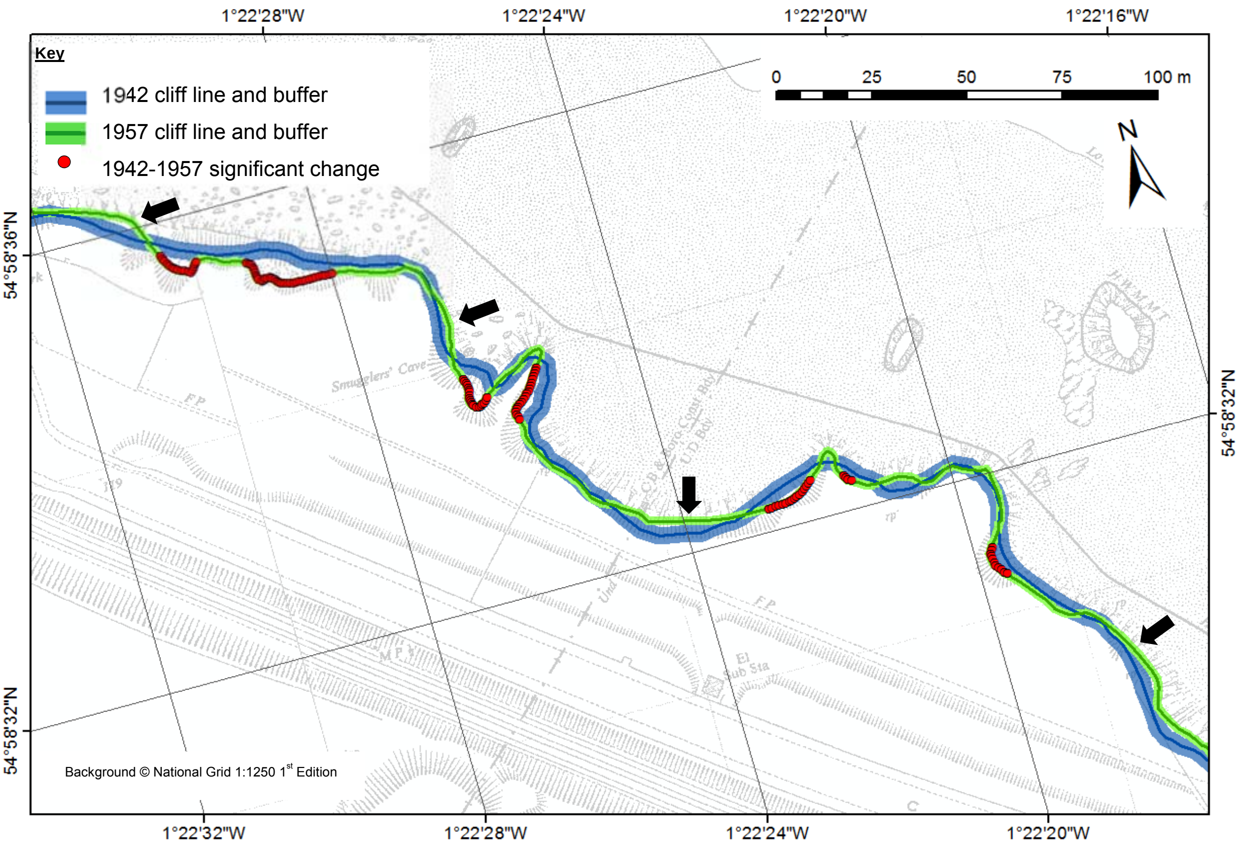

Figure 2: Filtering significant change (where the cliff line retreat which exceeds the limits of date-specific confidence buffers) for the period 1942 to 1957. Black arrows highlight areas where the cliff line appears to advance and are attributable to inaccuracies at the map production stage, georeferencing errors, and difficulties associated with interpreting the precise position of the cliff line from historical map sources.

