

TIME FOR CHANGE – QUANTIFYING LANDSLIDE EVOLUTION USING HISTORICAL AERIAL PHOTOGRAPHS AND MODERN PHOTOGRAMMETRIC METHODS

J. Walstra ^{a,*}, J.H. Chandler ^a, N. Dixon ^a, T.A. Dijkstra ^a

^a Dept. of Civil and Building Engineering, Loughborough University, Leicestershire LE11 3TU, UK – J.Walstra@lboro.ac.uk

Commission IV, WG IV/6

KEY WORDS: geomorphology, DEM/DTM, extraction, modelling, visualization, quality, change detection

ABSTRACT:

A sequence of historical aerial photographs captures morphological change, which can only be unlocked by using appropriate photogrammetric methods. There are several challenges: initially it is necessary to trace and acquire suitable imagery in an appropriate format; typically there is a lack of precise photo-control available at the time of photography and similarly, it is rare to have access to the original camera calibration certificate. Furthermore, it is essential to assess the quality of the extracted morphological data. Once these challenges have been overcome, such morphological change data can be used to develop landslide evolutionary models, which can be related to localised climate change. This paper describes the use of modern digital photogrammetric methods to extract high-resolution digital elevation models (DEMs) and orthophotographs using historical photography. Initial results from a case study at Mam Tor (Derbyshire, UK) show the potential of the methods to quantify past landslide movements. Photographs from four different epochs (1953, 1971, 1973 and 1990), of varying scale and quality, were processed. Difficulties caused by limited ground control and limited camera calibration data were solved by differential GPS and self-calibrating bundle adjustment methods. The quality of the data was at an adequate level to extract ground movements that were consistent with observations by other authors. A more detailed analysis of the displacements in both vertical and horizontal directions is expected to increase the understanding of the mechanics of the landslide. This is an ongoing research project in which these dated spatial data will be used to relate landslide evolution to climate change.

1. INTRODUCTION

It is generally acknowledged that global climate is changing (ICCP, 2001). Future climate change will have great impacts on human society, but prediction of these impacts is subject to large uncertainties. This paper is framed in a research project dealing with the consequences of climate change for active landslides in the UK. Understanding of the climatic controls on mass movements requires analysis of past climate and landslide activity patterns. However, only few high quality data records are available that are able to give a continuous picture (Dikau & Schrott, 1999).

As climate is highly variable in the short-term, a significant change can only be recognized over longer periods. Moreover, geomorphologic processes are subject to extrinsic and intrinsic thresholds, resulting in complex responses to environmental changes (Schumm, 1979; Brunsden & Thornes, 1979). These complex reactions mask the causality between climate change and geomorphologic response and makes modelling difficult. Usually, while extensive climate data records are available (systematic data collection started in the UK in the 1660s; Hulme et al., 2002), obtaining accurate historical data about landslide movements and landform change is more challenging. There is sophisticated equipment for monitoring present-day landslide movements: inclinometers, tiltmeters, extensometers, time domain reflectometry (TDR) (Kane & Beck, 2000), global positioning system (GPS), synthetic aperture data (SAR) (Buckley & Mills, 2000), satellite and aerial imagery (Brunsdan, 1993) and light detection and ranging (LIDAR)

(Adams & Chandler, 2002). However, most of these methods are usually not capable of revealing quantitative data about past movements, which restricts the length of these records. Historical aerial photographs are a resource of spatial data that can be unlocked using photogrammetric techniques, and hence are capable of being used to extend these records. Systematic aerial surveys started after the Second World War, providing potential data covering a period of more than 50 years. The aim of this paper is to present the digital techniques used to extract morphological change from a sequence of aerial photos and discuss their potential value for validating climate controlled landslide models.

2. EXTRACTING QUANTITATIVE MORPHOLOGICAL DATA USING DIGITAL PHOTOGRAMMETRIC TECHNIQUES

Historical aerial photographs can provide detailed information of past morphological change (e.g. Chandler & Cooper, 1989; Chandler & Brunsden, 1995). Despite its many advantages, use of analytical photogrammetric methods remain expensive, complex and require a significant amount of experience (Chandler, 2001; Brunsden, 1993). Recent developments in computer technology have had a significant impact upon photogrammetry. Advances in automated digital photogrammetry now allow high-resolution quantitative data to be extracted automatically (Walker, 1996; Brunsden & Chandler, 1996). Advantages of automated digital photogrammetry include (Chandler, 1999):

- applicable at any scale;
- allowing creation of regular grid-based digital elevation models (DEMs) of consistent precision and at very high sampling rates, thus able to record very detailed morphology;
- commercial software available at competitive rates;
- software runs on relatively cheap UNIX workstations and PCs;
- user-friendly interface of software makes techniques available to non-specialists.

