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Article (Accepted Version)

Barlow, John, Gilham, Jamie Mark and Ibarra Cofrã, Ignacio (2017) Kinematic analysis of sea cliff stability using UAV photogrammetry. *International Journal of Remote Sensing*, 38 (8-10). pp. 2464-2479. ISSN 0143-1161

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1 **Kinematic analysis of sea cliff stability using UAV photogrammetry**

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Kinematic analysis of sea cliff stability using UAV photogrammetry

Abstract

Erosion and slope instability poses a significant hazard to communities and infrastructure located in coastal areas. We use point cloud and spectral data derived from close range digital photogrammetry to perform a kinematic analysis of chalk sea cliffs located at Telscombe, UK. Our data were captured from an unmanned aerial vehicle (UAV) and cover a cliff face that is about 750 m long and ranges from 20 to 49 m in height. The resulting point clouds had an average density of 354 points m^{-2} . The models fitted our ground control network within a standard error of 0.03 m. Structural features such as joints, bedding planes, and faults were manually mapped and are consistent with results from other studies that have been conducted using direct measurement in the field. These data were then used to assess differing modes of failure at the site. Our results indicate that wedge failure is by far the most likely mode of slope instability. A large wedge failure occurred at the site during the period of study supporting our analysis. Volumetric analysis of this failure through a comparison of sequential models indicates a failure volume of about 160 m^3 . Our results show that data capture through UAV photogrammetry can provide a useful basis for slope stability analysis over long sections of coast. This technology offers significant benefits in equipment costs and field time over existing methods.

Keywords: UAV, photogrammetry, landslide, sea cliffs

1. Introduction

In recent years, digital surface model acquisition had been dominated by the use of airborne and terrestrial light detection and ranging (LiDAR) (Haala and Rothermel, 2012; Gonçalves and Henriques, 2015). However, the emergence of unmanned aerial vehicles (UAVs) or small Unmanned Aircraft Systems (sUAS) alongside the proliferation of inexpensive digital cameras and various software platforms for processing of this data (Hugenholtz et al., 2013)

have provided a method of data capture which can achieve results of comparable accuracy whilst significantly reducing costs and data capture time (Slatton et al., 2007; Remondino et al., 2011; Hugenholtz et al., 2013). The relative affordability of these various systems, when compared to airborne LiDAR and terrestrial laser scanning (TLS) surveys, has led to a significant rise in procurement for a diverse range of research applications (Dunford et al., 2009; Rango et al., 2009; Jaakkola et al., 2010; Lin et al., 2011; Stefanik et al., 2011; Hugenholtz et al., 2012; Hugenholtz et al., 2013; Colomina and Molina, 2014).

With regard to sea cliffs, high precision monitoring of erosion has typically been undertaken using TLS or a combination of TLS and terrestrial digital photogrammetry (e.g. Rosser et al. 2005; Lim et al. 2010; James and Robson 2012; Barlow et al. 2012; Martino and Mazzanti, 2014). Although these studies have provided improved control over the rate and processes of coastal cliff recession compared to those based on historical maps and aerial photographs (e.g. Dornbusch et al. 2008), the spatial extent of high precision monitoring has typically been limited by the logistics of terrestrial data collection from shore platforms (e.g. Rosser et al. 2005; Martino and Mazzanti, 2014). This research demonstrates the use of UAV photogrammetry to produce data of similar characteristics to that derived from TLS for sea cliff research. The rapid nature of data capture using UAVs means that much longer sections of cliff can be surveyed in much shorter periods of time than with previous studies.

The vast majority of digital photogrammetric applications using UAVs have relied on pure aerial triangulation or indirect sensor orientation (Colomina and Molina, 2014), whereby the navigation system and software determine an approximation of the image location and generate tie points with associated measurements in space which are later compared to the known GCPs. Rehak et al. (2013) report that the application of this method can produce models which are sub-decimetre in accuracy as reported by component or overall three dimensional standard error (3DSE) values. Many of these studies rely on the structure from motion (SfM)

method in which the bundle adjustment is based on features automatically extracted from multiple overlapping images (Westoby et al. 2012). SfM requires convergent imagery taken from multiple ranges in order to produce the best possible accuracy (James and Robinson, 2014). The method is therefore not well suited to coastal cliff research in that it requires multiple passes in order to photograph each section of cliff from multiple angles and ranges. Given the limited endurance of micro UAVs, the use of more traditional photogrammetry involving a calibrated camera and strip photography maximises the length of cliff that can be surveyed and this is the method that has been adopted for the current research.

The structural geology of cliffs often provides primary control over the type of slope failure that may occur. This is because the uniaxial compressive and shear strength of penetrative discontinuities are generally lower than those of the intact rock (Terzaghi, 1962). Kinematic analysis involves mapping the orientations of penetrative discontinuities within a rock slope in order to identify those that are oriented unfavourably for slope stability given the shear strength along discontinuity surfaces (Richards et al. 1978; Hoek and Bray, 1981; Wyllie and Mah, 2004). The analysis is based solely on the geometric conditions of rock slopes such that it does not locate discontinuities in space, gives no reference of their size, and does not consider the influence of hydrogeological or seismic boundary conditions on slope stability (Hoek and Bray, 1981). The assessment of the orientation of structural geology data requires plotting poles on a stereonet which indicates the dip and dip direction of discontinuities. This is executed with the aim of identifying clusters or sets of discontinuities, for which average dip and dip direction can be determined. The use of dense point clouds derived from close-range digital photogrammetry and terrestrial laser scanning in the characterization of rock slope morphology is well established within the research literature and has the advantage of allowing measurements to be taken from the entire rock surface rather than only those sections accessible to manual measurement (e.g. Lato et al. 2009; Sturzenegger and Stead, 2009a; Lim et al. 2010;

Salvini et al. 2013; Francioni et al. 2015). This research uses point cloud and spectral data derived from UAV photogrammetry to digitise structural features such as joints, faults, and bedding planes for kinematic analysis of the sea cliffs at Telscombe, UK. We also demonstrate a volumetric analysis of erosion through the use of sequential survey data.