Historic rates of cliff line retreat

The results of cliff line mapping for Marsden Bay are summarised in Figure 3 and suggest that cliff line retreat rates range from 0.028 to 1.435 m a^{-1}, depending on the differencing period. The mean historic cliff line retreat rate was found to be 0.326 ± 0.190 m a^{-1}. This retreat rate is largely governed by the higher rates produced from the aerial photo surveys, and the data derived from historic maps only derives a cliff line retreat rate of 0.088 m a^{-1} ± 0.049 m a^{-1} for the period 1896 - 1983, less than half that currently used for the site. The inclusion of aerial imagery should be used with caution because the majority of datasets were not collected expressly for the purpose of cliff line mapping and hence not processed in a suitable manner for this analysis. Removing the two aerial imagery surveys with clear georeferencing errors from the analysis to consider only the mapped data lowers the mean cliff line retreat rate to 0.136 ± 0.088 m a^{-1}. The data can be subdivided into two periods of relatively consistent rates of cliff line retreat; specifically the period 1896-2001, and 2001-2015 (Figure 3). This may indicate an increase in activity rates over the last 15 years, but it also appears that higher survey temporal resolutions produce greater variability of change, even on an annual to decadal timescale. This may indicate that the cliff line undergoes periods of higher activity and then quiescence that can become censored with longer durations between surveys.

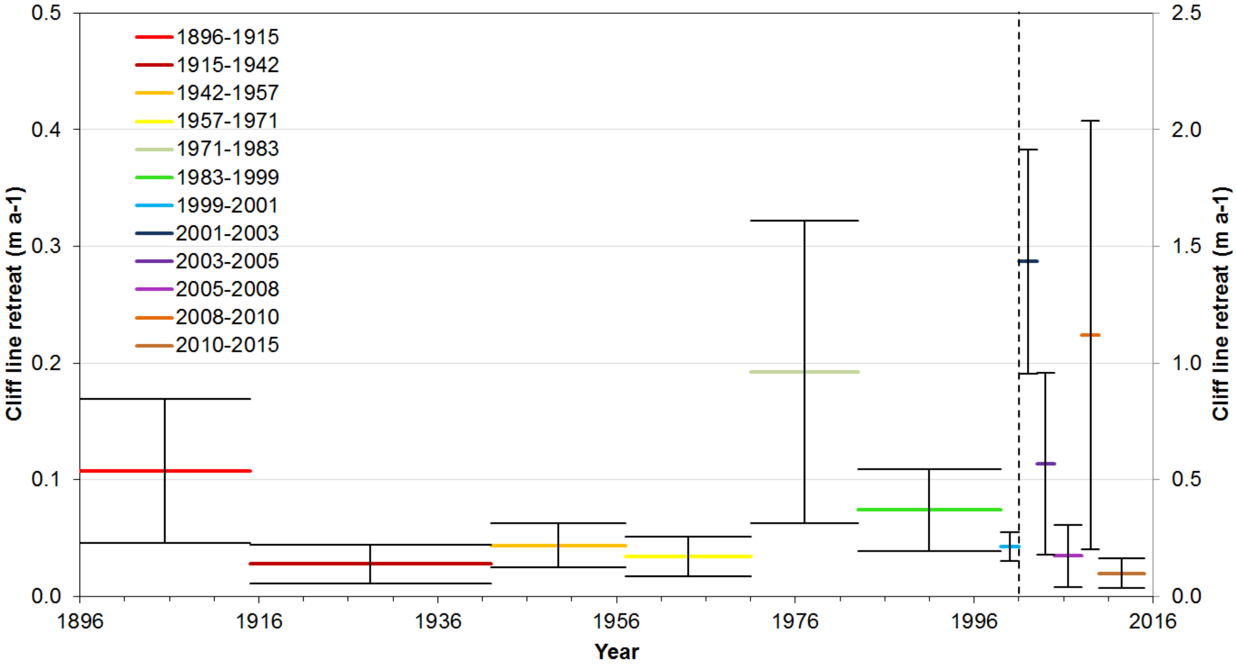

Figure 3. Mapped cliff line retreat rates based on historical map and aerial photograph data sources. Data represent only ‘significant’ change (see text for description). Upper and lower bounds denote one standard deviation around the mean value of significant (beyond mapping error) retreat. Note: data from 2001 onwards plot on the secondary (right) y-axis.