2.1 Theory

Theoretical principles underlying photogrammetric methods were established over a century ago (Finsterwalder, 1897) and developed for map production in the 1930s (Wolf & Dewitt, 2000; Slama, 1980). The concept of collinearity is critical, whereby a point on the object, centre of lens and resultant image point lie on a single line in three-dimensional space. Based on this principle the three-dimensional object space coordinates can be extracted from a stereopair of photographs, provided that interior and exterior orientation of the camera at the moment of exposure are known. Exterior orientation parameters of the camera can easily be determined with the help of a minimum of three ground control points (GCPs) for each image (Wolf & Dewitt, 2000).

When using archival photographs or a non-metric camera, the interior parameters of the camera are often unknown. However, these can be determined by using a self-calibrating bundle adjustment. In this numerical procedure the interior and exterior parameters of all frames are simultaneously estimated by using a least squares estimation, which minimizes and distributes the errors (Kenefick et al., 1972; Granshaw, 1980; Chandler & Cooper, 1989). Redundant photo control is recommended, as this will provide stochastic properties of the solution and checks on data consistency.

2.2 ADAPT – A Digital Archival Photogrammetric Technique

Chandler & Brunsten (1995) describe an analytical technique for extracting spatial data from historical photographs and prove its value in studies of land-form change. Their procedure is known as the archival photogrammetric technique and overcomes the main problems associated with archival photographs, the lack of camera calibration and control points, by using a self-calibrating bundle adjustment. The great advantage of the method is that it can be applied universally to all photographic formats: both vertical and oblique images, from small to large-scale. Additionally, all image epochs can be referenced to the same coordinate system, which is crucial for quantitative analyses. The approach described in this paper was developed from this method, but using the latest technologies in digital processing, which enables the method to be used more easily, and hence become more universally applicable.

First step is the acquisition of aerial photographs, using the following considerations (in order of importance):

- ground coverage; the area of interest should be completely covered by the stereoscopic overlap area of the images.
- scale; the scale of the photograph determines with what precision photo-coordinates can be measured and what feature sizes can be discerned.

- geometry; the parallax and hence heighting precision is affected by flying height, airbase, and focal length of the camera.
- format; best results are obtained when using high-resolution scans (15-20 μ) of contact diapositives from the original negatives, using a photogrammetric quality scanner. However, as these are not always available, use of scans from contact prints may have to be considered.

Obtaining historical aerial photographs is time-consuming. In the UK the imagery is distributed over numerous archives and libraries held by a range of institutions, among them the National Monuments Record, the collection of Cambridge University, commercial mapping companies and various local authorities. Some of these organisations have standardized their search and request systems, which makes the archives easily accessible to public. However, in some cases this standardization makes it more difficult to deal with specialist demands, for example high-resolution photogrammetric scans. Sometimes only contact prints are available, or access to a photogrammetric scanner is lacking.

Once imagery is acquired, ground control points must be identified and measured. Suitable control points are well-defined natural features, clearly identifiable on the photographs. For photoscales of 1/4,000-1/50,000 the use of differential GPS is recommended (Chandler, 1999). Geodetic receivers can achieve a precision of $\pm 10\text{mm} + 1\text{ppm}$ in plan over distances up to 15km; precision in height is 2-3 times more. A source of less-accurate coordinate data are large scale topographic maps, containing planimetric positions, spot heights and bench marks. A minimum of two planimetric and three height points is needed to define a datum, but more control points are desirable as redundancy provides appropriate checks. The control points should be evenly distributed over the images to gain a strong geometry. Ideal positions are points tying frames together and surrounding the volume of interest (Wolf & Dewitt, 2000).

During photogrammetric processing the relationship between photo and ground coordinates is established and the interior and exterior orientation of the camera determined. The processing involves a self-calibrating bundle adjustment, which implements rigorously the collinearity equations in a least-squares estimation procedure (Chandler & Brunsten, 1995). In order to transform the image coordinates to photo coordinates, it is necessary to measure the image positions of the fiducial marks (if present) and the control points.