2. Study Area

Telscombe cliffs are located between Saltdean and Peacehaven, East Sussex, UK and form one of the few undefended sections of coastline from Brighton to Newhaven (Figure 1). The cliffs are about 750 m long and are formed from Cretaceous Chalk of the Newhaven Formation with dry valleys present at either end of the study site (Mortimore, 1997). The cliffs are orientated to the dominant wave direction of the south-west and the maximum elevation is found centrally within the study area at 49 m. The sewage outfall pipe located to the far east of the site which is protected by a concrete groyne provides an artificial barrier to the movement of beach sediments. As a result the eastern extent of the cliff line is protected at the toe by a substantial pebble beach which tapers over approximately 300 metres to the west (Figure 1). At the extremities of the site the cliffs have been artificially regraded and disconnected from marine interaction through the construction of a sea wall and promenade to the west and the Portobello sewage works to the east. The site is macro tidal with an average spring tidal range of 6.1 m (CCO, 2015), submerging the shore platform and allowing wave interaction with the base of the cliff. Significant wave heights (H_s) recorded for this section of coast average 0.64 m in summer and 1.04 m in winter (CCO, 2015). The area receives an average of 720 mm of rain annually with the majority falling in the winter months. Rockfalls are most common in winter when a combination of winter storm damage and wet weather weaken the chalk (Mortimer et al., 2004a; Brossard and Duperret, 2004).

The cliffs at Telscombe are characterised by steeply inclined conjugate joint sets (Mortimore et al., 2004a). These, in conjunction with various bedding planes provide

discernible controls on the type and magnitude of failures along this stretch of coastline (Mortimore et al., 2004a). The most common types of instability within the Newhaven formation are wedge and planar failures which can lead to progressive block failures along conjugate discontinuity sets (Mortimore et al., 2004a). These fracture sets and failures produce a roughly ‘pyramidal’ cliff morphology which is illustrated in Figure 2B (Mortimore et al., 2004a).

3. Methods

The research methods are subdivided into five sections to represent the relevant stages of the workflow, these were: installation of ground control, UAV survey, photogrammetric processing, kinematic analysis, and change detection.

3.1 Ground Control

A total of 23 ground control points (GCPs), 5 at the cliff top and 18 at the cliff toe, were used to georeference our models (Figure 1). GCPs were located using a combination of differential global positioning system (dGPS) and total station surveying techniques. dGPS was used to locate 5 cliff top GCPs at accessible locations and to set up total station survey markers on the shore platform. To obtain ground control at the cliff toe, a total station was used in order to overcome the reduction in dGPS accuracy due to the ‘shadowing’ effect of the cliff, a common issue seen in complex terrain morphologies (Young, 2012). After processing (Awange, 2012; Awange and Kiema, 2013) the dGPS points were accurate to 0.02m in the x , y and z planes with PDOPs varying between 1.2 and 1.5. Total station surveying was used to obtain the cliff toe positions at equidistant locations along the base of the cliff, back sight locations were dual measured pre and post survey to attain an uncertainty value for the points surveyed by the laser scanner. The maximum deviation from the known dGPS back sight coordinates was 0.006 m such that the maximum error of our GCPs was within about 0.03 m.

3.2 UAV survey

A Nikon D810 FX DSLR 36 mega-pixel camera was used for the surveys with an AF Nikkor 24mm f/2.8D lens. Camera settings were optimised for lighting and aircraft flight speed as follows: aperture f/8, ISO 1250 and shutter speed 0.002 (1/5000) seconds. Ground control survey markers (Figure 2A) were installed on the GCPs to optimise precision and digitising in the ADAM 3DM photogrammetry software. The contrast between the white circle and the black background allows the software to auto locate the centre of the target to within $1/10^{\text{th}}$ of a pixel (ADAM Technology, 2010). The aircraft used was a DJI S1000 octocopter (Figure 3), an automated flight path was created that maintained a distance of about 50 metres between the camera and the cliff face with a flying altitude at approximately mid cliff height of 21 metres (Figure 1). During flight, the camera orientation was maintained orthogonal to the cliff face through live streaming video. Images were set to automated capture at a time interval of five seconds, with the UAV flying at a constant speed of 3 m s^{-1} resulting in an image capture every 15 m following a strip plan. This technique is best utilised for mapping a long stretch of cliff line from a relatively close distance with a short focal length (Birch, 2006). Two surveys were undertaken for this research, one on 05/08/2016 and another on 07/09/2016. Total flight time for each survey was 8 minutes.