The majority of errors incurred in the use of previous survey data may be attributable to georeferencing and there may be a genuine case for heightened recession rates in more recent times, perhaps due to sea-level rise. However, it is evident that caution should be exercised in interpreting and extrapolating map data, and questions are raised regarding the conceptual adequacy of summarising cliff recession, a three dimensional change process, with a single linear retreat rate. The use of error buffers enables only significant change to be considered but large differences in mapping style, resolution and accuracy and photograph quality, contrast and perspective make identification of the cliff line (often synonymous with the cliff ‘top’) difficult to identify consistently. The glacial till drape causes cuspate scars that are often mapped as the cliff edge rather than the hard rock line resulting in rates that are artificially high. Despite this, the mapping analysis has produced a lower cliff retreat than that currently used in the Shoreline Management Plan (Lane and Guthrie, 2007). In response to the questions raised by the historic map analysis, here we outline the application of a high resolution quantitative analysis of cliff recession at spatial and temporal resolutions sufficient to better document and interpret cliff changes.

High resolution erosion surveys

Terrestrial Laser Scanning (TLS) holds significant potential for the collection and analysis of cliff face surfaces and changes over time, but also involves a number of limitations and considerations. For example, the physical and spectral characteristics of the reflecting surface, such as its topographic roughness, wetness, and distance from the scanner and incident angle can potentially all affect the resolved positions and the strength, or intensity, of the return laser signal (Lichti and Harvey, 2002). Wet or damp surfaces, as typically surveyed at the coast, may possess a lower spectral reflectance, which degrades the signal strength of the reflected beam (Lim *et al.*, 2005). Unless paired with orthoimage data TLS data may also lack RGB colour information; this can limit the qualitative analysis and interpretation of data. An optimised TLS survey approach relies on being able to achieve a 'face-on' perspective to the surface being reconstructed. As a consequence of this the accessibility and morphology of the foreshore can also prove a key control in survey quality and feasibility. Here we combine terrestrial laser scanning (TLS) and Structure from Motion (SfM) to address the challenges associated with near vertical, inaccessible and hazardous cliffs from boulder strewn intertidal areas. A nested approach has been developed, which could potentially scale to much larger monitoring areas, conducting high resolution (0.05 m) monthly surveys at the key pinch point areas and large scale bay-wide surveys on an annual basis at slightly lower resolution (0.1 m).

The 3D point clouds generated have been registered to a local co-ordinate system and oriented and transformed to allow positive projection of the cliff face in Cartesian coordinates. All TLS datasets have been manually cleaned in Riegl RiSCAN PRO software (v. 1.5.9) to remove 3D point outliers (e.g. seabirds in flight) and any visible areas of the foreshore. Adjacent scans from each survey date have been aligned using a two-step procedure. Firstly, manual point-matching has been used to find identical points or features of interest in adjacent scans, such as clearly identifiable joints or bedding plane intersections. Secondly, a linear, least-squares minimisation solution has been applied to improve data alignment and reduce residual alignment errors. This second step typically reduced alignment errors by an order of magnitude relative to coarse feature-matching. The registered 3D point cloud data were surfaced in Quick Terrain Modeller software (v.8.0.3.4) to produce a digital surface model (DSM) for each survey date. Here, the DSM is a gridded representation of a 3D cliff surface, recording the surface elevation within each 0.05 m grid cell. The cliff face DSMs were imported into ESRI® ArcMap™ (v. 10). To extract surface change, DSMs from successive surveys have been differenced (e.g. Jan-Feb, Feb-Mar, Mar-April). For each differencing period, the most recent DSM has been subtracted from the earlier DSM in order to generate a digital elevation model (DEM) of difference, or 'DoD' (Williams, 2012). A threshold has been applied to retain only DoD surface losses that exceeded a distance of 0.10 m, which is in line with thresholding limits used in similar coastal erosion studies (e.g. Lim et al., 2010; Rosser et al., 2013). Additional filtering steps were also employed to eliminate instances of surface loss that were attributable to topographic occlusion and vegetation dieback. To eliminate the former, a moving window approach was used to identify extreme losses or gains which are diagnostic of issues associated with topographic occlusion or shadowing. A colour orthophotograph derived from terrestrial photogrammetry has been used to produce a vegetation mask, which was then applied to the DoD data to identify and remove areas of change, which corresponded to vegetation growth or dieback. This approach is capable of recording eroded volumes ≥2.5×10^{-4} m^3.