Finally, it is possible to extract coordinates of points anywhere on the images, by using the estimated interior and exterior parameters. A variety of products may be derived automatically including DEMs, orthophotographs and parameters indicating the accuracy of these products. The following products can be used to visualize the landslide movements:

- DEMs-of-difference (elevation differences between epochs);
- cross-section profiles;
- displacement vectors;
- animations.

2.3 Quality assessment

The quality of the photogrammetric solution is controlled by measurement errors associated with elements used in the functional model to relate image to object. Data quality can be described by three terms with respect to three types of error

(Cooper & Cross, 1988): precision (relating to random errors), reliability (gross errors) and accuracy (systematic errors). When using scanned archival photography, the main factors affecting precision include (Chandler, 1989; Scarpace & Saleh, 2000):

- geometry provided by the photographs;
 - camera characteristics;
 - image quality (quality of original film, geometry and fidelity of scanner, scanning resolution);
 - blurring due to image motion or use of focal plane shutter.
- The applied self-calibrating bundle adjustment procedure is capable of propagating stochastic properties through the model. This provides a measure of precision of the output parameters. Data reliability can only be improved by increasing the redundancy of measurements (Hottier, 1976). Reliability can be evaluated by inspecting the residuals of the photo- and control coordinates. Systematic errors result from erroneous, non-rigorous or an incomplete functional model, bad distribution of control points, image texture, terrain characteristics, film deformation, focal plane shutter and atmospheric effects (Chandler, 1989). Various systematic errors can be modelled (e.g. lens distortion), but the process is complicated as there is often high correlation between many of the estimated parameters (Granshaw, 1980). Accuracy can only be determined by using independent checkpoints to compare photogrammetrically coordinates with accepted survey-derived values (Chandler, 1999).

3. CASE STUDY MAM TOR

3.1 Study area

Mam Tor is a 517m high hill, located two kilometres west of Castleton (Derbyshire, UK; Ordnance Survey coordinates SK135835), forming the head of Hope Valley. The eastern flank is dominated by a steep scar with a large landslide beneath. The former main road between Sheffield and Manchester (A625), constructed across the slide, was abandoned in 1979 as a consequence of continuous damages due to the moving ground mass. The slope consists of predominantly sandstone sequences (Mam Tor Beds) overlying predominantly shale units (Edale Shales). The layers dip slightly inwards of the slope. South of the headscar, a fault cuts through the shales, which might have affected the slope stability (Skempton et al., 1989). Length of the slide from scarp to toe is about 1000m, while elevation drops from 510 to 230 m. Mean slope of the slipped mass is 12°. Maximum thickness of the mass is 30-40m (Skempton et al., 1989). The affected area is approximate 32ha.

The initial rotational failure has been dated back to 3600BP (Skempton et al., 1989). While advancing downslope the mass

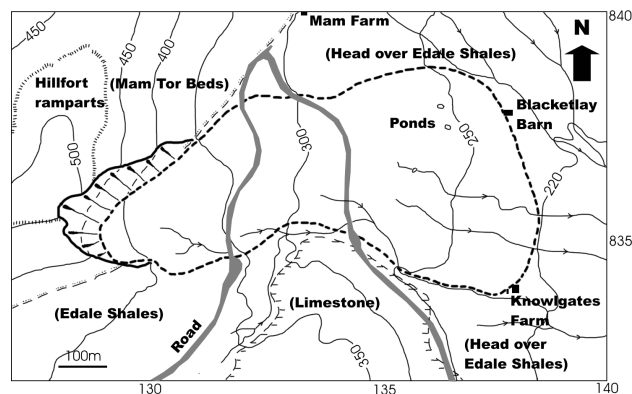


Figure 1. Map of the Mam Tor area; landslide is indicated by dotted line (after Skempton et al., 1989).

broke into a complex of blocks and slices. Disintegration of the front slices created a debris mass, sliding further down. The unstable transition zone, overlying the steepest part of the basal shear, is the most active part, moving on average 0.35m/a over the last century (Rutter et al., 2003). There is evidence that the movements are not continuous but accelerate during wet winters, when rain-fall exceeds certain limits, i.e. more than 250mm rain in a single month, while over 750mm in the preceding six months (Waltham & Dixon, 2000).