Digital photogrammetry allows the characterization of sub-vertical slopes if a fine (cm) to very fine (mm) resolution is obtained (Sturzenegger and Stead, 2009b). Birch (2006) noted that a ground pixel size of $0.01 \text{ m} \times 0.01 \text{ m}$, together with an expected image accuracy of 0.5 pixels is a good conservative value for engineering photogrammetric planning. This level of detail makes it possible to measure and map low to extremely high persistence discontinuities (ISRM, 2007; Sturzenegger and Stead, 2009a,b). Our surveys were designed to meet these criteria.

3.3 Photogrammetric processing

Photogrammetric processing was undertaken in ADAM 3DM Technology Mine Mapping Suite (Adam Technology, 2010). This software makes use of a precise camera calibration to generate the interior orientation and then uses these data to process the exterior orientation. An exterior orientation was undertaken by digitising the location of the 23 GCPs to an image accuracy of 0.1 pixels based on the centre of the circular target. Relative Only (RO) points were automatically generated and points with a residual greater than 0.5 pixels were removed. A bundle adjustment was then undertaken to account for the removal of these ‘bad’ RO points and the process was iteratively run until no RO points with residuals greater than 0.5 pixels were detected. This refining procedure effectively reduces error within the model. This processing produced an exterior orientation with component 3DSE’s of 0.023m in the x -axis (Eastings), 0.017m in the y -axis (Northings) and 0.009m in the z -axis (elevation) such that the overall 3DSE in both our models was 0.03m.

All overlapping image pairs were used in the generation of DTMs varying from 50% to 88% in overlap. A total of 136 DTMs were generated with 27,793,335 points. These DTMs were then combined to develop a merged DTM using the screened poisson surface reconstruction version 6.13a (Kazhdan et al., 2006; Kazhdan and Hoppe, 2013) built into the Adam 3DM DTM generator software. The minimum point spacing selected was 0.05 m and the minimum spacing factor (also known as a trimming factor) was set to 8 (by default) which is used to multiply the minimum spacing factor in areas where no data is generated. Therefore if no data point was found within 0.40 m the software would stop looking for data in this area and trim the model to the extent of the last known data point. In addition the epipolar images generated were merged into an orthophoto with 0.01 m pixel size to enable draping of imagery over the point cloud.

3.4 Kinematic Analysis of Cliff Stability at Telscombe

Digital discontinuity mapping was undertaken in Adam 3DM analyst and extraction of cliff properties in Cloud Compare. The kinematic analysis of these data was undertaken using Dips 7.0 Rocscience (2016a). Digitisation of discontinuities was accomplished by manually fitting planes on individual chalk surfaces as shown in Figure 4. This was achieved following the methodological approach described in Mathis (2011) who suggests mapping at approximately 0.5 m from the model surface. However this distance did vary depending on the rock exposure and effect of shadowing in the model. Fresh erosional Chalk surfaces were determined by either:

- A surface which met the weathering grades of ISRM (1981), a fresh rock mass (grade I) is characterized by no visible sign of material weathered; perhaps slight discoloration can be present (i.e. white Chalk, without vegetation or weathered surfaces);
- Smooth, flat and non-roughened Chalk surfaces, thus exhibiting characteristics of a recent failure.

Both the dip and dip direction (Figure 4) were derived through extraction of the direction cosines with respect to the normals of the digitized plane (Sturzenegger and Stead, 2009a). The dip direction of the cliff face was extracted by fitting a plane to the average direction of the cliff profile resulting in an angle of 204°. The dip of the cliff face was determined as the maximum inclination (76°) of the face below a horizontal plane which dissected the cliff face at mid cliff height. In addition to the discontinuity data, kinematic analysis requires the friction angle (ϕ) of the Newhaven Chalk. A peak friction angle value of 35° was adopted based on geotechnical testing undertaken at the nearby Brighton Marina (Ove Arup and Partners, 1984; Mott MacDonald, 2009). Kinematic analyses of our data were undertaken using the mean dip/dip direction of discontinuity sets through the use of great circles and through plots of all possible interactions within the spread of the data.

3.5 Change detection

A large wedge failure was observed to have occurred at the site between field visits on 17/08/16 and 24/08/16. As a result, sequential datasets captured on 05/08/16 and 07/09/16 were processed to perform a volumetric analysis of this failure. By exporting both point clouds to Cloud Compare the models were translated so that the dip direction or cliff azimuth was parallel to the y plane. Therefore any surface measurement was taken orthogonal to the cliff face so is representative of true depth change from the sequential models. Both point clouds were rasterised at a cell size of 0.05 m, representing the average points spacing. The distance and volumetric change between the two models was then completed by differencing the two rasters.

4. Results and discussion

The discontinuity mapping was completed on the first dataset obtained, this model generated 17,547,066 points with point density of 354 points m⁻². The model fitted our control network of GCPs with a 3DSE of 0.03 m. A total of 489 discontinuities were digitised within the study area (Table 1). Of these, only 24 were mapped within 2 m of the base of cliff such that about 95% would not have been recorded using manual measurement from the base of slope. Joints were divided into two sets (Joint Set 1 – JS1 and Joint Set 2 – JS2) based on a stereonet of the discontinuity mapping illustrated in Figure 5. This result is consistent with measurements reported by Lawrence (2007), Mortimore et al. (2004a), Mortimore et al. (2004b) and Lemos de Oliveira (2013).

