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COMBINED DIGITAL PHOTOGRAMMETRY AND TIME-OF-FLIGHT LASER SCANNING FOR MONITORING CLIFF EVOLUTION

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Abstract

Although cliffs form approximately 75% of the world's coastline, our understanding of the processes through which they evolve remains limited because of a lack of quantitative data on the morphological changes they undergo. In this paper we examine the combination of terrestrial time-of-flight laser scanning with high-resolution digital photogrammetry to generate high-quality data-sets pertaining to the geomorphic processes governing cliff development. The study was undertaken on a section of hard rock cliffs in North Yorkshire, UK, which has been monitored over a 12 month period. High-density, laser-scanned point clouds have been used to produce an accurate representation of these complex surfaces, free from the optical variations that degrade photographic data. These data have been combined with high-resolution photographic monitoring, resampled with the fixed accuracies of the terrestrial laser survey, to generate a new approach to recording the volumetric changes in complex coastal cliffs. This has led to significant improvements in our understanding of the activity patterns of coastal cliffs.

KEYWORDS: coastal retreat, digital photogrammetry, high-resolution monitoring, laser scanning, rock cliffs

INTRODUCTION

ROCK CLIFFS FORM some of the most impressive and widespread coastal landforms, accounting for approximately 75% of the total length of coastlines worldwide (Bird, 2000). Although cliffs form a critical interface between the terrestrial and marine environments, our understanding of the processes through which they evolve is limited. Cliff retreat is a significant threat to coastal communities around the world (Jones and Lee, 1994; Lee, 2001), especially in the context of increasing coastal populations (Haslett, 2000) and potentially accelerated process rates resulting from climate change (Houghton *et al.*, 2001). It is estimated for example that annual UK government spending on coastal and flood defences is set to reach £564 million in 2005 (DEFRA, 2001). Failure to understand the processes through which rock cliffs evolve means that many coastal protection schemes are poorly designed or inappropriate (Hall *et al.* 2002).

Coastal cliffs are complex landforms, comprising a steep, eroding rock slope that responds to a wide range of environmental variables. The strength of a cliff is derived from the properties of the materials from which it is formed. In most cases, these materials are broken into unevenly-sized segments by planes of weakness such as joints, faults or bedding surfaces. Retreat of the cliff occurs through incremental erosion and/or through detachment of parts of the cliff through falling, sliding or toppling (Hantz *et al.*, 2003). The mechanisms are driven by environmental factors such as weathering rates, groundwater levels, wave impact and human activity, all of which vary over time and through space (Robinson, 1974). In most cases it is the interaction between these processes and the resisting properties of the cliff itself that determine the rate of retreat.

Accurate descriptions of morphometric changes occurring over a range of spatial and temporal scales are required to enable an understanding of landform evolution. One established technique for collecting this data is through the use of photogrammetry, but this approach is hindered by the nature of the coastal environment. Near-vertical, unstable slopes are difficult environments for the manual collection of ground control points across image overlaps, and light contrasts, shadowing and perspective variations limit the success of automated stereomatching processes. However, the development of sophisticated, versatile terrestrial laser scanners offers a new method of field survey in geomorphology (Nagihara *et al.*, 2004). Laser scanning systems collect elevation information directly, removing many of the uncertainties associated with data processing and digital elevation model (DEM) generation. Emitting radiation at wavelengths beyond those of visible light, laser scanners are essentially unaffected by changes in the ambient conditions during data collection. However, laser scanning techniques alone do not currently provide adequate qualitative information on the environmental conditions at the site, such as the cliff lithology. To circumvent these problems, in this paper we examine the integration of terrestrial time-of-flight laser scanning with high-resolution digital photogrammetry to generate accurate information on the geomorphic processes governing cliff development. The aim is to promote a new approach to cliff monitoring, supplementing the data from aerial techniques with a better understanding of the processes in operation over the cliff face itself. The combination of photographic images resampled within the fixed accuracies of laser scanning has provided a promising source of qualitative and quantitative information.

MONITORING CLIFF CHANGE

Conventional techniques for quantifying cliff change include erosion pins located within the rock mass base (Lee *et al.*, 1976) and aerial surveys (Hua and Fairbairn, 2000). Erosion pins have proven useful in quantifying small scale changes caused by weathering effects, but remain limited spatially and temporally by the position and life of the nail networks. Aerial surveys, sometimes supplemented by the analysis of historic map data, by definition record cliff top and toe recession which is ultimately only the result of a more complex process of cliff surface erosion, but the errors involved can be considerable (Moore, 2000). Some improvement can be achieved with the use of a good quality ground control system, although the location of recognisable markers visible from an aerial perspective is often problematic, particularly in coastal locations. In the case of historic maps, problems occur because of errors associated with shrinkage and stretching of the physical document over time, in addition to general issues of accuracy and precision associated with map production (Snyder, 1987). The cumulative errors within the source documents and images are often several orders of magnitude larger than the rate of retreat being measured. As a result, measurements typically lack comparability both between separate surveys and within each mapping project (Crowell *et al.*, 1991). In the case of aerial surveys, two key disadvantages are clear. First, the high costs associated with data capture limit the frequency at which change can be monitored; even annual data on cliff top and toe positions are rare. Second, vertical aerial photography is poorly suited to the measurement of processes associated with near-vertical surfaces. Nonetheless, aerial surveys have remained the principal method of recording shoreline change (Boggett *et al.*, 2000).

An alternative approach to the measurement of cliff retreat rates is through the direct measurement of processes operating on the cliff face itself. Manual measurements are often impractical due to the difficult terrain and the danger posed by rockfalls and tides. Thus, remotely sensed rapid data acquisition techniques have much to offer studies of cliff slope processes and evolution (Wickens and Barton, 1971; Chandler and Moore, 1989), but until now have been insufficiently developed to allow the required level of precision to be achieved.

TERRESTRIAL DIGITAL PHOTOGRAMMETRY

The availability of increasingly sophisticated, cost-effective and automated digital systems has facilitated the use of photogrammetric techniques in a wide range of geomorphic studies (Baltsavias *et al.*, 2001). The ability to monitor the temporal evolution of three-dimensional forms at high resolutions has led to successful applications that have improved our understanding of a variety of fluvial (Latulippe *et al.*, 2001; Brasington *et al.*, 2003) and terrestrial environments (Genovois *et al.*, 2001). A detailed account of the effective use of established digital techniques for geomorphological investigations is provided by Chandler (1999). Digital photogrammetry has been shown to outperform analytical approaches for the recording of topographic features, both in terms of data collection times and overall accuracy (Bailey *et al.*, 2003). However, this technology can also widen the gap between the operator and an appropriate level of understanding of the system outputs (Krupnik, 2003). Whilst it is essential that the uncertainties associated with the process of deriving the data must be understood, it is clear that the relative ease of DEM generation has led to an emphasis in many projects on data analysis without adequate consideration of data quality (Huang, 2000). Indeed, the techniques that are used to assess the quality of DEMs are often inadequate to assess their reported accuracies.