There are several information sources available about displacements that have taken place over the last century. Notes about regular disturbance and repairs of the road, from 1907 until the final closure in 1979, are kept by Derbyshire County Council. In 1977-78 an extensive survey and stability analysis was carried out (Skempton et al., 1989). Since closure of the road, a few (temporary) monitoring schemes were set up by various universities: 1981-83 by Sheffield University, 1990-98 by students from Nottingham Trent University (Waltham & Dixon, 2000) and since 1996 by Manchester University (Rutter et al., 2003).

3.2 Acquired photographs

A search for aerial photography of Mam Tor revealed that there are numerous images available, both oblique and vertical, from 1948 until present. Unfortunately, the oblique images usually tend to be focussed on the archaeologically interesting site on top of the hill (iron age ramparts) and do not cover the whole landslide area. Vertical imagery from four different epochs were acquired and processed. The images are of varying quality and scales (Table 2), providing a good indication about the potentials of ADAPT, when applying to a range of commonly available material.

Date	Source	Scale	Scan resolution	Ground resolution	Media
1953	NMR	1/12,000	42 μ	0.50m	Scanned contact prints
1971	NMR	1/7,400	42 μ	0.31m	Scanned contact prints
1973	CUCAP	1/4,000	15 μ	0.06m	Scanned diapositives
1990	CUCAP	1/12,000	15 μ	0.18m	Scanned diapositives

Table 2. Details of acquired and processed aerial photographs (NMR = National Monuments Record; CUCAP = Cambridge University Collection of Air Photos).

3.3 Ground control

During a field survey, ground control points were measured in the Mam Tor area using two geodetic quality Differential GPS single frequency receivers. One receiver served as base station, while the other was used to collect GPS data at the selected ground control points. From a nearby active GPS station (part of the National GPS Network, established by Ordnance Survey), additional GPS data was obtained and used for the post-processing. Post-processing revealed the positions of the measured points in ETRS89 (European Terrestrial Reference System 1989) coordinates, with a precision of approximately 1cm. The processing was performed by using SKI-Pro software (Leica/Geosystems). Finally, the coordinates were transformed to national grid coordinates (OSGB36 datum) using the online coordinate transformation provided by Ordnance Survey (www.gps.gov.uk).

1953 images			
<i>Focal length (mm)</i>	547		
<i>Base length (m)</i>	750		
<i>Flying height (m)</i>	6140		
<i>B/H ratio</i>	1/8.2		
	(X)	(Y)	(Z)
<i>Residuals ground control (m)</i>	0.57	0.41	0.09
<i>Residuals photo control (μ)</i>	51.99	33.26	
<i>Precision of object points (m)</i>	0.48	0.99	4.26
1971 images			
<i>Focal length (mm)</i>	304		
<i>Base length (m)</i>	580		
<i>Flying height (m)</i>	2240		
<i>B/H ratio</i>	1/3.9		
	(X)	(Y)	(Z)
<i>Residuals ground control (m)</i>	0.45	0.54	0.19
<i>Residuals photo control (μ)</i>	30.22	35.46	
<i>Precision of object points (m)</i>	0.21	0.25	0.91
1973 images			
<i>Focal length (mm)</i>	153		
<i>Base length (m)</i>	280		
<i>Flying height (m)</i>	950		
<i>B/H ratio</i>	1/3.4		
	(X)	(Y)	(Z)
<i>Residuals ground control (m)</i>	0.085	0.12	0.17
<i>Residuals photo control (μ)</i>	19.66	18.59	
<i>Precision of object points (m)</i>	0.075	0.088	0.20
1990 images			
<i>Focal length (mm)</i>	153		
<i>Base length (m)</i>	1010		
<i>Flying height (m)</i>	2120		
<i>B/H ratio</i>	1/2.1		
	(X)	(Y)	(Z)
<i>Residuals ground control (m)</i>	0.025	0.021	0.013
<i>Residuals photo control (μ)</i>	15.44	16.03	
<i>Precision of object points (m)</i>	0.18	0.14	0.40

Table 3. Summary of the self-calibration performances.

3.4 Image processing

The images were processed using the IMAGINE OrthoBASE Pro 8.6 software package (ERDAS LLC, 1991-2002). An independent module performing the self-calibrating bundle adjustment was used for estimation of the interior parameters. This software (GAP, General Adjustment Program) was written and developed by Chandler & Clark (1992).

