Aerial photography and digital photogrammetry for landslide monitoring

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Abstract: A review is given of the techniques that are available to extract relevant information from multi-temporal aerial photographs for use in the monitoring stage of landslide assessments. It is shown that aerial photograph interpretation reveals qualitative information on surface characteristics, which is helpful in detecting landslide features and inferring the mechanisms involved. Photogrammetrically derived products can be used to quantify these processes, providing distinctive advantages. Comparison of digital elevation models (DEMs) from different times provides detailed information on changes in surface topography, whereas orthophotos can be used to measure horizontal displacements. The various factors influencing the quality of the products are also identified. Examples from a case study on the Mam Tor landslide are used to illustrate the benefits of the different approaches.

Aerial photographs are a generally accepted tool used in landslide studies. They not only provide a metric model from which quantitative measurements can be obtained, but also give a qualitative description of the Earth surface. These two capabilities are irrefutably related to each other, as 'one must know what one is measuring' (Lo 1976).

The application of aerial photographs to landslide investigation provides a number of distinct advantages. Reconnaissance of the study area can greatly benefit from the 3D representation that is provided by stereoscopic viewing, thereby showing relationships between the various landscape elements more obviously than from a ground perspective. Furthermore, photographically based derivatives provide a suitable base on which boundaries can be delineated accurately. In addition, photographs support the efficient planning of field investigations and sampling schemes, without the need for visiting the site physically, which is especially useful in remote and inaccessible areas (Crozier 1984, Van Zuidam 1985). A final and important advantage is the quantitative topographic information contained, which can be unlocked by appropriate photogrammetric techniques. However, quantitative use of aerial photographs create some difficulties, such as the requirement of experienced analysts and appropriate equipment, combined with sufficient knowledge of the site under investigation (Lo 1976).

Aerial photographs can be used in various stages of landslide investigations (Mantovani *et al.* 1996), and have been extensively used in the detection and classification of landslides. When properly interpreted they allow the identification of diagnostic surface features, such as morphology, vegetation cover, soil moisture and drainage pattern. Furthermore, recent photographs can be compared with historical imagery to assess landslide conditions over different periods of time and allow the progressive development to be examined. Characteristics of mass movements that can be monitored by sequential photographs are, for example, the areal extent of the landslide body, regression rate of the head scar, displacement velocity, surface topography, succession of vegetation and soil moisture conditions. Accurate quantification of change requires the application of rigorous photogrammetric techniques (Chandler 1989). Finally, aerial photography can be helpful in hazard mapping. The purpose of landslide hazard mapping is to analyse the susceptibility of the terrain to slope movements. Aerial photographs can be used to delimit terrain units and map the controlling factors affecting slope stability.

The aim of this paper is to give an overview of the ways in which aerial photographs and digital photogrammetric techniques can be used in the monitoring stage of landslide assessments. Particular attention will be paid to the quality of data derived from aerial photographs of differing type, when using the different techniques available. The various approaches can be roughly divided into three categories: those based on simple aerial photograph interpretations (APIs), those involving the extraction of digital elevation models (DEMs), and those based on the creation of orthophotos. The underlying techniques will be described and illustrated with some results that were obtained from a case study focusing on the Mam Tor landslide (Derbyshire, UK).

From: TEEUW, R. M. (ed.) *Mapping Hazardous Terrain using Remote Sensing*. Geological Society, London, Special Publications, **283**, 53–63.
DOI: 10.1144/SP283.5 0305-8719/07/$15.00

The study area: Mam Tor

The landslide of Mam Tor is situated on the eastern flank of this 517 m high hill, at the head of the Hope Valley, Derbyshire, UK [SK135835]. The former main road between Sheffield and Manchester (A625) was constructed across the slide, but abandoned in 1979 as a consequence of continuous damage caused by the moving ground mass (Fig. 1). The slope consists of predominantly sandstone sequences (Mam Tor Beds) overlying predominantly shale units (Edale Shales). The layers dip slightly inwards of the slope. From scarp to toe, the landslide measures *c.* 1000 m, and elevation varies from 510 to 230 m. The mean slope of the slipped mass is 12° and the maximum thickness 30–40 m (Skempton *et al.* 1989).