The accuracy of photogrammetric grid DEMs can be characterised by the root mean square error (rmse) of every interpolated point in the model. In practice such a complete evaluation of the surface is impractical. The function is therefore commonly performed on check point data, thereby providing a quantitative estimate of bilinear interpolations using localised errors associated with data independent from the DEM construction process. Several questions have been raised as to the validity of deriving a finite set of rmse values for an entire model. The variable accuracy and location of check points are key determinants in the impression of the DEM performance gained from rmse observations (Gooch and Chandler 2001). The distribution and quantity of residuals from discarded ground control points (GCPs) have been used to identify error trends across blocks, demonstrating statistically significant errors which are not conveyed in rmse calculations (Brasington *et al.*, 2003). Significant variability has also been noted within other error statistics such as mean error and standard deviation error for the same set of processes (Lane *et al.*, 2000). Statistical improvements in processing evaluations therefore do not necessarily equate to more accurately represented DEMs (Butler *et al.*, 1998).

Many softcopy digital photogrammetric suites produce spatial classifications of the matching performance associated with each DEM extracted. Interpolation of elevations may result if the parameters defining the matching algorithms are not met. The threshold for interpolation may prove a critical factor in the ultimate performance of the model (Lane *et al.*, 2003). Higher correlation minimums equate to greater confidence in the matching success of the model, but are also likely to generate increased interpolation as fewer points meet the acceptance criteria (Bailey *et al.*, 2003). The limitations of software-supported DEM assessments have led to the development of new, independent methods for checking data fidelity. DEM quality is heavily reliant on the adequacy of the algorithms used to reconstruct the terrain. The increasing range of choices and varied combinations of factors that influence DEM production raise questions over the most appropriate strategies for obtaining required accuracies. An idealised set of search parameters would generate an accurate DEM in which only successfully correlated points were used. In reality DEMs may often include unsuccessfully correlated areas and consequently distort or even reject some correctly matched points. Gooch and Chandler (2001) developed a strategy-based error detection scheme in order to analyse the spatial distribution of suspect correlations within a DEM. The technique involves subtracting two identical DEMs, varying only in the parameter settings used, to generate a difference DEM. The greatest change on the difference DEM will be principally determined by the heightened response of erroneous or “failed” areas which are commonly mismatched under different parameters. This failure warning model has proved to be a robust answer to the identification of poor performance within DEMs from a range of image scales.

In the case of dynamic natural features such as cliff faces, problems with generating surface models may occur because image quality is influenced by a variety of factors. Huang (2000) demonstrated that the changes in surface roughness across small sections of cliff face can cause differing levels of information loss in photogrammetrically-derived DEMs. In order to accurately identify and quantify the errors within a photogrammetric model, a more representative surface of comparable resolution is required (Chandler *et al.*, 2003).

TERRESTRIAL LASER SCANNING

The development of laser scanning technologies offers a new method of remote sensing for geomorphological applications. A wide variety of scanning systems are available, which fall within two broad concepts of data collection: triangulation and time-of-flight. Triangulating laser scanners emit a concentrated beam of light across a surface which is captured by a fixed digital sensor, enabling precise triangulations to be made of recorded surfaces. Triangulating systems are limited in terms of geomorphological applications by the size and weight of the devices, their fragility, the excessive data-sets generated and most significantly their scanning range; typically less than 10 m. Assuming the speed of an emitted laser pulse to be constant, time-of-flight technology uses the delay in return signal to calculate the distance to the target. The laser emitter is manipulated using motorised mirrors, enabling it to scan back and forth over surfaces to form a detailed impression of elevation. The time-of-flight approach allows for the increments between passes and within pulse emissions to determine the concentration of data collected. Designed to record surfaces under a wide range of conditions (Nagihara *et al.*, 2004), time-of-flight devices are generally well suited to data collection in the natural environment.

Terrestrial laser scanners involve certain limitations which must be considered (Kersten *et al.*, 2004). The absence of a calibrated target introduces numerous variables into the distance reading obtained. The characteristics of the reflecting surface, its roughness, wetness, distance from the scanner, material components and its incident angle all influence the strength of the return signal (Lichti and Harvey, 2002). Although beyond those of visible light, the band widths used (750 – 1500 nm) function on the periphery of atmospheric wavelengths, allowing certain portions of the radiation to be absorbed into the atmosphere. This causes wet surfaces to have a lower reflectance, degrading the signal strength of the reflected beam. The registration of the returning laser pulse assumes the strongest part of the returning beam originates from the centre of the footprint on the target. This concentric weighting is distorted when the span of the footprint overlaps areas of contrasting reflectance. When analysing the elevation data, the lack of RGB data also limits the qualitative assessment of data recorded, restricting interpretation of difference models. Despite these issues, the point cloud data produced over the ranges associated with typical monitoring of cliff faces are capable of producing accuracies within ±0.06 m. It is noted however that when recording complex features, point accuracies do not necessarily equate to comparable surface accuracies. Meshed (triangulated) point clouds are degraded by occlusions which cause holes in the data surface and errors associated with the precise location and orientation of the scanning system. It is clear therefore that the techniques for terrestrial laser scanning can benefit substantially from the application of rigorous approaches to data collection developed for example in photogrammetry.

STUDY AREA

The study area is centred upon a set of 60 m high coastal cliffs to the east of the village of Staithes, in North Yorkshire, NE England (National Grid coordinates NZ760192 – NZ784189) (Fig. 1). The cliffs are formed from middle Lias lithologies, capped by up to 10 m of glacial till. The Lias rocks consist of interbedded mudstones, shales and sandstones with occasional thin seams of ironstone. The indurated mudstone base of the cliff appears to provide the most resistance to erosion, often causing the toe to protrude from the rock mass. A range of rock strengths, bedding patterns, jointing and faulting mean that cliff profiles are variable in form, containing a mixture of smooth and angular surfaces. Factors promoting failure include wave erosion of the cliff toe (Rawson and Wright, 2000) and weathering of the shales in the middle cliff sections (Agar, 1960). The environmental processes that drive these two mechanisms lead to small scale failures across the exposed face. Interestingly, although often considered insignificant in determining the overall cliff form, the cumulative effects of multiple small failures on steep rock cliffs remain unquantified (Lee *et al*., 2002).