3.5 Results and accuracy

The self-calibration adjustment was performed successfully for all sets of photographs, with acceptable residuals of the control points. The self-calibration also provided an estimated object precision, based on the stochastic properties of the control points. The low height accuracy from the 1953 photographs can be attributed to the low base-height ratio, and hence weak geometry. A summary of the self-calibration performances is given in Table 3.

From the scanned imagery high resolution DEMs were extracted. In addition to the estimated object precision from the self-calibration, the DEM quality can be specified by a global Root Mean Square Error (RMSE), indicating the difference between the height values of the control points and their corresponding DEM values (see Table 4).

In addition to a poor base-height ratio, there are two other possible causes of errors. Firstly, discontinuities in the terrain are downgraded by interpolation (Petrie, 1990). Another error

<i>Epoch</i>	<i>Resolution</i>	<i>RMSE</i>
1953	4.0m	3.90m
1971	2.0m	1.31m
1973	0.76m	1.04m
1990	2.0m	0.54m

Table 4. Summary of DEM extractions.

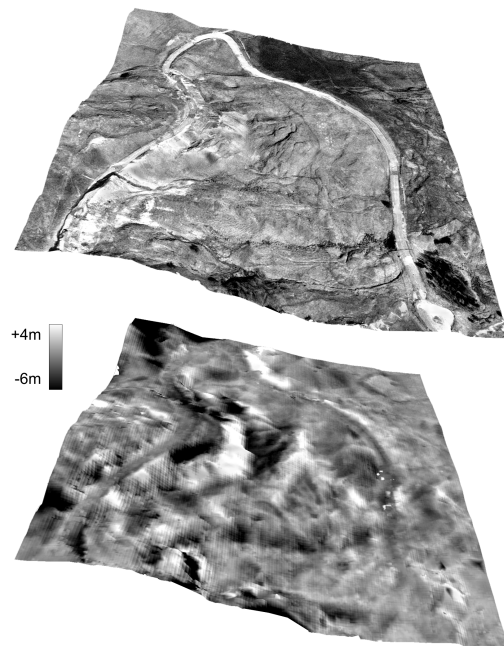


Figure 5. 3-D views of the centre part of the landslide: an orthophotograph (1990) and a DEM-of-difference (1990-1973) draped over a DEM.

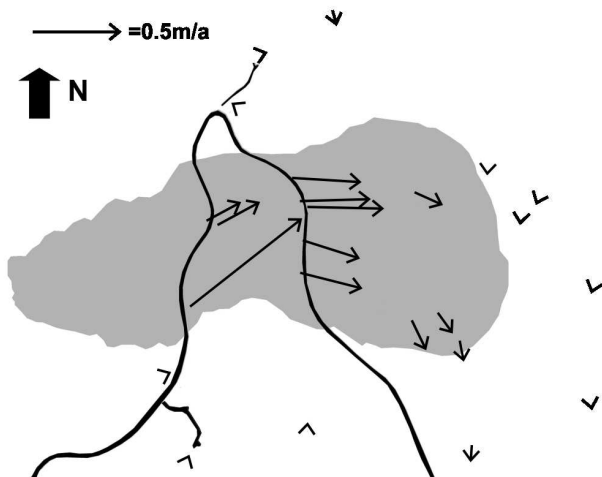


Figure 6. Movement vectors, showing direction and magnitude of the displacements between 1953 and 1990(m/a).

source is caused by areas of low reflective contrast, where digital image matching techniques have difficulty to automatically identify mass points for DEM extraction. This may lead to uneven spikes and dips in the model. A more objective way of accuracy assessment would be to identify a stable area and compare the photogrammetric derived product with an independent data set, for example a representative DEM based on GPS points.

Changes in morphology can be presented by DEMs-of-difference (change in height), cross-section profiles and movement vectors from the orthophotographs (change in plane). Figure 5 shows three-dimensional views created by draping respectively an orthophotograph and a DEM-of-difference over a DEM, which certainly demonstrates the potential of the approach for visualization.