Cliff face erosion processes

The results of the cliff face erosion indicate that the current rates of monitored cliff activity are an order of magnitude lower than those currently used for management purposes. The detected changes are dominated by small scale, iterative rock falls, with few events exceeding 1 m^3. The larger events that did occur reached 70 m^3 and showed a sustained period of activity for several months following the largest fall. A previously overhanging profile became realigned to a more continuously vertical cliff profile and this adjustment can potentially be used to identify other areas susceptible to cantilever collapse. The extent of divergence seaward (protrusion) or landwards (inversion) away from the average, smoothed plane of the cliff face may indicate cliff face material susceptible to larger scale adjustments. The largest protrusion distance also coincided with the largest rock fall event and significant areas of inversion at the cliff base highlight undercutting that may ultimately lead to larger scale collapses. Further modelling and validation are required to establish the effectiveness of this geometric analyses but it does not aid an understanding of the timing and connections between failure events, for this the distributions and interrelations between rock falls are needed.

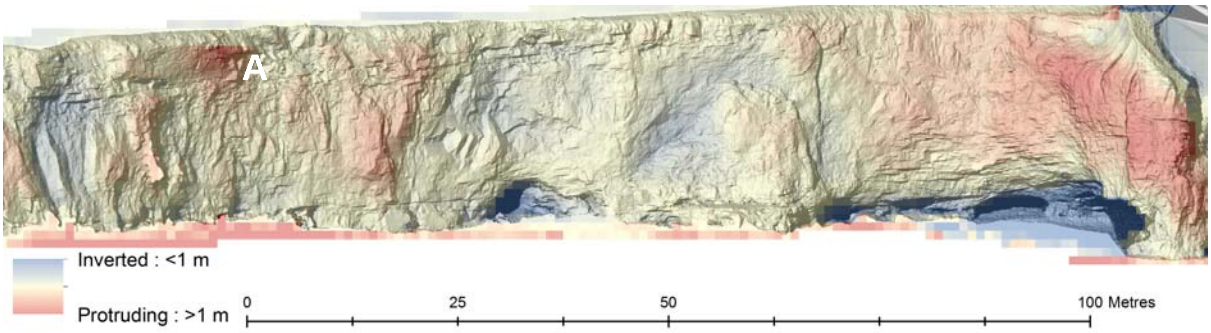

Figure 4. Cliff face surface render coloured according to the amount of protrusion or inversion from a generalised, smoothed cliff face. The area exhibiting the greatest protrusion, labelled A, coincided with the area of largest rock fall.

The wider spatial distribution of rock fall events correspond with the clear layering in the cliff geology and the highest concentrations of monthly losses often occurred in the brecciated zone at pinch point 2 (Figure 5; location annotated in Figure 1). By analysing the occurrence of rock falls on a monthly timescales, new insights as to the timing and sequencing of events are possible. Certain areas and times appear to be more susceptible to higher numbers of events than others, for instance winter storms (January to February 2015) led to higher numbers of failures in the brecciated rock layers and more generally in the mid and upper sections of the cliff at pinch point 2 whilst intense convectional summer rainfall may be connected with higher numbers of small changes occurring at pinch point 3 in August 2015.

The indication of geological control may aid analysis and interpretation of the spatial distribution of rock falls, and it is likely that rock layers of certain joint sets and orientations will generate distinct behaviour. The stacked monthly rates of change also show that changes are spatially concentrated (Figure 6). Single failure events have the potential to significantly increase localised rates of retreat and repeated events at the same site suggest that periods of rock face activity may persist over several months. The influence of foreshore controls may also be evident, with elevated rates of retreat occurring on the cliff sections adjacent to sites of restricted foreshore or incised channels. However, the changes in these areas do not appear to have been limited to the intertidal zone and thus a direct relation between nearshore wave energy and cliff response, if it exists, would require detailed consideration of the energy propagation through the cliff as a whole.