FIG 1. Location of monitored sites, Staithes, North Yorkshire.

.Previously estimated rates of recession for this stretch of cliffs are 0.05m per annum at the toe and 0.02 m per annum at the top, based on differences between Ordnance Survey maps dated 1892 and 1960 (Agar, 1960). The figures seem to suggest that the overall cliff morphology is changing through time, tending towards a steepening cliff profile. There appears to be little geomorphological evidence to support this, suggesting that there are substantial errors in retreat data. Despite its simplistic approach to cliff change, the retreat rates indicate sensitivity to the variety of geological settings along the coastline (Table I). In addition, these data suggest that there is also a morphological control on coastal retreat (Table II), with erosion in bays outstripping headland retreat. This would act to accentuate the large-scale coastal morphology over time. It is clear that there is considerable complexity of processes governing the recession of the cliffs at Staithes, raising further questions over the adequacy of aerial monitoring techniques for such an application. Therefore, despite extensive and detailed studies on the cliffs of North Yorkshire, the specific mechanisms by which these coastal forms evolve remain poorly understood.

TABLE I. Measured rates of cliff recession in North Yorkshire summarised by lithology (Agar, 1960).

	Shoreline erosion rates (m per annum)				
Location	*Lower Lias*	*Middle Lias*	*Upper Lias*	*Deltaic Series*	*Glacial drift*
Huntcliff Station	0.04				
Staithes, Cowbar Nab		0.05			
Staithes, Penny Nab		0.1			
Port Mulgrave, south pier			0.1		
Runswick Great Ship Rock			0.1		
Upgang, nr Whitby					0.26
Whitby West Cliff				0.03	
Whitby East Cliff			0.09		
Whitby East Cliff			0.19		
Saltwick Nab			0.04		
Near Black Nab			0.11		
Robin Hood's Bay	0.07				
Robin Hood's Bay					0.31
Robin Hood's Bay	0.16				
Low Peak	0.05				
AVERAGE	0.08	0.075	0.105	0.03	0.285

TABLE II: Measured rates of cliff recession in North Yorkshire summarised by morphology (Agar, 1960).

Morphological unit	*Cliff top erosion (m per annum)*	*Cliff toe erosion (m per annum)*
Headlands only	0.01	0.04
Bays only	0.04	0.07
Whole coast	0.02	0.05

DATA COLLECTION

Sites were surveyed at monthly intervals using a fully-calibrated, tripod-mounted, Kodak DCS Pro 14n fitted with an F mount Nikon Nikkor 28 mm 2.8d lens. The calibration procedure involved the collection of two sets of images of a testfield containing 111 targets from convergent stations. The image sets were converged at a range of angles from 0° to 60°, ensuring that a minimum of 66% of the control targets were covered by each image. The camera was rolled though 90° clockwise and anticlockwise and focused at infinity throughout. The targets were surveyed to millimetre accuracy in three dimensions and used analyse the interior orientation parameters of focal length, principal point offset, radial lens distortion (k_1, k_2, k_3) and tangential distortion. The calibrated camera was locked at infinity and used exclusively for monitoring purposes to maintain the geometric stability of the set-up. Studs were installed into the shore platform in order to allow the repeated capture of images from the same location. The minimum required resolution was set to ±0.02 m and used as the main determinant in positioning the base stations. This pixel spacing produces a DEM of 0.1 m resolution in ERDAS OrthoBASE, given the 5 × 5 pixel search area required for each elevation. Given the 28 mm focal length of the lens and the 4536 × 3024 size of the imaging array, the maximum required distance between the cliff face and the camera is about 70 m. The number of images captured at each site ranged from three (Site B) to six (Site D). The distance was reduced when the cliff height permitted. Base to height ratios of 0.6 or lower were used wherever possible. A pilot study indicated that a large overlap was necessary to reduce occlusion and maximise image correlation.

A Leica TPS1200 reflectorless total station was used to collect the precise coordinates of distinguishable natural features on the cliff, forming the basis of a control point network. The restriction of control points to areas of difference such as recognisable joints or the corners of overhangs may reduce the overall accuracy of the photogrammetric models (Fox and Gooch, 2001). Optimisation of ground control quality therefore required cliff features to be carefully selected, where a precise point target could be identified and considered generally representative of the wider rock face in that area. In order to assess the accuracy of the ground control under conditions experienced at the coast a test study was conducted. A grid of 25 control points was identified across Site A, the highest cliff section in the study area, and resurveyed ten times. The grid consisted of five rows of five points dissecting the cliff face horizontally at approximately 10 m height intervals forming five vertical columns. The total station was removed and reset in between each of the ten collections of the grid, establishing a measure of the repeatability and accuracy of the points. The standard deviation of measurements across the network showed error ranges consistently within 0.03 m (Table III). No significant relationships were identified with radial distance from the survey station, nor by GCP row either with increasing height up the cliff or GCP position across the cliff face. The reflectorless total station therefore provides highly accurate ground control relative to both the precision of the laser scan survey and the magnitude of changes under examination on the cliff face. The terrestrially orientated control point coordinates were processed through a transformation matrix to obtain Z as the photo direction. The block was then translated to create a zero base-level behind the cliff face. The conversion is necessary because of the nature of the algorithms used for DEM extraction in most softcopy photogrammetric suites, which have been developed for aerial applications.

TABLE III: Accuracy of control points obtained with the reflectorless total station, expressed as the average standard deviation in x, y and z axis for each point aggregated across the survey network.

GCP Row	*Standard Deviation (m)* *GCP column* *1*	*2*	*3*	*4*	*5*	*Average*
5	0.025	0.025	0.021	0.022	0.021	0.023
4	0.023	0.021	0.019	0.023	0.021	0.021
3	0.022	0.020	0.022	0.022	0.025	0.022
2	0.021	0.022	0.021	0.022	0.022	0.022
1	0.022	0.021	0.023	0.022	0.024	0.022

A LaserAce 600 terrestrial laser scanner from Measurement Devices Ltd was used to record the detailed surface of the cliff sections at a rate of 250 points per second. The resolution of each point is the size of the width of the laser lens, 0.046 m, plus the 0.003 m/m divergence of the beam. Prior to collection the LaserAce was calibrated to a range precision of 0.025 m at 200 m and the horizontal and vertical angles checked to within 0.01°. The scanner was positioned over the most central of the capture stations, levelled and orientated towards a triangulation point previously located with a differential Leica GPS1200. The azimuth orientation of the scanner was set to collect data in the same coordinate system as the photogrammetry. A required resolution of 0.05 m was specified to generate comparable spatial data coverage to the photogrammetric output. The LaserAce 600 instrument is designed to be water and dust resistant to IP66 specifications, making it a robust answer to the challenges of monitoring in coastal environments.