The horizontal precision is much better, and planar displacements can be detected from the orthophotographs (Figure 6). Simple statistical tests revealed the significance of the horizontal movement vectors. The 14 objects surrounding the landslide were assumed to be stable positions during all epochs; the apparent displacements are due to random errors in the orthophotographs and consistent with the horizontal precision estimated by the self-calibration adjustment. Two-sample difference of mean tests proved that the displacements in x-direction, and total vector length of the 15 selected points on the landslide are significant greater than these errors, at a 95% confidence level. Movements in the y-direction are not proven

to be significant. Note that the measured movements over the period 1971-1973 are not statistical significant, due to the relative large contribution of noise to the small total displacement over this short time-interval. The statistical properties of all samples are summarized in Table 7.

3.6 Comparison with traditional methods

The mean displacement of the landslide over the period from 1953 to 1990 is $\pm 0.32\text{m/a}$ (Table 7), varying from $\pm 0.11\text{m/a}$ at the toe up to $\pm 0.81\text{m/a}$ in the central, most active part. It is particularly satisfying that this value is of comparable size to movement rates found by Ruther et al. (2003), $0.04\text{-}0.35\text{m/a}$ over the last century and up to 0.50m/a in recent years.

4. CONCLUSION AND FURTHER RESEARCH

These initial results demonstrate the value of historical aerial photographs for quantifying past landslide movements. Due to the poor base-height ratio of some of the photographs, the extracted height data were not precise enough to detect significant vertical displacements. Nevertheless, the accuracy in plane was sufficient to analyse horizontal movements of the landslide, even in the cases of a rather low image resolution. What is encouraging is that the extracted displacements were consistent with movement rates observed by other researchers, obtained by direct ground measurement.

Incorporation of more epochs would improve the temporal resolution; extension of the time series with more recent images would be particularly useful, as this would provide a overlap with recent traditional surveys. More detailed analysis of the displacements in both vertical and planar directions is expected to gain more insight in the mechanics of the landslide.

In further research a relationship between the extracted mass movements and climate variables will be determined. The main challenge is expected to be the temporal scarcity of photo information. The time between photo epochs will be in the order of 10 years, while major slide movements take place every 4-5 years on average (Waltham & Dixon, 2000). The ultimate aim will be the ability to obtain a climate-landslide model that is able to predict the response to future climate change. The described method should be applicable to any active landslide worldwide, provided that historical aerial photography is available.

	1953-1971	1971-1973	1973-1990	1953-1990
Stable objects				
sample size	14	13	11	12
x (mean \pm std, in m/a)	0.03 ± 0.02	-0.13 ± 0.06	-0.02 ± 0.02	0.00 ± 0.01
y (mean \pm std, in m/a)	-0.03 ± 0.09	0.15 ± 0.33	-0.02 ± 0.03	-0.02 ± 0.04
total (mean \pm std, in m/a)	0.09 ± 0.04	0.37 ± 0.17	0.03 ± 0.03	0.04 ± 0.02
On landslide				
sample size	15	15	12	12
x (mean \pm std, in m/a)	0.24 ± 0.17	0.22 ± 0.41	0.29 ± 0.21	0.27 ± 0.18
y (mean \pm std, in m/a)	-0.02 ± 0.23	-0.13 ± 0.72	0.04 ± 0.17	0.01 ± 0.18
total (mean \pm std, in m/a)	0.33 ± 0.17	0.71 ± 0.47	0.33 ± 0.22	0.32 ± 0.19

Table 7. Statistical properties of the displacement vectors (averaged movements in m/a).