The initial rotational failure has been dated back to 3600 BP (Skempton *et al.* 1989). While advancing downslope the mass broke into a complex of blocks and slices. Disintegration of the front slices created a debris mass, which slid further down. The unstable transition zone, overlying the steepest part of the basal shear, is the most active part, moving on average 0.35 m a^{-1} over the last century (Rutter *et al.* 2003). There is evidence that the movements are not continuous but accelerate during wet winters, when rainfall exceeds certain limits; that is, more than 250 mm rain in a single month and over 750 mm in the preceding 6 months (Waltham & Dixon 2000).

There are several information sources available that quantify 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 and stability analysis was carried out (Skempton *et al.* 1989). Since closure of the road, temporary monitoring schemes were set up by Sheffield University (1981–1983; Al-Dabbagh & Cripps 1987), Nottingham Trent University (1990–1998; Waltham & Dixon 2000) and Manchester University (since 1996; Rutter *et al.* 2003).

Fig. 1. Damaged road section at Mam Tor.

Aerial photographs

A conventional photo search for aerial photography of Mam Tor revealed that there are numerous image epochs available, both oblique and vertical, from 1948 until the present. Vertical imagery from eight epochs was acquired and processed (Table 1). The images are of varying quality and scales, and can be used in an assessment of the potential of the various techniques applied to a range of commonly available material.

Photogrammetric data processing was achieved using the IMAGINE OrthoBASE Pro 8.6 software package (ERDAS LLC 1991–2002). During photogrammetric processing the relationship between photo co-ordinates and the Ordnance Survey national grid co-ordinate system was

Table 1. *Characteristics of the acquired image epochs of Mam Tor*

Date	Source	Scale	Scan resolution (μm)	Ground resolution (m)	Media
1953	NMR*	1/10 700	42	0.45	Scanned contact prints
1971	NMR	1/6 400	42	0.27	Scanned contact prints
1973	CUCAP†	1/4 300	15	0.065	Scanned diapositives
1973	CUCAP	Oblique	15	–	Scanned diapositives
1984	ADAS‡	1/27 200	15	0.41	Scanned diapositives
1990	CUCAP	1/12 000	15	0.18	Scanned diapositives
1995	CUCAP	1/16 400	15	0.25	Scanned colour negatives
1999	Infoterra	1/12 200	21	0.26	Scanned colour negatives

*National Monuments Record.
†Cambridge University Collection of Air Photos.
‡Agricultural Development and Advisory Service.

established. An independent module performing a self-calibrating bundle adjustment was used for estimating the camera's interior parameters (camera constants), if the original calibration certificate was unavailable (as described by Chandler & Clark 1992). Ground control was collected by means of a differential global positioning system (GPS) survey.

Aerial photograph interpretation (API)

Photo-interpretation involves the systematic examination of photographic images for the purpose of identifying objects and judging their significance (Colwell 1960). Although aerial photographs can be interpreted with a specific theme in mind, interpretation relies on using the same basic characteristics of the surface: tone, texture, pattern, shape, context and scale, which were created by reflection of natural electromagnetic light energy from the objects that make up the scene and their arrangement. The use of these qualitative attributes is very much a matter of experience and personal bias (Drury 1987).

The quality of an API is affected by several factors, which can be separated into four main categories: photographic parameters, natural factors, equipment and analysis techniques, and the qualification of the interpreter (Rib & Liang 1978).

Photographic parameters

The effects of the different photographic parameters on landslip detection have been described by Norman *et al.* (1975) and Soeters & Van Westen 1996). Natural colour and panchromatic (black-and-white) films are the most widely available film types. Colour film is especially valuable for outlining differences in soil conditions, drainage and vegetation. Colour IR films are most suitable for detecting landslides, mainly because of the capability of identifying the presence of water and thus showing the vigour of vegetation cover. Panchromatic films, on the other hand, provide a better image resolution (Lo 1976) and are generally less expensive. Most historical imagery is of this form, although resolution tends to degrade with photo age, as a result of developments in photographic emulsion that have subsequently occurred.

Aerial photographs for mapping purposes are typically vertical, with 60% overlap between successive frames to provide stereoscopic coverage. Stereoscopic viewing is important, as landslide features are most frequently recognized by their morphology. Vertical exaggeration, when viewing stereoscopically, can be enhanced if a super wide angle lens is used during photo acquisition. The lower flying height increases the base/distance ratio. However, this may create problems of 'dead ground' on far side of hills and in narrow valleys. Oblique photographs sometimes can provide a more unobstructed view of steep slopes and cliffs (Rib & Liang 1978), and give a more familiar perspective for the less experienced interpreter (Chandler 1989).