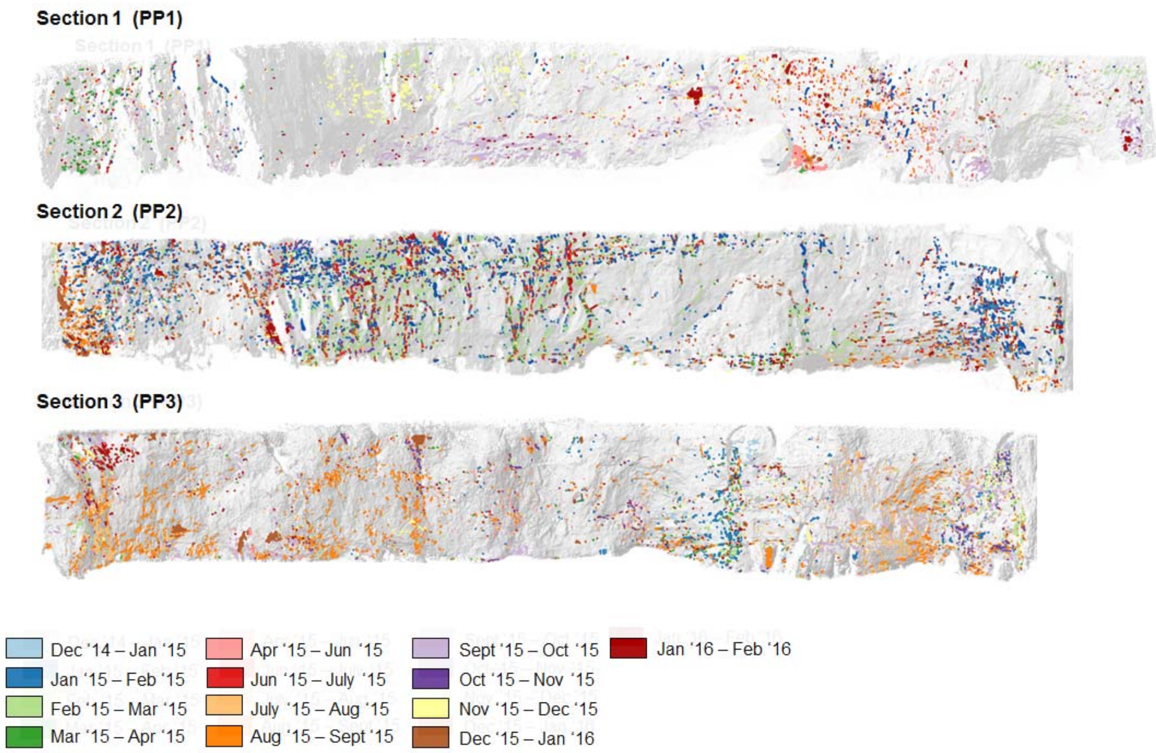

Figure 5. Detected surface losses recorded at the pinch point cliff sections for monthly differencing periods between December 2014 and February 2016.