REFERENCES

- Adams, J.C. & Chandler, J.H., 2002. Evaluation of lidar and medium scale photogrammetry for detecting soft-cliff coastal change. *Photogrammetric Record*, 17(99), pp. 405-418.
- Brunsdon, D., 1993. Mass movement; the research frontier and beyond: a geomorphological approach. *Geomorphology*, 7 (1-3), pp. 85-128.
- Brunsdon, D. & Chandler, J.H., 1996. Development of an episodic landform change model based upon the Black Ven mudslide, 1946-1995. In M.G. Anderson and S.M. Brooks (eds), *Advances in hillslope processes, Vol. 2*. John Wiley & Sons Ltd, Chichester, pp. 869-896.
- Brunsdon, D. & Thorne, J.B., 1979. Landscape sensitivity and change. *Transactions of The Institute of British Geographers*, 4(4), pp. 463-484.
- Buckley, S. & Mills, J., 2000. GPS and the wheel – how integrating the world's greatest inventions is helping to monitor coastal erosion. *Surveying World*, 9(1), pp. 41.
- Chandler, J.H., 1989. *The acquisition of spatial data from archival photographs and their application to geomorphology*. PhD Thesis. The City University, London.
- Chandler, J.H., 1999. Effective application of automated digital photogrammetry for geomorphological research. *Earth Surface Processes and Landforms*, 24(1), pp. 51-63.
- Chandler, J.H., 2001. Terrain measurement using automated digital photogrammetry. In J.S. Griffiths (ed) *Land Surface Evaluation for Engineering Practice*. Geological Society, London, pp. 13-18.
- Chandler, J.H. & Brunsdon, D., 1995. Steady state behaviour of the Black Ven mudslide: the application of archival analytical photogrammetry to studies of landform change. *Earth Surface Processes and Landforms*, 20(3): pp. 255-275.
- Chandler, J.H. & Clark, J.S., 1992. The archival photogrammetric technique: further application and development. *Photogrammetric Record*, 14(80), pp. 241-247.
- Chandler, J.H. & Cooper, M.A.R., 1989. The extraction of positional data from historical photographs and their application to geomorphology. *Photogrammetric Record*, 13(73), pp. 69-78.
- Cooper, M.A.R. & Cross, P.A., 1988. Statistical concepts and their application in photogrammetry and surveying. *Photogrammetric Record*, 12(71), pp. 637-663.
- Dikau, R. & Schrott, L., 1999. The temporal stability and activity of landslides in Europe with respect to climatic change (TESLEC): main objectives and results. *Geomorphology*, 30(1-2), pp. 1-12.
- Finsterwalder, S. 1897. Der Vernagtferner. *Wissenschaftliche Ergänzungshefte zur Zeitschrift des Deutschen und Österreichischen Alpenvereins*, 1(1), pp. 1-96.
- Granshaw, S.I. 1980. Bundle adjustment methods in engineering photogrammetry. *Photogrammetric Record*, 10(56), pp. 181-207.
- Hottier, Ph., 1976. Accuracy of close range analytical solutions. *Photogrammetric Engineering & Remote Sensing*, 42(3), 345-375.
- Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassell, D., Boorman, P., McDonald, R. & Hill, S., 2002. *Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report*. Tyndall Centre for Climate Change Research, Norwich.
- ICCP, 2001. *Climate change 2001: the scientific basis*. Cambridge University Press, Cambridge.
- Kane, W.F. & Beck, T.J., 2000. Instrumentation Practice for Slope Monitoring. In: *Engineering Geology Practice in Northern California*. Association of Engineering Geologists Sacramento and San Francisco Sections.
- Kenefick, J.F., Gyer, M.S. & Harp, B.F., 1972. Analytical self-calibration. *Photogrammetric Engineering*, 38, pp. 1117-1126.
- Petrie, G., 1990. Photogrammetric methods of data acquisition for terrain modelling. In: G. Petrie and T.J.M. Kenne (eds) *Terrain Modelling in Surveying and Civil Engineering*. Whittles, Caithness.
- Rutter, E.H., Arkwright, J.C., Holloway, R.F. & Waghorn, D., 2003. Strains and displacements in the Mam Tor landslip, Derbyshire, England. *Journal of the Geological Society*, 160(5), pp. 735-744.
- Scarpace, F.L. & Saleh, R.A., 2000. Effects of scanning resolution on surface accuracy. In: *Proceedings of ASPRS 2000*, Washington.
- Slama, C.C., 1980. *The manual of photogrammetry (4th edition)*. American Society for Photogrammetry, Falls Church.
- Schumm, S.A., 1979. Geomorphic thresholds: the concept and its applications. *Transactions of the Institute of British Geographers*, 4(4), pp. 485-515.
- Skempton, A.W., Leadbeater, A.D. & Chandler, R.J., 1989. The Mam Tor landslide, North Derbyshire. *Philosophical Transactions of the Royal Society of London A*, 329, pp. 503-747.
- Walker, S., 1996. Digital photogrammetric workstations 1992-1996. *International Archives of Photogrammetry and Remote Sensing*, 31(2), pp. 384-395.
- Waltham, A.C. & Dixon, N., 2000. Movement of the Mam Tor landslide, Derbyshire, UK. *Quarterly Journal of Engineering Geology and Hydrogeology*, 33(2), pp. 105-123.
- Wolf, P.R. & Dewitt, B.A., 2000. *Elements of Photogrammetry. With Applications in GIS*. McGraw-Hill, Boston.