The most suitable scale is inevitably a compromise. Large-scale photographs provide a high level of detail, but may require many frames to cover the study area. Small-scale photography provides less detail, but allows a better interpretation of the overall context. Quoted optimum scales for site studies are in the range between 1/5000 and 1/15 000 (Norman *et al.* 1975; Mantovani *et al.* 1996; Soeters & Van Westen 1996).

The time of the day when photographs are taken determines the length of shadows. In general, photographs taken when the sun is high and shadows on the hillsides and slopes are minimal are best for interpretation. However, in areas of low topography, the relief will be enhanced by long shadows. The time of the year influences the effects of soil moisture and vegetation (Norman *et al.* 1975; Soeters & Van Westen 1996). The quality of photographs depends on the various processes the images go through. Norman *et al.* (1975) used the following criteria for assessing photo quality: sharpness, over- or under-exposure, cloud cover, shadow and print quality.

In spite of recent developments in the field of airborne digital sensors (Eckhardt *et al.* 2000), the most common way of obtaining digital imagery is by scanning the original film. Photogrammetric scanners have a high geometric resolution, but radiometric performance may be rather poor (Baltsavias 1999). Modern software packages allow digital images to be easily adjusted to the needs of the user, for example, zooming in on particular areas or enhancing the contrast.

Natural factors

Photo-interpretation is also influenced by natural factors. Steep slopes, forest canopy and shadows may hide certain surface features. Optimal conditions for detecting anomalies in vegetation may be expected in either the very early or very late stages of the growing season. Differences in drainage conditions are most pronounced shortly after the start of the wet season or shortly after the snowmelt period in spring (Soeters & Van Westen 1996). Weather conditions have an important influence on photo quality: clouds and snow cover may obscure the ground surface, haze decreases contrast, and solar angle influences shadowing (Rib & Liang 1978).

Qualification of interpreter

The quality of API is also influenced by the capability of the human interpreter, particularly experience in photo-interpretation, and knowledge of the phenomena and processes being studied. Various researchers have shown the large subjective element in photo-interpretation by comparing maps of the same landslide area created by different interpreters (Van Westen 1993; Carrara *et al.* 1995). Identification of the exact positions of morphological features can be difficult, especially delineation of the boundaries. Moreover, different classes may be assigned to a specific feature as a result of different interpretation (Chandler 1989). Obviously, different mapping legends will lead to very different maps (Van Westen *et al.* 1999).

Diagnostic features

The interpretation of landslides from aerial photographs is mainly based on features indirectly related to slope movements, such as characteristic morphology, anomalous vegetation and drainage conditions, or disturbed infrastructure. Soeters & Van Westen (1996) have provided an extensive overview of terrain features associated with landslides and their characterization on aerial photographs. Based on these diagnostic features, statements can be made on the type of movement, degree of activity and depth of movement (Mantovani *et al.* 1996).

Geomorphological mapping

A useful tool in presenting photo-interpreted information is a geomorphological map. Geomorphological maps are transmitters of information about the form, origin, age and distribution of landforms together with their formative processes, rock type and surface materials (Brunsden *et al.* 1975). They are not only a way of presenting data, but also the result of a method of research, revealing associations of landforms, which is essential for understanding of both individual landforms and landscapes (De Graaff *et al.* 1987). Parise (2003) pointed out the importance of large-scale geomorphological mapping, and especially its repetition in time, in the study of active mass movements. A combination of detailed multi-temporal mapping of surface features, indirect indicators of deformation and displacements may result in better understanding of the landslide and its zonation in different elements, characterized by different styles of deformation.

Geomorphological maps can emphasize different aspects of landforms: form, origin, age and relations. Dependent on the purpose of the map, these aspects can be depicted by coloured area symbols, patterns and line symbols (Van Zuidam 1985). A great variety in geomorphological mapping systems have been designed in the course of time. Savigear 1965) developed a purely morphological legend, aiming to describe the form of slopes, without reference to the origin. The ITC system (Van Zuidam 1985), designed for multipurpose use at all scales, distinguishes the highest level on the basis of morphogenesis. The importance of geomorphological mapping has also been recognized by engineering geologists, judging from the proposed legend for engineering geological maps by the Geological Society Engineering Group Working Party, which contains a large number of symbols for geomorphological features (Anonymous 1972).