4.1 Kinematic Analysis

The cliff face strikes at 114° (or Dip direction = 204°), which correlates well with the fracturing direction of the coastline of East Sussex of WNW/ESE (Duperret et al., 2012). JS1 is concentrated in the N quadrant of the stereogram, JS2 is located in the ENE-WSW quadrants. Remaining pole plots of joints show more scatter and are distributed preferentially towards the perimeter of the aforementioned sets. Faults do not lie within any interval of density concentrations in the stereogram. However based on the pole plots it is possible to distinguish

a clustering of 19 faults (FS) in direction ESE (Figure 5), representing a set with a great circle of dip/dip direction $61^{\circ}/290^{\circ}$. The majority of the remaining faults are located in the NW quadrant. In contrast, Bedding Planes (BP) exhibit the highest density concentration, with all of the measurements clustered at the centre of the stereogram, conforming a great circle of $01^{\circ}/87^{\circ}$.

The great circles associated with each set of discontinuities, the cliff face, and the intersections between them are also shown in Figure 5. JS1 has a great circle with dip/dip direction of $75^{\circ}/178^{\circ}$, while JS2 reports $80^{\circ}/242^{\circ}$. They intersect at a wider oblique angle of 117° , marginally outside the great circle of the cliff face, since the cliff face dips at 76° , while the plunge of the line of intersection (I_1) is 75° . This result demonstrates that JS1 and JS2 form the planes of a wedge failure that would slide in the direction of the trend of $I_1(192^{\circ})$. This represents the most likely mode of failure at the site. Figure 6A shows an example of this mode of failure involving JS1 and JS2. The left (yellow) disk represents JS1 ($72^{\circ}/181^{\circ}$) while the right (orange) disk depicts JS2 ($68^{\circ}/240^{\circ}$). As illustrated JS1 and JS2 are representative surfaces of two intersecting planes dipping out of the cliff face. The specific kinematic analysis of these discontinuities based on the Markland test (Hoek and Bray, 1981) is shown in Figure 6B. It is evident that the great circles of JS1 and JS2 intersect within the primary critical zone (sliding on both planes) for wedge failure. The line of intersection dips at 67° and the model suggests a direction of sliding of 221° .

The characteristics of intersections between all discontinuity sets is displayed in Table 2. The great circle of JS1 intersects the great circle of FS ($61^{\circ}/290^{\circ}$) at an acute angle (79°). In this case, the trend/plunge of the line of intersection (I_2) is $247^{\circ}/53^{\circ}$, which indicates the possibility of wedge instability ($76^{\circ}>53^{\circ}$), if they are frictionally unstable and if the cohesion of rock bridges along joints are neglected. Since the angle between the planes JS1 and JS2 is higher than the angle formed between JS1 and FS, an open v/s a narrow wedge could be

expected, respectively for both systems of discontinuities (Hoek and Bray, 1981). The plane of JS2 (80/242°) intersects the plane of FS at a wider oblique angle (131°). As the line of intersection (I_3) is 315°, which dips inside of the cliff face there is no possibility of wedge instability between these sets. Finally, the great circle of BP is the shallowest (01°) dipping toward the East of the stereogram at 87° which intersects FS, JS1 and JS2 at acute oblique angles (62°, 75° and 81°, respectively) however since the trend of the line of intersections between BP-FS (I_4) and BP-JS1 (I_5) lie inside the cliff face (at 20° and 88° respectively), any wedge formed by BP and FS or JS1 is unlikely to slide. In contrast, the trend of the line of intersection between BP and JS2 (I_6) is 152° which is outside the cliff face. Nonetheless, due to the almost horizontal dip of the BP, an effective kinematic failure of this wedge is not possible.

Kinematic analysis was also undertaken using the entire spread in the data in order to assess relative frequency with which the mapped discontinuities met the failure criteria for differing modes of rock slope instability. Stereo plots were analysed for wedge failure, flexural toppling, planar sliding, and direct toppling as illustrated in Figure 7. Both wedge failure and direct toppling require an intersection of discontinuities. In the case of wedge failure, the potential intersection points between all joints and faults are illustrated in Figure 7A. Results indicate that 18,758 (25.9%) intersections out of 72,383 possible intersections lie within the primary critical zone (sliding on both planes). A further 9,577 intersections or 13.2% lie within the secondary critical zone (sliding on a single plane) such that a total of 39.1% of all possible intersections are favourable to wedge failure. Intersections favourable to direct toppling were investigated using all joint, fault, and bedding plane data as illustrated in Figure 7B. Out of 119,302 possible intersections, 691 or 0.6% fall within the direct toppling zone. A further 8,866 or 7.4 % fall within the oblique toppling zone. Planar sliding and flexural toppling only involve failure across a single discontinuity. These modes of failure were investigated using the pole

plots as shown in Figure 7C and 7D respectively. The pole plot for planar sliding (7C) includes all 489 discontinuities mapped, of these only 40 (8.2%) lie inside the daylight envelope for planar sliding indicating a low probability of occurrence at Telscombe. The pole plot for flexural toppling included all joints and faults and is shown in figure 7D. This mode of failure is of very low probability at Telscombe with only 20 (5.3%) out of 381 mapped discontinuities meeting the failure criteria.