IMAGE PROCESSING

The raw image data was processed in OrthoBASE Professional. The most important aspect of the digital rectification process involves automatic aerial triangulation of the image block. The procedure links images through the exterior orientation and control point parameters determined at the point of capture. A similarity transformation is then applied to this information, connecting each image to all those around it. Once the images have been geometrically related, feature extraction and image matching are undertaken in order to collect around 500 distinct tie points within overlapping areas. OrthoBASE uses feature-based matching with additional area correlation and geometrical and topological constraints in order to define point collection (Wang *et al.*, 2002). A hierarchical system of searching is employed and least squares matching performed on the last iteration in order to calculate errors (Chandler *et al.*, 2003). Tie point numbers, concentrations and matching strength can be user-defined to suit the specific characteristics of the overlapped area (ERDAS, 2001). Increased numbers of tie points are thought to be important in ensuring block stability (Wang, 1996). When less than 300 tie points were automatically detected during processing, the default correlation of 0.8 was lowered to 0.7, reducing the inclusion thresholds for accepted ties. Reducing the correlation below this to the minimum of 0.6

produced relatively small increases in the number of detections and higher tendencies for gross errors. The collection performed significantly better on the red and blue portions of the images, which were more closely linked with changes in contrast. Bundle adjustment procedures were conducted and gross error detection applied to identify correlations with an increased likelihood of error. Rmse was also available as a method of assessing the overall triangulation performances. The triangulated blocks were edited to a predefined degree of accuracy, typically with ground control residuals restricted to within 0.1 m, before being accepted. Once confirmed, the co-registration of images defines the relationship between the internal geometry, external positions and orientations of the sensor at the point of capture (Schenk, 1997). The block adjustment converts image tie point coordinates into ground coordinates.

Scanned point clouds were orientated through the same transformation matrix used for the ground control points in order to enable comparability between models. The Archaeoptics Demon software package was used to converge each scan to the next in the monthly monitoring sequence to remove any errors associated with the external orientation of the scanner at the time of capture. The convergence operation processes the point clouds in two stages to find a least-squares best fit between the three-dimensional coordinate sets. Firstly every point in the first scan is searched for the point of closest Euclidean distance within the second scan. The best fit between the paired data-sets is then calculated using a three-dimensional transformation algorithm to determine the vector translation and quaternion required for an optimal transformation (Horn, 1987). The rms deviation between the two scans is then computed and if it is greater than the desired deviation, the algorithm reiterates. The weighting in Horn's (1987) solution also limits the contribution of poor quality points, containing weaker matches than surrounding pairs, to the overall transformation. By specifying each mesh as non-deformable, the sequential epochs are drawn together based on the reduction of the distance separating the majority of points, ignoring the localised areas of genuine change. By monitoring a section of cliff face of sufficient size to avoid the influences of actual change to the cliff face, the errors associated with the positional accuracy of the scanner can be significantly reduced.

In order to generate orthoimages, ASCII data files containing the X, Y and Z coordinates of every point in the raster were interpolated into a surface DEM using the ERDAS 3D surfacing tool. Cell resolution was set to 0.05 m and a non-linear rubber-sheeting interpolation was used to better reflect the actual contours of the cliff faces. The high-resolution DEM was used to minimise the amount of information lost between the reconstructed surface, of finite interval, and the ground surface (Huang, 2000). The output TIFF file was then imported into OrthoBASE in order to correct for the distortions within the imagery caused by variations in terrain elevation. Orthorectification is the process of correcting raw images to form a planimetrically true representation of the surface. Accurately orthorectified images have a consistent photo scale, allowing real-world measurements to be taken of the subject matter (Schenk, 1997). The images were resampled with output cell sizes of 3 × 3 pixels and mosaicked to adjoining orthophotos.

In addition to producing orthophotos integrated with laser-scanned DEMs, photogrammetrically derived DEMs were generated to compare the efficacy of the two techniques in cliff face monitoring. ERDAS OrthoBASE has a number of default terrain settings which can be applied to differing topographic situations within the same block (Table IV). The presets were used to assess the effects on DEM production of the parameters of search area, correlation size, coefficient limit, topographic relief type and land cover object type. High levels of image texture over cliff surfaces and the availability of adequate control allowed more stringent acceptance levels to be applied (Zhang and Miller, 1997). The search area was lowered to the minimum allowable 5 × 5 pixels after the suggestion that template size should be minimised over complex topography, despite the propensity for increased interpolation (Lane *et al.*, 2000). In order to directly compare the performance of the photogrammetric process, no manual editing was performed on the DEMs. The derived elevations from both the laser scanning and the photogrammetry were finally resampled to the same spatial extent and resolution (0.05 m).

TABLE IV: Terrain parameter settings used for OrthoBASE (ERDAS, 2001).

	Search size		*Correlation size*		*Coefficient limit*	*Topographic type*	*Object type*	*DTM filtering*
Parameter Strategy	*X*	*Y*	*X*	*Y*				
Custom	5	5	3	3	0.8	Rolling hills	Low urban	Low
Default	21	3	3	3	0.8	Rolling hills	Open area	Low
High mountains	27	3	3	3	0.8	Mountainous	Open area	Moderate
Middle mountains	21	3	3	3	0.8	Mountainous	Open area	Moderate
Rolling hills	15	3	3	3	0.8	Rolling hills	Open area	Moderate
Flat areas	7	3	3	3	0.8	Flat	Open area	High
High urban	19	3	3	3	0.8	Rolling hills	High urban	Low
Low urban	11	3	3	3	0.8	Rolling hills	Low urban	Moderate
Forest	17	3	3	3	0.8	Mountainous	Low urban	High

RESULTS

The use of laser-scanned elevations removed many of the uncertainties of photogrammetric DEM generation, producing consistent and repeatable models. Employing the same coordinate systems for both approaches meant the common control points could be matched between data-sets, enabling the combination of the relative advantages from both techniques. The laser point clouds were collected in a variety of conditions and over a range of rock surface types, but all scans were statistically related to within 0.04 m convergence of the previous survey. The result was a detailed three-dimensional impression of the cliff face in which the physical characteristics can be clearly identified and quantified (Fig. 2). The ortho-image of Site C demonstrates the ability to accurately locate and monitor the cliff top and toe positions within the scans (subsections A and B). Important information was also generated on the processes, such as seepage from the till above (subsection C) and on the mechanisms of failure, seen in the fresh rock face exposed following a recent fall (subsection D). By resampling the rectified imagery with the laser-scanned point clouds, substantially larger portions of cliff face can be accurately monitored without multiplying errors of contrast, shadowing, perspective and geometry. The cliff section at Site D for example comprises a mosaic of six images and covers over 100 m of coastline (Fig. 3). The laser-scanned data performed well over gently curved topography such as the points of headlands or backwalls of embayments. The differencing of successive models reliably identified the loss of rock blocks as small as 0.1 m throughout the monitored period, verified with the use of the ortho-imagery and stereo viewing of triangulated blocks.