API is a valuable tool in geomorphological mapping, although field work remains necessary for checking the photo-interpretation and mapping of small features (Hayden 1986). Accurate definition and coding of geomorphological boundaries by rigorous photogrammetric techniques combines the benefits of geomorphological interpretation with positional relevance (Chandler & Brunsden 1995). Photogrammetric measurements allow quantitative comparison between photo-interpreted maps from different periods (Chandler & Cooper 1989). Multi-temporal geomorphological maps from sequential aerial photographs have been used to document the evolution of the Black Ven landslide, UK (Chandler & Brunsden 1995), and the Tessina landslide, Italy (Van Westen & Getahun 2003). Kalaugher *et al.* (1987) used oblique aerial photographs to identify geomorphological processes on sea cliffs in East Devon, UK.

Figure 2 displays a simple geomorphological map of the Mam Tor landslide, created by photo-interpretation of the 1990 images. The mapped features were placed in the exact spatial context by using photogrammetry. Contour lines were obtained from a DEM, extracted from the same photographs.

Digital elevation models (DEMs)

Digital photogrammetric techniques have the capability of automatically deriving very high-resolution DEMs from stereo photographs, providing a detailed representation of the surface topography (Chandler 1999). Photogrammetry is based on the concept of collinearity, whereby a point on the object, centre of lens and resultant image point lie on a single line in 3D space. Based on this principle, 3D co-ordinates representing the object can be extracted from a stereopair of