4.2 Wedge failure – kinematics and change detection analysis

Between field visits on the 17/08/2016 and the 24/08/2016 a rock fall had occurred in the central portion of the cliff (Figure 8). This failure coincided with a two day period (20/08-21/08/2016) of strong winds, which were driven from the south west (orientation of the cliff) averaging 8.45ms^{-1} , with average and peak gusts of 11.29ms^{-1} and 19.2ms^{-1} respectively recorded from the nearby Brighton Marina meteorological station. The maximum high tides for this period were recorded between 6.3 and 6.9 m (Chart Datum) at Brighton Marina confirming substantial wave attack at the cliff toe. Figure 8 identifies the discontinuity set which led to the wedge failure, discontinuity 'J' is a joint that does not belong to either identified set, a dip and dip direction of $69^{\circ}/71^{\circ}$ were recorded for this plane. The other joint is representative of JS2 and had a dip and dip direction of $79^{\circ}/233^{\circ}$. The joints intersect towards the base of the cliff and are limited at the top by harder bands of nodular flint. It is inferred that the wedge failure between these two joints occurred from the release surface along JS2 and the sliding of material along J forming the wedge type failure. A kinematic analysis of the wedge failure was undertaken (Figure 8D) with the intersection of the great circles between the two joints located within the secondary critical zone.

In addition the sequential models were used to quantify the volume involved in the failure. Figure 8C illustrates the surface change between 05/08/16 and 07/09/16. The wedge failure is located in the centre of Figure 8a, b and c and was the larger of the two observed

failures. The failure approximately five metres to the west (left of image) was generated through collapse of the upper arch of a small cave. The surface change detected in the lower right of the image is noticeable across the eastern section of the study area and represents the beach volume lost between the two surveys. This evidence of marine erosion at the site strongly suggests that wave action at the base of slope triggered the failures. The volumetric analysis of the rock falls indicate failures of about 160 m³ and 49 m³ for the wedge and arch respectively.

5. Conclusions

Our research has shown that UAV photogrammetry can generate 3D models of a cliff face with a point density and accuracy that is similar to those produced using TLS but with an order of magnitude reduction in equipment costs. These data allow coastal erosion to be constrained far more precisely than traditional methods involving sequential aerial photographs and historical maps (e.g. Dornbusch et al. 2008). Each survey consisted of an 8 minute flight, this rapid rate of data capture is such that our method can generate dense point clouds over much larger sections of sea cliff than previous studies involving TLS or terrestrial photogrammetry (e.g. Rosser et al. 2005; James and Robson 2012; Martino and Mazzanti, 2014). The resulting models also capture the structural geology of the site such that it can be mapped for kinematic analysis. Our analysis at Telscombe indicates the dominant failure type as wedge failure, one of which occurred between successive data captures. Both planar sliding and oblique toppling could also be significant at the site being kinematically allowable by 8.2% and 7.4% of all possible interactions respectively. Our analysis indicates flexural toppling is the least likely type of failure with only 5.3% of all mapped discontinuities falling within the critical zone. Change detection between sequential surveys quantified the volume of a recent wedge failure at about 160 m³. This research provides the basis for high-resolution monitoring of rock falls over large spatial scales within the coastal region and offers the potential to provide greater insight into the environmental and geological controls on rockfalls and resulting coastal

cliff retreat. However, to get best results, a full frame camera with a prime lens is required such that a larger UAV is required to lift the sensor. UAV systems using this method are heavier and therefore less portable than those suited to SfM.

6. Acknowledgements

This research was supported by the Engineering and Physical Sciences Research Council. The authors wish to thank two anonymous reviewers for their helpful comments.

References

- ADAM Technology. 2010. *3D Measurement, Camera Calibration and Block Adjustment Software. User's Manual*. ADAM technology, Australia.
- Awange, J. 2012. *Environmental monitoring using GNSS, global navigation satellite system*. Berlin: Springer. doi:10.1007/978-3-540-88256-5.
- Awange, J., and J. B. K. Kiema. 2013. *Environmental geoinformatics: monitoring and management*. Berlin: Springer. doi:10.1007/978-3-642-34085-7.
- Barlow, J., M. Lim, N. Rosser, D. Petley, M. Brain, E. Norman, and M. Geer, 2012. "Modelling rock cliff erosion using negative power law scaling of rockfalls." *Geomorphology*, 139-140: 416-424. doi: 10.1016/j.geomorph.2011.11.006.
- Birch, J.S. 2006. "Using 3DM Analyst mine mapping suite for rock face characterization." In: Tonon, F., and J. Kottenstette. (Eds.), *Laser and Photogrammetric Methods for Rock Face Characterization*, ARMA.
- Brossard, J., and A.Duperret. 2004. "Coastal Chalk cliff erosion: experimental investigation on the role of marine factors." In: Mortimore, R., and A. Duperret(Eds.). *Coastal Chalk Cliff Instability*. Geological Society, London, Engineering Geology Special Publications, 20, 109-120. doi:10.1144/GSL.ENG.2004.020.01.13.
- Channel Coastal Observatory (CCO). 2015. *Channel Coastal Observatory - Regional Coastal Monitoring Programmes Seaford Wave Buoy*.
http://www.channelcoast.org/data_management/real_time_data/charts/?chart=81andtab=infoanddisp_option=
- Colomina, I., and P. Molina. 2014. "Unmanned aerial systems for photogrammetry and remote sensing: A review." *ISPRS Journal of Photogrammetry and Remote Sensing*, 92: 79-97. doi: 10.1016/j.isprsjprs.2014.02.013.