The photogrammetrically produced DEMs were consistently sensitive to change, precisely identifying topographic variations across the cliff face. The accuracy of the photogrammetric models however varied considerably, depending on the specifics of the triangulation used. Comparisons between the photogrammetrically derived DEMs and the laser-scanned surfaces highlight the advantages of the integrated approach used. A model of the difference between the two techniques is illustrated for Site A (Fig 4). The differences between the models increase with height and surface complexity, which in this instance is reflected in the increase in topographic roughness from left to right. The differences are particularly noticeable in the sharp protrusion in subsection “A”, in which weak control and radial distortion reduce matching performance. Profiles taken through both the laser and photogrammetric DEM surfaces demonstrate a broad agreement in the overall cliff geometry, with the photogrammetry marginally more sensitive to the small-scale undulations across the face. The most noticeable difference is the increasing disparities in depth above 10 m from the cliff toe. Editing the ground control within the blocks to refine the triangulations consistently required the removal of points towards the upper sections of the cliff face. Attempts to maintain the full constraints of the points in the extremities of the overlap led to poor DEM performance despite the consistent accuracies of the control points with cliff height (Table III). Removing the upper control allowed high quality triangulations to be achieved but raised questions over the accuracies of the DEMs they would generate. This suggests the photogrammetric performance was limited not by the accuracies of the control, but by the reliance on natural features which become increasingly harder to match towards the extremes of the images. The inability of the stereo configuration of the photography to gather sufficient image content for the bundle adjustment highlights a major limitation of the photogrammetric application to monitoring high-sided cliff faces. Software-based quality assessments identified suspicious pixel matches as geometric irregularities but failed to detect any systematic errors in the triangulation. The direct effect of perspective errors on elevation has limited the use of photogrammetry in the study of rock slopes, which commonly recede from the base. Interestingly the subtle changes in the cliff face are still detected in the upper portion of the photogrammetric DEMs. The implication is that despite losing accuracy with increasing height up the cliff, the precision of the photogrammetric technique, and consequently its ability to detect change, remains high.

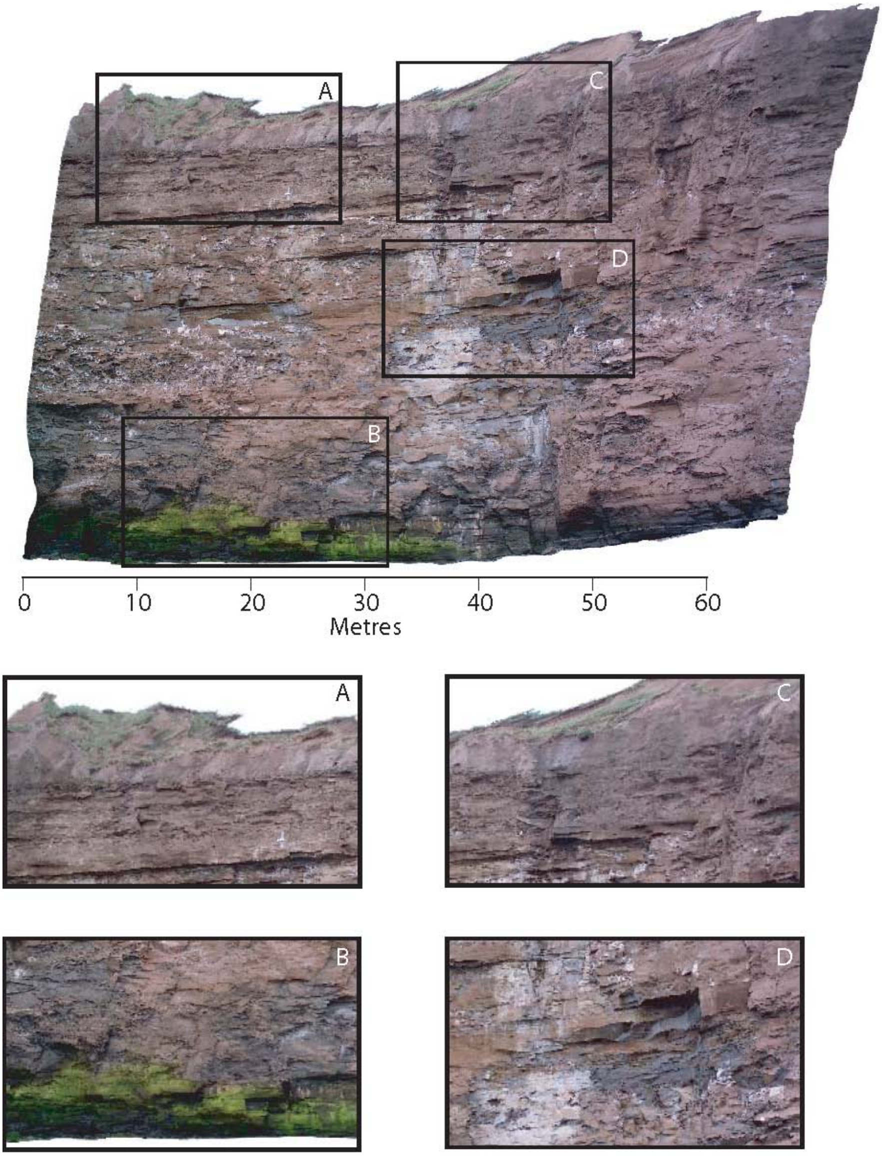

FIG. 6. An orthoimage of a monitored cliff section

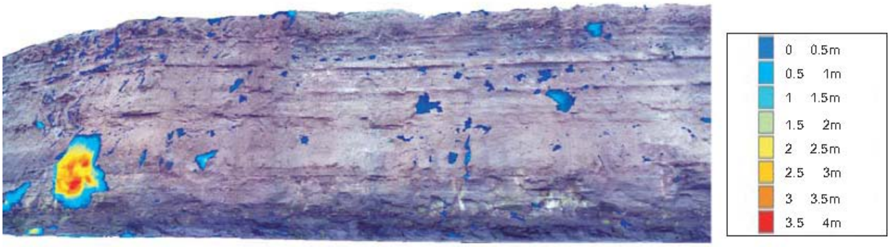

FIG 3. Orthoimage of Site D, re-sampled with laser scanned DEM overlaid with detected differences from September '03 to July '04.