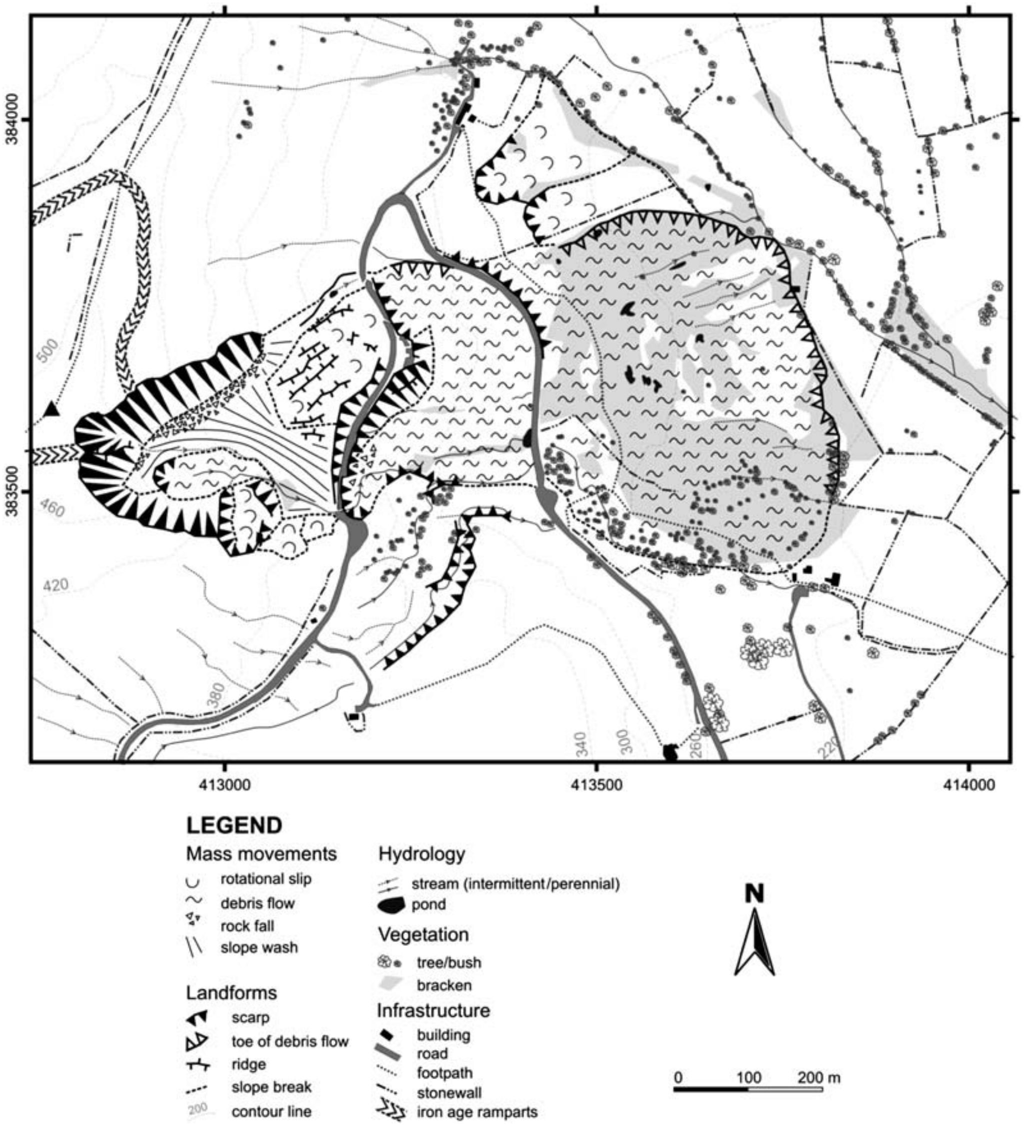

Fig. 2. A geomorphological map, created through photo-interpretation of the 1990 images.

photographs, provided that the inner geometry (interior orientation) and the position and orientation of the camera at the moment of exposure (exterior orientation) are known. The exterior orientation parameters of all frames in a block can be simultaneously estimated in a bundle block adjustment, with the help of ground control points of which both ground and image co-ordinates are known (Wolf & Dewitt 2000).

Once the relationship between the photographs and ground surface has been established, co-ordinates can be extracted from anywhere on the site, and used to create a DEM. A significant recent development is the automation of this process. Automatic generation of DEMs from a stereomodel comprises three tasks: image matching, surface fitting and quality control (Schenk 1996). The process of image matching involves the identification of conjugate points in the overlap portion of the images. A commonly applied matching strategy is area-based cross-correlation, in which small image patches are compared according to their grey-level distribution. Perfect matches will never occur in reality because of noise, small differences in illumination, and small geometric distortions. Because a regular gridded DEM is often required, surface fitting needs to be performed. This procedure comprises the interpolation of intermediate points, as the points obtained by image matching do not represent the entire surface.

The quality of a DEM is a function of the accuracy, reliability and precision of the photogrammetric measurements and the block bundle adjustment itself (Butler *et al.* 1998). As defined by Cooper & Cross 1988), precision is related to random errors, inherent in the measurement process. The bundle adjustment procedure is capable of propagating stochastic properties through the model, providing an estimation of precision. Reliability can be related to gross errors. Fortunately, gross errors are normally easy to detect and eradicate because of their size. Accuracy is related to the presence of undetected systematic errors, which are more difficult to isolate and generally provide a limiting constraint on the quality of the derived data. The mean and standard deviation of the discrepancies with independent check points provide a measure of DEM accuracy (Butler *et al.* 1998).

Controls on DEM quality

As pointed out by Fryer *et al.* (1994) and Lane *et al.* (2000), the ease with which terrain data may be generated using digital photogrammetric techniques has focused attention more on analysis and interpretation of the acquired results than on issues of data quality. In addition to the conventional controls on photogrammetry, the automated algorithms in digital processing have important influences on the quality of results.

The precision that can be achieved by photogrammetric measurements is mainly dependent on the quality of the source data (i.e. the aerial photographs). Photographic resolution is a function of the optical quality of an image, and influenced by the resolving power of the film and camera lens, image motion during exposure, atmospheric conditions and the conditions of film processing. The effects of scale and resolution can be combined in terms of ground resolution distance, which determines the level of detail that is visible on the photographs (Lillesand & Kiefer 1994). When using digital images, scan resolution and the quality of the scanner (geometric and radiometric) are important controls. To preserve an original film resolution of 30–60 lines per mm, a scanned pixel size of 6–12 μm would be needed. For many practical applications, such as DEM generation, good results can be achieved with 25–30 μm resolution (Baltsavias 1999). The height precision of photogrammetric measurements is also dependent on the geometry provided by stereo-photographs. A strong convergence (high base/distance ratio), and large relief displacement, gives rise to highly precise object coordinates (Wolf & Dewitt 2000). According to Fryer *et al.* (1994), the best vertical precision that can be expected using standard mapping configurations is about 1–3 parts per 10 000 of flying height.