- Dornbusch, U., D.A. Robinson, C.A. Moses, and R.B.G. Williams. 2008. "Temporal and spatial variations of chalk cliff retreat in East Sussex, 1873 to 2001." *Marine Geology*, 249: 271-282.
- Dunford, R., K. Michel, M., Gagnage, H. Piégay, and M.-L. Trémelo. 2009. "Potential and constraints of unmanned aerial vehicle technology for the characterization of Mediterranean riparian forest." *International Journal of Remote Sensing*, 30(19): 4915–4935. doi:10.1080/01431160903023025.
- Duperret, A., S. Vandycke, R. N. Mortimore, and A. Genter. 2012. "How plate tectonics is recorded in chalk deposits along the eastern English Channel in Normandy (France) and Sussex (UK)." *Tectonophysics*, 581: 163-181.
- Francioni, M., R. Salvini, D. Stead, R. Giovannini, S. Riccucci, C. Vanneschi, and D. Gullì. 2015. "An integrated remote sensing-GIS approach for the analysis of an open pit in the Carrara marble district, Italy: Slope stability assessment through kinematic and numerical methods." *Computers and Geotechnics*, 67: 46-62. doi:10.1016/j.compgeo.2015.02.009.
- Gonçalves, J. A., and R. Henriques. 2015. "UAV photogrammetry for topographic monitoring of coastal areas." *ISPRS Journal of Photogrammetry and Remote Sensing*, 104: 101-111. doi: 10.1016/j.isprsjprs.2015.02.009.
- Haala, N., and M. Rothermel. 2012. "Dense Multi-Stereo Matching for High Quality Digital Elevation Models." *PFG Photogrammetrie-Fernerkundung-Geoinformation*, 2012 (4): 331-343. doi:10.1127/1432-8364/2012/0121.
- Hoek, E., and J. Bray. 1981. *Rock Slope Engineering, 3rd ed.* London, UK: Institution of Mining and Metallurgy, ISBN: 0419160108, 9780419160106.
- Hugenholtz, C. H., N. Levin, T. E. Barchyn, and M. Baddock. 2012. "Remote sensing and spatial analysis of aeolian sand dunes: a review and outlook." *Earth-Science Reviews*, 111(3-4): 319–334. doi:10.1016/j.earscirev.2011.11.006.
- Hugenholtz, C. H., K. Whitehead, O. W. Brown, T. E. Barchyn, B. J. Moorman, A. LeClair, K. Riddell, and T. Hamilton. 2013. "Geomorphological mapping with a small unmanned aircraft system (sUAS): Feature detection and accuracy assessment of a photogrammetrically-derived digital terrain model." *Geomorphology*, 194: 16-24. doi:10.1016/j.geomorph.2013.03.023.
- International Society for Rock Mechanics (ISRM). 2007. The complete ISRM suggested methods for rock characterization, testing and monitoring: 1974–2006. In: Ulusay R, Hudson J.A. (Eds.). *Commission on testing methods. International Society of Rock*

416 *Mechanics*. Compilation arranged by the ISRM Turkish National Group, Ankara,
417 Turkey.

418
419 International Society of Rock Mechanics (ISRM). 1981. *Rock Characterization, Testing and*
420 *Monitoring; ISRM Suggested Methods*. Oxford, UK: Pergamon Press. ISBN:
421 0080273084, 9780080273082.

422
423 Jaakkola, A., J. Hyypä, A. Kukko, X. Yu, H. Kaartinen, M. Lehtomäki, and Y. Lin. 2010.
424 “A low-cost multi-sensoral mobile mapping system and its feasibility for tree
425 measurements.” *ISPRS Journal of Photogrammetry and Remote Sensing*, 65 (6): 514–
426 522. doi:10.1016/j.isprsjprs.2010.08.002.

427
428 James, M.R., and S. Robson. 2012. “Straightforward reconstruction of 3D surfaces and
429 topography with a camera : Accuracy and geoscience application.” *Journal of*
430 *Geophysical Research*, 117: F03017. doi:10.1029/2011JF002289.

431
432 James, M.R., and S. Robson. 2014. “Mitigating systematic error in topographic models
433 derived from UAV and ground-based image networks.” *Earth Surface Processes and*
434 *Landforms*, 39: 1413-1420. doi:10.1002/esp.3609.

435
436 Jenner, H.N., and R.H. Burfitt. 1974. *Chalk: An engineering material*: Paper read at meeting
437 of the Southern Area of the Institution of Civil Engineers, Brighton on 6th March,
438 (unpublished).

439
440 Kazhdan, M., and H. Hoppe. 2013. “Screened Poisson surface reconstruction.” *ACM*
441 *Transactions on Graphics (TOG)*, 23(3): 29:1-29:13. doi:10.1145/2487228.2487237.

442
443 Kazhdan, M., M. Bolitho, and H. Hoppe. 2006. “Poisson Surface Reconstruction.” Proceedings
444 of the fourth Eurographics Symposium on Geometry Processing, June 26-28, 2006,
445 Cagliari, Sardinia, Italy: 1-10.

446
447 Lato, M., M.S. Diederichs, D.J. Hutchinson, and R. Harrap. 2009. “Optimization of LiDAR
448 scanning and processing for automated structural evaluation of discontinuities in
449 rockmasses.” *International Journal of Rock Mechanics & Mining Sciences*, 46: 194-
450 199.