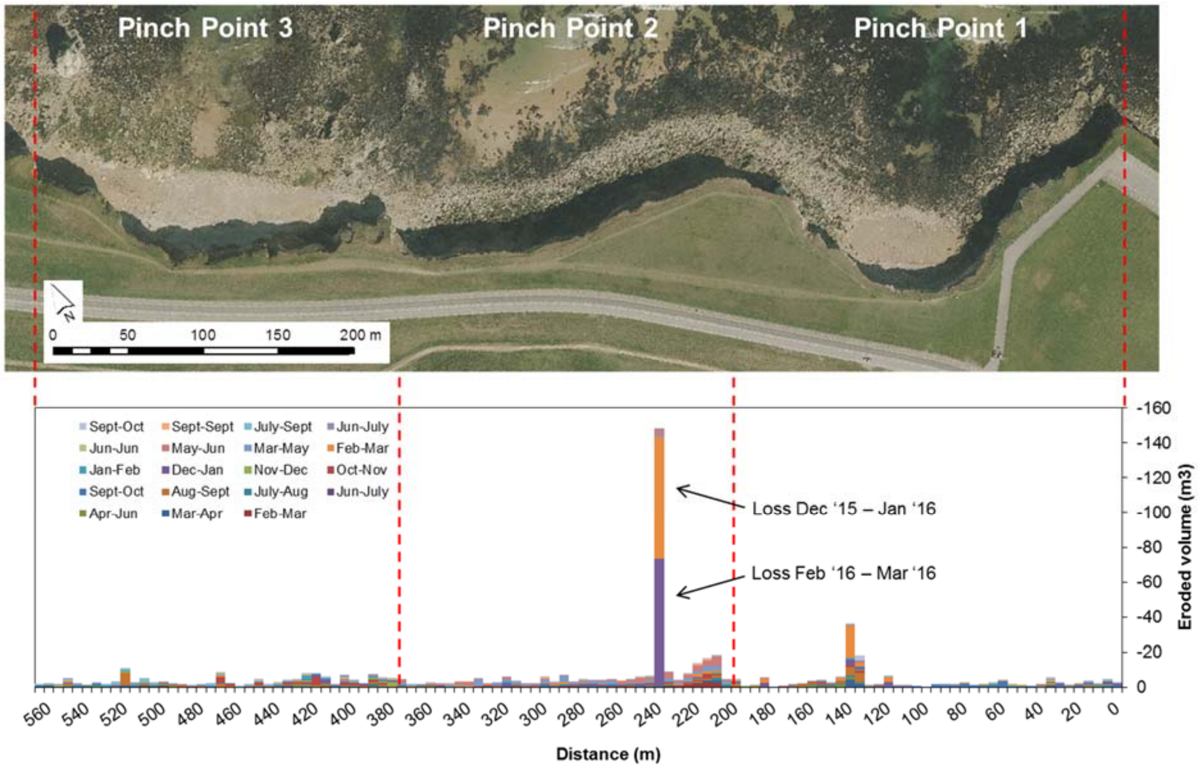

Figure 6. Example volumetric loss data the pinch point areas for the period December 2014 to February 2016. Data are represented as monthly, stacked losses in 5 m vertical strips.

Implications for management

Baseline erosion rates have been indicated at 0.1 m - 0.2 m per year for the wider study area, although the Shoreline Management Plan (Lane and Guthrie, 2007) has stated that erosion rates are uncertain due to the lack of long-term monitoring. Where erosion has been observed this has occurred in an episodic nature, often retreating up to 5 m during any one episode. This restricts management decisions to static assessments based on low quality data. Furthermore, questions have been raised as to how appropriate it is to reduce a complex three dimensional recession process down to a single rate of change for the coastline. Whilst this may be valid over the centennial or higher timescales over which embayments and headlands evolve and respond, it offers little for management decisions on timescales aligned to the planning framework required by the Shoreline Management Plan (Lane and Guthrie, 2007). A re-analysis of the historic and contemporary data available for the study area has shown the challenges of achieving a representative and consistent rate across datasets of differing quality and the wide range of rock fall events that are not detected by linear mapping approaches.

The application of TLS has enabled several advances to be made to help inform management decision on more practical timescales. A static analysis of the cliff face geometry relative to a smoothed interpolation of the generalised cliff face highlights areas of cliff that are protruding or inverted from this planar geometry. This indicates that these areas have become destabilised by peripheral erosion and undercutting or have been preferentially eroded resulting in a less stable cliff form respectively. This simple geometric interpretation of the three-dimensional form of the cliff face may aid a risk based interpretation of different cliff sections, focussing investigation efforts on critical areas of potential instability.

The identification of areas of sustained or repeated change will also help identify current and recent erosion ‘hotspots’ or sections where the cliff is undergoing a period of enhanced morphological change. Given that specific layers and geometries of cliff material appear to be responding to the drivers of change with differing spatial and temporal patterns, these need to be reflected in the approaches used to characterise cliff behaviour and to underpin short to medium term management decisions. Current projections from historic data at the study site would result in the loss of 10 m of cliff during the next 50 years but the new 3D data indicate that in the critical pinch point areas would be closer to 2.75 m; although the new data are of limited temporal extent and such extrapolations should be used with caution. Further linkages between cliff failures, erosion rates and baseline conditions in process drivers such as storm waves, wave direction and rainfall may be possible using high resolution monitoring approaches such as these. In this instance, ‘high resolution’ relates to sufficient spatial and temporal scales to detail the full range of cliff slope behaviour and to allow analyses of the distributions produced. It is evident that the incorporation of such data has the potential to significantly aid understanding of cliff behaviour, and slope process in general, and hence to aid and inform decision making. These approaches highlight some inadequacies inherent in the data currently available to coastal planners and managers but to realise their full value, more appropriate and sophisticated policy tools are required to reflect the spatial and temporal patterns in erosion processes.

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