Systematic errors are always inherent in the stereo-model, arising from a variety of sources including lens distortion, atmospheric effects, film deformation, scan distortions, and inaccurate or poorly distributed control points, or result from errors during the image matching procedure (Chandler 1989; Buckley 2003). If camera calibration parameters are not available, which is sometimes the case when using archival imagery, these can be estimated in a self-calibrating bundle-adjustment. However, accounting for all systematic effects is difficult, because many systematic errors cannot be modelled explicitly, and there is usually high correlation between the modelling parameters (Granshaw 1980).

Control points should be evenly distributed over the images to gain a strong geometry. Ideal locations tie frames together and surround the volume of interest. 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 (Wolf & Dewitt 2000). Automated image matching is affected by surface texture and geometric distortion caused by different viewing angle. These controls upon automated generation of elevation data are of special relevance to complex terrain surfaces (Lane *et al.* 2000). If there is insufficient texture, the software is unable to match two points successfully and an interpolated estimate may be created. Surface roughness has a positive effect on texture, and consequently on matching. However, this effect may be countered by the increasing differences in the viewing of areas, which thus reduce the level of correlation between the images. In addition, interpolation will be least effective in areas of great roughness. DEM collection parameters can be optimized, but these control individual matches rather than affecting the resulting surface accuracy (Lane *et al.* 2000). Surface quality is also affected by its point density. An increase in grid spacing will smooth the topography; the minimum grid spacing is, however, bound by the object space pixel dimension (Lane *et al.* 2000).

Gross errors are genuine mistakes or blunders that arise during photogrammetric measurement (Cooper & Cross 1988). They can be detected by increasing the redundancy of measurements

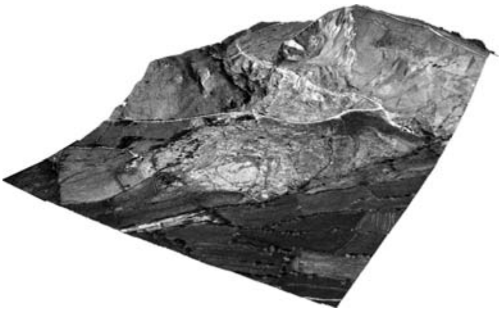

Fig. 3. A 3D view of Mam Tor, created by draping an orthophoto over a DEM, obtained from the 1990 images.

(Hottier 1976), which gives rise to datasets that are 'internally reliable' (Cooper & Cross 1988). Gross error sources that commonly affect the determination of exterior orientation include misidentified or mistyped control points. Fortunately, these errors give rise to large residuals at the block bundle adjustment stage and, if data redundancy is high, are normally readily identifiable. In the context of DEM generation a measure of internal reliability can be derived by comparing two DEMs of the same area but extracted from different stereopairs (Butler *et al.* 1998). DEMs can provide a perspective view of the area from any specified position. In combination with an orthophoto realistic views can be created, which are useful in analyses (Fig. 3).

Multi-temporal DEMs

DEMs not only provide a useful tool to enhance data analysis by perspective viewing, but also contain quantitative topographical data. Subtracting a DEM of one epoch from an earlier DEM creates a grid surface representing the change of form over the period. This surface of change, or 'DEM-of-difference', quantifies the effects of geomorphological processes. Areas experiencing removal of material will be indicated by depressions, whereas those receiving material are indicated by peaks. Caution should be taken, as areas exhibiting no change are not necessarily inactive regions; they can represent areas where input of material has equalled output during the time interval (Chandler & Brunsden 1995).

A photogrammetric method was developed in the late 1980s that was able to derive quantitative spatial information from historical aerial photographs (Chandler & Cooper 1989; Chandler & Clark 1992). This offered potential to unlock the photographic archive for obtaining quantitative terrain data, covering a time span of more than 50 years. Developments in digital photogrammetry allowed the acquisition of much denser DEMs (Brunsden & Chandler 1996). Following the efforts by Brunsden & Chandler in their studies on the Black Ven landslide (Chandler & Brunsden 1995; Brunsden & Chandler 1996), the use of multi-temporal DEMs has become more widely adopted in landslide research (e.g. Cheng 2000; Adams & Chandler 2002; Gentili *et al.* 2002; Van Westen & Getahun 2003; Ager *et al.* 2004; Bitelli *et al.* 2004).