451
452 Lawrence, J. A. 2007. *Engineering properties of chalk in relation to coastal cliff slope*
453 *instability*. Ph.D. Thesis. University of Brighton.

454
455 Lemos de Oliveira, V. 2013. *Structural Geology and Fracture Patterns in the Chalk of*
456 *Sussex, UK. (BSc dissertation in Geology)*. University of Brighton. UK.

- Lim, M., N.J. Rosser, R.J. Allison, D.N. Petley. 2010. "Erosional processes in the hard rock coastal cliffs at Staithes, North Yorkshire." *Geomorphology*, 114: 12-21. doi:10.1016/j.geomorph.2009.02.011.
- Lin, Y., J. Hyypä, and A. Jaakkola. 2011. "Mini-UAV-borne LiDAR for fine-scale mapping." *IEEE Geoscience and Remote Sensing Letters*, 8(3): 426–430. doi:10.1109/LGRS.2010.2079913.
- Martino, S., and P. Mazzanti. 2014. "Integrating geomechanical surveys and remote sensing for sea cliff slope stability analysis: the Mt. Pucci case study (Italy)." *Natural Hazards and Earth System Sciences*, 14: 831-848. doi:0.5194/nhess-14-831-2014.
- Mathis, J.I. 2011. *Photogrammetric discontinuity mapping as applied to structural interpretation and drillhole planning at Barrick's Williams pit*. Slope Stability 2011, Vancouver, Canada September, 2011.
- Molina, P., I., Colomina, T. Vitoria, P. F. Silva, J. Skaloud, W. Kornus, R. Prades, and C. Aguilera. 2012. "Searching lost people with UAVs: the system and results of the close-search project." *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XXXIX-B1, 2012 XXII ISPRS Congress, 25 August – 01 September 2012, Melbourne, Australia*, pp. 441-446.
- Mortimore, R. N. 1997. *The Chalk of Sussex and Kent*. London: The Geologists Association.
- Mortimore, R., J. Lawrence, D. Pope, A. Duperret, and A. Genter. 2004a. "Coastal cliff geohazards in weak rock: the UK Chalk cliffs of Sussex." In: Mortimore, R., and Duperret, A. (Eds.). *Coastal Chalk Cliff Instability*. Geological Society, London: Engineering Geology Special Publications, 20. doi:10.1144/GSL.ENG.2004.020.01.13.
- Mortimore, R., K. Stone, J. Lawrence, and A. Duperret. 2004b. "Chalk physical properties and cliff instability." In: Mortimore, R., and Duperret, A. (Eds.). *Coastal Chalk Cliff Instability*. Geological Society, London: Engineering Geology Special Publications, 20. doi:10.1144/GSL.ENG.2004.020.01.13.
- Mott MacDonald. 2009. *Brighton and Hove WWT Scheme Black Rock Quaternary Cliff Stability Study*. London, UK.
- Ove Arup and Partners. 1984. *Black Rock Interchange: Geotechnical Report*. London, UK.
- Rango, A., J. E. Herrick, K. Havstad, and D. Browning. 2009. "Unmanned aerial vehicle-based remote sensing for rangeland assessment, monitoring, and management." *Journal of Applied Remote Sensing*, 3(1): 1-15. doi:10.1117/1.321682.

- Rehak, M., Mabillard, R., and Skaloud, J. (2013). A micro-UAV with the capability of direct georeferencing. *ISPRS – Int. Arch. Photogramm. Remote Sens. Spatial Inform. Sci. XL-1/W2*, pp. 317–323. DOI: 10.5194/isprsarchives-XL-1-W2-317-2013.
- Remondino, F., Barazzetti, L., Nex, F., Scaioni, M., and Sarazzi, D. (2011). “UAV Photogrammetry for mapping and 3D modelling – current status and future perspectives.” International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XXXVIII-1/C22, 2011 ISPRS Zurich 2011 Workshop, 14-16 September 2011, Zurich, Switzerland.
- Richards L.R., G.M.M. Leg, R.A. Whittle. 1978. “Appraisal of stability conditions in rock slopes.” In: Bell F.G. (Ed.) *Foundation engineering in difficult ground*. London: Newnes-Butterworths.
- Rocscience (2016a). *Rocscience software products – DIPS 7.0*. <http://www.rocscience.com>.
- Rosser, N.J., D.N. Petley, M. Lim, S.A. Sunning, and R.J. Allison. 2005. “Terrestrial laser scanning for monitoring the process of hard rock coastal cliff erosion.” *Quarterly Journal of Engineering Geology and Hydrogeology*, 38: 363–375.
- Salvini, R., M. Francioni, S. Riccucci, F. Vonciani, and I. Callegari. 2013. “Photogrammetry and laser scanning for analyzing slope stability and rock fall runout along the Domodossola–Iselle railway, the Italian Alps.” *Geomorphology*, 185:110-122. doi:10.1016/j.geomorph.2012.12.020.
- Slatton, K. C., W .E. Carter, R. L. Shrestha, and W. Dietrich. 2007. “Airborne laser swath mapping: achieving the resolution and accuracy required for geosurficial research.” *Geophysical Research Letters*, 34: L23S10. doi:10.1029/2007GL031939.
- Stefanik, K. V., J.C. Gassaway, K. Kochersberger, and A. L. Abbott. 2011. “UAV-based stereo vision for rapid aerial terrain mapping.” *GIScience and Remote Sensing*, 48(1): 24–49. doi:10.2747/1548-1603.48.1.24.
- Sturzenegger, M., and D. Stead. 2009a. “Close-range terrestrial digital photogrammetry and terrestrial laser scanning for discontinuity characterization on rock cuts.” *Engineering Geology*, 106(3): 163–182. doi:10.1016/j.enggeo.2009.03.004.
- Sturzenegger, M., and D. Stead. 2009b. “Quantifying discontinuity orientation and persistence on high mountain rock slopes and large landslides using terrestrial remote sensing techniques.” *Natural Hazards and Earth System Sciences*, 9(2):267–287. doi:10.5194/nhess-9-267-2009.
- Terzaghi, K. 1962. “Stability of steep slopes on hard unweathered rock.” *Géotechnique*, 12 (4): 251-270.