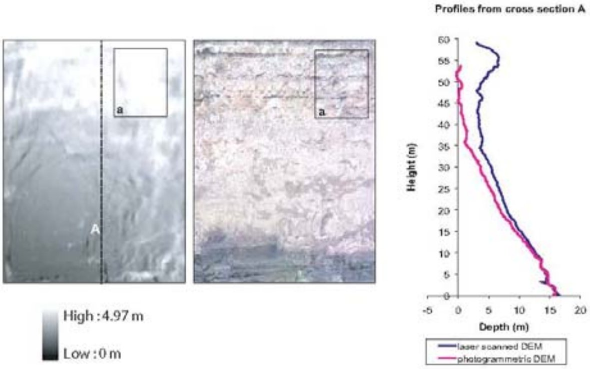

FIG 4: Comparison of photogrammetric and laser scanned DEMs.

The nature of the target terrain also produced errors within the laser scans. The limited number of scans permitted by the tidal exposure of the monitoring stations raised concerns over the adequacy of the field of view of the cliff faces obtained by the scanner. The reliability of the scanned results was tested by generating two 0.05 m resolution point clouds of the same cliff section in immediate succession. No changes were recorded during the scans, meaning that two theoretically identical surface representations should be produced. The difference model of the scans revealed small errors between the meshed surfaces, which typically appear as triangular irregularities caused by subtle differences in mesh generation (Fig. 5). There are however more substantial geometric differences, highlighted in the subsection, that result from occlusion. Such line-of-sight errors are concentrated towards the edges of scans and on protruding ledges. Although the errors caused are comparatively small, within 0.03 m, the benefit of validating genuine change with the use of orthoimages is again realised. In this way sites can be characterised and problem areas such as ledges and overhangs identified for targeted checking of difference models.

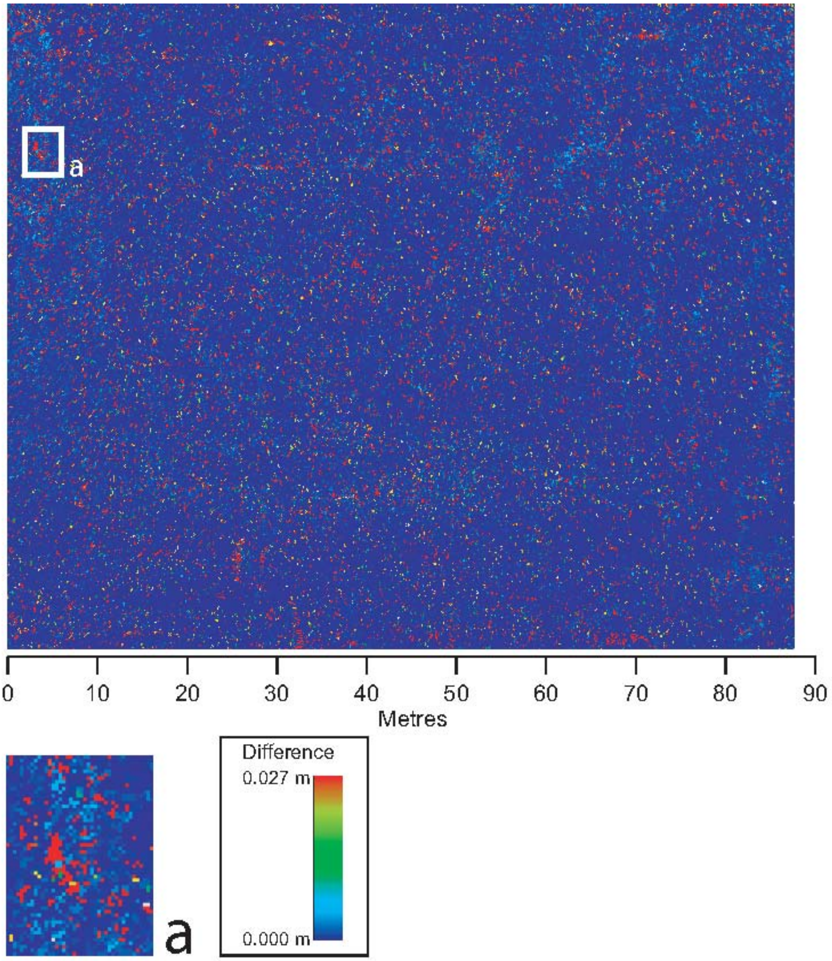

FIG. 5: Occlusion error in laser scanned DEMs

In terms of monitoring the present rate of cliff retreat, the integration of the two approaches has enabled changes to be accurately detected and assessed well beyond the acceptable error margins for a purely photogrammetric approach. Orthoimages and difference models were generated for the total change monitored across two sites over a nine month period (Figs. 6a and b). The resolution of the data revealed that despite being located adjacent to one another (Fig. 1), the mechanisms determining change were markedly different. Site A shows a relatively even spatial distribution of change throughout the rock face, with small concentrations within certain lithological bands in the mudstone toe and the weaker shales in the middle portion of the cliff. Site B reveals significantly more concentrated areas of difference with the majority of change occurring within arched failures propagating up from the cliff toe. A second band of change is detected at the junction between the harder sandstone strata and the weaker shales below. Incremental weathering of the shales reduces support for the sandstone ledge resulting in the occasional loss of large angular rocks.

FIG. 6a: Site A: orthoimage and superimposed difference model (September 2003 May 2004).

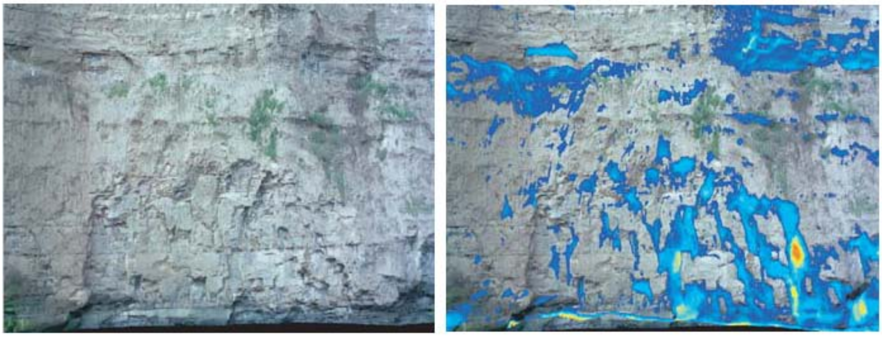

FIG. 6b: Site B: orthoimage and superimposed difference model (September 2003 May 2004).