Figure 4 shows a 'DEM-of-difference' of the central part of the Mam Tor landslide, created by subtracting DEMs of 1990 and 1973. The change in elevation is draped over a standard DEM for a better interpretation. Dark areas represent a lowering in elevation, whereas bright areas depict an increase in height.

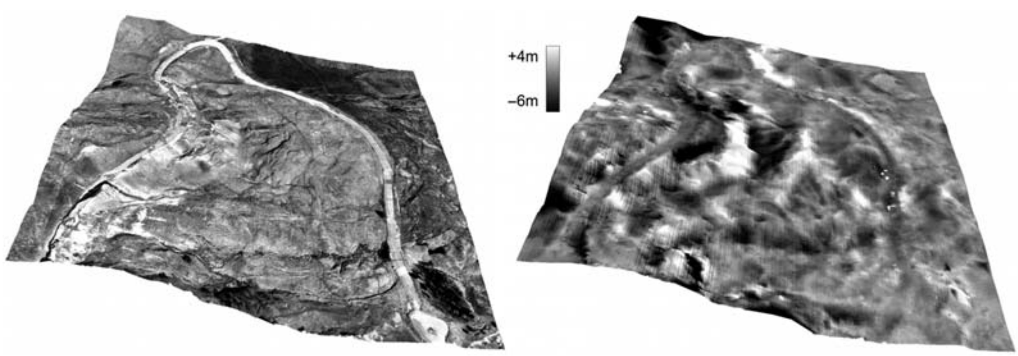

Fig. 4. On the right a 'DEM-of-difference' of the central part of the Mam Tor landslide, created by subtracting DEMs of 1990 and 1973; the elevation change is draped over a standard DEM for better interpretation. Left image is an orthophoto of the same area.

Orthophotos

Orthophotos combine the image characteristics of a photograph with the geometric qualities of a map. Unlike normal aerial photographs, relief displacement is removed so that all ground features are displayed in their true ground position. This allows the direct measurement of distances, areas, angles and positions. Orthophotos are created through differential rectification, which eliminates image displacements caused by photographic tilt and terrain relief. The rectification procedure requires a photograph with known orientation parameters and a DEM. The collinearity concept can be used to determine the corresponding photo co-ordinates of all DEM points (Wolf & Dewitt 2000). The geometric quality of orthophotos is dependent on its source data; that is, the original photographs, the functional model that relates photo to ground co-ordinates, and the quality of the DEM (Krupnik 2003). Hence, the quality controls are similar to those for DEMs. The minimum grid spacing is bounded by the resolution of the original photographs, as a higher resolution would imply over-sampling.

The combination of interpretative capabilities of the original photographs with the positional relevance of a map makes orthophotos particularly valuable for Earth scientists (Chandler 2001). Several researchers have shown the use of multi-temporal orthophotos to map horizontal surface displacements. Powers *et al.* (1996) measured movements of the Slumgullion landslide by determining the displacement of surface features, such as trees and rocks, between two orthophotos acquired at different times. Gentili *et al.* (2002) measured the displacements of building corners on the Corniglio landslide, Italy, from orthophotos.

Automatic extraction of displacement vectors

Digital techniques allow the potential of automatic measurement of objects on images. Kääb & Vollmer (2000) used an area-based cross-correlation algorithm to automatically map the velocity field of a rock glacier in the Swiss Alps from multi-temporal, orthorectified photographs. The high density and accuracy of the velocity data provided by the technique make it possible to extract meaningful strain-rate information. In related studies their approach was successfully applied to other types of superficial movements,