545

546 Wyllie, D. C., and C. Mah. 2004. *Rock slope engineering*. London and New York: CRC
547 Press. ISBN: 0-203-49908-5.

548

549 Westoby, M.J., J. Brasington, N.F. Glasser, M.J. Hambrey, J.M. Reynolds. 2012. “‘Structure-
550 from-Motion’ photogrammetry: A low cost, effective tool for geoscience applications.”
551 *Geomorphology*, 179:300-314. doi:10.1016/j.geomorph.2012.08.021.

552

553 Young, E. 2012. “dGPS.” In: Cook, S.J., Clarke, L.E. and Nield, J.M. (Eds.)
554 *Geomorphological Techniques (Online Edition)*. London: British Society for
555 Geomorphology. ISSN: 2047-0371.

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557 **Table 1:** Discontinuity mapping results

Discontinuity type	Total number	Mean Dip (°)	Mean Dip Direction (°)
Joint Set 1 (JS1)	142	75	178
Joint Set 2 (JS2)	104	80	242
Faults (total)	41	65	227.9
Faults (FS)	19	61	290
Bedding Planes	108	01	87

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560 **Table 2:** Characteristics of intersections between discontinuities sets

Line of intersection (I_n)	Sets	Angle between great circles (°)	Trend/Plunge (°)	Type of intersection	Possibility of slope instability
I_1	JS1&JS2	117	192/75	Oblique	Wedge
I_2	JS1&FS	79	274/53	Oblique	Wedge
I_3	JS2&FS	131	247/58	Oblique	No
I_4	BP&FS	62	20/00	Oblique	No
I_5	JS1&BP	75	88/01	Oblique	No
I_6	JS2&BP	80.9	152/00	Oblique	No

561

List of Captions

Figure 1: Study area at Telscombe, UK with GCPs and UAV flight line indicated. Transect of the cliff produced through photogrammetry shown below with GCPs indicated.

Figure 2: Survey Target Markers (a) Example of the target marker (b) placement of markers taken from an image captured from the UAV (13/04/2016), with an example of 'pyramidal' Newhaven chalk character from Telscombe Cliffs.

Figure 3: UAV (left) with characteristics.

UAV model	DJI S1000 octocopter
	Max. take-off load	10.89kg
	Max. wind	10m/s
	Max. altitude	1000m
	Max. flight time	15 mins (with load)
	Motors and type	8 motors (model 4114-11)
	Batteries	LiPo 16000 mAh
	Flight modes	Manual or GPS aided navigation

Figure 4: Example of discontinuity mapping of the Telscombe cliffs in 3DM analyst (Software shows planes as disks with circumference following the extremities of digitised features, Blue disks: undifferentiated joints; Yellow disks: Joint Set 1; Orange disks: Joint Set 2; Green disks: Bedding Planes; Red disks: faults).

Figure 5: Wolff equal angle equatorial stereographic projection (lower hemisphere) of discontinuity data at Telscombe showing the pole densities and great circles. The cliff face and lines of intersection (I_n) are also shown.

Symbol	Feature
■	Intersection

Color	Density Concentrations
	0.00 - 2.20
	2.20 - 4.40
	4.40 - 6.60
	6.60 - 8.80
	8.80 - 11.00
	11.00 - 13.20
	13.20 - 15.40
	15.40 - 17.60
	17.60 - 19.80
	19.80 - 22.00

Contour Data	Pole Vectors
Maximum Density	21.38%
Contour Distribution	Fisher
Counting Circle Size	1.0%

Color	Dip	Dip Direction	Label
	Great circle		
1	76	204	Cliff face
2	80	242	Joint Set 2 (JS2)
3	75	178	Joint Set 1 (JS1)
4	61	290	Fault Set (FS)
5	1	87	BP set

Figure 6: (a) Observed wedge failure with mapped joints overlaid. Yellow surface is JS1 and orange surface is JS2. (b) Kinematic analysis of the failure according to the Markland test. Also, a circle representing the friction angle of 35° is highlighted.

Figure 7: Stereographic representation of discontinuity data. (a) Points of intersection between joints and faults for wedge failure. (b) Points of intersection between joints, faults, and bedding planes for direct toppling failure. (c) Pole plots for joints and faults for planar sliding failure. (d) Pole plots of joints and faults for flexural toppling failure.

Legend

- + Joint
- × Fault
- Intersection
- Critical Intersection

Figure 8: Observed wedge failure at the site during the period of study. (a) imagery before the failure with joints indicated; (b) imagery after failure with joints indicated; (c) volumetric analysis; and (d) kinematic analysis by means of the Markland test.