The changes detected across the two sites can be represented graphically, calculating the area affected by the detachment of material as a percentage of the total two-dimensional area of the monitored cliff sections (Fig. 7). This was done to enable comparisons of the rate of change between the two, despite the greater area monitored at Site A. The recorded changes display considerably different temporal variations throughout the time series which spans from autumn through to the following spring. Site A lost low percentages of material at relatively consistent rates in terms of surface area affected from month to month. There appears to be a weak seasonality to the volume losses with the autumn and late spring months found to be more stable than those of winter. Site B shows a reversal of this temporal pattern, with changes not synchronised with the seasonally expected variance. The spatial concentration of change at the cliff toe indicates that the cliff may be responding to localised controls such as wave impact. The influence that the different failure mechanisms exerted on the overall development of the cliffs is shown in the summary column showing the total surface area affected as a percentage of the monitored rock face. The strength of the toe at Site A has restricted change to incremental and sporadic losses throughout the cliff. Failure of the toe at Site B by contrast has destabilised the cliff base, propagating instability up through the heavily jointed strata. Temporary stability has been reached in the natural arch formations which appeared to gradually expand and coalesce.

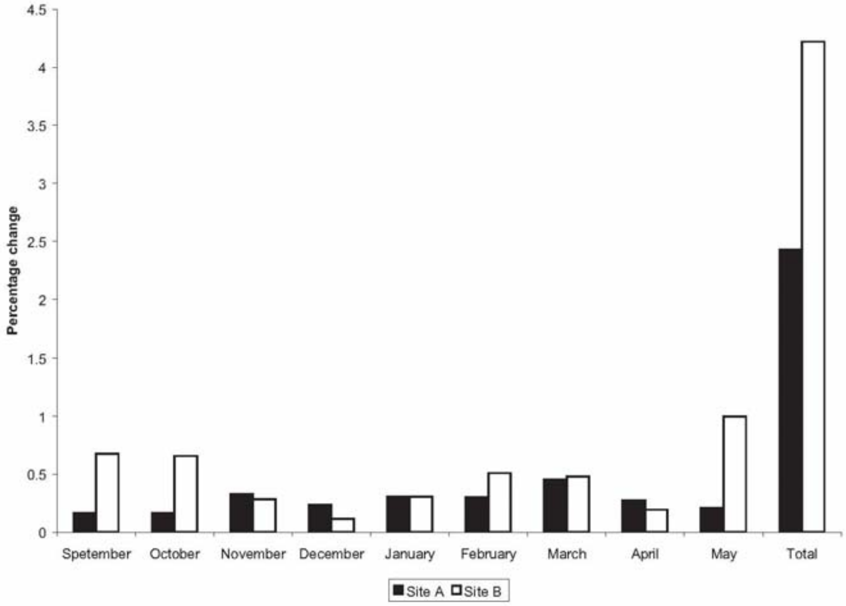

FIG. 7: Percentage of the monitored cliff face affected by detachment of material: September 2003 to May 2004.

DISCUSSION

The mechanisms governing the evolution of hard rock cliffs are poorly understood due to the poor quality data-sets describing the changes that they undergo (Lee and Clark, 2002). The pressing need for planning organisations and management strategies to make assessments based on an average rate of retreat however remains. The suggested retreat rate for this area of coast, based on the current aerial survey methods is 0.075m per annum. The two main sites of this study have two-dimensional surface areas of 2520 m^2 and 2130 m^2 respectively. This would suggest the loss at Site A of 15.75 m^3 and 13.31 m^3 at Site B on average every month. The actual average changes recorded however were significantly lower at 6.80 m^3 per month for Site A and 9.99 m^3 per month for Site B. At present it is not possible to say whether this is because of the low levels of accuracy associated with the conventional methods of cliff retreat analysis, or the episodic nature of the cliff retreat process. The data raises interesting questions over the interplay between events of low magnitude but high frequency, and less frequent, larger scale losses from the cliff, and how they determine cliff form.

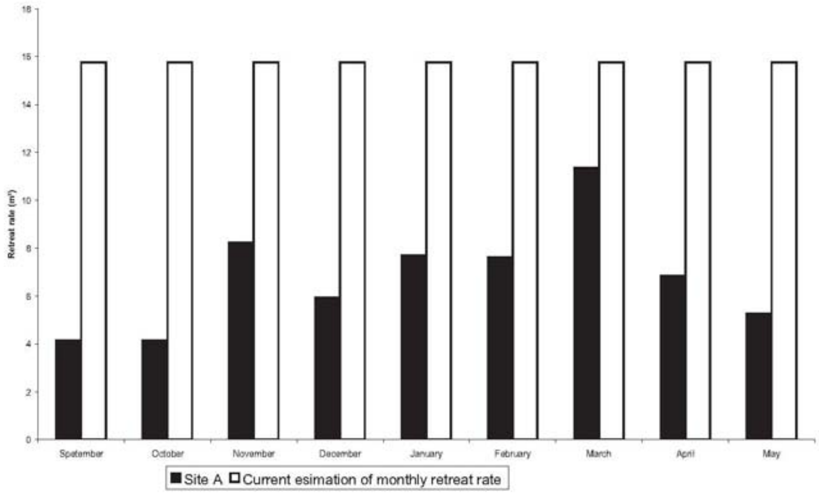

FIG. 8. Volumetric losses predicted for Site A by aerial survey methods and the actual volumetric loss monitored with the high resolution approach.

The disparities between the general level for change set by aerial approaches and the reality of a more stable rock face are demonstrated in Fig. 8. The over-estimation demonstrated by the comparison with actually monitored rates highlights the limitations of averaging two-dimensional records of retreat for extensive sections of coastline. Even across the two sites illustrated, just 350 m apart, clear differences have been detected in the pattern and nature of failure events. These differences demonstrate that cliff retreat is a spatially and temporally specific process. The generation of high-resolution data-sets offers significant potential to subdivide existing classifications of cliffs and rock slopes in general to account for the local mechanisms of failure.