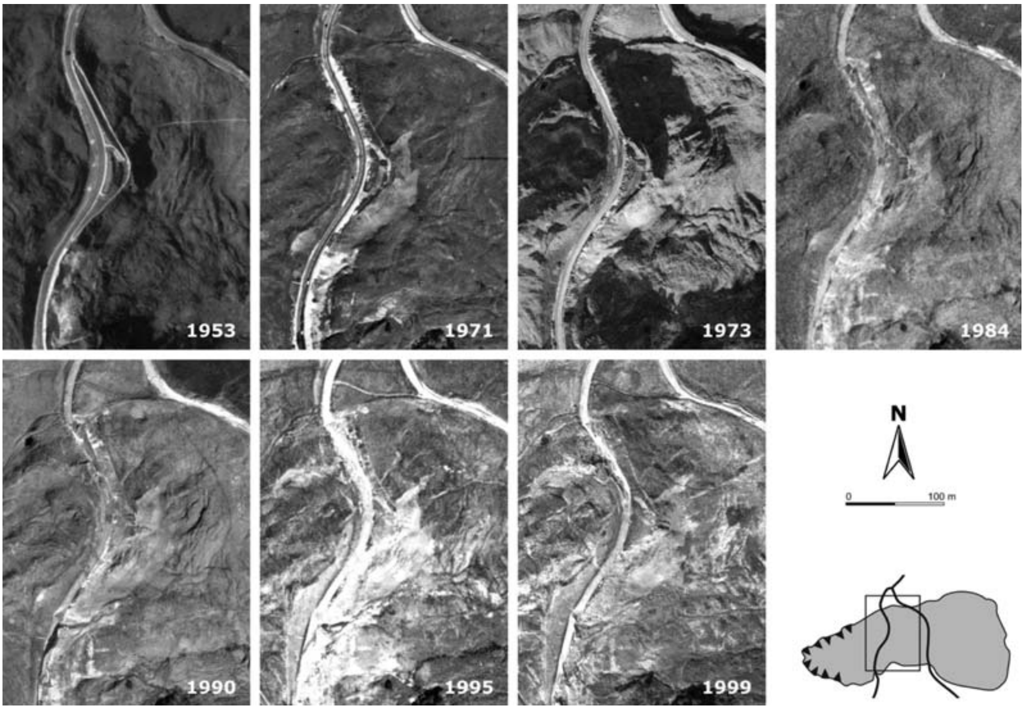

Fig. 5. A sequence of orthophotos obtained from different epochs, showing the progressively changing terrain surface in the central part of the Mam Tor landslide.

such as those of glaciers and rockslides (Kääb 2002).

Nevertheless, some researchers have indicated that the accuracy of displacement vectors is limited by the relatively poor DEMs used in the orthorectification process. Casson *et al.* (2003) developed an alternative approach, allowing the creation of better DEMs than by most commercial software packages. Their approach corrects for topographic distortion by estimating local slopes, to improve the image matching performance. Kaufmann & Ladstädter (2002, 2004) used the concept of pseudo-orthophotos, which, in combination with a rough DEM, still contain the same stereo-information as the original photos, thus allowing strict 3D reconstruction. Pseudo-orthophotos are better suited for matching than original photo scans, as perspective distortions have been removed to a great extent. An additional advantage of this approach is that the obtained vectors are 3D, rather than horizontal.

Orthophotos were created from all photographic epochs of Mam Tor (Fig. 5). Some clear features can be identified throughout the entire series, and can be manually measured to obtain displacement vectors. The mean displacement of the landslide over the period from 1953 to 1990 is 0.32 m a^{-1}, varying from 0.11 m a^{-1} at the toe to 0.81 m a^{-1} in the central, most active part. These values are of comparable size to movement rates found by Rutter *et al.* (2003), 0.04–0.35 m a^{-1} over the last century and up to 0.50 m a^{-1} in recent years. Automatic measurements can provide much denser displacement vector fields, allowing more detailed comparison with the alternative surveys. However, in the case of the Mam Tor images, differences in image quality, illumination conditions and vegetation cover hampered this procedure.

Further research

The applied techniques have the ability to provide both qualitative and quantitative information on landslide movements from aerial photographs. Continuing research aims at a thorough analysis of their extra value to landslide investigations in terms of photographs available, techniques available and the usefulness of the products (type and quality) in the analysis of landslide mechanisms. Further research will focus on how the different datasets can be integrated to allow a comprehensive analysis of the evolution of a landslide. Eventually, the techniques that have been developed at Mam Tor will be validated in a case study in South Wales, which should confirm their practical applicability.

Conclusion

This review has demonstrated the valuable information, qualitative as well as quantitative, that is captured by aerial photographs. It has also been shown that these data can be extracted relatively easily, using established techniques, and are well suited for use in the monitoring stage of landslide assessments. API reveals qualitative information on surface characteristics, which is very helpful in detecting landslide features and in formulating statements about the mechanisms involved. Photogrammetrically derived products can provide quantification of the inferred processes: DEMs provide detailed data on surface topography, whereas orthophotos can be used to measure surface displacements. Automated methods allow very dense and accurate data to be collected. In this way, the photographic archive can provide invaluable data on landslide evolution, thus leading to a better understanding of landslide mechanisms.

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