The integration of high-resolution photographic monitoring resampled with the fixed accuracies of terrestrial laser surveys enables rock faces to be reliably monitored and qualitatively assessed in a variety of conditions (Fig. 9). Successful integration requires the careful consideration of the format, orientation and resolution of the outputs from both techniques. Recent technological developments are generating greater opportunities for the use of combinations of techniques in order to overcome the challenges of monitoring geomorphological change. The Leica High-Definition Survey series and Riegl LMS range of time-of-flight laser scanners, for example, have the capability to capture colourised point clouds. Although such instruments are currently beyond the financial constraints of many projects, particularly small-scale repeated monitoring surveys, in the foreseeable future the development of complete integrated capture systems will hold enormous potential for geomorphological applications.

In this study it has been possible to consider in detail the spatial pattern of change in three dimensions and to assess differences throughout the cliff face in addition to the landward retreat rates at the cliff top. The ability to view volumetric change across rock faces has enabled the investigation of the factors that determine the contemporary evolution of the coastline at Staithes. The relative importance of different failure modes can be quantified for each specific cliff section. The change detected within the basal 10 m of Site A for example accounted for only 11.7% of the total volume lost for the monitoring period. The geotechnical properties and lack of vertical jointing generate a highly resistant cliff toe. The majority of material lost was restricted to the middle and upper sections of the cliff face which would remain unrecorded by aerial surveys. The lower 10 m at Site B by contrast lost 36.4 m^3 of material, 40.4% of the total recorded recession. It is clear from the spatial analysis of the patterns and quantities of changes that mitigation strategies such as armouring the cliff toe would have a far greater impact at Site B than at Site A. In this way development strategies can be targeted to better meet the needs of coastal managers.

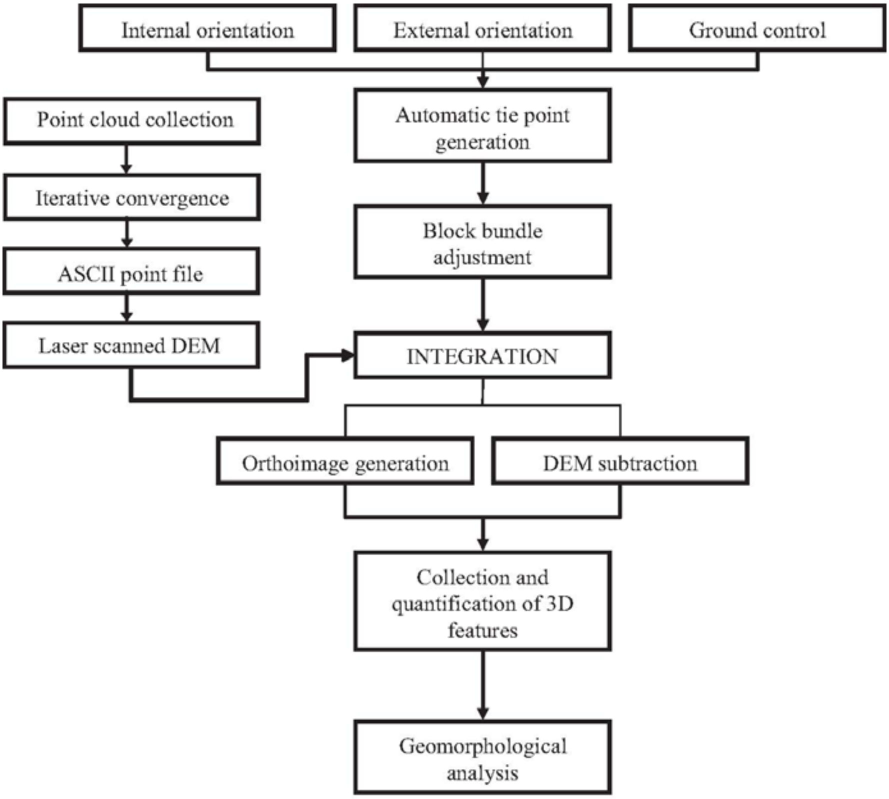

FIG. 9. Workflow combining digital photogrammetry and terrestrial laser scanning for geomorphological analysis.

With the introduction of high-resolution data-sets detailing the changes across rock faces over time, the opportunities to link detected differences to their controlling factors can also be explored. Cliff face changes for example can be linked to intense rainfall events or storm waves. The varied responses of the monitored sites to individual events reveal much about the sensitivity or resistance of each site to specific triggering mechanisms. The significant differences in the volume change recorded between the sites during September and October 2003 for example (Fig. 7), may reflect a particularly destructive wave regime associated with the strong easterly winds that buffeted the Yorkshire coast during these months. By accurately and precisely monitoring contemporary cliff forms, observations of materials and processes can be used to define, classify and model their evolution (Hantz *et al*., 2003). In time, the collection of more extensive datasets will adequately establish base levels for the characteristics and rates of change. Grounded in the background rates of change for contemporary recession processes, predictions of cliff responses to future impacts such as sea-level rise or coastal defences could be made. It is therefore important that the potential of new techniques such as those examined here are adequately explored with respect to improving our understanding of complex landforms such as hard rock cliffs. Ultimately, advances in understanding will only be achieved by increasing the number of accurately constrained monitoring datasets of high spatial and temporal resolution and then using them to establish new deterministic and probabilistic models of cliff evolution.

CONCLUSIONS

This study has used rectified images resampled with consistent, accurate laser-scanned data to monitor the monthly changes occurring over sections of the hard rock cliffs at Staithes, North Yorkshire. Photogrammetric techniques proved sensitive to changes in cliff face topography despite the challenges posed by scale and nature of the environment. This suggests that significant potential exists for the application of digital photogrammetry to less extreme cliff heights. The combination of the precise and qualitative information generated by digital photogrammetry and the extensive coverage and consistently high accuracies of time-of-flight laser scanning provides an answer to the challenges of recording change from large scale landforms in dynamic coastal environments.

The changes detected here reveal the inadequacies of widely used aerial survey approaches in quantifying retreat in near-vertical coastal cliffs. The apparent stability of hard rock cliffs masks significant variability both between and within monitored sections, confirming the importance of a site-specific approach to forming an understanding of cliff change. Distinct mechanisms of failure have been identified and related to the volumes of material lost to determine their relative contribution to cliff form. The data holds important implications for the formulation of adequate coastal development strategies, which should seek to combine the high-resolution terrestrial techniques presented here with established aerial and obliquely captured information. The solution to the challenges of recording, quantifying and explaining cliff change therefore lies in the continued development, integration and quality assessment of available techniques.

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